Public Transit Investment and Sustainable Transportation:

A Review of Studies of Transit's Impact on Traffic Congestion and Air Quality

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Abstract

In this paper we provide a framework for evaluating public transit investment, taking account of the effects of transit investment on traffic congestion and air quality. We discuss how to assess the sustainability of transit investment and the mechanisms through which public transit investment can affect equilibrium auto travel volumes and the associated congestion and air quality outcomes. Several related issues are addressed: the differences between short-run and long-run equilibria; the role of regional heterogeneity; regulatory and policy considerations; and the potential endogeneity of transit investment when conducting empirical analyses. As the transportation policy landscape evolves and technological advancements continue, a complete evaluation of the social benefits of transit investment is essential both for allocating investment funds and for designing policies that result in an efficient level of investment and travel in the long run. Does the existing evidence bolster public transit's 'green' reputation? Reviewing the recent empirical literature, it appears that transit can both reduce congestion and improve air quality, but the magnitudes of these benefits are uncertain and may be specific to each location.

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1 Introduction

The cost of time spent in congested traffic conditions is readily apparent to commuters across the U.S. The Texas Transportation Institute (TTI) made headlines with its estimate of the annual costs of traffic congestion in the U.S. exceeding $120 billion in 2011 (Schrank et al., 2012), owing primarily to the costs imposed by excessive traffic levels on travel times for freight and personal travel.

Additionally, there are other less salient costs of urban transportation. Congestion leads to wasted fuel, and vehicle emissions also have additional costly adverse public health effects. Levy et al. (2010) estimate that in 2010 vehicle emissions in the U.S. contributed to 2200 premature deaths and more than $18 billion in public health expenditures. A sizable body of literature is developing regarding the costs of climate change; given the significant contribution of transportation activity to carbon emissions, a large portion of these costs is attributable to transportation.

There have been reports that the cost of congestion is predicted to increase by fifty percent by 2030 (Guerrini, 2014). This scenario is related to forecasted growth in population and GDP, declining fuel prices and increasing car ownership. However, such projections typically do not account for the potential adaptive behavior of individuals in response to the presence of congestion, nor the effects of technological innovation and regulatory and policy changes that may occur over time.

One policy that could alter the trajectory of the traffic congestion and air pollution costs is investment in public transit infrastructure and increased transit service. In 2012, $18.2 billion was spent on public transit capital in the U.S. and $39.7 billion was spent on transit operating expenses, increasing from $5.4 billion and $16.8 billion in 1992, respectively[1] (American Public Transportation Association, *2014 Fact Book*). Public transit is viewed as an important component of efficient transportation systems, enhancing the mobility of travelers and improving the accessibility and livability of a region. Investment in public transit is often advocated on the basis of its purported role in reducing traffic congestion and improving air quality. However, whether public transit actually does reduce congestion and improve air quality is the subject of debate. To forecast the future impact of transit on congestion and air quality, it is necessary to examine the historical data concerning these relationships, and the empirical evidence is equivocal – and fairly limited – in this

[1] These values are in nominal terms; adjusting for inflation via the Consumer Price Index implies that capital outlays increased by 106% and operating expenditures increased by 44% in real terms.

regard.

In this paper we outline a framework for evaluating the effects of public transit investment on congestion and air quality and review the empirical literature examining these relationships. An understanding of these issues is critical for informing policy debates regarding current and future investment in transit and to help policymakers make sustainable urban transportation decisions.

2 Theoretical Framework

2.1 Defining 'Sustainable' Transportation

Transit is often anointed as a key component of 'sustainable' transportation policy, though the well-intentioned concept of sustainability is nebulous in practice. The Brundtland Commission defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987). The challenge is to operationalize this concept for urban transportation in relation to congestion and emissions. From an economic standpoint, 'sustainable transportation' should be synonymous with dynamic efficiency, where the present discounted value of the entire stream of net social benefits of urban transportation travel is maximized,[2] incorporating the full social costs of congestion and emissions. The objective should not be to minimize congestion or to completely eliminate air pollution, but rather to balance the marginal benefits and marginal social costs of investment decisions in order to generate the welfare-maximizing travel volumes and modal allocations, forecasted over the life of the investment. To achieve sustainable urban transportation, the status quo necessitates not only short-run action to ameliorate the existing external costs of inefficiently high auto travel volumes and improve the welfare of the current generation, but also appropriate investments today in order to maintain the welfare of future generations and achieve efficient travel levels in the long run.

Policymakers are faced with the difficult task of converting observed and forecasted measures of congestion and air quality to monetized valuations under various investment and policy scenarios so that these values can be compared with the costs of investments in order to allocate investment funds, design policies and assess whether the efficient volume of travel is achieved.

[2] Whereby the social discount rate determines how inter-generational welfare tradeoffs are evaluated.

2.2 Measuring Congestion and Air Quality

Traffic congestion is fundamentally related to the ratio of the volume of travel and the capacity of the roadways. The TTI's Urban Mobility Report (Schrank et al., 2012) provides the most comprehensive measures of congestion available, including the Travel Time and Roadway Congestion indices, which compare observed travel times to counterfactual travel times in the absence of any congestion. Other examples of congestion measures include annual hours of delay per commuter and the percentage of peak period travel occurring in congested conditions. The effects of vehicle emissions are typically measured by the ambient levels of relevant pollutants that individuals are exposed to and the concomitant adverse health impacts.

2.3 Public Transit Investment and the Urban Travel Equilibrium

We now discuss the mechanisms through which public transit investment can lead to changes in auto traffic and the associated congestion and air quality outcomes, in the context of evaluating public transit investment; this framework is illustrated in Figure 1.

Public transit investment influences the transportation equilibrium in the short run by reducing the non-monetary cost of transit travel, and (potentially) inducing some auto users to switch to transit. In the long run, transit investment affects land-use development patterns and decisions relating to home and work location choices and vehicle ownership.[3]

To evaluate public transit investment, its effect on congestion and air quality must be quantified by comparing the new predicted equilibrium following the investment with the baseline scenario that would persist in the absence of this investment. A proper evaluation of the economic viability of potential public transit investments requires a full cost-benefit analysis that incorporates the change in the volume of auto travel attributable to changes in transit supply. This analysis should include monetized valuations of changes in the deadweight loss of auto travel due to inadequately regulated negative externalities. These externalities include traffic congestion and emissions of both localized pollutants such as sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3) and particulate matter

[3] While this paper focuses on the impact of public transit on personal auto use, transit investment may also influence the amount of freight travel in urban areas via reductions in congestion in the short run and via spatial changes relating to land use and population density in the long run. This induced effect on aggregate freight activity and its spatial distribution may affect equilibrium congestion and air quality. This is an important consideration that is not explored further here.

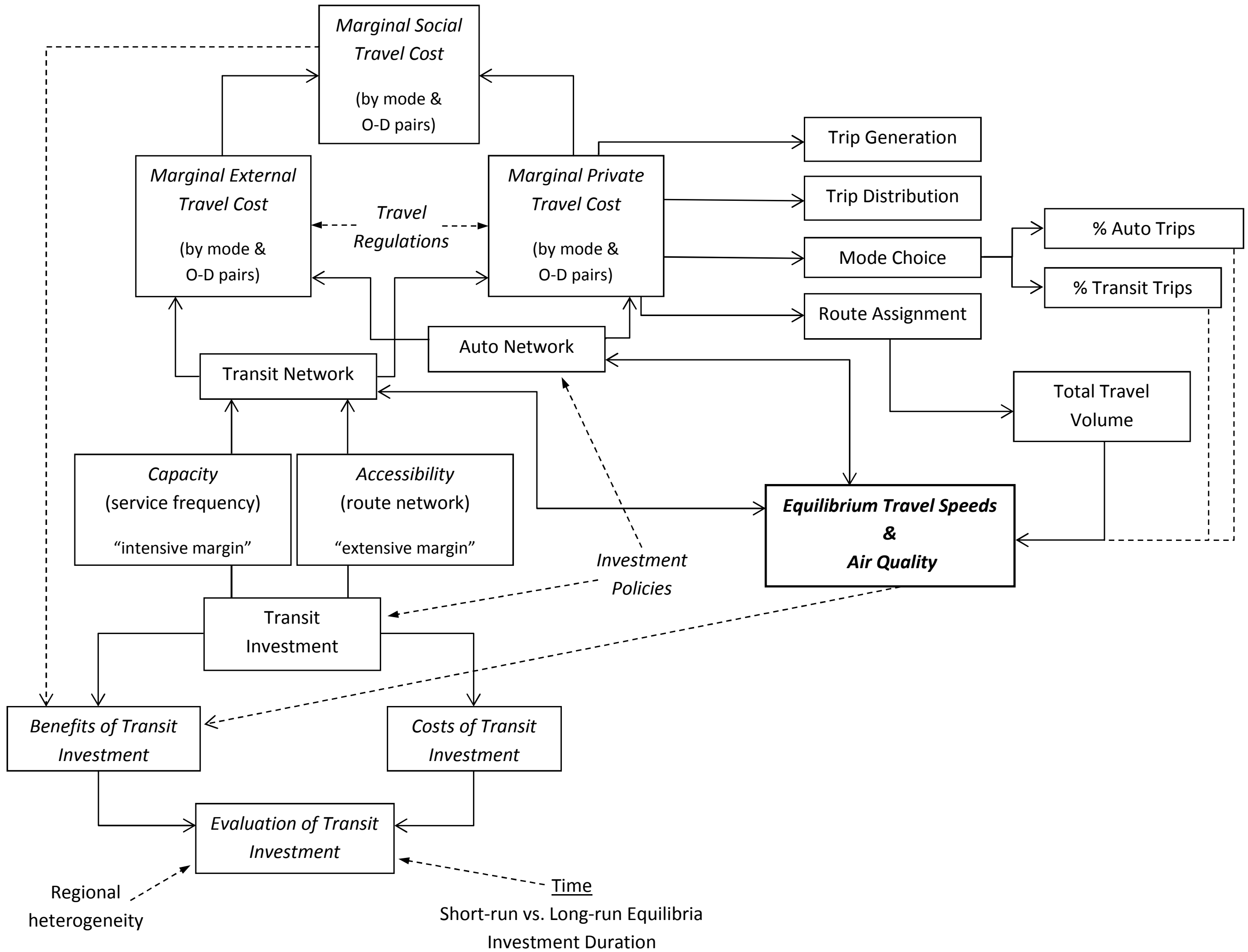

Figure 1: Framework for Evaluating Public Transit's Effect on Congestion and Air Quality

(PM), as well as global pollutants such as carbon.

The equilibrium of a transportation network is often modeled via the traditional four-step 'classical urban transportation planning system model' (for a description of this model, see McNally (2007)). This framework is a useful way of summarizing the channels through which transit supply can affect congestion levels and air quality.

2.3.1 Trip Generation

By reducing the generalized cost[4] of transit travel – through the reductions in waiting, access/egress or travel times accompanying improvements in transit accessibility and/or service frequency – transit investment can generate an increase in the total number of transit trips by moving down the demand curve for transit travel. Localized economic development following transit investment may also spur additional auto trips. The number of trips is typically modeled by trip purpose for each origin-destination pair for a group of geographic zones, accounting for land uses and other household and regional demographic and socioeconomic attributes.

2.3.2 Trip Distribution

The spatial distribution of transit investment and changes in service levels influences the relative marginal cost of transit travel to and from different origin-destination pairs, leading to a change in the spatial allocation of trips. In the long run this process contributes to land-use changes which can spur additional changes in the geographic distribution of trips. The distribution of trips is typically modeled by the relative attractiveness (or impedance, equivalently) between origin-destination pairs, often via some form of a gravity model function which accounts for the generalized travel cost between various origin-destination pairs and the spatial distribution of travel sources and attractions, such as residential and employment centers.

2.3.3 Mode Choice

Transit supply affects the modal choice of travelers by influencing the relative generalized marginal cost of travel by auto and transit. This cost ratio factors into the discrete choice framework typically

[4] The generalized cost of travel represents the full marginal opportunity cost of travel, including both monetary (such as fuel or fare) and non-monetary costs (such as time). This cost excludes the fixed cost of transit investment and service provision.

used to model the distribution of trips across the modal alternatives available to an individual between a given origin-destination pair.

2.3.4 Route Assignment

The final stage of the four-step model allocates trips between origin-destination pairs for all possible modes and routes. For highway travel, Wardrop's principle of user equilibrium (Wardrop, 1952) is often imposed, which is equivalent to a Nash equilibrium insofar as each individual's mode-route choice minimizes their average generalized cost of travel, conditional on the equilibrium choices of all other individuals in the network. This requires that the marginal cost of travel is equalized across modes and routes (and potentially time of day). Intuitively, a given transit investment will affect the choices of a subset of individuals in the network, which will lead to recalibrated travel decisions across the network until a new equilibrium is reached.

Additional modeling complexity may be required depending on the question of interest. Examples include the timing of trips, heterogeneous preferences and attributes of individuals, and the type of transit investment undertaken (such as light rail systems versus bus service). We next highlight several other important considerations when evaluating the potential for transit investment to reduce congestion and improve air quality.

2.4 Short-run vs. Long-run Equilibria

Ideally, the feedback effects from one step to another are modeled within the four-step model so that the short-run outcome will converge to a long-run equilibrium outcome, as the effects of transit investment depend on the time horizon under consideration. When anticipating the effects of transit investment, it is important to distinguish between short-run effects (such as peak shifting and trip diversion) and long-run effects (such as changes in land use and vehicle fleet composition) arising from any policy change or investment in transit.

It may be expected that transit investment will have the greatest effect on congestion and air quality in the long run as commuters are able to adapt and make long-run decisions to better utilize transit, such as relocating residential or employment locations. However, Wardrop's principle of travel equilibrium is relevant as it relates to the concept of 'induced demand' (often referred to as latent demand). In theory, while transit investment may lead to short-term reductions in congestion, in the long run it will be ineffective in the absence of efficient pricing on auto travel. This conjecture is known as the ‘fundamental law of traffic congestion’ and relates to the open access nature of most highways. As Hau (1997) states:

> “Latent demand – demand that has heretofore been suppressed as a result of peak-hour congestion – emerges as soon as the traffic situation is improved. Travelers that are currently discouraged from taking a trip during their most preferred times by the major form of abatement – traffic congestion itself – will respond by traveling closer to their desired time of travel. Because of the fundamental law of traffic congestion, traffic will converge on preferred places and times until there is congestion. Thus the sole reliance on supply measures would not be helpful in solving the congestion conundrum without further differentially pricing road use via peak/off-peak charges.” (Hau, 1997, pp. 267)

Duranton and Turner (2011) show that this effect exists for auto travel in the U.S., with travel volumes having increased proportionally with the available auto capacity in recent decades. While induced auto travel following improved travel conditions has been central to road investment analyses, the concept also applies to investment in public transit. Such investment initially increases the relative attractiveness of transit travel by reducing the access, wait or travel time of transit travel, which may initially cause a subset of commuters to switch from auto to transit. This then results in reduced congestion on the roadways, decreasing the cost of auto travel and leading to replacement auto trips. For example, Small and Verhoef (2007, pp. 174) note that the introduction of Bay Area Rapid Transit (BART) service between Oakland and San Francisco in the early 1970s initially lead to 8,750 automobile trips being diverted to BART; however, 7,000 new automobile trips were subsequently generated, eroding much of the potential short-run congestion reduction.[5]

2.5 Regional Heterogeneity

Public transit’s impact on congestion and air quality is determined by the combined effects of trip generation and distribution and the associated modal and route allocation. It is possible that these factors may exhibit spatial heterogeneity (both within and between regions) due to various socioeconomic and geographic factors, as well as the characteristics and structure of the transportation network and the type of transit technology in place (see Beaudoin, Farzin and Lin Lawell (2015a) for discussion). Accordingly, the external validity of model predictions or empirical analysis must be considered, as the effects of transit investment predicted or observed in one region

[5] Nevertheless, the introduction of BART may still have been dynamically efficient – and therefore considered sustainable – if it has maximized the present discounted value of the stream of net social benefits of travel in the region since its inception, relative to all other investment options (including the foregoing of BART construction).

may not generalize to another region.

2.6 Regulatory and Policy Considerations

It is generally agreed that in theory the congestion and emission externalities associated with auto travel should be corrected via the price mechanism (such as congestion and emission fees), though such Pigouvian fees have not yet garnered widespread implementation, for a variety of political and economic reasons (Anas and Lindsey, 2011). If these externalities are uncorrected in practice, then the investment rule characterizing the optimal level of transit investment is what is known as a 'second-best' scenario that deviates from the 'first-best' rule. This issue is discussed in Beaudoin et al. (2015a) and the implication is that the efficient level of transit investment is higher when the beneficial effect of transit investment on reducing auto congestion (and emissions) is accounted for than when such effects are ignored, though the importance of this consideration is subject to considerable heterogeneity. Any evaluation of public transit investment must be undertaken in consideration of any other existing and forecasted policies affecting the demand and cost of urban travel.

2.7 Endogeneity of Transit Investment and Supply

The correlation between transit supply and congested roads may yield the perception that transit is ineffective in reducing congestion (for example, Rubin and Mansour (2013)). However, in the counterfactual scenario without this higher transit supply, what level of congestion would arise? This question is of added importance when evaluating congestion levels within the context of growing population and per capita income over time. Evaluations of transit investment are complicated by the endogeneity of public transit investment in relation to congestion and air quality.

First, in utilizing the four-step model in Section 2.3, the generalized cost of travel is a function of the volume of travel, and the volume of travel is a function of the cost of travel (denoted the 'bilevel problem' in transportation engineering, or the simultaneity issue in econometrics). Second, the endogeneity issue also arises when undertaking empirical analyses: transit investment is most likely to occur in densely populated and congested urban areas, and new investments may be used as a policy measure to address existing congestion and/or as a component of a regional growth and development strategy. If investments in mass transit lead to localized economic development and land-use changes, they may generate automobile trips that offset potential traffic congestion reductions due to the initial cross-modal travel substitution, even if categorized as 'transit-oriented development' (Stopher, 2004, pp. 125; Small and Verhoef, 2007, pp. 12).

Any empirical analysis of the effects of transit on congestion or air quality must be cognizant of potential endogeneity and the identification issues surrounding the estimation of the investment effect; Beaudoin et al. (2015a) find that ignoring the endogeneity of transit supply levels understates the congestion-reduction benefit of transit by approximately 40%.

3 Literature Review

In this section we review recent studies relating to public transit's effect on congestion and air quality. Jones (2008) provides a historical overview of the relationship between public transit and the automobile in the U.S. dating back to the late nineteenth century, documenting the decline of transit's role in the U.S. to the present day.

3.1 Congestion Studies

Early research on the implications of underpriced auto travel for the evaluation of investments in roadway capacity (see e.g., Wheaton, 1978; Friedlander, 1981; d'Ouville and McDonald, 1990; Gillen, 1997) was extended to account for the interaction between auto and transit when formulating the transit investment decision (see Arnott and Yan, 2000; Pels and Verhoef, 2007; Ahn, 2009; and Kraus, 2012). Generally, these second-best models with endogenous transit capacity assume that the speed of auto travel is independent of the volume of transit service. With this assumption, Kraus (2012) finds that second-best transit capacity – the optimal capacity when accounting for the distortion in the auto market – is higher than the first-best capacity that would be provided if one does not account for this distortion. However, if there is interdependency between the congestion externalities across the auto and transit modes within the transportation network (a feature of the models of Sherman, 1971; Ahn, 2009; Basso and Silva, 2014; and Beaudoin et al., 2015a), then there is uncertainty surrounding the relative values of the optimal level of transit capacity to provide, depending upon the extent to which public transit affects the deadweight loss associated with auto travel.

While public transit receives plenty of political support for its 'green' reputation and its contribution to 'sustainability', there have been relatively few studies examining the *ex post* effects of public transit investment on traffic congestion or air quality. Most studies have been *ex ante* cost-benefit analyses of potential large-scale investments; for example, Berechman and Paaswell (2005) study the public transportation network of New York City, and most government agencies are required to conduct a formal cost-benefit analysis before undertaking a project. We next summarize the existing empirical studies of the relationship between public transit investment and traffic congestion.

Baum-Snow and Kahn (2005) study the effects of rail transit investment on the share of public transit ridership. Their dataset includes 16 new and/or expanded rapid rail transit systems over the period 1970-2000; these systems are generally located in large, dense U.S. cities. Their theoretical model suggests that new rail service will mostly lead to commuters switching from bus to rail and would have an insignificant effect on auto travel, based on the spatial distribution of commuters and the travel characteristics of the modes. Empirically, they employ a difference-in-difference approach that exploits variation over time within census tracts in terms of the accessibility of rail service. They find the seemingly paradoxical result that rail transit investment does not reduce congestion levels, though it does lead to reduced commuting times (for the subset of commuters that switch from bus to rail); however, this result is fully consistent with the 'fundamental law of traffic congestion' and the presence of induced demand. They find that variation in metropolitan area structure (primarily population density) both within and between regions is an important factor contributing to heterogeneous responses of commuters with respect to mode choice following expanded rail service.

Winston and Langer (2006) study the effects of roadway expenditures on the cost of congestion, analyzing 72 large urban areas in the U.S. over the period 1982-1996. Using cross-sectional variation in their panel, they find that increases in the mileage of rail transit leads to a reduction in congestion costs, but that increases in bus service actually increase congestion costs. This finding is consistent with the congestion externality interdependency between auto and transit travel, and the possibility that the factors affecting the extent to which transit is expected to reduce congestion may vary according to the transit technology (both the extent to which transit investment reduces the cost of transit travel and the magnitude of the cross-modal demand elasticity).

Winston and Maheshri (2007) focus on the overall social welfare of urban rail investment, examining

25 rail systems in the U.S. from 1993-2000. They derive the congestion cost savings of rail systems by comparing observed congestion costs with those that would arise in the counterfactual scenario where the rail systems were not constructed, imputed based on the empirical results of Winston and Langer (2006). As a result, their approach does not provide an estimate of the marginal congestion reduction attributable to incremental changes in existing rail service levels. They use cross-sectional variation, presenting results that are pooled across different groupings of rail system size. They also show how the network configuration of the transit system has a significant relationship with ridership levels, in particular for the largest rail systems.

Nelson et al. (2007) use a simulation model calibrated for Washington, DC to estimate the effect of rail on congestion in the city. They find that rail transit generates significant congestion-reduction benefits that exceed the total subsidy that the rail system receives. Of note, this effect is derived relative to a scenario where the rail system is not in operation, similar to the approach taken by Winston and Maheshri (2007). They also find that the congestion-reduction benefit of rail is roughly 7 times as large as that of bus service in the region.

Duranton and Turner's (2011) principal objective is testing the 'fundamental law of traffic congestion', analyzing 228 Metropolitan Statistical Areas (MSAs) across the U.S. for the three years 1983, 1993 and 2003. They find compelling evidence of induced auto demand, with increases in road capacity being met with commensurate increases in auto travel. As a test of their hypothesis, they also find that the level of public transit service does not affect the volume of auto travel, which is consistent with Wardrop's equilibrium. They report results using both cross-sectional variation across MSAs and time series variation via MSA fixed effects. Notably, their empirical model accounts for the potential endogeneity of transit service and auto travel via instrumental variables. Their measure of transit supply is the number of large buses during peak service, and does not include fixed guideway transit, nor a measure of the overall service level provided by the buses.

Anderson (2014) utilizes a regression discontinuity design that exploits a quasi-natural experiment of a transit labor dispute within the Los Angeles transit system in 2003, comparing travel speeds before and during the strike. His main finding is that the average highway delay increased by 47% when transit service ceased operation. As with Winston and Maheshri (2007) and Nelson et al. (2007), this provides convincing evidence of the effects of transit on congestion at the *extensive* margin (comparing the outcome of an existing transit network with the counterfactual outcome without any transit service), but it does not identify the effect of transit on congestion at the *intensive* margin (the change in congestion due to an incremental change in transit service). Also of interest is the persistence of this effect in the long run, and whether the magnitude of this effect would be similar in other cities.

The existing empirical evidence of the effect of transit on traffic congestion is unclear. There is also an ongoing debate in policy circles regarding the efficacy of public transit investment as a means to address traffic congestion; for example, Rubin et al. (1999), Stopher (2004), and Rubin and Mansour (2013) all display skepticism regarding the congestion-reduction possibilities of public transit, while Litman (2014) advocates for transit investment. Anderson (2014) summarizes the academic 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. This is consistent with "Downs' Law" (Downs, 2004) and the way in which induced demand occurs along the various margins of the travel decision, as discussed in relation to the four-step model in Section 2.

Beaudoin et al. (2015a) estimate the effect of past public transit investment on traffic congestion by applying instrumental variables to account for the potential endogeneity of public transit investment to a panel of 96 urban areas across the U.S. for the years 1991-2011. Their dataset includes both fixed guideway transit modes (including rail) and mixed traffic modes (buses), measuring the total capacity by the vehicle-miles of service provided. The panel setting allows for an estimate of the marginal effect on congestion due to incremental changes in transit supply over time by controlling for urban area fixed effects.

Their results indicate that the congestion-reduction effects of public transit supply warrants a higher level of public transit investment than would be provided on the basis of the isolated valuation of public transit ridership net benefits; this finding is consistent with the theoretical models headlined by Kraus (2012). The magnitude of this benefit is subject to considerable uncertainty, and is dependent upon the characteristics of the existing transportation network, the technology of the proposed transit system, and the socioeconomic attributes of the region. While increases in public transit supply lead to a small overall reduction in auto traffic congestion (on average, a 10% increase in overall transit capacity leads to a 0.8% reduction in congestion, as measured by daily auto vehicle-miles traveled per freeway lane-mile), there is considerable heterogeneity across urban areas, varying from an elasticity of auto travel with respect to transit capacity of -0.02 for smaller, less densely populated regions with less-developed public transit networks, to -0.4 in the largest, most densely populated regions with extensive public transit networks. These findings suggest that the existing mixed evidence of previous studies may be due in part to the heterogeneity across urban regions of the U.S. in terms of population size and density, as well as characteristics of the transportation networks: the existing congestion level, the existence of a rail system, and transit accessibility, capacity, and current usage.

Both Winston and Langer (2006) and Beaudoin et al. (2015a) find that the type of transit service has a differential effect on congestion, though it is unclear whether this is directly due to the transit technology, or whether rail happens to be located in the largest and most dense regions where public transit is best positioned to reduce congestion. Baum-Snow and Kahn (2005) and Anderson (2014) emphasize the importance of accounting for *intra*-city heterogeneity across commuters when estimating the effect of transit supply on congestion, whereas the results of Beaudoin et al. (2015a) focus on the importance of *inter*-city heterogeneity.

Various approaches have been taken to estimate the impact of public transit on congestion: theoretical models (Arnott and Yan, 2000; Pels and Verhoef, 2007; Ahn, 2009; and Kraus, 2012), simulation exercises (Nelson et al., 2007) and empirical analyses (Baum-Snow and Kahn, 2005; Winston and Langer, 2006; Winston and Maheshri, 2007; Duranton and Turner, 2011; Anderson, 2014; and Beaudoin et al., 2015a). In reviewing these studies, there is no clear consensus regarding the relationship between public transit supply and the level of congestion. There appear to be three main factors contributing to the varying conclusions reached by previous studies: (1) how the congestion-reduction benefit of transit is measured, via the extensive or intensive margin; (2) the region and type of transit service included in the dataset; and (3) whether the potential endogeneity of transit investment is accounted for. It is clear, however, that there is limited scope for extrapolating the past effects of one city's transit investment to forecast the impact of a potential transit investment in another city.

3.2 Air Quality Studies

While several studies have considered the relationship between *auto* travel and air quality, there have been relatively few empirical studies looking at the effect of *public transit* on air quality. By and large, recent studies of auto travel's environmental impact have primarily been interested in the linkage between travel volumes and health outcomes, extending the analysis beyond measures of emissions and/or ambient air quality to estimate the associated social cost of auto pollution.

Friedman et al. (2001) examine the effects of traffic volume changes on the local air quality in Atlanta during the 1996 Summer Olympic Games and find that the imposed traffic restrictions in downtown Atlanta (which reduced weekday morning traffic counts by 22.5%) were associated with a 27.9% decrease in peak daily ozone concentrations and a 41.6% reduction in the number of acute care asthma events. Levy et al. (2010) model traffic congestion and emissions to estimate the health costs associated with auto travel for 83 urban areas in the U.S., finding that the public health costs are approximately half the magnitude of reported congestion costs related to delays and wasted fuel.

Currie and Walker (2011) use the introduction of a new tolling technology in New Jersey and Pennsylvania over the years 1997-2001 which led to reduced congestion and emissions in the region around toll plazas. They consider variation in congestion and emissions according to the distance of infants' residences in relation to these toll plazas and find that the prevalence of prematurity and low birth weight decreased for families living within 2 kilometers of a toll plaza, though their data does not measure actual reductions in pollution associated with reduced traffic congestion. Knittel et al. (2014) analyze the effects of both local traffic levels and ambient pollution on infant mortality rates and find that traffic levels have a negative – though relatively small – effect on infant health.

However, Sun et al. (2014) find that though recently imposed driving restrictions reduced congestion in Beijing, there was no discernible effect on local air quality. The mixed evidence may again imply that there is heterogeneity in the relationship between urban travel and air quality.

While there is generally a consensus that auto travel leads to adverse health outcomes, there is very little empirical evidence of the incremental effect that transit supply may or may not have on air quality. Two recent studies have provided an initial look at the relationship between transit supply and air quality. Chen and Whalley (2012) apply a regression discontinuity approach to the level of transit utilization of a new rail system in Taiwan to identify the air quality effects of rail transit infrastructure. Using hourly air quality data from Taipei, they find that the system's opening reduced carbon monoxide by 5-15% but had little effect on ground level ozone pollution. They also found little evidence that auto travelers adjusted their time or route of travel in response to the new rail availability, though the empirical methodology is not able to estimate long-run equilibrium effects. Lalive et al. (2013) assess the environmental effect of expanded rail service in Germany over the period 1994-2004. They find that increases in rail service frequency lead to a reduction in some pollutants (NO, NO_2 and CO), though not others (SO_2 and O_3). Their study exploits geographic variation in rail service and accounts for the potential endogeneity of rail provision.

Building on these recent studies, Beaudoin, Farzin and Lin Lawell (2015b) analyze the effects of public transit supply on air quality. They find that while there is potentially an additional co-benefit of public transit in reducing the emission externality associated with auto travel, this has not been the case for the large urban areas of the U.S. from 1991-2011. Although there have been signficant improvements in air quality over this period, these reductions are not attributable to the large increase in transit service that occurred over this time.

The effects of public transit on air quality depend on the extent to which the emission rates vary between auto and transit travel, and the relative demand substitutability between modes. The anticipated environmental benefit of transit has typically been thought to be limited by a very low cross-elasticity of demand between auto travel and public transit (this issue was discussed in Glaister and Lewis (1978) in relation to the role of transit subsidies in reducing auto congestion). The net effect of transit on air quality becomes an empirical issue, complicated by the following factors: (1) the equilibrium effects outlined above in the context of congestion; (2) the chemical and ecological processes between vehicle operation and ambient pollution concentration; and (3) heterogeneity in the characteristics of the commuters comprising marginal transit users (whether they are newly generated trips or are switching from other modes of travel, the characteristics of their vehicle, the timing and location of their trips, etc.). Harford (2006) discusses the theoretical ambiguity of the relationship between transit and observed pollution levels, with the implication that it is difficult to impute the effect of transit on air quality based on previous studies focusing on auto travel's effects on air quality.

The physical link between congestion and emissions should also be noted. Barth and Boriboonsomsin (2009) summarize the empirical relationship between travel speeds and vehicle emissions, and Berechman (2009, pp. 259) discusses how low speeds of congested urban travel contribute to emissions. Johansson-Stenman (2006) discusses how the optimal taxation of auto travel should reflect the fact that the costs of emissions increase along with the greater pollution exposure in densely populated areas: when congestion increases, speed decreases and vehicle density and exposure increase, and the optimal emissions charge should reflect this higher exposure. However, there has not been an empirical study of the interaction between congestion and air quality in terms of public transit. This may be a relevant factor in evaluating public transit investments, as the highest levels of transit supply occur in the densest and most congested cities in the U.S.

4 Concluding Discussion

As the transportation policy landscape evolves and technological advancements continue, a complete evaluation of the social benefits of transit investment is essential both for allocating investment funds and for designing policies that result in an efficient level of investment and travel in the long run. The effects of public transit investment on congestion and air quality are two components that should be integrated into a holistic cost-benefit framework.[6]

It should be noted that the preceding empirical results have been estimated within the context of inadequate road pricing. Small (2005) discusses the potential complementarity of road pricing and public transit provision; the ability of public transit to reduce congestion and improve air quality may be much greater if auto users are made to internalize the full marginal social cost of their travel. In the long run, public transit investment may only lead to congestion reduction and air quality improvements if carried out in conjunction with other policies aimed to influence travel behavior. Care should also be taken when extrapolating these past findings into the future. The modal choices that individuals make are dependent upon both the existing policies and the characteristics of the modal options they face. For example, the substitutability between auto and transit may be a function of the level of transit supplied, thereby complicating forecasts of the impact of

[6] In addition to the efficiency of transit investment and ridership, there are also distributional issues such as equitable access of transportation options that should be considered in conjunction with the cost-benefit analysis; see Berechman (2009) for a guide to cost-benefit analysis of transit investment.

large scale transit investments.

Does the evidence above bolster public transit's 'green' reputation? It appears that transit can both reduce congestion and improve air quality, though the magnitudes of these benefits are uncertain and may be specific to each location. Anderson (2014) estimates that the Los Angeles transit system reduces the cost of congestion in the city by \$1.2-4.1 billion annually, while Winston and Maheshri (2007) estimate that the 25 rail systems they studied generated approximately \$2.5 billion in congestion cost savings in 2000. Beaudoin et al.'s (2015a) results imply that a 10% increase in transit capacity from its current level could reduce congestion costs for the U.S. by approximately \$1 billion per year.[7] There does not yet appear to be any large-scale quantification of transit's impact on air quality. While a proper evaluation of transit investment should incorporate any associated benefits in the form of reduced congestion and/or improved air quality, these effects – though they may be significant – are unlikely to entirely justify public transit investment. As new data sources emerge, these issues remain in need of additional empirical evidence to help shape future urban transportation policy.

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[7] Assuming that the elasticity of auto travel with respect to transit capacity is -0.08, a 10% increase in transit capacity yields a 0.8% reduction in congestion, implying an approximate \$1 billion reduction relative to the TTI's estimated annual congestion cost of \$120 billion (Schrank et al., 2012).

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