Public Transit Investment and Traffic Congestion Policy*

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January 6, 2017

Abstract

Public transit is often advocated as a means to address traffic congestion within urban transportation networks. This paper develops a theoretical model to analyze what role, if any, public transit investment should play in traffic congestion policy. In particular, we evaluate the extent to which traffic congestion should be accounted for when evaluating investment in public transit infrastructure when a Pigouvian congestion tax cannot be levied on auto travel. Our second-best model of public transit investment contributes to the literature by allowing for both demand and cost interdependencies across the auto and transit modes. The results indicate that the level of transit investment should be higher relative to that chosen when the congestion-reduction effects of transit are not accounted for, but the importance of this consideration is dependent upon the interaction of demand and cost interdependencies across the auto and transit modes, which may vary across regions.

JEL Classifications: D62, H23, H54, Q58, R41, R42, R48, R53

Keywords: traffic congestion, public transit investment, urban transportation, second-best policies, externality regulation

*We thank Erik Hurst, Doug Larson, Marcel Oesterich, Chad Sparber, and Matthew Turner; participants at the 2013 International Transportation Economics Association Conference and the 2013 Canadian Resource and Environmental Economics Study Group Conference; and participants in seminars at the University of California at Davis, California State University at Fullerton, Colgate University, University of Washington Tacoma, and Furman University for helpful comments and discussions. Beaudoin gratefully acknowledges the support of a Doctoral Dissertation Grant from the University of California Transportation Center (UCTC) and a Provost's Dissertation Year Fellowship in the Arts, Humanities and Social Sciences from the University of California at Davis. Farzin is an emeritus member and Lin Lawell is a member of the Giannini Foundation of Agricultural Economics. All errors are our own.

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1 Introduction

While there are multiple sources of market failure associated with urban transportation, congestion costs comprise the majority of the external costs of automobile travel for urban commuters in the U.S.[1] Anyone who has idled in traffic anxiously watching the clock is all too familiar with the costs of traffic congestion. Congestion is ubiquitous across urban roadways and is a persistent topic of policy debate. The external costs of congestion – which include increased operating costs for both private and freight vehicles, increased fuel usage and emissions, and, most significantly, the delay costs and uncertain travel times confronting motorists – are substantial and have been steadily increasing. In 2011, these costs of traffic congestion alone have been estimated to have exceeded $121 billion in the U.S. (Schrank et al., 2012). Congestion has steadily increased in recent decades: from 1983 to 2011, average car travel time increased by 30% and average transit travel time increased by 62.5% (Berechman, 2009, pp. 123-125).

It is clear that the market failures endemic to the urban transportation sector are not being adequately addressed by existing regulatory policies. As Winston (2000, pp. 411) notes: "Large public transit deficits, low transit load factors and severe highway congestion...suggest that the US public sector is not setting urban transportation prices and service to maximise net benefits." The U.S. Government Accountability Office has recently outlined the failure of transportation infrastructure investment programs to incorporate rigorous economic analysis and the ongoing absence of a link between investment and system performance, and there has been increasing concern about the fiscal sustainability of highway and transit operations (Libermann, 2009).

Public transit is often advocated as a means to address traffic congestion within urban transportation networks. Recent expenditures on public transit capital in the U.S. have exceeded $18 billion per year (American Public Transportation Association, *2012 Fact Book*). This paper develops a theoretical model to analyze what role, if any, public transit investment should play in traffic congestion policy.

Public transit investments should be evaluated on their contribution to overall net social welfare, taking into account the cost of the investment and any associated operating subsidies. While the broader question as to how public transit should be funded and its role in the U.S. urban transportation sector is important and has been addressed by others such as Viton (1981) and Winston and Shirley (1998), the congestion-reduction effect of public transit is a potentially important com-

[1] Of the combined per vehicle-mile costs of congestion, accidents, and environmental externalities for urban commuters in the U.S., congestion costs represent 71.7% of the short-run average variable social cost of auto travel and 74.3% of the short-run marginal variable social cost (Small and Verhoef, 2007, pp. 98). Similarly, of the externalities associated with gasoline consumption that Lin and Prince (2009) analyze in their study of the optimal gasoline tax for the state of California, the congestion externality is the largest and should be taxed the most heavily, followed by oil security, accident externalities, local air pollution, and global climate change.

ponent of this evaluation process.

Moreover, the optimal level of public transit infrastructure and service to provide depends on the policy instruments employed to address traffic congestion. In the first-best, a Pigouvian congestion tax is levied on auto travel, which generates a direct price for the congestion externality and not only limits the deviation from the socially optimal level of travel and helps utilize existing capacity more efficiently, but also results in a volume of travel that provides an appropriate signal of the optimal level of capacity investment in the future. In this case, efficient public transit investment can be determined in a first-best setting, with the relevant welfare effects of public transit investment confined to the direct effects in the transit market.

The critical assumption required for the first-best framework to be appropriate is that there are no uncorrected distortions in the transportation market and its related markets. In general, however, this is not the case for urban transportation in the U.S. As has been well-documented,[2] transportation involves a number of social costs that are not currently being internalized by individual users, with the distortion receiving the most attention being the absence of marginal cost pricing related to the congestion externality associated with fixed road capacity. Congestion taxes remain underutilized in practice, due to a combination of economic factors (for example, the transaction costs of implementing the tax) and political reticence (Anas and Lindsey, 2011). In this case, second-best public transit investment policies (rather than first-best public transit investment policies) are appropriate, and this is indeed the policy-relevant landscape in the U.S. at present.

If it is accepted *a priori* that policy instruments that would in theory achieve a first-best outcome cannot be employed due to various economic and political constraints, then it is of interest to analyze potential second-best solutions available to policymakers. The general concept of subsidizing a substitute good in the presence of an uncorrected distortion has long been established (Baumol and Bradford, 1970); in this paper, we apply this concept by developing a model of public transit investment in the absence of congestion pricing on auto travel to evaluate the effects of public transit supply on equilibrium traffic congestion. Specifically, we address the following question: Is there a theoretical justification for increasing public transit investment as a means of dealing with traffic congestion?

Our second-best model of public transit investment contributes to the literature by allowing for cost interdependencies between the auto and transit modes in addition to the demand substitutability across modes, with auto travel costs potentially varying with the type and level of transit capacity provided due to the interaction between auto and transit vehicles in the roadways. The results indi-

[2] See Small and Verhoef (2007, Table 3.3, pp. 98) and Parry et al. (2007) for recent empirical estimates of the internal and external costs of automobile travel.

cate that the level of transit investment should be higher relative to the level that would be chosen when the congestion-reduction effects of transit are not accounted for.[3] However, the importance of this consideration is dependent upon these demand and cost interdependencies, which may vary across regions. The ambiguous predictions of our model and the potential spatial heterogeneity of the congestion-reduction effect of public transit help to reconcile the existing inconclusive evidence in the literature regarding the impact of public transit on congestion levels.

Our results suggest that urban mass transit may have a co-benefit of congestion reduction. As a result, prospective public transit projects should not be evaluated exclusively in terms of the forecasted net welfare generated by public transit users, but instead should also include interactions between auto and transit users in the cost-benefit analysis framework. Whether this consideration is important will vary significantly across cities, and past experiences in one city may not generalize to potential new investments in another. While public transit investment may be able to play a complementary role, efficient pricing of auto travel remains necessary to address traffic congestion in the U.S.

2 Literature Review

The link between pricing and investment in auto travel was recognized in the seminal papers by Mohring and Harwitz (1962) and Vickrey (1969), with a recent treatment by Lindsey (2012). While investment in roadway infrastructure may lead to short-term reductions in congestion, in the long run it will be ineffective in the absence of efficient pricing, as improvements in travel conditions will induce additional demand for auto travel (Hau, 1997). This predicted effect is known as the 'fundamental law of traffic congestion' and traces back to Downs (1962); it is analogous to the Tragedy of the Commons associated with any non-excludable and congestible resource. This effect has been demonstrated empirically by Duranton and Turner (2011) and necessitates a second-best framework when analyzing the effects of transportation infrastructure investment on equilibrium traffic levels. Recognizing the institutional reality that the first-best benchmark is generally not attainable due to the absence of a congestion tax on auto travel, a variety of 'second-best' approaches have since been examined.

Most studies relating to second-best investment have focused on how distortions in the transportation market should be accounted for in evaluating road investments (see e.g., Wheaton, 1978; Friedlander, 1981; d'Ouville and McDonald, 1990; Gillen, 1997). Recent research has incorporated endogenous investment in public transit capacity along with second-best pricing, including

[3] If other transportation externalities, such as pollution, were taken into account, then the second-best investment level would be higher still.

applications to the ‘two-mode problem’ that accounts for the interaction between auto and transit (see Berechman (2009, pp. 38-39) for a discussion of first-best versus second-best public transit investment, and models by Henderson, 1985; Arnott and Yan, 2000; Pels and Verhoef, 2007; Ahn, 2009; and Kraus, 2012). The results of these previous second-best models with endogenous transit capacity have relied on an assumption that the costs of travel for auto are independent of the level of transit supplied. This assumption leads Kraus (2012) to find a global result that second-best transit capacity – accounting for the distortion in the auto market – is higher than the first-best capacity that does not account for this distortion. A key feature of our model that distinguishes it from the existing second-best investment models in the literature is that it relaxes this assumption and allows for both demand and cost interdependencies across the auto and transit modes.

The concept of induced auto travel following improved travel conditions is also applicable to investment in public transit. Increasing the relative attractiveness of transit travel may initially cause a subset of commuters to switch from auto to transit. However, by reducing congestion, increasing accessibility, and/or increasing economic activity, transit investment may generate additional automobile trips that were previously not undertaken (Beaudoin and Lin Lawell, 2017). As Small and Verhoef (2007, pp. 174) note, the introduction of Bay Area Rapid Transit (BART) service between Oakland and San Francisco in the early 1970s led to 8,750 automobile trips being diverted to BART; however, 7,000 new automobile trips were subsequently generated, diminishing the net reduction in travel during peak periods. Additionally, investments in mass transit may lead to localized economic development and land-use changes, which even if considered to be ‘transit-oriented development’ may still generate automobile trips that countervail potential traffic congestion reductions due to the initial cross-modal travel substitution (Stopher, 2004, pp. 125; Small and Verhoef, 2007, pp. 12).

Existing empirical studies of the relationship between public transit investment and traffic congestion can be summarized as follows.[4] Baum-Snow and Kahn (2005) estimate the effects of investment in rail transit on the share of public transit ridership. They analyze 16 new and/or expanded rapid rail transit systems in large, dense U.S. cities over the period 1970-2000. Their model suggests that new rail service mostly leads to commuters switching from bus to rail and would not have a significant effect on car ridership. They find that rail transit investment does not reduce congestion levels and that variation in metropolitan area structure (primarily population density) both within and between regions is an important factor leading to heterogeneous responses of commuters with respect to mode choice following expanded rail service.

Winston and Langer (2006) analyze the effects of roadway expenditures on the cost of congestion in

[4] See Beaudoin, Farzin and Lin Lawell (2015) and Beaudoin and Lin Lawell (forthcoming) for detailed discussions and comparisons of these studies.

72 large urban areas in the U.S. over the period 1982-1996. They find that rail transit mileage leads to a decrease in congestion costs, but that increases in bus service actually exacerbate congestion costs.

Winston and Maheshri (2007) examine 25 rail systems in the U.S. from 1993-2000. They estimate that in 2000 these rail systems generated approximately $2.5 billion in congestion cost savings. This estimate is derived by comparing observed congestion costs with those that would arise in the counterfactual scenario where the rail systems were not constructed, based on the empirical results of Winston and Langer (2006); their approach does not provide an estimate of the marginal congestion reduction attributable to incremental changes in existing rail service levels. Nelson et al. (2007) use a simulation model calibrated for Washington, DC and find that rail transit generates congestion-reduction benefits large enough to exceed total rail subsidies.

Duranton and Turner (2011) are primarily interested in finding empirical support for the 'fundamental law of traffic congestion' mentioned above. They find convincing evidence of induced demand: increases in road capacity are met with commensurate increases in auto travel. In the course of their analysis, they also find that the level of public transit service does not affect the volume of auto travel, though they do not estimate the effect on congestion *per se*. Controlling for the potential endogeneity of transit service and auto travel, their analysis covers 228 Metropolitan Statistical Areas in the U.S. for the three years 1983, 1993, and 2003.

Anderson (2014) uses a regression discontinuity design based on a 2003 labor dispute within the Los Angeles transit system, finding that average highway delay increases by 47% when transit service ceases operation. His model predicts that transit users are most likely those commuting along the most congested corridors and since the marginal commuter in this case has a greater impact on congestion than does the average commuter, transit users can potentially have a large impact in terms of congestion reduction. His model also implies that heterogeneity in congestion levels within a city leads to congestion reduction from transit roughly six times larger than when there is homogeneous congestion levels facing commuters. As was the case with Winston and Maheshri (2007), this provides strong evidence of the effects of transit on congestion at the *extensive* margin (i.e. comparing the outcome of an existing transit network with the counterfactual absence of any transit services), but in addition to only being a short-term effect that may potentially be specific to the Los Angeles transportation network, it does not address the effect of transit on congestion at the *intensive* margin (i.e. comparing incremental changes in the level of transit service provided relative to the existing network).

Hamilton and Wichman (2016) study the impact of bicycle-sharing infrastructure on urban transportation, and find that the availability of a bikeshare reduces traffic congestion upwards of 4%

within a neighborhood. They also estimate heterogeneous treatment effects using panel quantile regression, and find that the congestion-reducing impact of bikeshares is concentrated in highly congested areas.

Overall, the existing empirical evidence of the effect of transit investment on traffic congestion is mixed. Anderson (2014) summarizes the literature by recognizing that while public transit service may have a minimal impact on total travel volumes, it may still have a large impact on congestion levels, depending on how induced demand occurs along the various margins of the travel decision (whether to travel, which mode to use, which route to take, and the timing of the trip if taken). The conflicting conclusions of previous studies may also be due to differences in empirical methodologies employed and the characteristics of the dataset used.

Beaudoin and Lin Lawell (2017) estimate the effect of past public transit investment on the demand for automobile transportation by applying an instrumental variable approach that accounts for the potential endogeneity of public transit investment to a panel dataset of 96 urban areas across the U.S. over the years 1991-2011. The results show that, after controlling for the underlying factors that generate auto traffic growth, increases in public transit supply lead to a small overall reduction in auto travel volumes. In the short run, when accounting for the substitution effect only, they find that on average a 10% increase in transit capacity leads to a 0.8% reduction in auto travel in the short run. However, in the longer run, when accounting for both the substitution effect and the induced demand effect, they find that on average a 10% increase in transit capacity is expected to lead to a 0.3% reduction in auto travel. They also find that public transit supply does not reduce auto travel when traffic congestion is below a threshold level. Additionally, they find that there is substantial heterogeneity across urban areas, with public transit having significantly different effects on auto travel demand in smaller, less densely populated regions with less-developed public transit networks than in larger, more densely populated regions with extensive public transit networks. By using a broader set of urban areas over a longer time period than previous studies, and by allowing for regional heterogeneity, the results of Beaudoin and Lin Lawell (2017) help reconcile the literature's seemingly conflicting evidence.

3 Theoretical Model

We develop a model of public transit investment in the presence of an uncorrected congestion externality related to auto travel. Our model allows for both demand and cost interdependencies across the auto and transit modes. In particular, in addition to the demand substitutability across modes, our model also allows for cost interdependencies between the auto and transit modes, with auto travel costs potentially varying with the type and level of transit capacity provided due to the interaction between auto and transit vehicles in the roadways.

3.1 Model Overview

The transportation network of an urban area is assumed to consist of two modes of travel – auto and public transit – with both demand and cost interdependence between modes. The network is modeled at an aggregate level and a static framework (representing stationary-state travel volumes) is used to evaluate the extent to which transit investment influences the equilibrium travel volumes across the network. This framework is known as the speed-flow model and can be viewed as a reduced form representation of a dynamic bottleneck model (Small and Verhoef, 2007, pp. 93). This approach is appropriate "when traffic conditions do not change too quickly or when it is thought sufficient to focus policy attention on average traffic levels over extended periods" (Small and Verhoef, 2007, pp. 121; Parry, 2009). Since congestion is most prominent during peak periods, we abstract from the dynamics of bottleneck behavior to use the static equilibrium model that incorporates the net effect of induced demand.

3.2 Travel Demand

Aggregate modal travel volumes V_j are determined by the relative generalized costs of each mode C_j, with $j \in \{\text{auto (A), transit (T)}\}$. The aggregate inverse demand curves are derived by summing the individual travel decisions of a region's residents, including the decision about whether or not to undertake a trip. We assume the existence of continuous aggregate modal demand functions; while *individual* travelers may face a discrete choice between the two modes, the *aggregate* demand for the entire network – on a per unit of travel basis – is well represented as a continuous function of the marginal unit cost of travel. The inverse demand functions $D_A(\cdot)$ and $D_T(\cdot)$ for auto and transit, respectively, represent the marginal willingness to pay for travel via each mode, and it is assumed that the marginal private benefit of travel is equal to the marginal social benefit of travel.[5] For each mode j, $\frac{\partial D_j}{\partial C_k} \geq 0$ represents the cross-modal demand substitutability. The model does not incorporate other margins of travel behavior (such as route choice and trip timing), given the aggregate network-level of analysis undertaken.

[5] While there may be external benefits associated with the construction of infrastructure in some cases (primarily relating to economies of agglomeration due to improved accessibility, and reductions in market power brought about by reduced transaction costs), the marginal unit of travel is unlikely to confer such positive externalities, particularly in highly-developed urban regions in the U.S. (see discussion in Small and Verhoef, 2007, pp. 187-188).

3.3 Infrastructure Investment and Capital Provision

The model assumes a fixed level of auto capacity, denoted by $\overline{K}_A$. The supply of public transit service can be varied for any given time period, with the optimal transit investment being chosen conditionally with knowledge of the existing auto capacity (road network).

Public transit investment can occur along two dimensions. First, the size of the public transit network can be expanded by increasing the route coverage. Such investment occurs along the extensive margin and is related to the accessibility of public transit service. Transit network size is denoted by K_T^S. Second, the capacity of the public transit network can be expanded by increasing the service frequency provided across the public transit network. This investment occurs along the intensive margin and is related to the waiting and travel time associated with public transit travel. Transit capacity is denoted by K_T^C. Together, transit investment is denoted via the vector $\mathbf{K_T} = \left(K_T^S, K_T^C\right)$, and the public transit investment cost function is given by $I_T\left(\mathbf{K_T}; \overline{K}_A\right)$.

3.4 Travel Cost

The generalized cost of travel C_k encapsulates the full per-unit[6] cost of travel via mode k, combining both monetary and non-monetary aspects, and represents an individual's opportunity cost of travel. Total travel time is disaggregated into various activities to reflect the different effects that the size of the transport network and the capacity provided over the network can have on travelers' choices, and the differences in the value of time associated with different travel activities. The amount of time $\tilde{T}_j^i$ is identified separately by mode and activity, where j represents the mode and i represents the activity, with $i \in \{$access (A), wait (W), travel (T)$\}$. Similar notation is used for the value of time VOT_j^i, which is also assumed to differ across modes and activity types. The monetized value of time spent per activity is then calculated as $T_A^T = \tilde{T}_A^T \cdot VOT_A^T$ for auto travel time, and $T_T^i = \tilde{T}_T^i \cdot VOT_T^i$ for transit travel activity i.

3.4.1 Travel Cost: Auto

The marginal per-unit private cost of auto travel MPC_A is given by the sum of the monetary cost of auto travel P_A (which includes the variable out-of-pocket expenses such as fuel), the monetized value of time T_A^T, and the per-unit tax levied on auto travel τ:

$$MPC_A\left(V_A, V_T, \tau; K_T^C, \overline{K}_A\right) \equiv P_A\left(\frac{V_A}{\overline{K}_A}, \frac{K_T^C}{\overline{K}_A}, \frac{V_T}{K_T^C}\right) + T_A^T\left(\frac{V_A}{\overline{K}_A}, \frac{K_T^C}{\overline{K}_A}, \frac{V_T}{K_T^C}\right) + \tau \tag{1}$$

[6] Per-unit measures are on a 'per mile of travel' basis throughout.

With a fixed level of auto capacity, increases in travel volume beyond a threshold lead to congestion, and each marginal unit of travel thus imposes an external congestion cost on all other users in the network; this effect is manifested in longer travel times for auto, and potentially longer travel and waiting times for transit if there is physical interaction between auto and transit vehicles within the transportation network.[7] It is assumed that auto travel time is homogeneous of degree zero in auto travel volume and capacity, such that a proportionate increase in volume and capacity leaves average travel time unchanged; however, given a fixed level of auto capacity, the auto travel time function is assumed to be convex with respect to travel volume, consistent with empirical estimates of travel speed-flow relationships (see Small and Verhoef (2007), Section 3.3).

The cost of auto travel depends on the congestion experienced over the network, determined by the following factors: (1) the volume-to-capacity ratio $\frac{V_A}{\overline{K}_A}$, representing the relationship between auto congestion and travel speeds; (2) $\frac{K_T^C}{\overline{K}_A}$, representing the congestion effect associated with transit vehicles interacting with autos on the roadways, which causes the cost of auto travel to depend on the level of transit capacity; and (3) $\frac{V_T}{K_T^C}$, representing the congestion effect associated with passengers boarding and disembarking transit vehicles and affecting auto travel speeds through the auto-transit interaction, which also causes the cost of auto travel to depend on transit supply. These potential effects of transit capacity on the cost of auto travel cost have been discussed by Sherman (1971), Viton (1981), Ahn (2009) and Basso and Silva (2014).

3.4.2 Travel Cost: Transit

Similarly, the marginal per-unit private cost of transit travel MPC_T is given by the following sum of the transit fare P_T and the monetized values of access, wait and travel times:

$$MPC_T\left(V_A, V_T, K_T^S, K_T^C; \overline{K}_A\right) \equiv P_T + T_T^A\left(K_T^S\right) + T_T^W\left(\frac{K_T^C}{K_T^S}, \frac{V_A}{\overline{K}_A}, \frac{V_T}{K_T^C}\right) + T_T^T\left(\frac{V_A}{\overline{K}_A}, \frac{V_T}{K_T^C}, \frac{K_T^C}{\overline{K}_A}, \frac{K_T^S}{\overline{K}_A}\right) \quad (2)$$

The transit access time cost T_T^A is a function of the size of the public transit network K_T^S. Transit wait time T_T^W is affected by the following factors: (1) $\frac{K_T^C}{K_T^S}$, which is a measure of the average headway per route; (2) $\frac{V_A}{\overline{K}_A}$, which represents auto congestion and affects transit schedule delay costs associated with uncertain departure times, and which causes the cost of transit travel to depend on the auto mode; and (3) $\frac{V_T}{K_T^C}$, which represents the transit congestion associated with passengers boarding and disembarking the vehicle and also influences the probability of encountering a full transit vehicle and the requirement to wait for the subsequent vehicle's arrival. Transit travel time

[7] Access and wait times are assumed to be negligible for auto travel.

T_T^T is affected by the following factors:[8] (1) auto congestion, measured by $\frac{V_A}{\overline{K}_A}$, which also causes the cost of transit travel to depend on the auto mode; (2) the direct transit congestion effect, represented by $\frac{V_T}{K_T^C}$; (3) the transit congestion associated with transit vehicles interacting with autos on the roadways, represented by $\frac{K_T^C}{\overline{K}_A}$, which similarly causes the cost of transit travel to depend on the auto mode; and (4) the average potential trip distance that is influenced by overall transit route coverage, measured by $\frac{K_T^S}{\overline{K}_A}$, and again causes the cost of transit travel to depend on the auto mode. Appendix IV shows how increased transit investment leads to a reduction in the marginal private cost of transit travel.

3.4.3 The External Cost of Travel

Each individual views the various cost components as parametric with respect to their travel decision and thus independent of their own travel volume (analogous to the incentive structure of an open access resource). In doing so, each individual ignores the external effects of their travel decisions on the other individuals in the network, and in congested conditions each individual's travel adversely affects the other individuals in the network.

The marginal *social* cost of travel MSC_j for each mode j accounts for both the marginal private costs incurred by the individual, as well as the external effects transmitted via the marginal increase in the average travel cost throughout the network that they generate; this is a technological externality whereby each individual's average travel cost is dependent upon the travel volumes chosen by other users across the network. With the above specifications of the generalized cost functions, the average cost functions are interdependent across modes, and there are thus intra- and inter-mode externalities.

For a given auto capacity level $\overline{K}_A$, there is a threshold travel volume $\overline{V}_A$ where the congestion externality becomes relevant:

$$\frac{\partial MPC_A}{\partial V_A} \quad \text{and} \quad \frac{\partial MPC_T}{\partial V_A} \begin{cases} = 0 & \text{if } V_A \leq \overline{V}_A \\ \\ > 0 & \text{if } V_A > \overline{V}_A \end{cases} \tag{3}$$

The marginal *external* cost of auto travel MEC_A is then the difference between the marginal social cost and marginal private cost of travel. In congested conditions, each marginal unit of auto travel increases the average cost of auto travel through increases in operating costs and travel time, and

[8] Empirical evidence regarding the effects of auto and transit vehicle interaction was provided by the introduction of the congestion pricing scheme in central London in 2003, where a 15% reduction in auto travel was associated with a 6% increase in bus travel speeds in the area (Small and Verhoef, 2007, pp. 100).

increases the average cost of transit travel through increases in waiting and travel time:

$$MEC_A = MSC_A - MPC_A = \begin{cases} 0 & \text{if } V_A \leq \overline{V}_A \\ \\ V_A \frac{\partial MPC_A}{\partial V_A} + V_T \frac{\partial MPC_T}{\partial V_A} & \text{if } V_A > \overline{V}_A \end{cases} \tag{4}$$

It is assumed that observed equilibrium travel volumes exceed $\overline{V}_A$, consistent with peak travel conditions in urban areas. By definition, the marginal external cost must be convex with respect to the volume of travel (see Baumol and Oates (1988, pp. 90) for a proof of the convexity of a general congestion externality). This implies that the marginal external cost exceeds the average external cost, with $\frac{\partial MPC_A}{\partial V_A} > 0$ and $\frac{\partial^2 MPC_A}{\partial {V_A}^2} > 0$, implying that the magnitude of the congestion externality varies with the volume-to-capacity ratio $\frac{V_A}{\overline{K}_A}$.

Because our model allows for demand and cost interdependencies across the auto and transit modes, the level of transit supplied affects equilibrium travel volumes through two channels: (1) by shifting the demand curves for auto and transit travel, and (2) by shifting the marginal private cost MPC_A and marginal external cost MEC_A curves through its effects on the monetary cost of auto travel $P_A(\cdot)$, the monetized values of time for auto travel $T_A^T(\cdot)$, transit access time $T_T^A(\cdot)$, transit wait time $T_T^W(\cdot)$, and transit travel time $T_T^T(\cdot)$, which are all functions of transit investment $\mathbf{K_T}$. While the marginal private and external costs of auto travel are assumed to be independent of the size of the transit network, i.e. $\frac{\partial MSC_A}{\partial K_T^S} = 0$, the level of capacity supplied over the transit network affects both the marginal private and external costs of auto travel:

$$\begin{aligned} \frac{\partial MSC_A}{\partial K_T^C} &= \frac{\partial MPC_A}{\partial K_T^C} + \frac{\partial MEC_A}{\partial K_T^C} \\ &= \left[\frac{\partial MPC_A}{\partial K_T^C}\right] + \left[\frac{\partial MPC_A}{\partial V_A}\frac{\partial V_A}{\partial K_T^C} + V_A \frac{\partial \frac{\partial MPC_A}{\partial V_A}}{\partial K_T^C}\right] + \left[\frac{\partial MPC_T}{\partial V_A}\frac{\partial V_A}{\partial K_T^C} + V_T \frac{\partial \frac{\partial MPC_T}{\partial V_A}}{\partial K_T^C}\right]. \end{aligned} \tag{5}$$

The net effect of changes in transit capacity on MSC_A is uncertain. There is an ambiguous direct effect of transit capacity K_T^C on the marginal private cost of auto travel (see Appendix III). An increase in transit capacity also has an undetermined effect on the marginal external cost of auto travel: by reducing auto travel volume V_A through cross-modal demand substitution, transit capacity serves to decrease the magnitude of the marginal external cost, while the additional transit capacity increases the magnitude of the marginal external cost by intensifying the interaction between auto and transit vehicles. As a result, the net effect depends upon the relative magnitudes of the various components; theoretically, an increase in transit investment could shift the auto cost function upwards, downwards, or leave it unaffected.

While there are several other potential distortions inherent to urban transportation beyond congestion – including vehicle emissions, accidents, noise, or various market distortions resulting from government intervention – for the purposes of exposition the model assumes that the congestion-related effects embedded in the generalized cost functions are the only externalities associated with urban travel. For urban commuters in the U.S., congestion costs (considering travel time, schedule delay, and uncertainty regarding travel times) comprise the majority of the external costs associated with automobile travel (Small and Verhoef, 2007).[9]

3.5 Equilibria

On the basis of the preceding demand and cost structure, we next specify several equilibria to illustrate how the evaluation of transit investment is dependent on the regulatory policy in place.

3.5.1 Case I: The Unregulated User Equilibrium

The unregulated case has no congestion tax in place, such that $\tau = 0$. Then for fixed auto capacity $\overline{K}_A$ and for any given transit investment level $\overline{\mathbf{K}}_{\mathbf{T}}$, the short-run capacity usage results in equilibrium travel volumes V_A^u and V_T^u that equate the marginal benefit of travel with the marginal private cost of travel for each mode. This outcome, where individuals do not account for any external costs associated with their travel decision, is denoted as the *user equilibrium*:

$$D_j\left(V_j^u\right) = MPC_j\left(V_j^u\right) \quad \forall\, \mathbf{K}_{\mathbf{T}},\ \text{and } j \in \{A, T\}. \tag{6}$$

The user equilibrium is the manifestation of the 'fundamental law of traffic congestion': with the user equilibrium, any capacity expansion that decreases travel costs will subsequently induce additional travel that eliminates any (short-run) benefits from reduced congestion as equilibrium is reached. The absence of a tax on the congestion externality yields an open access congestible resource, with the equilibrium outcome failing to maximize the net social benefits of travel.

3.5.2 Case II: The First-Best Pareto Optimal Equilibrium

To maximize the *social* net benefits of auto and transit travel, both the volume of travel *and* the level of transit investment must be simultaneously optimized, conditional on fixed auto capacity. Here the level of public transit investment $\mathbf{K}_{\mathbf{T}} = \left(K_T^S, K_T^C\right)$ is endogenous. The regulator must account for the congestion externality by levying a tax τ on each mile of auto travel. The efficient

[9] Of the combined per vehicle-mile costs of congestion, accidents, and environmental externalities for urban commuters in the U.S., congestion costs represent 71.7% of the short-run average variable social cost of auto travel and 74.3% of the short-run marginal variable social cost (Small and Verhoef, 2007, pp. 98).

tax τ^* (i.e. the Pigouvian tax) is equal to the marginal external cost of auto travel evaluated at the efficient travel volumes and transit investment levels, while also accounting for the induced cross-modal demand and cost curve shifts brought about by the tax. If τ^* is imposed, then the user equilibrium travel volume that arises coincides with the efficient level V_A^*.

It should be noted that the Pigouvian tax is a function of the level of capital in both the auto and transit markets. With the Pigouvian tax applied, the net marginal benefit is equalized with the net marginal social cost of auto travel, and the private incentives facing each individual are aligned with the desired social incentives. Figure 1 illustrates the user equilibrium and the efficient equilibrium in the auto market and shows how the Pigouvian tax internalizes the congestion externality and eliminates the deadweight loss associated with the unregulated user equilibrium, DWL_A^0, by reducing auto travel from V_A^0 to V_A^*.

With $\frac{\partial MPC_A}{\partial V_A} > 0$ and $\frac{\partial^2 MPC_A}{\partial {V_A}^2} > 0$, it must be the case that $MSC_A > MPC_A \; \forall V_A \in \left(\overline{V}_A, \overline{K}_A\right]$. With $\frac{\partial D_A}{\partial V_A} < 0$ and $\frac{\partial^2 D_A}{\partial {V_A}^2} \geq 0$, there are unique user and first-best equilibria with $V_A^0 > V_A^*$, and thus $DWL_A^0 > 0$ and $\tau^* > 0$.

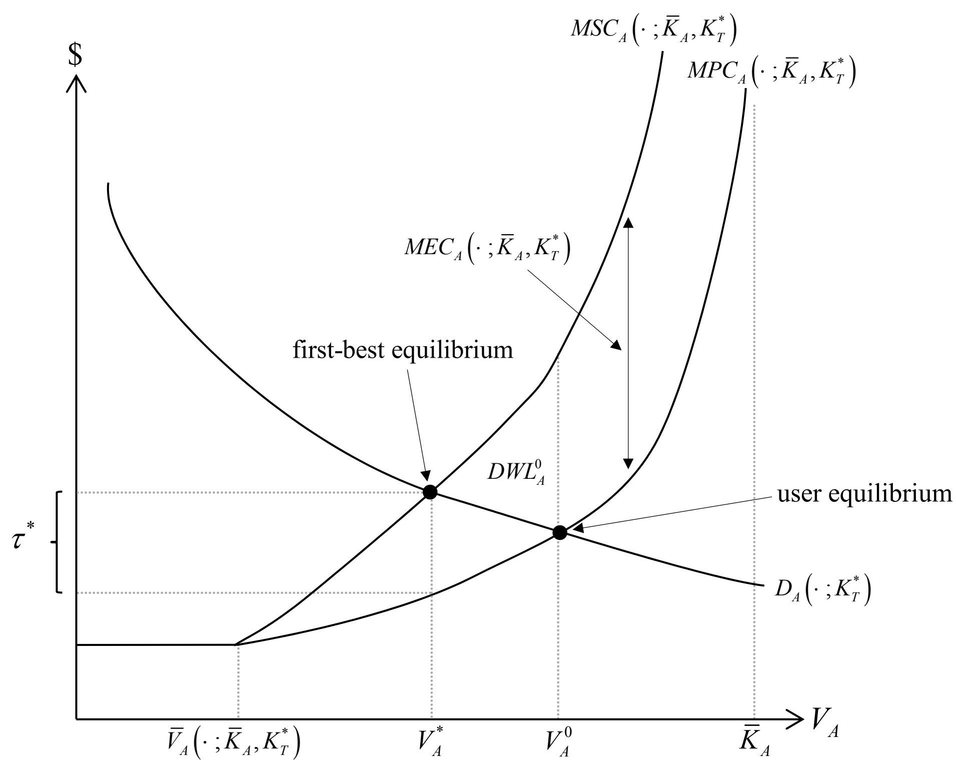

Figure 1: First-best equilibrium outcome vs. the user equilibrium in the auto market

3.5.3 Case III: The Second-Best Equilibrium

The general theory of the second-best applies to the urban transportation sector. If there is an uncorrected distortion in one market, then the optimality conditions in interconnected markets must be adjusted to account for the welfare implications of this distortion. Congestion taxes have had limited application in practice (apart from relatively successful implementation in Singapore, London and Stockholm) and are essentially not employed in the U.S., and the taxes on travel in place (predominantly fuel taxes) are not equivalent to Pigouvian taxes insofar as they are not set at the correct level, nor do they exhibit the temporal and spatial variation necessary to induce the first-best equilibrium. As a result, the second-best framework is appropriate when evaluating potential transit investments and we now consider the case where the value of τ is assumed to be set at the (fixed) suboptimal value of $\overline{\tau} \neq \tau^*$. In practice, it is usually the case that $\overline{\tau} < \tau^*$.

With this *a priori* assumption that the regulator cannot levy the optimal tax, we consider the second-best optimization problem whereby social net benefits are maximized by choosing the auto and transit volumes and the level of transit investment, given the existing auto network. In this case, the user equilibrium in (6) will be reached whereby the marginal private costs of travel are equated to the marginal benefit of travel across modes, and this equilibrium is imposed as a constraint in the optimization problem.[10] While the deadweight loss in the auto market cannot be completely eliminated in this case, the level of transit investment will influence the auto demand and travel cost functions and thus determine *which* user equilibrium is reached. This constraint also incorporates potential induced travel demand brought about by the marginal cost reductions associated with transit capacity increases, and captures the indirect effects in the auto market due to the induced modal substitution accompanying changes in the supply of transit.

[10] This is a manifestation of Wardrop's first principle of traffic equilibrium (Wardrop, 1952), applied to the modal distribution of travel as opposed to the route distribution of travel, and an application of the "general theory of the second-best" found in early work such as Davis and Whinston (1965), Davis and Whinston (1967), and Baumol and Bradford (1970).

The second-best constrained optimization problem is given by:

$$
\begin{aligned}
\max_{\{V_A,V_T,K_T^S,K_T^C\}} SNB = & \int_0^{V_A} D_A\left(v_A; MPC_T\left(V_A, V_T, K_T^S, K_T^C, \overline{K}_A\right)\right)\mathrm{d}v_A \\
& + \int_0^{V_T} D_T\left(v_T; MPC_A\left(V_A, V_T, K_T^C, \overline{\tau}, \overline{K}_A\right)\right)\mathrm{d}v_T \\
& - V_A MPC_A\left(V_A, V_T, K_T^C, \overline{\tau}, \overline{K}_A\right) - V_T MPC_T\left(V_A, V_T, K_T^S, K_T^C, \overline{K}_A\right) \\
& - I_T\left(K_T^S, K_T^C, \overline{K}_A\right) + \overline{\tau} V_A \\
\text{s.t.} \qquad & K_A = \overline{K}_A \\
& \overline{\tau} < \tau^* \\
& D_A(\cdot) = MPC_A\left(V_A, V_T, K_T^C, \overline{\tau}, \overline{K}_A\right) \qquad (\lambda_A) \\
& D_T(\cdot) = MPC_T\left(V_A, V_T, K_T^S, K_T^C, \overline{K}_A\right) \qquad (\lambda_T).
\end{aligned}
\tag{7}
$$

Forming the Lagrangian of (7), λ_A and λ_T are the Lagrange multipliers on the user equilibria constraints, representing the marginal social welfare loss of not imposing the Pigouvian tax, or equivalently the shadow price of non-optimal pricing and the marginal social benefit of an incremental movement towards the first-best equilibrium from the user equilibrium (and thus $\lambda_A \geq 0$ when $\tau < \tau^*$). Assuming that there is no budget constraint relating to the level of transit investment and that transit travel is priced at its marginal social cost,[11] so that $\lambda_T = 0$, this yields the first-order conditions that determine the second-best solution vector $\{V_A', V_T', K_T^{S\prime}, K_T^{C\prime}; \overline{K}_A\}$. Absent efficient pricing of auto travel, the envelope theorem does not apply and indirect effects in the auto market must be incorporated into the first-order conditions for transit investment.

[11] If the Pigouvian tax on auto is in place, the optimal transit fare P_T^* satisfies the first-order conditions for Pareto optimality when:

$P_T^* = V_A^* \frac{\partial MPC_A}{\partial V_T} + V_T^* \frac{\partial MPC_T}{\partial V_T} - \int_0^{V_A^*} \frac{\partial D_A}{\partial MPC_T}\frac{\partial MPC_T}{\partial V_T}\mathrm{d}v_A - \int_0^{V_T^*} \frac{\partial D_T}{\partial MPC_A}\frac{\partial MPC_A}{\partial V_T}\mathrm{d}v_T$. If $P_T < P_T^*$, then $\lambda_T \geq 0$, and if $P_T > P_T^*$, then $\lambda_T \leq 0$; in these cases, the under- or over-pricing of transit relative to the efficient price will require an adjustment to the conditions determining the optimal supply of transit service, analogous to the results of Wheaton (1978) for the relationship between auto pricing and investment. However, in the second-best case with inefficiently priced auto travel – auto is underpriced relative to its marginal social cost and the second-best transit fare must account for this distortion – there is a rationale for transit fare subsidies (Glaister and Lewis, 1978; Parry and Small, 2009). The transit fare would then satisfy condition (8b) when:

$P_T' = \left(V_A' - \lambda_A\right) \frac{\partial MPC_A}{\partial V_T} + V_T' \frac{\partial MPC_T}{\partial V_T} - \int_0^{V_A'} \frac{\partial D_A}{\partial MPC_T}\frac{\partial MPC_T}{\partial V_T}\mathrm{d}v_A - \int_0^{V_T'} \frac{\partial D_T}{\partial MPC_A}\frac{\partial MPC_A}{\partial V_T}\mathrm{d}v_T + \lambda_A \left[\frac{\partial D_A}{\partial MPC_T}\frac{\partial MPC_T}{\partial V_T}\right]$.

While future work should explore the interrelationship between transit investment and pricing in the second-best setting, this aspect is not accounted for in the present analysis in order to isolate the transit investment effect.

These conditions are shown in equations (8) below, with the bold terms indicating the second-best adjustment terms relative to the first-order conditions arising from the first-best equilibrium:

$$D_A + \int_0^{V_A'} \frac{\partial D_A}{\partial MPC_T} \frac{\partial MPC_T}{\partial V_A} \mathrm{d}v_A \boldsymbol{-\lambda_A} \left[\boldsymbol{\frac{\partial D_A}{\partial V_A} + \frac{\partial D_A}{\partial MPC_T} \frac{\partial MPC_T}{\partial V_A}} \right] + \int_0^{V_T'} \frac{\partial D_T}{\partial MPC_A} \frac{\partial MPC_A}{\partial V_A} \mathrm{d}v_T$$

$$= P_A + T_A^T + \left(V_A' \boldsymbol{-\lambda_A}\right) \frac{\partial MPC_A}{\partial V_A} + V_T' \frac{\partial MPC_T}{\partial V_A} \tag{8a}$$

$$D_T + \int_0^{V_A'} \frac{\partial D_A}{\partial MPC_T} \frac{\partial MPC_T}{\partial V_T} \mathrm{d}v_A \boldsymbol{-\lambda_A} \left[\boldsymbol{\frac{\partial D_A}{\partial MPC_T} \frac{\partial MPC_T}{\partial V_T}} \right] + \int_0^{V_T'} \frac{\partial D_T}{\partial MPC_A} \frac{\partial MPC_A}{\partial V_T} \mathrm{d}v_T$$

$$= P_T + \sum_{i \in \{A,W,T\}} T_T^i + \left(V_A' \boldsymbol{-\lambda_A}\right) \frac{\partial MPC_A}{\partial V_T} + V_T' \frac{\partial MPC_T}{\partial V_T} \tag{8b}$$

$$- V_T' \frac{\partial MPC_T}{\partial K_T^C} - \left(V_A' \boldsymbol{-\lambda_A}\right) \frac{\partial MPC_A}{\partial K_T^C} + \int_0^{V_A'} \frac{\partial D_A}{\partial MPC_T} \frac{\partial MPC_T}{\partial K_T^C} \mathrm{d}v_A \boldsymbol{-\lambda_A} \left[\boldsymbol{\frac{\partial D_A}{\partial MPC_T} \frac{\partial MPC_T}{\partial K_T^C}} \right]$$

$$+ \int_0^{V_T'} \frac{\partial D_T}{\partial MPC_A} \frac{\partial MPC_A}{\partial K_T^C} \mathrm{d}v_T = \frac{\partial I_T}{\partial K_T^C} \tag{8c}$$

$$- V_T' \frac{\partial MPC_T}{\partial K_T^S} + \int_0^{V_A'} \frac{\partial D_A}{\partial MPC_T} \frac{\partial MPC_T}{\partial K_T^S} \mathrm{d}v_A \boldsymbol{-\lambda_A} \left[\boldsymbol{\frac{\partial D_A}{\partial MPC_T} \frac{\partial MPC_T}{\partial K_T^S}} \right] = \frac{\partial I_T}{\partial K_T^S} \tag{8d}$$

$$D_A = P_A + T_A^T + \overline{\tau} \tag{8e}$$

$$D_T = P_T + \sum_{i \in \{A,W,T\}} T_T^i. \tag{8f}$$

With $\lambda_A > 0$, both the level of transit investment and the modal travel volumes differ from the first-best case. Equations (8a)-(8b) reflect the conditions for second-best auto and transit travel usage, respectively, where the efficient travel volumes are such that the marginal benefit of travel for each mode is equated with its marginal *social* cost, incorporating cross-modal shifts in the demand and cost curves brought about by the inter- and intra-modal externalities of travel, until the modal shares equilibrate to the efficient mix across modes. The bold terms represent the welfare effects in the auto market due to the marginal unit of travel of each mode.

Equation (8c) specifies the second-best level of transit capacity, where the marginal cost of providing additional capacity is equated with the marginal benefit of reduced user costs, incorporating the cross-modal demand and cost curve shifts attributable to the level of transit capacity. The bold terms represent the welfare effects in the auto market due to the marginal unit of transit capacity. Equation (8d) determines the second-best level of transit network size, with the marginal cost of increasing the coverage of the network equated with the marginal benefit of reduced transit user costs, accounting for the welfare effects in the auto market due to the change in network size.

The preceding conditions are in the context of the travel network reaching the user equilibrium of equations (8e)-(8f). We next discuss the factors contributing to the differences between the first- and second-best equilibria, and the implications for evaluating potential transit investments.

4 Results

Our theory model yields several results and insights. If the Pigouvian tax τ^* is in place and the first-best equilibrium is achieved, then the marginal benefit of transit investment is confined to the transit sector as there is no deadweight loss associated with auto travel.[12] However, if $\tau < \tau^*$ and $\frac{\partial D_A}{\partial K_T} < 0$ or $\frac{\partial MPC_A}{\partial K_T} \neq 0$, such that there is demand and/or cost interdependency across modes, then the welfare implications of public transit investment will extend to the auto market as well.

Because our model allows for demand and cost interdependencies across the auto and transit modes, transit investment can affect the user equilibrium in the auto market through two channels: (1) cross-modal substitution via shifts in the auto demand curve, and (2) shifts in the auto travel cost function, including changes to the marginal private costs MPC_A and marginal external costs MEC_A of auto travel. Thus, in the second-best case the change in welfare in the auto market attributable to investment in transit infrastructure may be nonzero, and if so, should be accounted for when evaluating the net benefit of potential transit investments.[13]

If $\tau < \tau^*$, then $\lambda_A > 0$ and the second-best investment rule will deviate from the first-best rule.

[12] While this is true in a static framework, in a dynamic model of the transportation network the effects of transit investment on the auto market should be incorporated, insofar as transit investment in a given time period can be expected to influence the demand – and resulting equilibria – in subsequent periods.

[13] For further discussion on this issue, refer to Small and Verhoef (2007, pp. 137 and pp. 188-189).

From the first-order conditions in equations (8), there are four different factors affecting the magnitude of the marginal effect of transit investment on the welfare in the auto market: (1) the severity of existing congestion levels, represented by λ_A; (2) the cross-elasticity of auto demand with respect to the generalized cost of transit travel, given by $\frac{\partial D_A}{\partial MPC_T}$; (3) the magnitude of the change in transit generalized costs due to transit investment, measured by $\frac{\partial MPC_T}{\partial K_T^S}$ and $\frac{\partial MPC_T}{\partial K_T^C}$; and (4) the strength of *intra*- and *inter*-mode congestion externalities, given by $\frac{\partial MPC_T}{\partial V_T}$, $\frac{\partial MPC_A}{\partial V_T}$ and $\frac{\partial MPC_T}{\partial V_A}$.

Following an investment in transit, if only the demand shift in the auto market is considered and there is no cross-modal cost interdependence, such that $\frac{\mathrm{d}MPC_A}{\mathrm{d}K_T} = 0$, then there is an unambiguous ancillary benefit in the auto market associated with a reduction in the deadweight loss (DWL) of the congestion externality, with $DWL_A^1 < DWL_A^0$; this is consistent with the theoretical results of Kraus (2012). This case is shown in Figure 2, with the magnitude of the deadweight loss reduction being proportional to the responsiveness of auto demand to changes in transit investment.

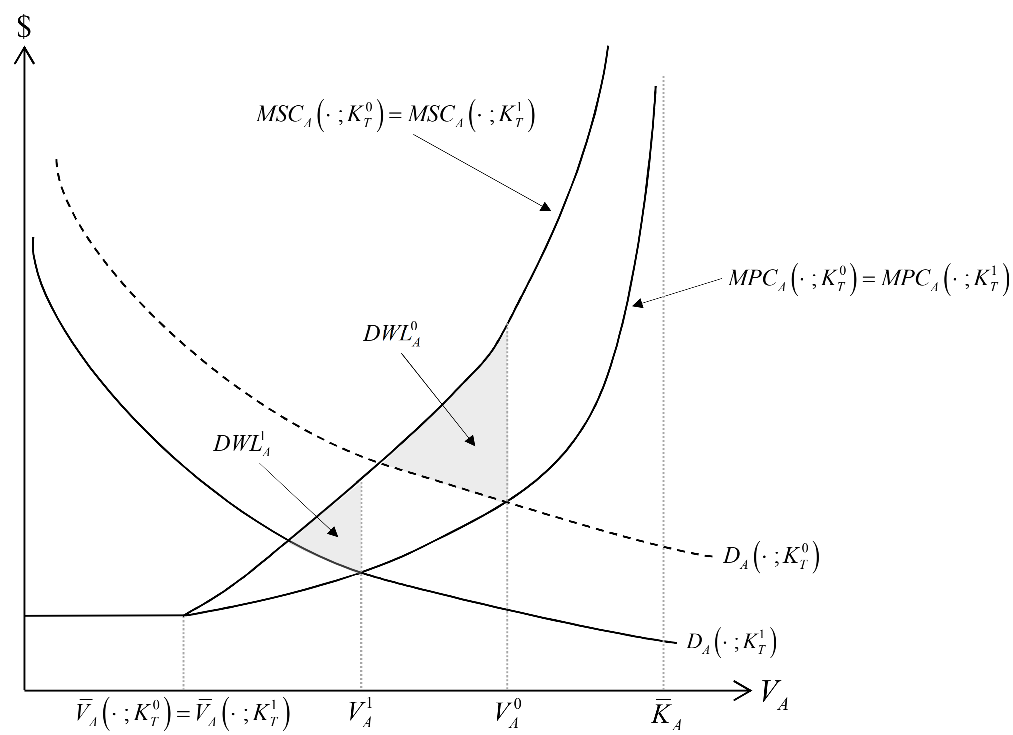

Figure 2: Change in deadweight loss in auto market (no cost interdependence)

Transit investment can be characterized as one of two types: 'fixed guideway' whereby it has its own separate right-of-way and does not directly interact with auto traffic (and the auto travel cost *function* is independent of transit capacity), and 'mixed traffic' whereby it shares the right-of-way with auto traffic (and this interaction of transit vehicles and autos implies that the auto travel cost is functionally dependent on the level of transit capacity). As a result, the functional dependence of the auto and transit cost curves may vary across these two types of transit modes.

Two scenarios where the auto travel cost functions are dependent upon the level of transit investment are shown in Figure 3. When transit investment increases from $\mathbf{K_T^0}$ to $\mathbf{K_T^1}$, transit travel increases from V_T^0 to V_T^1 and auto travel decreases from V_A^0 to V_A^1. The change in deadweight loss in the auto market is affected by the initial user equilibrium auto travel volume, V_A^0, and the associated deadweight loss, DWL_A^0, as well as the combined effects of shifts in the auto demand and travel cost curves. The net effect on the *ex post* deadweight loss in the auto market relative to the *ex ante* deadweight loss is ambiguous.

The example on the right-hand side of Figure 3 shows a case in which transit investment has a beneficial effect in the auto market, with $DWL_A^1 < DWL_A^0$, since $R < (P+Q)$. This case may be characteristic of an investment in fixed guideway transit, such as a new light rail line, where there is the potential for a sizable reduction in auto demand, and there may be a downward shift in the auto congestion cost function (due to the new light rail system substituting for mixed traffic bus service that interacts with autos).

Conversely, the example on the left-hand side of Figure 3 shows a case where transit investment has an adverse effect in the auto market, with $DWL_A^1 > DWL_A^0$, since $(F+G+H) > (I+J+K)$. This case may be characteristic of an increase in the supply of mixed traffic transit service; a marginal increase in bus service likely leads to a smaller reduction in auto travel, and may cause an upward shift in the congestion cost function due to the increased interaction between these buses and autos on congested roadways.

The second-best level of transit capacity is ambiguous in magnitude relative to the first-best level, due to the indeterminate sign of $\frac{\partial MPC_A}{\partial K_T^C}$ (see Appendix III for details); while the demand interdependency component in condition (8c) given by $\lambda_A \cdot \left[\frac{\partial D_A}{\partial MPC_T}\frac{\partial MPC_T}{\partial K_T^C}\right]$ is beneficial in the auto market (provided $\frac{\partial D_A}{\partial MPC_T} < 0$), the sign and magnitude of the cost interdependency effect given by $\lambda_A \cdot \frac{\partial MPC_A}{\partial K_T^C}$ is ambiguous:

$$K_T^{C\prime} > K_T^{C*} \quad \text{iff} \quad \left[\frac{\partial D_A}{\partial MPC_T}\frac{\partial MPC_T}{\partial K_T^C} - \frac{\partial MPC_A}{\partial K_T^C}\right] < 0. \tag{9}$$

Comparisons of first-best and second-best investment levels are complicated by the fact that not only do the investment decision rules differ, but these decision rules are evaluated at different equilibria. Based on condition (8d), however, the model implies that the second-best level of transit network size K_T^S exceeds that of the first-best case: $\lambda_A \cdot \left[\frac{\partial D_A}{\partial MPC_T}\frac{\partial MPC_T}{\partial K_T^S}\right] < 0 \Rightarrow K_T^{S\prime} > K_T^{S*}$. Here there is a co-benefit of transit investment in the auto market due to the auto demand reduction

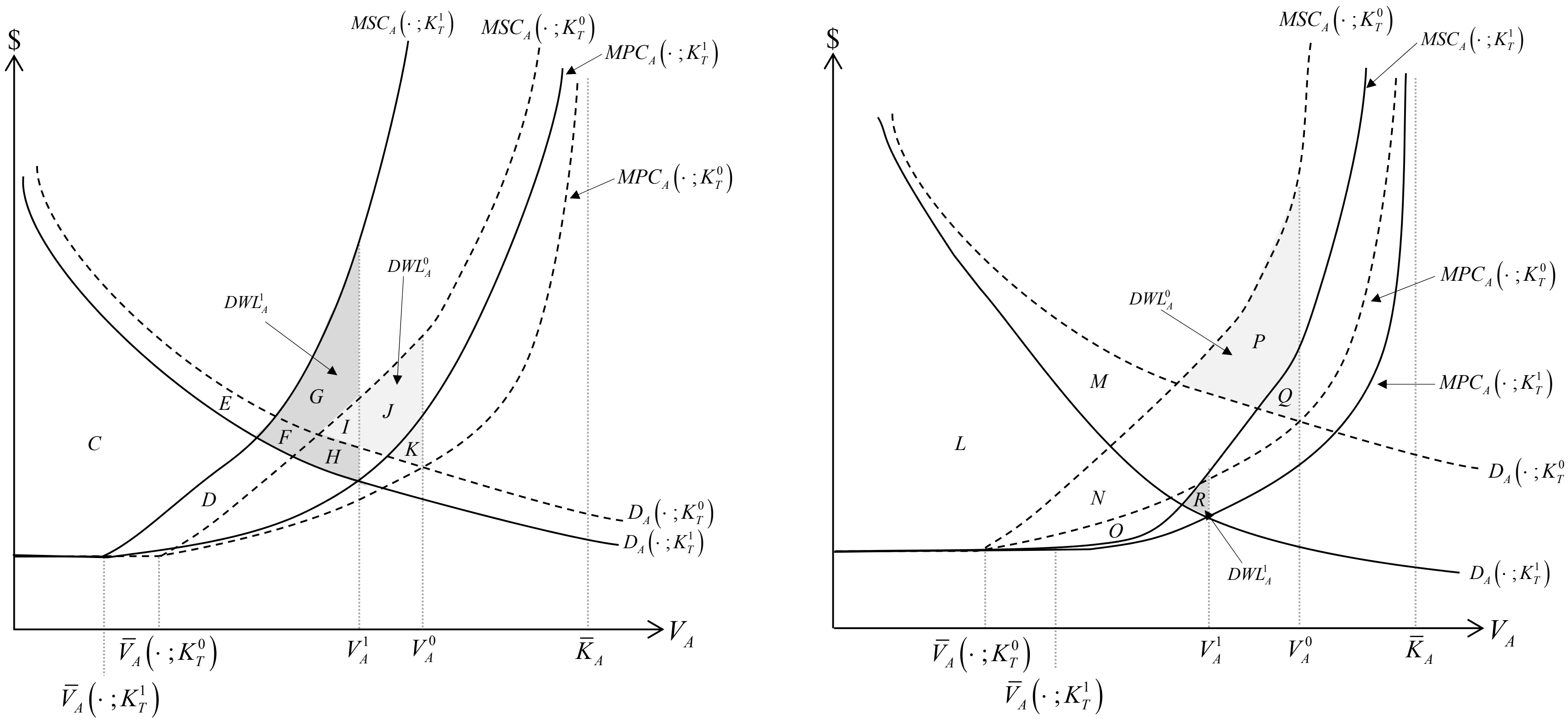

Figure 3: Change in deadweight loss in auto market after transit investment: (Left) Increase in DWL (Right) Decrease in DWL

brought about by the increase in transit network size K_T^S, and it is assumed that the marginal private cost of auto travel MPC_A is independent of transit network size.

The model suggests that second-best transit service should be increased relative to its first-best level, provided that the net benefit of demand substitution from auto to transit outweighs any adverse effects of transit investment on the auto cost function. The extent to which future transit investments can be expected to reduce the deadweight loss in the auto market becomes an empirical issue that can be informed by estimating the effects of past transit investments on traffic congestion.

The model helps reconcile the mixed empirical evidence summarized in Section 2. The studies referenced have varied datasets with differing geographical scope, types of transit modes included, and time periods covered. The net effect of transit on observed congestion is the product of several factors, summarized by the extent to which the demand and cost curves shift in the auto market in response to changes in public transit investment. The parameters in the second-best 'adjustment terms' in equations (8) may be heterogeneous across different regions and different types of transit modes, in part due to demand and cost interdependencies across the auto and transit modes, and may also be affected by the structure and characteristics of the existing transportation networks. Accordingly, the ability of transit investments to reduce the deadweight loss in the auto market may also exhibit heterogeneity.

5 Simulation Model

We now undertake a simulation exercise to estimate the effects of transit investment on the deadweight loss of congestion in the auto market.

To calibrate our simulation model, we construct a panel dataset spanning 21 years from 1991 to 2011, covering 96 urban areas within 351 counties and 44 states across the U.S. An 'urban area' (UZA) is defined by the U.S. Census Bureau and refers to a region that is centered around a core metropolitan statistical area (MSA). A UZA does not align directly with other geographic and/or political boundaries; while each UZA has a core MSA, a UZA can be contained within multiple MSAs, counties, and/or States, and a UZA is smaller in overall size than an MSA.

We simulate the first-best and unregulated user equilibria in Figure 1 for a representative UZA in the U.S. We calibrate the model using plausible specifications of the auto travel demand and cost functions along with parameter values that yield a user equilibrium auto travel volume equivalent to the median value of the 96 UZAs in the dataset. The initial deadweight loss of the user equilibrium in the auto market is calculated as a reference point to normalize the relative reduction in deadweight loss following increased transit investment.

The first objective of our simulation is to estimate the percentage reduction in deadweight loss in the auto market due to a 10% increase in transit capacity and to compare this effect with the results of the empirical model in Beaudoin and Lin Lawell (2017). The second objective is to calculate the first-best auto travel volume V_A^* and to compare V_A^* with the volume in the user equilibrium V_A^u to estimate the degree of excess auto travel. To simulate the equilibrium outcomes we must specify functional forms for the auto travel demand curve and the marginal private and external costs of auto travel. The functional forms and parameter values used are linked to the theoretical model developed in Section 3. The full details of the simulation model are contained in Appendix V.

There are three scenarios representing the various pre-existing congestion levels: 'Low', 'High' and 'Severe'. The simulation results are shown in Tables 1, 2 and 3 in Appendix V for 'Low', 'High' and 'Severe' congestion, respectively. The elasticity of the deadweight loss with respect to transit capacity exhibits similar patterns across the three scenarios, varying between -0.04 and -0.4. As expected, the magnitude of this elasticity is critically dependent upon the extent to which transit investment is able to reduce the generalized cost of transit travel (by decreasing access, wait and/or travel times) and, especially, the degree to which these lowered transit costs engender commuters to switch from auto to transit travel. The range of elasticity values mirrors the range of empirical estimates discussed in Beaudoin and Lin Lawell (2017). Intuitively, the characteristics along which the empirical elasticity estimates may vary – regional population size and density, and aspects of the public transit network – are manifested in inter-regional heterogeneity of $\frac{\%\Delta MPC_T}{\%\Delta K_T}$ and ϵ_T, ultimately leading to variation across regions in the effectiveness of transit in reducing auto congestion.

Though observed congestion levels typically relate to the volume-to-capacity ratio and our simulation results relate to the effect of transit supply on deadweight loss, we can see the link between the these two measures in Figure 8 in Appendix V, which shows how the deadweight loss varies with the volume-to-capacity ratio. Of note is the convexity of the deadweight loss with respect to the volume-to-capacity ratio, which implies that the marginal effect of transit investment in reducing congestion will be much greater in the most congested regions, again highlighting the importance of accounting for the heterogeneity of transit's congestion-reduction effect.

With 'Low' congestion, auto travel volumes should be reduced by 21% to achieve the first-best equilibrium; 30% and 34% reductions would be optimal under 'High' and 'Severe' congestion, respectively.

6 Conclusion

Traffic congestion has increased significantly in the U.S. over the last 30 years. For 96 of the largest urban areas, traffic volumes in 1982 caused an average trip to take 10% longer than it would in uncongested conditions; by 2011, this congestion delay penalty increased to 23%. The issue of congestion is attracting heightened awareness and a greater sense of urgency for policymakers as we strive for an economically and environmentally sustainable transportation sector. This paper examines the role that public transit investment can play in reducing traffic congestion.

Approximately $18 billion was spent on public transit capital in the United States in 2011 (Federal Transit Administration, *National Transit Database*). It is imperative to assess whether these investment levels are efficient and being allocated appropriately, what the effects of these expenditures are on transportation activity and the environment, and what path future investment should take. More effective management of the country's transportation infrastructure can lead to a reduction in traffic congestion, a change that would directly improve the economic competitiveness of many of the country's commercial sectors and the livability of its communities. Given the aggregate costs of congestion, even modest improvements entail significant social value.

We show that if a Pigouvian tax is not levied on auto travel, there is justification for incorporating congestion-reduction benefits in the auto market brought about by transit investment when evaluating proposed changes in transit services. A general equilibrium framework that incorporates ancillary benefits in the auto market is warranted when evaluating the efficiency of public transit supply; public transit projects should not be evaluated exclusively in terms of the forecasted net welfare generated by public transit users, but instead should also include interactions between auto and transit users in the cost-benefit analysis framework.

Transit supply tends to occur predominantly in the most heavily congested regions, largely due to the fact that these congested regions tend to be the largest and thus most suitable to support public transit operations. This underlying relationship underscores the importance of addressing the endogeneity of transit investment when evaluating the effects of transit supply on congestion. The correlation between transit operations and congested roads may yield the perception that transit is ineffective in reducing congestion; however, our results indicate that congestion would be higher if transit supply decreased.

Overall, our analysis indicates that the congestion-reduction effects of public transit supply warrant a higher level of public transit investment than would be provided on the basis of the isolated valuation of public transit ridership; this effect would be larger still if the additional negative externalities of auto travel were incorporated into this framework. The magnitude of this benefit is subject to considerable variability, and is dependent upon the characteristics of the existing transportation network, the technology of the proposed transit system, and the socioeconomic and geographic attributes of the region. The implication is that transit cost-benefit analyses must be carried out on a case-by-case basis and there may be limited scope for the external validity of regional studies, as past experiences in one city may not generalize to potential new transit investments in another.

While our results suggest that fixed guideway transit investments in dense regions yield higher congestion-reduction benefits than do mixed transit modes, this should not be construed as advocating for fixed guideway modes over mixed transit modes *per se*. In the analysis, we have only considered the benefits in the auto market due to transit investment, and have not considered the costs of the various transit modes. Both construction and operating costs of transit vary widely by region and type of transit.[14] Further, proponents of public transit may argue that investment in public transit today is necessary to develop transit ridership in the future and to influence land-use patterns in order to sow the roots for a more efficient public transit system in the future.

Having characterized the extent to which equilibrium travel volumes are affected by transit investment, the preceding analysis can be used to develop a dynamic model of the *optimal* transit investment path in the presence of uncorrected auto market distortions that can be utilized by policymakers in conducting cost-benefit analyses of potential transit investments. This can serve as a guide in formulating and evaluating long-run regional transportation plans, as a proper cost-benefit analysis accounts for the transition from the time of investment until the equilibrium is reached, factoring in the rate of induced demand and the timing of the resulting costs and benefits.

The results of this paper are consistent with Parry's (2009, pp. 462) summary of research in this area: "Expanding transit and subsidizing fares has limited impacts on automobile congestion, given relatively modest own-price elasticities for transit... Nonetheless, urban transit fares are heavily subsidized... Improving service quality (e.g. increasing transit speed, reducing wait times at stops, and improving transit access) may be more effective in deterring automobile use." This paper contributes to the literature by developing a model that allows for demand and cost interdependencies across the auto and transit modes and by accounting for heterogeneity in these interdependencies. While there is modest evidence that public transit's reputation as a 'green' policy instrument is justified, the results also reaffirm the theoretical and empirical argument that traffic congestion can only be fully addressed by devising economically and politically accepted approaches to efficiently pricing auto travel across the U.S.

[14] For recent estimates of the construction costs of different transit modes, see Table 3.5 in Small and Verhoef (2007, pp. 117).

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Appendix I - Supplementary Figures

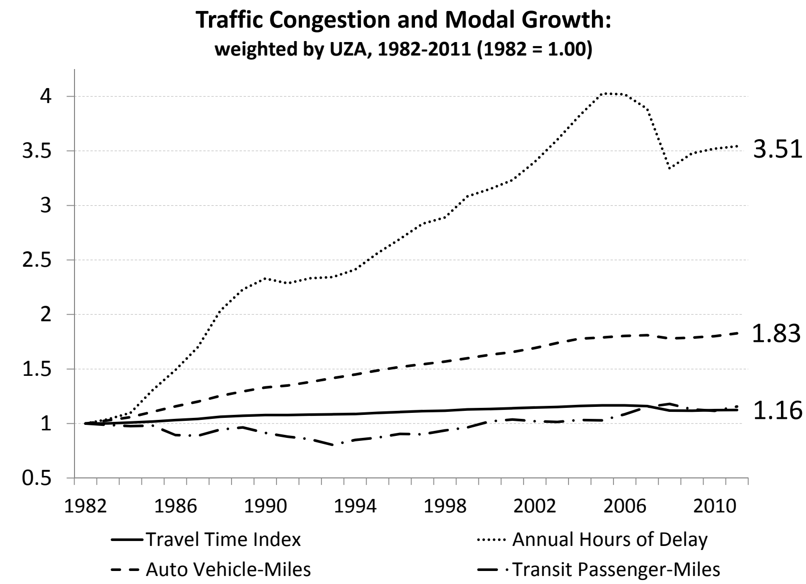

Figure 4: Congestion and travel growth for a representative urban area

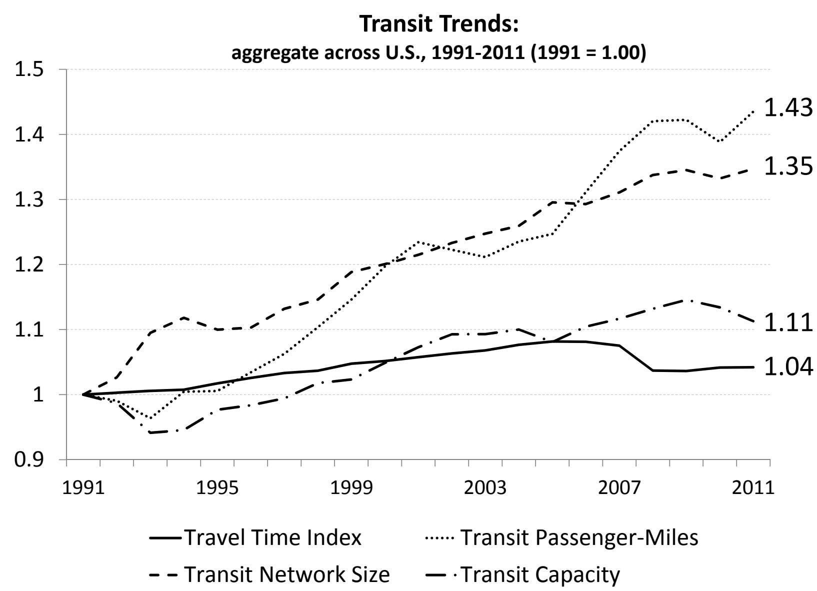

Figure 5: Trends in transit travel, transit supply and traffic congestion

Appendix II - Modal Cost Interdependency

Here we show that the cost interdependence of our theoretical model yields an uncertain effect of changes in transit supply on the cost of auto travel. From (1), the generalized marginal private cost of auto travel is given by:

$$MPC_A\left(V_A, V_T, \tau; K_T^C, \overline{K}_A\right) \equiv P_A\left(\frac{V_A}{\overline{K}_A}, \frac{K_T^C}{\overline{K}_A}, \frac{V_T}{K_T^C}\right) + T_A^T\left(\frac{V_A}{\overline{K}_A}, \frac{K_T^C}{\overline{K}_A}, \frac{V_T}{K_T^C}\right) + \tau.$$

Due to the various interaction effects across modes, the capacity of public transit service may influence the marginal private cost of auto travel as follows:

$$\begin{aligned}\frac{\partial MPC_A}{\partial K_T^C} &= \frac{\partial P_A}{\partial K_T^C} + \frac{\partial T_A^T}{\partial K_T^C} = \frac{\partial P_A}{\partial \frac{V_T}{K_T^C}}\frac{\partial \frac{V_T}{K_T^C}}{\partial K_T^C} + \frac{\partial P_A}{\partial \frac{K_T^C}{\overline{K}_A}}\frac{\partial \frac{K_T^C}{\overline{K}_A}}{\partial K_T^C} + \frac{\partial T_A^T}{\partial \frac{V_T}{K_T^C}}\frac{\partial \frac{V_T}{K_T^C}}{\partial K_T^C} + \frac{\partial T_A^T}{\partial \frac{K_T^C}{\overline{K}_A}}\frac{\partial \frac{K_T^C}{\overline{K}_A}}{\partial K_T^C} \\ &= \underbrace{\left[\overbrace{\frac{\partial P_A}{\partial \frac{V_T}{K_T^C}}}^{(+)} + \overbrace{\frac{\partial T_A^T}{\partial \frac{V_T}{K_T^C}}}^{(+)}\right]\left(\overbrace{\frac{-V_T}{\left(K_T^C\right)^2}}^{(-)}\right)}_{(-)} + \underbrace{\left[\overbrace{\frac{\partial P_A}{\partial \frac{K_T^C}{\overline{K}_A}}}^{(+)} + \overbrace{\frac{\partial T_A^T}{\partial \frac{K_T^C}{\overline{K}_A}}}^{(+)}\right]\left(\overbrace{\frac{1}{\overline{K}_A}}^{(+)}\right)}_{(+)}.\end{aligned}$$

The sign of $\frac{\partial MPC_A}{\partial K_T^C}$ is ambiguous, dependent on the relative magnitudes of (1) the benefit of reducing the cost of transit travel and inducing users to switch from auto to transit, thereby decreasing the transit congestion effect related to $\frac{V_T}{K_T^C}$, and (2) the disbenefit of transit capacity on auto congestion through the increased roadway interaction related to $\frac{K_T^C}{\overline{K}_A}$:

$$\frac{\partial MPC_A}{\partial K_T^C} = \begin{cases} > 0 \text{ if } \left|\left[\frac{\partial P_A}{\partial \frac{V_T}{K_T^C}} + \frac{\partial T_A^T}{\partial \frac{V_T}{K_T^C}}\right]\left(\frac{-V_T}{\left(K_T^C\right)^2}\right)\right| < \left|\left[\frac{\partial P_A}{\partial \frac{K_T^C}{\overline{K}_A}} + \frac{\partial T_A^T}{\partial \frac{K_T^C}{\overline{K}_A}}\right]\left(\frac{1}{\overline{K}_A}\right)\right| \\ = 0 \text{ if } \left|\left[\frac{\partial P_A}{\partial \frac{V_T}{K_T^C}} + \frac{\partial T_A^T}{\partial \frac{V_T}{K_T^C}}\right]\left(\frac{-V_T}{\left(K_T^C\right)^2}\right)\right| = \left|\left[\frac{\partial P_A}{\partial \frac{K_T^C}{\overline{K}_A}} + \frac{\partial T_A^T}{\partial \frac{K_T^C}{\overline{K}_A}}\right]\left(\frac{1}{\overline{K}_A}\right)\right| \text{ or } \frac{\partial P_A}{\partial K_T^C} = \frac{\partial T_A^T}{\partial K_T^C} = 0 \\ < 0 \text{ if } \left|\left[\frac{\partial P_A}{\partial \frac{V_T}{K_T^C}} + \frac{\partial T_A^T}{\partial \frac{V_T}{K_T^C}}\right]\left(\frac{-V_T}{\left(K_T^C\right)^2}\right)\right| > \left|\left[\frac{\partial P_A}{\partial \frac{K_T^C}{\overline{K}_A}} + \frac{\partial T_A^T}{\partial \frac{K_T^C}{\overline{K}_A}}\right]\left(\frac{1}{\overline{K}_A}\right)\right|. \end{cases}$$

As a result, the auto cost function may shift upwards or downwards (or be unaffected) following an increase in transit supply, depending on the technological characteristics of the existing and introduced transit service.

Appendix III - Transit Investment and the Cost of Transit Travel

Here we show how investing in public transit by either increasing the network size or increasing capacity is expected to lower the marginal private cost of transit travel. From (2), the generalized marginal private cost of transit travel is given by:

$$MPC_T\left(V_A, V_T, K_T^S, K_T^C; \overline{K}_A\right) \equiv P_T + T_T^A\left(K_T^S\right) + T_T^W\left(\frac{K_T^C}{K_T^S}, \frac{V_A}{\overline{K}_A}, \frac{V_T}{K_T^C}\right) + T_T^T\left(\frac{V_A}{\overline{K}_A}, \frac{V_T}{K_T^C}, \frac{K_T^C}{\overline{K}_A}, \frac{K_T^S}{\overline{K}_A}\right).$$

We first consider expansion of the transit network. Assuming that the marginal benefits of reduced access and travel times following an increase in the network size outweigh the marginal disbenefit of the indirect increase in wait time due to the transit congestion effect, i.e. $\left|\frac{\partial T_T^A}{\partial K_T^S}\right| + \left|\frac{\partial T_T^T}{\partial K_T^S}\right| > \left|\frac{\partial T_T^W}{\partial K_T^S}\right|$, then $\frac{\partial MPC_T}{\partial K_T^S} < 0$ and the transit cost function shifts downward, since:

$$\frac{\partial MPC_T}{\partial K_T^S} = \frac{\partial T_T^A}{\partial K_T^S} + \frac{\partial T_T^W}{\partial K_T^S} + \frac{\partial T_T^T}{\partial K_T^S} = \frac{\partial T_T^A}{\partial K_T^S} + \frac{\partial T_T^W}{\partial \frac{K_T^C}{K_T^S}} \frac{\partial \frac{K_T^C}{K_T^S}}{\partial K_T^S} + \frac{\partial T_T^T}{\partial \frac{K_T^S}{\overline{K}_A}} \frac{\partial \frac{K_T^S}{\overline{K}_A}}{\partial K_T^S}$$

$$= \underbrace{\frac{\partial T_T^A}{\partial K_T^S}}_{(-)} + \underbrace{\left[\overbrace{\frac{\partial T_T^W}{\partial \frac{K_T^C}{K_T^S}}}^{(-)}\right]\left(\overbrace{\frac{-K_T^C}{\left(K_T^S\right)^2}}^{(-)}\right)}_{(+)} + \underbrace{\left[\overbrace{\frac{\partial T_T^T}{\partial \frac{K_T^S}{\overline{K}_A}}}^{(-)}\right]\left(\overbrace{\frac{1}{\overline{K}_A}}^{(+)}\right)}_{(-)}.$$

We next consider an increase in transit capacity. Assuming that the marginal benefit of reduced waiting time outweighs the marginal disbenefit of increased travel time due to the transit congestion effect associated with increasing transit capacity, i.e. $\left|\frac{\partial T_T^W}{\partial K_T^C}\right| > \left|\frac{\partial T_T^T}{\partial K_T^C}\right|$, then $\frac{\partial MPC_T}{\partial K_T^C} < 0$ and the transit cost function shifts downward, since:

$$\frac{\partial MPC_T}{\partial K_T^C} = \frac{\partial T_T^W}{\partial K_T^C} + \frac{\partial T_T^T}{\partial K_T^C} = \frac{\partial T_T^W}{\partial \frac{K_T^C}{K_T^S}} \frac{\partial \frac{K_T^C}{K_T^S}}{\partial K_T^C} + \frac{\partial T_T^W}{\partial \frac{V_T}{K_T^C}} \frac{\partial \frac{V_T}{K_T^C}}{\partial K_T^C} + \frac{\partial T_T^T}{\partial \frac{V_T}{K_T^C}} \frac{\partial \frac{V_T}{K_T^C}}{\partial K_T^C} + \frac{\partial T_T^T}{\partial \frac{K_T^C}{\overline{K}_A}} \frac{\partial \frac{K_T^C}{\overline{K}_A}}{\partial K_T^C}$$

$$= \underbrace{\left[\overbrace{\frac{\partial T_T^W}{\partial \frac{V_T}{K_T^C}}}^{(+)} + \overbrace{\frac{\partial T_T^T}{\partial \frac{V_T}{K_T^C}}}^{(+)}\right]\left(\overbrace{\frac{-V_T}{\left(K_T^C\right)^2}}^{(-)}\right)}_{(-)} + \underbrace{\left[\overbrace{\frac{\partial T_T^W}{\partial \frac{K_T^C}{K_T^S}}}^{(-)}\right]\left(\overbrace{\frac{1}{K_T^S}}^{(+)}\right)}_{(-)} + \underbrace{\left[\overbrace{\frac{\partial T_T^T}{\partial \frac{K_T^C}{\overline{K}_A}}}^{(+)}\right]\left(\overbrace{\frac{1}{\overline{K}_A}}^{(+)}\right)}_{(+)}.$$

Appendix IV - Simulation Model

In this Appendix, we outline the full details of the simulation model introduced in Section 5. Figure 7 below illustrates the simulation model with the assumed functional forms. A Base Case equilibrium provides a reference value for the unregulated and first-best equilibria, and the concomitant deadweight loss attributable to the congestion externality DWL_A. Several scenarios are then examined whereby an increase in transit supply decreases the generalized cost of transit travel and leads to some degree of modal shift from auto to transit travel, generating new user and first-best equilibria and thus a change in the deadweight loss in the auto market. Of primary interest is the percentage reduction in deadweight loss in the auto market due to a 10% increase in transit capacity, $\frac{\%\Delta DWL_A}{\%\Delta K_T}$, which is simulated for a wide range of different parameter value combinations.

Demand Curve for Auto Travel

The inverse demand curve for auto travel $D_A(\cdot)$ is assumed to exhibit constant elasticity with respect to the generalized costs of auto and transit travel, given by $\epsilon_A < 0$ and $\epsilon_T > 0$, respectively. Defining the quantity of auto travel as $V_A = \alpha_1 MPC_A^{\epsilon_A} MPC_T^{\epsilon_T}$ yields the desired result that $\frac{\partial V_A}{\partial MPC_A} < 0$ and $\frac{\partial V_A}{\partial MPC_T} > 0$, where the cross-elasticity of auto demand with respect to the generalized cost of transit travel incorporates shifts in the auto demand curve due to the change in the marginal private cost of transit travel following transit investment.[15] Modal prices are normalized by setting the baseline value of the per-unit cost of transit travel as $MPC_T = 1$, and the magnitude of the effect of transit supply on the generalized cost of transit travel $\frac{\partial MPC_T}{\partial K_T} < 0$ is assumed to vary across scenarios.

Litman (2013) provides a thorough review of existing studies estimating various transportation demand elasticities, summarizing several studies that have estimated ϵ_A. There is a wide variation in magnitudes depending on the context in which this elasticity is measured.[16] Oum et al. (2008) review nine studies and report that the range of ϵ_A generally lies between -0.1 and -0.5 for peak auto travel demand, and we use the midpoint value of -0.3 as our value for ϵ_A. Relatively few studies have examined ϵ_T. Past changes in transit fares or travel time have been estimated to have a minor effect on auto demand levels; Litman (2013) summarizes these past studies[17] and reports that the elasticity of auto travel demand with respect to changes in transit cost or travel time typically ranges from 0.01 to 0.09. We use the midpoint value of 0.05 as our baseline value for ϵ_T and vary this parameter across scenarios. α_1 is calibrated by initializing the baseline user equilibrium auto travel volume V_A^u to reflect observed 2011 data.

[15] The α values are calibration parameters throughout.

[16] See Tables 4, 9, 10, 18, and 29 in Litman (2013).

[17] See Tables 7, 31, 33, and 35 in Litman (2013).

Marginal Private Cost of Auto Travel

The marginal private cost of auto travel function in Equation (1) should have the following characteristics: (1) a threshold volume-to-capacity ratio $\widehat{\left(\frac{V_A}{K_A}\right)}$ where the congestion externality begins, and (2) the function is strictly convex beyond $\widehat{\left(\frac{V_A}{K_A}\right)}$. As we are interested in the effects of transit supply on the auto market in a second-best setting, we assume that $\tau = 0$.

The MPC_A function has two components: the monetary cost of auto travel P_A and the monetized value of travel time T_A^T. In our dataset, the median fuel cost in 2011 was \$0.1586 per vehicle-mile traveled. This value is similar to that computed by AAA in its 2011 report: the average gas cost per mile was \$0.1234, and the per-mile operating costs (including gas, maintenance and tires) were estimated to be \$0.1774.[18] Fuel efficiency is dependent upon the distribution of travel speeds and thus is a function of the level of congestion, in part due to the stop-and-start driving necessary in congested conditions. Overall, there is typically a U-shaped relationship between fuel consumption and travel speeds (see Barth and Boriboonsomsin (2009) for a related discussion of the relationship between vehicle emissions and travel speeds). Parry (2009) notes that it is typically assumed that heavily congested conditions increase fuel consumption by 30%, though there is considerable uncertainty surrounding this magnitude. According to Greenwood et al. (2007), congestion increases fuel consumption by 13-36% on average across a sample of different vehicle types. To represent this relationship, we use the following functional form:

$$P_A = \begin{cases} \tilde{P_A} & \text{if } \left(\frac{V_A}{K_A}\right) \leq \widehat{\left(\frac{V_A}{K_A}\right)} \\ \\ \tilde{P_A}\left(1 + \alpha_2\left(\frac{V_A}{K_A} - \widehat{\left(\frac{V_A}{K_A}\right)}\right)^2\right) & \text{if } \left(\frac{V_A}{K_A}\right) > \widehat{\left(\frac{V_A}{K_A}\right)}. \end{cases} \tag{10}$$

This assumes that fuel efficiency is maximized at a volume-to-capacity ratio less than or equal to $\widehat{\left(\frac{V_A}{K_A}\right)}$ and decreases at higher travel volumes; we assume that $\widehat{\left(\frac{V_A}{K_A}\right)} = 0.5$. The minimum per-unit fuel cost is given by $\tilde{P_A}$ and we use the AAA value, since our estimated per-unit fuel cost is averaged across the largest (and generally most congested) regions. With $\tilde{P_A} = \$0.1234$, α_2 is calibrated to 1.7 to generate an increase in fuel consumption that approaches 42.5% (per-unit value of \$0.176) as the volume-to-capacity ratio increases from 0.5 to 1.

The monetized value of travel time T_A^T is the product of the value of travel time and the travel duration $\tilde{T}_A^T$. Time-averaged speed-flow functions relate the average speed over a specified period to the average vehicle inflow over that period, consistent with the static equilibrium model we are

[18] See http://exchange.aaa.com/wp-content/uploads/2012/04/DrivingCosts2011.pdf.

using. This relationship can be modeled as a power function of the volume-to-capacity ratio:

$$\tilde{T}_A^T = \begin{cases} T_f & \text{if } \left(\frac{V_A}{\overline{K}_A}\right) \leq \widehat{\left(\frac{V_A}{\overline{K}_A}\right)} \\ \\ T_f \left[1 + \alpha_3 \left(\frac{V_A}{\overline{K}_A}\right)^{\alpha_4}\right] & \text{if } \left(\frac{V_A}{\overline{K}_A}\right) > \widehat{\left(\frac{V_A}{\overline{K}_A}\right)} \end{cases} \tag{11}$$

where $\tilde{T}_A^T$ denotes travel time per mile and T_f is free-flow travel speed with no congestion. We assume that $T_f = \frac{1}{60}$ hours per mile. This function is used by the U.S. Department of Transportation. With $\alpha_3 = 0.2$ for freeways and $\alpha_4 = 10$, it is known as the 'updated Bureau of Public Roads (BPR) function' and was proposed by Skabardonis and Dowling (1996).

$\overline{K}_A$ is calibrated based on V_A^u and three alternative levels of congestion: low congestion (Level of Service (LOS) 'B'), high congestion (LOS 'D') and severe congestion (LOS 'F').[19] In 2011, the median daily auto travel volume V_A^u on the freeways of the 96 UZAs was 8,492,500 vehicle-miles. For the LOS 'B' scenario we assume that $\left(\frac{V_A^u}{\overline{K}_A}\right) = 0.5$ which implies that $\overline{K}_A = 16,985,000$; for the LOS 'D' scenario we assume that $\left(\frac{V_A^u}{\overline{K}_A}\right) = 0.825$ which yields $\overline{K}_A = 10,293,939$; and for the LOS 'F' scenario we assume that $\left(\frac{V_A^u}{\overline{K}_A}\right) = 1.05$ and thus $\overline{K}_A = 8,088,095$.

This then yields the monetized value of travel time as:

$$T_A^T = \begin{cases} VOT_A^T \cdot T_f & \text{if } \left(\frac{V_A}{\overline{K}_A}\right) \leq \widehat{\left(\frac{V_A}{\overline{K}_A}\right)} \\ \\ VOT_A^T \cdot T_f \left[1 + \alpha_3 \left(\frac{V_A}{\overline{K}_A}\right)^{\alpha_4}\right] & \text{if } \left(\frac{V_A}{\overline{K}_A}\right) > \widehat{\left(\frac{V_A}{\overline{K}_A}\right)}. \end{cases} \tag{12}$$

Taken together, the marginal private cost of auto travel is:

$$MPC_A = \begin{cases} \tilde{P}_A + VOT_A^T \cdot T_f & \text{if } \left(\frac{V_A}{\overline{K}_A}\right) \leq \widehat{\left(\frac{V_A}{\overline{K}_A}\right)} \\ \\ \tilde{P}_A \left(1 + \alpha_2 \left(\frac{V_A}{\overline{K}_A} - \widehat{\left(\frac{V_A}{\overline{K}_A}\right)}\right)^2\right) + VOT_A^T \cdot T_f \left[1 + \alpha_3 \left(\frac{V_A}{\overline{K}_A}\right)^{\alpha_4}\right] & \text{if } \left(\frac{V_A}{\overline{K}_A}\right) > \widehat{\left(\frac{V_A}{\overline{K}_A}\right)}. \end{cases} \tag{13}$$

[19] The Transportation Research Board classifies Levels of Service according to ranges of the volume-to-capacity ratio. LOS 'B' is associated with a volume-to-capacity ratio of 0.35-0.58 and "represents reasonably free-flowing conditions but with some influence by others." LOS 'D' occurs with a volume-to-capacity ratio of 0.75-0.90 and "represents traffic operations approaching unstable flow with high passing demand and passing capacity near zero, characterized by drivers being severely restricted in maneuverability." LOS 'F' implies a volume-to-capacity ratio greater than 1 and "represents the worst conditions with heavily congested flow and traffic demand exceeding capacity, characterized by stop-and-go waves, poor travel time, low comfort and convenience, and increased accident exposure." See Transportation Research Board (2010).

For simplicity, we assume there is no congestion interdependence across modes, with the auto congestion function independent of the level of transit supplied. The value of auto travel time is typically assumed to be equal to 50% of the wage rate, though the value of time in congested conditions is approximately twice as high as that in uncongested conditions, as an indication of the value that commuters place on reliable travel times (Berechman, 2009, pp. 71). We assume that VOT_A^T = \$16.30 per hour (the 2011 value of time used by Schrank et al. (2012)).[20] With an average vehicle occupancy of 1.25, this implies a per-vehicle value of time of \$20.375 per hour.

Marginal External Cost of Auto Travel

The marginal external cost of auto travel MEC_A can be derived from the marginal private cost above: $MEC_A(\cdot) = V_A \frac{\partial MPC_A}{\partial V_A} = V_A \left[\frac{\partial P_A}{\partial V_A} + \frac{\partial T_A^T}{\partial V_A}\right]$. This implies:

$$MEC_A = \begin{cases} 0 & \text{if } \left(\frac{V_A}{K_A}\right) \leq \widehat{\left(\frac{V_A}{K_A}\right)} \\ \frac{V_A}{K_A}\left[2\alpha_2 \tilde{P}_A\left(\frac{V_A}{K_A} - \widehat{\left(\frac{V_A}{K_A}\right)}\right) + \alpha_3\alpha_4 VOT_A^T \cdot T_f \left(\frac{V_A}{K_A}\right)^{\alpha_4 - 1}\right] & \text{if } \left(\frac{V_A}{K_A}\right) > \widehat{\left(\frac{V_A}{K_A}\right)} \end{cases} \tag{14}$$

This function is assumed to contain only the congestion externality and it is an increasing function of the volume-to-capacity ratio. The magnitude of the congestion externality thus varies across the three scenarios outlined above: for LOS 'B' the marginal external cost is negligible, while for LOS 'D' the marginal external cost of auto travel (evaluated at the user equilibrium) is 43% of the marginal private cost, and this ratio increases to 212% for LOS 'F'. Figure 6 shows how the volume-to-capacity ratio relates to travel speeds based on the model parameters.

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[20] This value abstracts from any non-pecuniary cost which may be associated with time spent traveling on a congested road. For a discussion of the effect of non-pecuniary factors on the valuation of work time, and hence on travel time, see Farzin (2009).

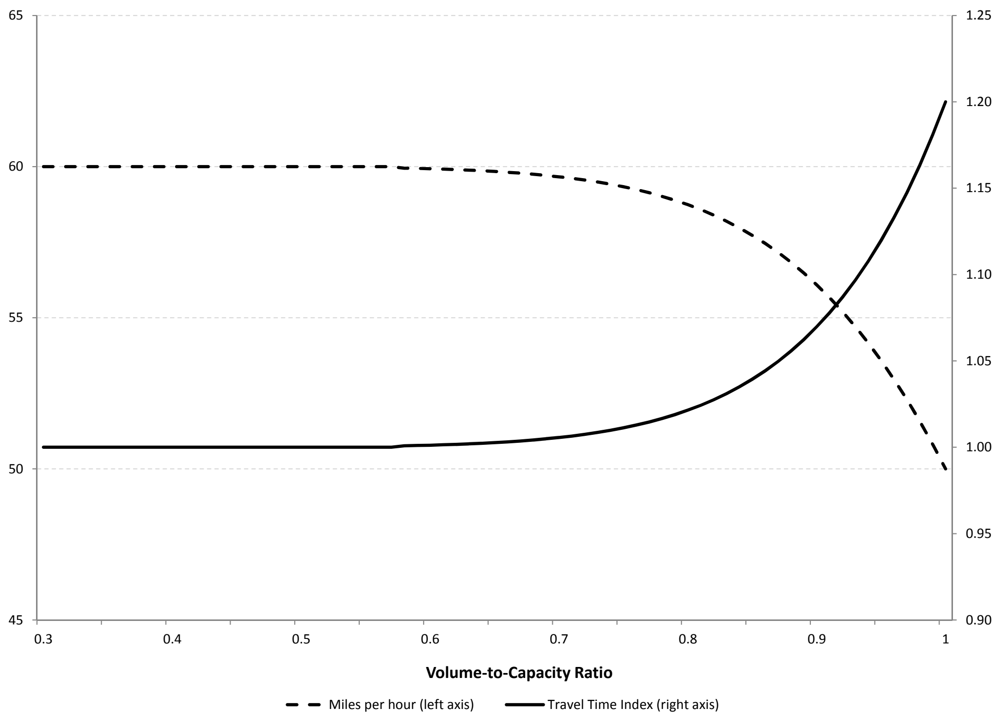

Figure 6: Relationship between volume-to-capacity ratio and travel speeds for simulation model

Marginal Social Cost of Auto Travel

The marginal social cost of auto travel MSC_A is derived by summing the marginal private and external costs above, accounting for the threshold value:

$$MSC_A = \begin{cases} \tilde{P_A} + VOT_A^T \cdot T_f & \text{if } \left(\frac{V_A}{\overline{\overline{K}}_A}\right) \leq \widehat{\left(\frac{V_A}{\overline{\overline{K}}_A}\right)} \\ \tilde{P_A}\left(1+\alpha_2\left(\frac{V_A}{\overline{\overline{K}}_A} - \widehat{\left(\frac{V_A}{\overline{\overline{K}}_A}\right)}\right)^2\right) & \\ + VOT_A^T \cdot T_f\left[1+\alpha_3\left(\frac{V_A}{\overline{\overline{K}}_A}\right)^{\alpha_4}\right] & \text{if } \left(\frac{V_A}{\overline{\overline{K}}_A}\right) > \widehat{\left(\frac{V_A}{\overline{\overline{K}}_A}\right)} \\ + \frac{V_A}{\overline{\overline{K}}_A}\left[2\alpha_2\tilde{P_A}\left(\frac{V_A}{\overline{\overline{K}}_A} - \widehat{\left(\frac{V_A}{\overline{\overline{K}}_A}\right)}\right) + \alpha_3\alpha_4 VOT_A^T \cdot T_f\left(\frac{V_A}{\overline{\overline{K}}_A}\right)^{\alpha_4 - 1}\right] & \end{cases} \tag{15}$$

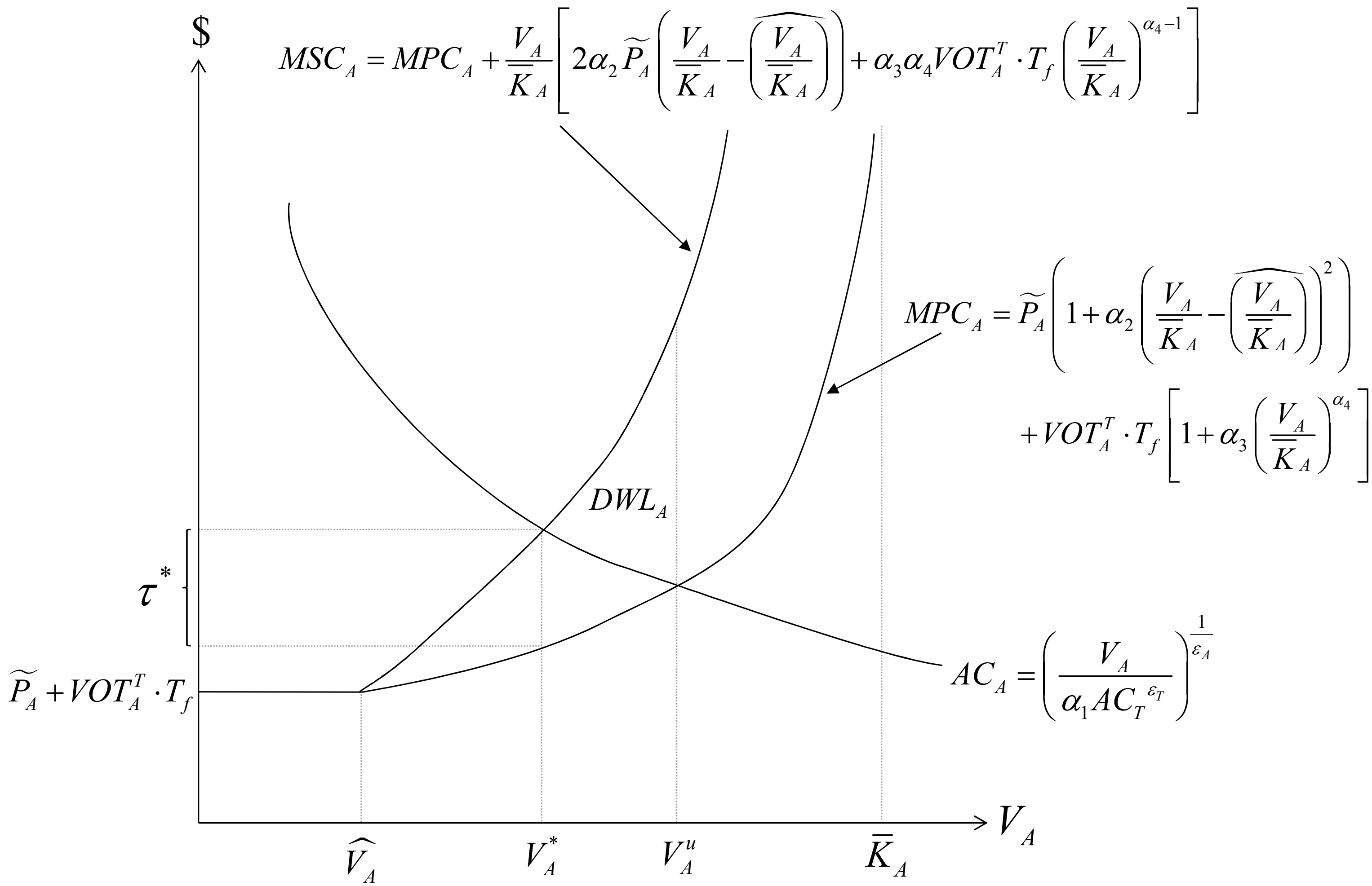

Figure 7: Simulation model with assumed functional forms

Model Results

There are three scenarios representing the various pre-existing congestion levels: 'Low', 'High' and 'Severe'. We are interested in two parameters: (1) the effect of transit investment on the generalized cost of transit travel, $\frac{\%\Delta MPC_T}{\%\Delta K_T}$, which translates a 10% increase in transit supply to a given percentage reduction in the normalized cost of transit travel MPC_T, and (2) the cross-elasticity of auto demand with respect to the cost of transit travel, ϵ_T. In order to isolate the effect of these parameters, each scenario has a Base Case and ten alternative cases where one of the parameters is varied.

Cases 1-5 hold ϵ_T constant at 0.05 and vary $\frac{\%\Delta MPC_T}{\%\Delta K_T}$ between -0.2 and -1 (which implies that a 10% increase in transit supply leads to a 2-10% reduction in the average generalized cost of transit travel). Cases 6-10 hold $\frac{\%\Delta MPC_T}{\%\Delta K_T}$ constant at -0.5 and varies ϵ_T between 0.02 and 0.2. The simulation results are shown below in Tables 1, 2 and 3 for 'Low', 'High' and 'Severe' congestion, respectively.

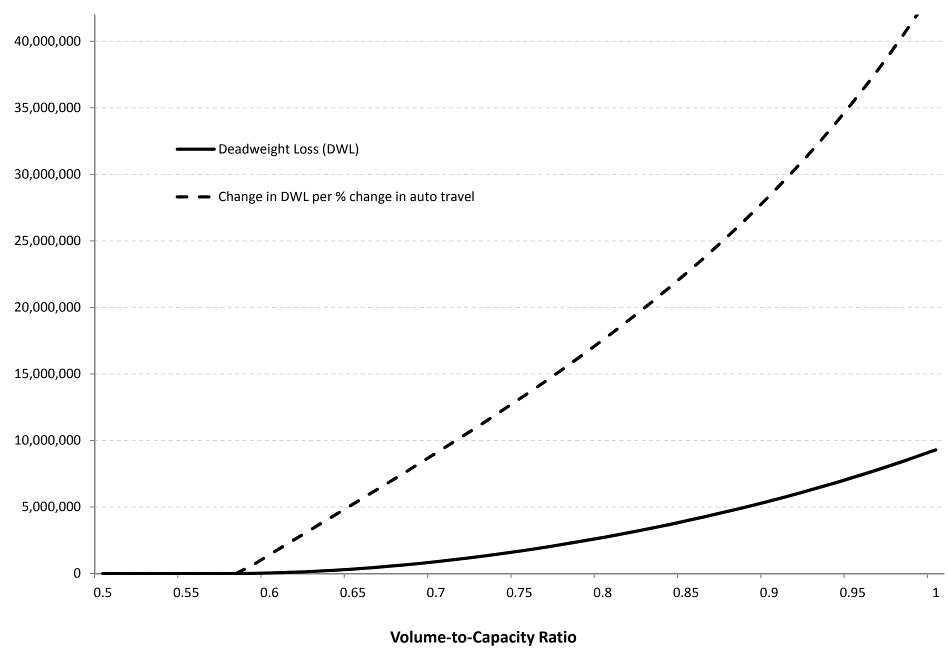

Figure 8: Congestion deadweight loss as volume-to-capacity ratio varies

Table 1: Simulation results: LOS ‘B’, Low Congestion

		Base Case	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Fixed Values	α_1	6,740.7	6,740.7	6,740.7	6,740.7	6,740.7	6,740.7	6,740.7	6,740.7	6,740.7	6,740.7	6,740.7
	α_2	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
	α_3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	α_4	10	10	10	10	10	10	10	10	10	10	10
	$\tilde{P}_A$	0.1234	0.1234	0.1234	0.1234	0.1234	0.1234	0.1234	0.1234	0.1234	0.1234	0.1234
	$\overline{K}_A$	16,985.0	16,985.0	16,985.0	16,985.0	16,985.0	16,985.0	16,985.0	16,985.0	16,985.0	16,985.0	16,985.0
	$\widehat{\left(\frac{V_A}{K_A}\right)}$	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	T_f	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$
	VOT_A^T	20.375	20.375	20.375	20.375	20.375	20.375	20.375	20.375	20.375	20.375	20.375
	ϵ_A	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
Varied	$\frac{\%\Delta MPC_T}{\%\Delta K_T}$	-	-0.2	-0.4	-0.6	-0.8	-1	-0.5	-0.5	-0.5	-0.5	-0.5
	MPC_T	1.00	0.98	0.96	0.94	0.92	0.9	0.95	0.95	0.95	0.95	0.95
	ϵ_T	0.05	0.05	0.05	0.05	0.05	0.05	0.02	0.05	0.1	0.15	0.2
Output	V_A^u	8,492.5	8,483.9	8,475.2	8,466.2	8,457.1	8,447.9	8,483.8	8,470.7	8,449.0	8,427.4	8,405.8
	V_A^*	6,739.5	6,734.3	6,729.0	6,723.7	6,718.2	6,712.5	6,734.2	6,726.4	6,713.3	6,700.2	6,687.1
	$\frac{V_A^*}{V_A^u}$	0.794	0.794	0.794	0.794	0.794	0.795	0.794	0.794	0.795	0.795	0.796
	DWL_A	812.1	808.9	805.6	802.2	798.8	795.3	808.8	803.9	795.8	787.8	779.8
Implied elasticity of auto market deadweight loss with respect to transit capacity												
$\frac{\%\Delta DWL_A}{\%\Delta K_T}$		-	-0.040	-0.080	-0.122	-0.163	-0.206	-0.040	-0.101	-0.201	-0.300	-0.398

Table 2: Simulation results: LOS 'D', High Congestion

		Base Case	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Fixed Values	α_1	6,835.9	6,835.9	6,835.9	6,835.9	6,835.9	6,835.9	6,835.9	6,835.9	6,835.9	6,835.9	6,835.9
	α_2	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
	α_3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	α_4	10	10	10	10	10	10	10	10	10	10	10
	$\tilde{P}_A$	0.1234	0.1234	0.1234	0.1234	0.1234	0.1234	0.1234	0.1234	0.1234	0.1234	0.1234
	$\overline{K}_A$	10,293.9	10,293.9	10,293.9	10,293.9	10,293.9	10,293.9	10,293.9	10,293.9	10,293.9	10,293.9	10,293.9
	$\widehat{\left(\frac{V_A}{\overline{K}_A}\right)}$	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	T_f	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$
	VOT_A^T	20.375	20.375	20.375	20.375	20.375	20.375	20.375	20.375	20.375	20.375	20.375
	ϵ_A	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
Varied	$\frac{\%\Delta MPC_T}{\%\Delta K_T}$	-	-0.2	-0.4	-0.6	-0.8	-1	-0.5	-0.5	-0.5	-0.5	-0.5
	MPC_T	1.00	0.98	0.96	0.94	0.92	0.9	0.95	0.95	0.95	0.95	0.95
	ϵ_T	0.05	0.05	0.05	0.05	0.05	0.05	0.02	0.05	0.1	0.15	0.2
Output	V_A^u	8,492.5	8,484.5	8,476.3	8,467.9	8,459.4	8,450.7	8,484.3	8,472.1	8,451.8	8,431.6	8,411.3
	V_A^*	5,938.3	5,934.1	5,929.8	5,925.5	5,921.0	5,916.5	5,934.0	5,927.7	5,917.1	5,906.5	5,895.9
	$\frac{V_A^*}{V_A^u}$	0.699	0.699	0.700	0.700	0.700	0.700	0.699	0.700	0.700	0.701	0.701
	DWL_A	3,297.7	3,286.0	3,274.2	3,262.1	3,249.8	3,237.3	3,285.9	3,268.2	3,238.9	3,209.9	3,181.2
Implied elasticity of auto market deadweight loss with respect to transit capacity												
$\frac{\%\Delta DWL_A}{\%\Delta K_T}$		-	-0.035	-0.071	-0.108	-0.145	-0.183	-0.036	-0.090	-0.178	-0.266	-0.353

Table 3: Simulation results: LOS 'F', Severe Congestion

		Base Case	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Fixed Values	α_1	7,005.6	7,005.6	7,005.6	7,005.6	7,005.6	7,005.6	7,005.6	7,005.6	7,005.6	7,005.6	7,005.6
	α_2	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
	α_3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	α_4	10	10	10	10	10	10	10	10	10	10	10
	$\tilde{P}_A$	0.1234	0.1234	0.1234	0.1234	0.1234	0.1234	0.1234	0.1234	0.1234	0.1234	0.1234
	$\overline{K}_A$	8,088.1	8,088.1	8,088.1	8,088.1	8,088.1	8,088.1	8,088.1	8,088.1	8,088.1	8,088.1	8,088.1
	$\widehat{\left(\frac{V_A}{\overline{K}_A}\right)}$	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	T_f	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$	$\frac{1}{60}$
	VOT_A^T	20.375	20.375	20.375	20.375	20.375	20.375	20.375	20.375	20.375	20.375	20.375
	ϵ_A	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
Varied	$\frac{\%\Delta MPC_T}{\%\Delta K_T}$	-	-0.2	-0.4	-0.6	-0.8	-1	-0.5	-0.5	-0.5	-0.5	-0.5
	MPC_T	1.00	0.98	0.96	0.94	0.92	0.9	0.95	0.95	0.95	0.95	0.95
	ϵ_T	0.05	0.05	0.05	0.05	0.05	0.05	0.02	0.05	0.1	0.15	0.2
Output	V_A^u	8,492.5	8,485.0	8,477.3	8,469.5	8,461.5	8,453.3	8,484.9	8,473.4	8,454.3	8,435.2	8,416.2
	V_A^*	5,594.7	5,590.9	5,587.0	5,583.1	5,579.1	5,575.0	5,590.8	5,585.1	5,575.5	5,565.9	5,556.4
	$\frac{V_A^*}{V_A^u}$	0.659	0.659	0.659	0.659	0.659	0.660	0.659	0.659	0.659	0.660	0.660
	DWL_A	6,781.5	6,754.7	6,727.6	6,700.0	6,672.0	6,643.5	6,754.3	6,713.9	6,647.1	6,581.1	6,516.0
Implied elasticity of auto market deadweight loss with respect to transit capacity												
$\frac{\%\Delta DWL_A}{\%\Delta K_T}$		-	-0.039	-0.079	-0.120	-0.161	-0.203	-0.040	-0.100	-0.198	-0.295	-0.391