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Transit in Washington, DC: Current benefits and optimal level of provision

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Abstract

The discrepancy between transit's large share of local transportation resources and its generally low share of local trips has raised questions about the use of scarce transportation funds for this purpose. We use a regional transport model consistent with utility theory and calibrated for the Washington, DC metropolitan area to estimate the travel benefits of the local transit system to transit users and the congestion-reduction benefits to motorists. We find that (i) rail transit generates congestion-reduction benefits that exceed rail subsidies; (ii) the combined benefits of rail and bus transit easily exceed local transit subsidies generally; (iii) the lowest income group received a disproportionately low share of the transit benefits, both in absolute terms and as a share of total income; and (iv) for practical purposes, the scale of the current system is about optimal.

JEL classification: R40; R41

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0. Introduction

Many local and state governments devote a substantial share of their transportation expenditures to mass transit. In some areas, transit spending can account for more than 50% of

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expenditures in the regional transportation budget.[1] Because most urban transportation programs face tight fiscal constraints and intense competition for funds, the level of transit investment is often a point of contention.

To skeptics, public expenditures on mass transit are often wasteful [9]. In most areas, transit carries a very small share of daily trips. Furthermore, with the exception of a few areas, transit's mode share has declined over the past several decades. Nationwide, the percentage of transit commute trips has dropped from 12.6% in 1960 to 4.7% in 2000 [39]. Critics also point to inefficiencies in transit systems arising from above-market wages and contracts as well as an oversupply of routes to low-ridership, but politically powerful, suburban areas [58].

Transit's defenders reply that in urban areas it is too often the only transportation available for the poor and the handicapped, that it provides substantial congestion-reduction benefits by removing cars from the roads during rush hour, and that it is an alternative to auto travel that will be increasingly appreciated as fuel prices increase. The public seems to agree, for provision of substantial local funding for transit enjoys a degree of public support out of proportion to the ridership level.[2] The public likes transit, it would appear, but for the other guy.

In this paper we contribute to this debate by estimating the benefits of the bus and rail transit systems in the Washington, DC metropolitan area. We use a transport model, consistent with microeconomic theory and calibrated for Washington, and we estimate both benefits to transit users and the congestion-reduction benefits to motorists. We find that the rail transit system generates congestion-reduction benefits that exceed rail subsidies. Moreover, the combined benefits of bus and rail transit easily exceed total transit subsidies. However, all travelers do not enjoy the benefits equally. The lowest income group receives a disproportionately low share of benefits, both in absolute terms and as a share of total income. Finally, we look for the optimal scale of the Washington transit system, holding route configurations and fares constant, and we find that the current system is not far away from the optimum.

In the first section of the paper we describe the issue in more detail and discuss the relevant literature. This is followed in Sections 2 and 3 by a description of the Washington, DC's transportation system and the Washington-START simulation model, respectively. In Section 4 we present our estimates of the net benefits from the existence of the transit system. In addition, we identify the main beneficiaries of the current transit system, both by income group and geographically. The optimal level of transit provision in the area and the relative cost-effectiveness of investments in bus and rail are considered in Section 5. The final section concludes and discusses limitations of the study.

1. Background

1.1. Arguments for subsidization

Traditionally, three major justifications have been offered in support of government subsidies to transit. First, numerous social benefits arise from reducing auto travel, particularly improve-

[1] For example, expenditures on transit account for 60% of total spending in the regional transportation plan for Washington, DC and over 63% in San Francisco [35,44].

[2] For example, four in ten respondents to the Star-Tribune Minnesota Poll said that transit improvement was the number 1 funding public spending priority. "Poll shows support for roads and public transit" (Minneapolis Star-Tribune March 12, 2000. Online at http://www.startribune.com/dynamic/mobile_story.php?story=40409, accessed August 19, 2006).

ments in traffic flows and air quality. Drivers do not pay the full marginal social costs of their vehicle use, including increased congestion, pollution, noise, and accidents [12]. In the absence of corrective taxes, which have proven exceedingly difficult to implement, a second-best alternative is to subsidize the automobile's main competitor, public transportation [28].

Distributional equity is a second rationale. Increased investment in transit and subsidized fares expand the mobility options for low-income population. In an auto–dependent transportation system, poor households that cannot afford private vehicles may be limited in their ability to take advantage of economic opportunities. The provision of transit may reduce spatial barriers to employment, especially in large metropolitan areas [19].

Third, there are economies of scale to transit investment, particularly for rail, where right-of-way and capital requirements are relatively insensitive to the volume of passengers [5]. Bus investment, while showing only modest economies of scale in terms of cost, demonstrates increasing returns to scale with respect to service provision. As service frequencies and route density increase, wait and walk times decrease, demand increases, and transit frequencies can increase again (the so-called Mohring effect [34]). As long as marginal social cost is below average social cost for both rail and bus, setting fares equal to marginal social cost will be insufficient to cover the financial requirements of the system. From an economic efficiency perspective, this is the most compelling argument for subsidization, because the other issues mentioned above can be addressed more effectively with other instruments [53].[3]

Critics of public provision and subsidization of mass transit offer several main rebuttals to these arguments (summarized in [47]). First, the cross price elasticities of auto usage with respect to transit costs are rather low [18], indicating that subsidizing transit may be a relatively inefficient way to discourage automobile use. Transit own-price elasticities are typically low as well—on the order of -0.33 to -0.22 [14,24]—implying that the social benefit from pricing at marginal cost versus average cost may not be very high. On the issue of equity, transit users in dense urban areas are often relatively affluent, and the transfer of income from taxpayers to transit users may not have the desired distributional effects [33]. Finally, the subsidies themselves can lead to new inefficiencies. Many authors [1,7,38] found that when operations are subsidized the operators' costs increase because of higher salaries and reduced productivity. In addition, subsidizing public transit instead of pricingthe congested auto mode may lead to suboptimally low use of non-motorized modes that are efficient in terms of congestion and pollution [25].

1.2. Optimal provision

A substantial theoretical literature has looked at optimal transit supply, usually in conjunction with optimized fare levels. Several microeconomic public transport operation models have optimized different characteristics of service such as fleet, vehicle size, and route spacing in a single corridor [20,21,34]. Later such models have been extended to simple network cases [22]. It has been established that optimal frequencies increase less than proportionally with demand, following a square root rule if everything else is fixed, and a cubic root if route density is allowed to vary. Because of the presence of scale economies, optimal fares will be lower than the operator's costs making a subsidy necessary. In most of those models congestion is not explicitly modeled.

[3] A more efficient way to address motor vehicle externalities would be to price them with congestion tolls and pollution tax. The equity problem can be better addressed through direct monetary transfers.

However, one can conjecture that in the absence of congestion pricing the auto mode is underpriced, which makes the optimal subsidy even larger under a social optimum scheme. Including congestion effect, Mohring [34] found a negative optimal fare for a bus system. However, other operational variables, such as access, wait and in-vehicle times, may have more influence on ridership than fares [26].

Given the necessarily simple structure of theoretical models, their quantitative results cannot be easily extrapolated to actual transportation systems. They are complemented by empirical models that are often calibrated to particular transit systems and are able to incorporate an array of local factors that strongly influence the results. Viton [54] finds that optimal fares in San Francisco and Pittsburgh should be close to zero, producing a substantial increase in transit's mode share supply. On the other hand, Winston and Shirley [58] employ an aggregate joint-choice model to estimate optimal transit supply in a set of US metropolitan areas and conclude that average service frequencies should fall dramatically for both bus and rail—a 73% decline for bus and a 60% drop for rail. They also find that fares should double for rail and quadruple for bus, to the point that fares for both modes come close to covering full marginal costs.

Other empirical studies focus on the interaction between transportation sector and the rest of the economy, and most notably taxes and the fiscal system. De Borger and Wouters [10] employ a model of the Belgian transport market and find optimal fares decreasing and service increasing from the baseline. Transit prices decrease by 61 percent in the peak and 84% in the off-peak, while supply rises 13% and 54%, respectively.

Van Dender and Proost [52] use TRENEN, a non-spatial partial equilibrium transport model calibrated to specific urban areas, to determine optimum bus and rail fares and frequencies in Brussels and London. Under the assumption of road pricing, optimal fares rise dramatically for both modes. If auto use is not priced, however, optimal fares fall close to zero during peak hours but double those from the baseline during the off-peak. Optimal service frequencies increase for both modes in Brussels during the peak period, while they fall for bus and increase for rail in the off-peak. For London, they find optimal frequencies rise for rail and drop for bus in both time periods.

The wide range of estimates can partly be explained by different modeling approaches (e.g. some take into account the marginal cost of public funds and others do not, some account for economies of scale from increased frequency and others do not). Another major factor accounting for the discrepancy is the differing geographic scope of the studies. The studies showing increased optimal frequencies are based on specific, relatively dense, metropolitan areas, like Brussels, London and San Francisco. The Winston and Shirley [58] study is based on a sample of large metropolitan areas in the US and includes many areas where transit is very unproductive.

1.3. Rail against bus

Due to the fact that rail generally exhibits a higher degree of economies of scale, it would be natural to assume that rail transit is more efficient serving larger markets while buses are more practical in dispersed environments. A number of studies (see [37] for a review) confirmed this idea in settings where various transit services are provided in a transport corridor.

In the last thirty years more than a handful of US cities designed and implemented rail transit projects. However, when newly built rail systems opened, in many cases it turned out that the ridership was far lower than the forecast level [15,23] and therefore higher subsidies were needed to keep the systems afloat. Moreover, in many systems the costs of construction were also higher than the ones forecast, sometimes by as much as 50% [37].

On the other hand, rail proponents cite counterbalancing factors. They point out that grade-separated transit, such a rail, reduces delays on parallel roadways and therefore benefits all travelers, even those who continue to drive. In addition, they assert that since fixed rail implies a long-term commitment to provide service at a particular location, rail transit can provide assurance to investors and thereby stimulate transit oriented development—compact walkable urban enclaves where residents tend to drive less [29]. Bus rapid transit—a bus-only network of grade-separated lanes—has recently been touted for its supposed ability to combine the development benefits and convenience of rail with low investment costs of bus networks, but its actual impact and performance yet remain to be seen.

The analysis is further complicated by the fact that in real cities where bus and rail coexist in a complex urban network, the relationship between the two modes can be much more complicated. While on major corridors bus and rail provide substitute services, feeder buses complement rail. Therefore, estimation of separable efficiency of the transit subsystems in a large metropolis is not a straightforward task.

1.4. Benefits of transit

Estimates of the overall benefits of the transit system are less common, at least in an academic context. The Texas Transportation Institute [45] includes a measure of time-savings from the existence of a public transportation system using an aggregated approach based on the relationship between lane miles and VMT in urbanized areas. For 85 urban areas in the United States, they find that average per city annual benefits from public transit amount to $217 million, due to reduced congestion costs. For the 13 largest urban areas in the survey, they estimate the average benefits to be almost $1.2 billion annually.

Winston and Shirley's [58] examination of US transit policy concluded that on average reducing rail spending is essentially a break-even proposition and eliminating bus service would actually increase welfare because of the improvement in the government's fiscal balances. They note, however, that this is a nationwide average. In certain dense metropolitan areas, transit investment may be more attractive.

Although most studies focused on indirect indicators of transit effectiveness, such as mode share and congestion reduction, the dominant view of economists has been that investments in public transit, and rail, have been ineffective and expensive [2,47]. Moreover, some studies go as far as to question whether any public investment in transit is warranted [57]. Of course, the answers to these questions will depend greatly on the context in which the question is asked. Studies that have looked at the factors explaining transit ridership have found that key demographic and spatial factors (such as vehicle ownership levels and employment density) play a paramount role [2,4,6,48]. Another important factor is the spatial configuration of the transit network within the city that is inevitably ignored in an aggregate analysis yet might be important for the system's performance. Finally, long-term investments in infrastructure might fundamentally alter population and employment distribution in the study areas that can make the analysis even less reliable [55].

In this paper, we look at the transit efficiency from a somewhat different standpoint. Instead of analyzing the long-term path of investments and ridership, we would like to know whether at present the transit system as a whole produces benefits in excess of its costs. While a complete dismantling of public transit is not a viable political option, our theoretical exercise is meant to shed light on the size and structure of costs and benefits of public transit system.

2. The Washington, DC transportation system

Washington, DC is often cited as having some of the worst traffic congestion in the United States [45]. In Washington, like many large metropolitan areas, investment in new road capacity has failed to keep pace with rising vehicle miles traveled. Severe congestion is now found on most of the region's major highways, including I-95, I-270, and the Capital Beltway [49].

From 1990 to 2000, nearly 900,000 people moved to the region as a whole even as the core city population dwindled by 120,000 [50]. Notwithstanding this trend of intra-regional outward population movement, the federal government remains the major engine of the local economy, anchoring economic activity in the region's downtown core. The Washington, DC metropolitan area remains comparatively dense, with population densities comparable to those of other East Coast metropolitan areas like Boston and Philadelphia.

Given its population density and congestion levels, it is not surprising that the area has one of the nation's top performing transit systems. The Washington Metropolitan Area Transit Authority (WMATA) is the area's main transit operator and runs the Metrobus and Metrorail systems. WMATA is the fourth-largest transit system in the US in terms of annual trips and the rail system is second only to MTA in New York in terms of ridership. During rush hour, 18% of all person trips in WMATA's service area use transit, the second highest percentage in the country. Over 40% of peak period trips to the downtown core use transit [32].

However, beyond the city and inner suburbs, transit options are fairly limited and public transportation accounts for just 3 percent of all trips in the region as a whole [51]. Outside WMATA's service area, transit mainly consists of two regional commuter rail systems, MARC and VRE, as well as various local jurisdictional bus systems.

WMATA's heavy rail system recovers around 60% of its operating expenses at the fare box, one of the highest recovery rates in the nation. The recovery ratio for bus is only about 30%, a relatively low figure, although this is partly because bus is designed to be a feeder into rail [32]. For comparison, the nation's top performing transit system, New York City's MTA, had cost recovery factors of 67.3% and 40.9%, and the average cost recovery factor across all transit systems nationwide was 39% in 2000 [13]. WMATA's total operating budget for weekday service in 2000 was $642 million, with subsidies for rail and bus services at $95 million and $170 million, respectively, [13]. Also, per trip, bus is cheaper to ride. WMATA estimates the average bus fare is about 40% of the average rail fare. This is partly because MetroRail riders face time-of-day pricing, with peak fares costing two to three times more than fares during off-peak times.

WMATA's long-run funding situation has become a topic of concern, with the lack of a dedicated funding source identified as a major hurdle to WMATA's long run financial stability [40]. In what has become an annual affair, WMATA labors to justify its growing operating subsidy at Federal, State, and county-level appropriations meetings. More recently, a regional sales tax has been proposed to help with this recurrent problem.

3. Description of the Washington-START model

Washington-START is a strategic planning simulation model that is rigorously grounded in household optimization, computes welfare measures that take into account behavioral responses to policy changes, and has relatively short run times, enabling a wide range of policy simulations and sensitivity analysis. It has been used to conduct policy simulations of gasoline taxes, HOT lanes [43], and congestion pricing [42,43], as well as to compute network-based marginal congestion costs of urban transportation [41].[4]

The START modeling suite was developed by the University of Leeds and MVA Consultancy and has been applied to a range of urban centers in the United Kingdom, including Birmingham, Edinburgh, and South England [8,31]. More recently, this model has been enhanced by MVA and RFF and calibrated for Washington, DC. The main enhancements are the following:

(i) the introduction of high-occupancy vehicles (two persons or more) as a separate travel mode;
(ii) explicit modeling of the rail network;
(iii) placing busses and other on-road modes on the same road network; and
(iv) the addition of a park-and-ride capability at Metrorail stations.

The last three enhancements have been made since 2004.

3.1. Road supply

The Washington-START model incorporates 40 travel zones. Each zone contains three stylized links (inbound, outbound, and circumferential) that aggregate arterials and side streets. The model also includes various "special links," which represent freeway segments and bridges, as shown in Fig. 1.[5] Some of these special links have high-occupancy vehicle (HOV) lanes, where HOV is defined by two or more occupants.[6] Motorists traveling between any two zones can choose among as many as nine "routes" connecting the zones, where a route consists of a set of links and for each link, a distance in miles.

We attempted in several ways to make the Washington-START model consistent with the Metropolitan Washington Council of Governments (MWCOG) transportation planning model (version 1), which at the time (2001) was the region's official model for federal transportation funding purposes.[7] First, each of the 40 zones in the Washington START model is a contiguous group of the smaller traffic analysis zones (TAZes) in the 2100-zone COG model. Second, to define the START routes we ran the COG model under several scenarios with respect to trip demands and optimization criteria. Each scenario generated a route connecting each pair of zones in the START model. For example, to get a route connecting START zones A and B, aggregate all the trips in the COG model connecting each TAZ in zone A with each TAZ in zone B, assign to inbound, outbound, circumferential and special links and then divide by the number of trips.[8]

Third, we used the multiple runs of the COG model to define the transportation supply and congestion relationships in the START model. Except for the special links, such relationships cannot be represented by a speed–flow curve, as in a standard traffic assignment model (such as the COG model), because the distance traveled on each link varies from one route to another. Instead of speed–flow curves, the ordinary links in START have speed–flow $\times$ distance curves. To obtain these curves we again used the runs of the COG model, aggregating speeds and flows

[4] We refer to Washington implementation as Washington START.

[5] Six main corridors of special links, I-270, 95, and US-50 in Maryland and I-66, I-95, and US-267 in Northern Virginia, connect the outer suburbs to the central region within the circular Beltway, I-495/I-95.

[6] In the region, on several freeways HOV lanes require three occupants to be present.

[7] MWCOG is the regional organization of Washington area local governments.

[8] What made this possible was that in the COG planning model, each link in the network carried a tag indicating whether it was radial or circumferential.

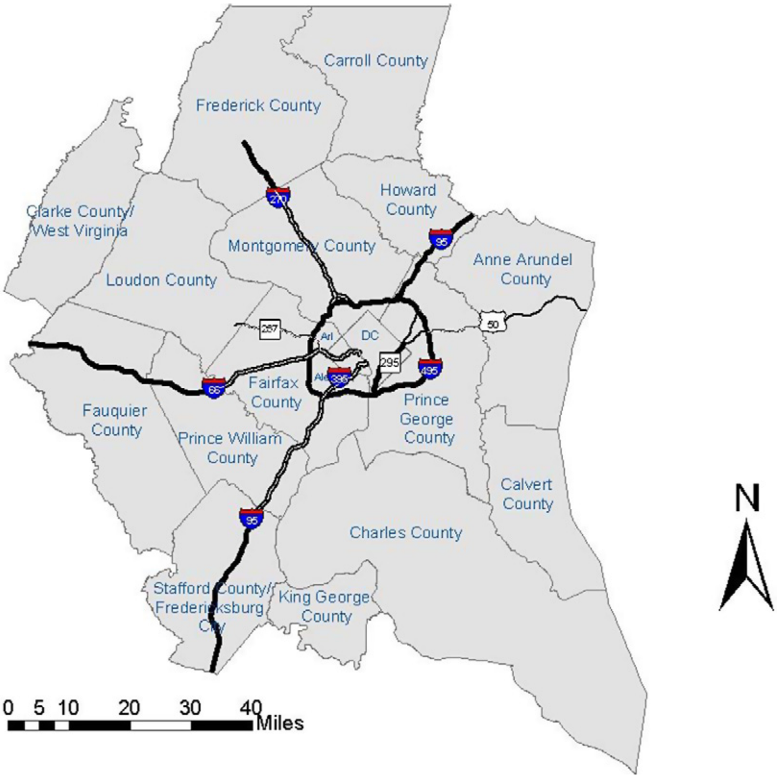

Fig. 1. Washington-START zones and special links.

(weighted by distance) for each link (of the same type) in the COG model within a START zone. This procedure gave us a series of points in a plot of speed against flow × distance, which we interpolated to get the speed–flow × distance curve for each link.

Existing HOV lanes on these freeways at peak period (or at all times, in the case of US 50) are taken into account. Special rail links for the Metrorail heavy rail and VRE and MARC suburban commuter rail systems also span the zones (Fig. 2).

3.2. Public transit supply

Bus and rail transit supply are distinct, matching the demand-side decision structure. Data for frequency, fare and capacity for the Metrobus, Metrorail, VRE and MARC commuter rail, and local jurisdictional bus systems were collected from the agencies directly whenever possible to make the model representation of the two networks maximally accurate.

3.2.1. Rail transit

In the current version of Washington-START rail routes are modeled as a series of "special links" where each rail line in each zone is treated as an individual link, complete with individual capacity and frequency characteristics. Rail routes are made up of a succession of links along a path of zones leading from origin to destination, and were created based on usage patterns derived from a 2002 WMATA Passenger Survey and MARC and VRE boarding numbers. This

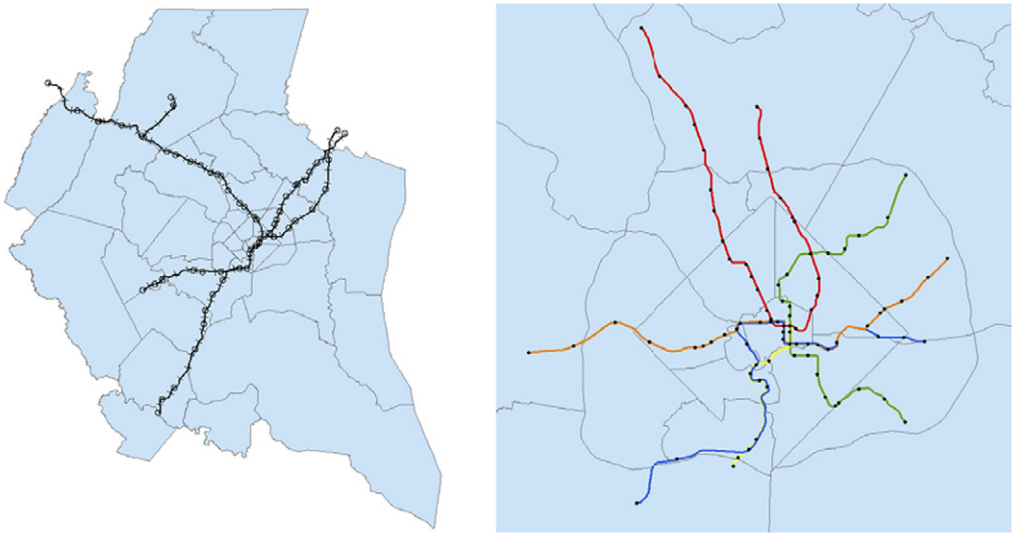

Fig. 2. Commuter rail (left) and MetroRail.

disaggregated modeling is feasible because of the small number of Metro- and commuter-rail lines in the DC metro area.

In addition to rail links, usage-weighted park and ride legs on the road network are added to all rail routes. Thus urban commuters, who generally do not drive to the rail station, encounter short to non-existent park-and-ride legs, while suburban commuters face longer park and ride routes.

3.2.2. Bus transit

Bus routes are much less tractable than rail and are defined to be routes on the existing road network[9] for each origin–destination pair. For each time period, buses are assumed to travel the most frequently-used car route from the origin to the destination. In this way, congestion on the road network also affects bus riders. It follows that benefits from reduced congestion can also accrue to bus users. This is a marked improvement over the state of Washington-START in [43], when buses were modeled as if they operated on a distinct network of bus-lanes and bus travel times were unaffected by automobile congestion.

3.2.3. Transit crowding

A crowding penalty is established at four different levels of crowding within a public transit vehicle. The levels are established based on vehicle occupancy, such that when riders sit comfortably there is no penalty, when they sit crowded there is a slight penalty. Standing comfortably invokes even higher penalty, and standing uncomfortably leads to a high penalty. Within the model, the penalty is a scale factor used to increase perceived trip time as passengers are subjected to more crowded public transit vehicles [27]. The same crowding penalty applies to bus and rail trips. The crowding formula is applied in a time-windowed approach, us-

[9] As traditional in transportation network modeling, a bus is considered to consume the equivalent of two “car units” of road space on the network.

ing WMATA demand characteristics in half hour intervals for each time period. This method ensures that the crowding calculation fully captures the "peakiness" of the morning and afternoon rush hour periods. Taking into account peaking attributes is important: there are 2.7 times as many peak WMATA rail trips as off-peak. For WMATA bus service, the ratio is 2.4 [13].

3.3. Trip demands

Travel decision-making is modeled as a nested logit tree; in successive nests, households choose whether to take a trip, then destination, mode, time of day and route. The transit mode decision is further nested into two submodes: bus and rail transit. Utility functions at each nest are linear in full travel costs, which combine time and money costs. The value of time is a fraction of the driver's wage rate, with a higher rate attributed to unpleasant tasks of waiting or traveling in crowded conditions.

Transit user costs reflect fares, wait time, travel time and various costs associated with park and ride. Details are given in Appendix A. Rather than working with absolute costs, the Washington-START model uses cost differentials between the calibrated baseline and simulated policy scenarios to determine the costs that drive the logit model. For this reason, the costs that do not change between the baseline and policy simulations will not change results and are not included. For example, time needed to walk to a bus stop is not included in the bus cost formula because this time is assumed to be the same in the baseline and policy scenarios.

Households are aggregated into four income groups. Five trip purposes, in addition to freight, are distinguished: home-based trips either originate or terminate at home and are classified as commuting to work, shopping, or other (such as recreation), and non-home-based trips are distinguished between work-related and non-work related. There are four travel modes, including single-occupancy vehicle (SOV), high-occupancy vehicle (HOV), bus/rail and walk/bike. And there are three times of day: morning peak, afternoon peak, and off-peak (weekend travel is excluded).

Trip demands are estimated for each of these origin, destination, purpose, mode, and time period nests using methods discussed in [43]. Data sources used include the Census Transportation Planning Package (CTPP), the Metropolitan Washington Council of Governments (COG) Version 1 transportation planning model and 1994 Travel Survey, as well as wage and price indices obtained from the Census and Bureau of Labor Statistics. The model has been recalibrated since the 2004 study using more recent CTPP 2000 data.

Washington-START takes the distribution of households by demographic segment and residential location as given. Travel demand response parameters were chosen to satisfy the hierarchical structure of the logit model and to be largely consistent with empirical literature. For example, Washington-START's computed fuel price elasticity of vehicle-miles traveled in the baseline scenario is −0.169. It should be noted that there are no "elasticity" parameters in START; computed elasticities are not constant and are computed results obtained from model runs. Therefore, they reflect not only the direct effect of increase in fuel price, but also the secondary effects related to reduced traffic congestion. This value corresponds well with values in the literature of −0.16 [11] and −0.1 [17]. See Table 1 for various computed transit elasticities, also evaluated in the baseline scenario. It should also be noted that transit supply is exogenous; operators do not respond to reduced demand by changing service levels.

Table 1
Washington-START computed elasticities

Elasticity	Washington-START	Compare to
PT trips WRT fuel price	0.088	0.07 [30]
Bus trips WRT bus fare	−0.291	Compare at −0.28 short run, −0.55 long run [16]
Train trips WRT train fare	−0.732	Compare at −0.65 short run, −1.08 long run [16]

4. Estimating the benefits of Washington, DC's transit system

The policy scenarios here look only at weekday transit supply. Fares, the geographical pattern of investment, and the relative mix of peak and off-peak service do not change from the baseline. These simplifications help us to best characterize the transit system as it is, rather than as it optimally could be. The simulations use 2000 as the analysis year for traffic patterns, prices, and travel volumes.

In these simulations, expansion/contraction is enacted by simulating a percentage change of rail and/or bus revenue miles operated by the transit agencies in the modeled area. The revenue mile increase or decrease is achieved by simultaneously manipulating route frequency and vehicle capacity, leaving the network of routes and fares unaltered. From the users' perspective, frequency affects waiting time at the bus or rail station and capacity influences the number of potential passengers (and thus crowding) on each transit vehicle. We model scenarios where we change the frequency and capacity by the same percentage.

To estimate total net benefits of the weekday Washington area transit system, we reduce transit supply to zero and calculate the resulting aggregate welfare change. The decline in traveler welfare minus the business as usual (BAU) regional subsidy to the system can be interpreted as a measure of the net benefits of the BAU system. Obviously, such an extreme scenario raises questions about what the results mean and whether we are exercising our model beyond its ability to tell us anything useful. We discuss these issues of interpretation below, but for now let us present some reasons why we think the analysis is useful. First, it enables a comparison with other studies that have estimated the aggregate value of the transit system [57,58]. It can also produce estimates of partial measures of benefits, such as changes in travel times for road users. Finally, it provides a picture of the distribution of current benefits from the transit system.

4.1. Total benefits and comparison to other studies

The benefits generated by transit system are the inverse of the welfare losses incurred when the transit system is eliminated. We test three scenarios: eliminating bus and rail separately and eliminating both modes together. Thus we estimate the benefits of all transit, the benefits of rail in the presence of the existing bus system, and the benefits of bus in the presence of the existing rail system. The basic results are shown in Table 2.

Our first result is that the time savings to motorists alone easily exceed operating subsidies for both the entire system and for the rail system. Thus it seems to us that transit advocates in the Washington metropolitan area are on solid ground when they cite rail transit's effect on highway congestion. The bus system alone generates relatively little in the way of driver time savings, both because buses and cars compete for scarce roadway space and because bus users that switch to rail do not affect drivers (unlike when rail is removed, and rail users move to the roads, either via car or by bus). Of the benefits to drivers, about two thirds are congestion-related; the rest are parking-related costs.

Table 2
Overall benefits of the weekday Washington, DC transit system ($2000)

	Bus	Rail	Both modes
Daily ridership (000s)	515.2	646.2	1161.5
Traveler welfare per transit trip	$7.57	$5.16	$7.97
Annual motorist benefits (Millions)	$68	$454	$736
Annual traveler welfare (Millions)	$975	$833	$2313
Annual operating subsidy (Millions)	$228	$110	$338
Annual net benefits (Millions)	$743	$728	$1975
Net benefits per transit trip	$5.81	$4.51	$6.80

The motorist benefits are dwarfed by the total traveler benefits of the transit system, $2.3 billion per year. As seen from Table 2, traveler benefits from the weekday bus system are $975 million per year, or $7.57 per bus trip in 2000 dollars. Weekday rail produces about $833 million in traveler benefits, or $5.16 per rail trip. Taking into account the regional subsidies for the two modes, these per trip net benefits drop to $5.81 and $4.51 for bus and rail, respectively. These per trip net benefit figures are substantially higher than those estimated by Winston and Shirley, who found net benefits from bus and rail to be on the order of $3.10 and $2.96 per transit work trip.[10] Winston and Shirley's calculations are for a national average in 1990, so the fact that Washington, DC is a relatively hospitable setting for a large transit system undoubtedly explains a large part of the discrepancy.

Shutting down both modes simultaneously produces an estimate of total weekday traveler benefits of around $2.3 billion annually and a per-trip figure of $7.97. The traveler benefits from the complete system are greater than the sum of the traveler benefits for each individual system (superadditivity). This is to be expected since bus and rail are close, albeit imperfect, substitutes.

Of course, capital costs are also an important element of the total costs the transit system. A large portion of the Washington transit system's capital outlays are paid for by the federal government rather than the local and state governments [46]. As a result, these costs are often ignored in local discussions of transit's performance and cost-effectiveness. From an efficiency perspective, however, they should be taken into account. This is not a straightforward exercise, unfortunately, because capital outlays for the DC metro system stretch back over 35 years. A simple approach to come up with a capital cost can be created by collecting historical capital outlays [46], and assuming the money spent was raised via 5% yield 30-year bonds (see Fig. 3). Under these assumptions, the expenditures on repaying debt from capital spending amount to payments of around $225 million per year in 2000. Adding this capital cost figure to the operating costs in Table 2 results in annual net benefits of the system of over $1.7 billion for the year 2000, or $6 per transit trip.

This estimate is obviously imperfect; such an analysis ignores important long-term land use changes and other adjustments associated with the development of a major transit system over many decades. Thus, rather than testing the costs of the "what if there was never a transit" counterfactual, we are looking at the costs of a shutdown of the current system, or the benefits provided by that system.

The fact is, our total benefit estimate is a mix of some extremely short-term effects, medium term effects and long-term effects. For example, if we scale the traveler benefit numbers pre-

[10] Figures converted into 2000 dollars using CPI. For a direct per transit work trip comparison, we calculate $22.94 dollars in benefits per bus work trip and $7.12 per rail work trip.

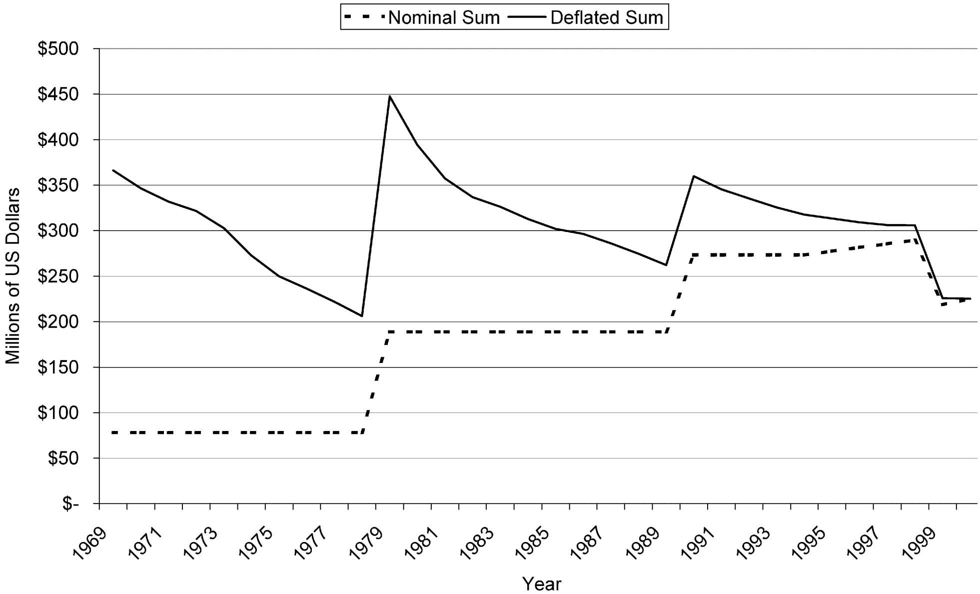

Fig. 3. Hypothetical WMATA capital payment stream.

sented in Table 2 to an unanticipated one-week shutdown, such as might result from a sudden transit strike, the loss of a rail disruption amounts to $16.6 million, a bus disruption $19.5 million and $46.3 million for both modes. These losses appear to us to be quite reasonable, and they are incurred by travelers only. It is certainly possible that they would pale in comparison to the economic costs to businesses associated with a strike. However, losses of this magnitude are not likely to endure, or be endured, for a year, so we suspect our $2.3 billion estimate of the annual losses is a bit high.

Indeed, as we reduce the revenue mileage of the transit system from 100% of the current system to 0%, we find that the welfare losses increase very rapidly as 0% transit supply is approached. For example, when both the frequency and vehicle capacity are 25% of baseline (and system vehicle revenue miles are 6% of baseline), the welfare losses compared to the baseline are $894 million, quite a bit smaller than the $2.3 billion in losses after a complete shutdown of transit. Whereas the shutdown case assumes that no private party would step in and fill the gap, one way of thinking of the 6% scenario is that it illustrates a possible outcome if market forces created some transit provision along profitable routes. At this level of reduction, providing options that offer even a relatively small expansion of travel opportunities could have a large effect on traveler welfare.

START, as a logit-based choice model, imposes high welfare costs for completely eliminating traveler options. But a severe change in those options could lead to the development of new options not previously available. On the demand side, travelers would adjust to the loss of the transit system by moving, purchasing a vehicle, changing jobs, or joining a van- or car-pool in the medium- to long-term. These options are also outside of the model. We note that the losses resulting from elimination of bus alone or rail alone are much smaller than the losses from eliminating both, further suggesting that it is the elimination of the transit choice altogether is very costly until there is some adjustment to it. However, it is not the case that *all* the losses are

Table 3
Distribution of benefits from the Washington transit system

Income group	Per trip benefits (2000 ¢)	Change in average car trip time (min)	Value of time ($/h)
1	9.6	−0.273	2.70
2	30.5	−0.439	5.64
3	40.3	−0.594	9.01
4	97.1	−0.908	18.80

short term. For example, driver costs from increased congestion and unavailability of sufficient parking ($736 million at 0% PT provision) will not be easy to overcome quickly.

The results presented here are dramatically different from those estimated for Washington by Winston and Maheshri [57], who find that DC's WMATA rail system produces *negative* net benefits of over $200 million a year in 2000, compared to the over $700 million in benefits that we find for the rail system alone. There are a number of reasons why these results would be different. The main differences seem to be in the figure used for the transit agency deficit ($110 million versus $657 million) and in the benefits to drivers ($453 million versus $181 million), which together account for over 80 percent of the gap. Concerning the transit agency deficit, we use the operating deficit for WMATA rail, but even if we add WMATA capital expenditures for bus and rail ($232 million), we would only arrive at $342 million. In any case the source of Winston and Maheshri's $657 million is not clear to us. As for the driver benefit discrepancy, part of the difference is accounted for by the scope of the benefits. While Winston and Maheshri's estimate includes only time savings (their number is estimated for San Francisco and applied to Washington), ours also includes parking search time. A final difference between our approaches is that START includes commuter rail in addition to the WMATA rail system and encompasses a greater geographic area.

4.2. The distribution of transit's benefits

The benefits of the transit system accrue both to transit riders, who take advantage of the increased travel options, and drivers, who benefit from reduced congestion. The impact of transit on driving times is greatest on especially crowded roads. To take one example, removing transit reduces the average speed on a portion of I-395 North during the morning peak from 39 miles per hour to 33 miles per hour. Overall, we estimate drivers save about 45.9 million hours per year in travel time thanks to the existence of a transit system.

The simulation results shed light on the distribution of benefits among income groups from the transit system. Table 3 shows the benefits of the transit system normalized by total trips (car, transit and other) for each income group. In contrast to conventional wisdom, we find wealthy travelers receive by far the largest per trip benefit, approximately ten times larger than the benefits received by the lowest income group.

Two factors drive this result. First, value of time[11] to travelers in different income groups is proportional to wages. Under this assumption, reductions in travel times are valued more highly by wealthier travelers and even a policy that produces equal travel time reductions across income classes will generate more benefits to the wealthy. The results might not be so dramatic if the

[11] Value of time is 40% of the wage rate for the majority of the travel times modeled. Exceptions include times associated with parking and waiting for public transit, valued at the full wage rate.

Table 4
Benefits per capita ($ per year) and % of annual income

Inc. group	Both		Bus		Rail	
1	106	1.12%	41	0.43%	41	0.43%
2	438	1.57%	204	0.73%	138	0.49%
3	750	1.45%	354	0.69%	264	0.51%
4	1714	1.42%	599	0.50%	663	0.55%

elasticity of the value of time with respect to income is less than unity, as suggested in a recent paper by Wardman [56].

Even ignoring time valuation differences, however, time savings break down differently across the income groups, as Table 3 shows. Savings in terms of minutes per trip accrue disproportionately to the upper income groups. This could be because wealthier individuals take more trips along congested corridors than do lower-income individuals. Overall, benefits per capita are significantly lower for the lowest income group compared to the others, as shown in Table 4, but the overall pattern differs between bus and rail. For bus (and for both), the group with highest benefits relative to income is group 2, the second-lowest group. For rail, however, benefits are strictly increasing in income. This is not a totally surprising result, considering that the rail system was designed primarily to improve access from suburban areas (especially wealthy ones) to the downtown core.

Finally, we are able to observe the geographic distribution of benefits.[12] Figure 4 shows the expected result: those that benefit from transit travel within the core and inner suburbs. The differentials in the benefits are striking. Per trip traveler welfare gain from the transit system is over $1 for trips beginning in the downtown core, and less than 5 cents for trips originating in the distant suburbs. Basically, benefits accrue to zones with a large transit presence and congested roadways.

5. The optimal level of transit

While the total benefits of the existing transit system is an interesting academic and political question, it is something of a moot point practically. Most of the costs are sunk and there is little prospect of the system being disassembled. Of more practical significance is whether the current scale of service is close to the optimum. In this calculation we hold routes and fares constant and scale bus-miles and/or rail miles by adjusting capacity and frequency simultaneously on the existing network links. For example, to obtain a bus network that is 1.1025 times larger than the existing one, we adjust frequencies by a factor of 1.05 and capacities by a factor of 1.05.

Results are presented in Table 5. After netting out operating costs, we find an optimal level of provision 14% above the current amount of daily bus and rail vehicle miles. Increasing the supply of transit by this amount increases the overall operating subsidy by $78 million annually and increases traveler welfare by $82 million. The net improvement from moving to the optimum is only $4.5 million dollars per year, or roughly 2% of the current operating subsidy. It appears that the marginal social benefit from increased transit in Washington is very much in line with the marginal cost, if the operating subsidy is the only cost considered.

[12] Since the majority of trips are home-based, the distribution by trip origin is correlated with the residential pattern.

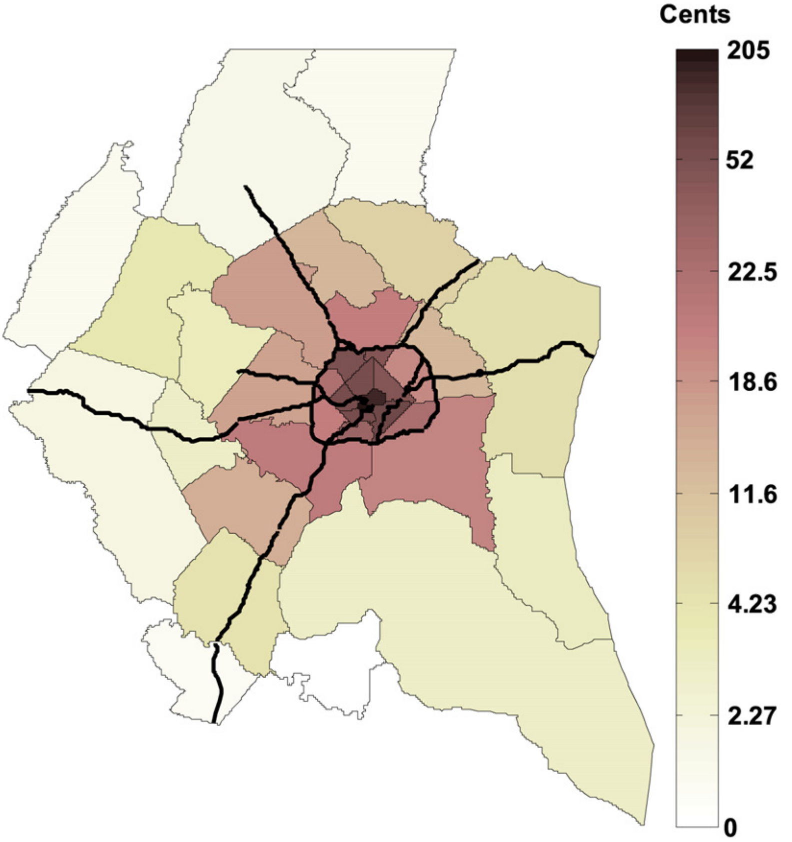

Fig. 4. Per trip traveler benefits by trip origin.

Table 5
Optimal provision compared to base case (ignoring capital expenditures)

	Bus	Rail	Both modes
Change in supply	16.6%	14.5%	14.5%
Traveler welfare (Millions)	$51.22	$37.84	$82.25
Operating subsidy (Millions)	$48.79	$35.06	$77.73
Capital expenditure	$10.25	$32.24	$41.16
Net welfare (Millions)	$2.44	$2.78	$4.52

As noted above, from an efficiency perspective, capital costs should be considered as well. Accounting for capital costs is difficult because of their nonlinear nature. However, WMATA's estimates of the capital costs associated with expanding service are publicly available in WMATA's annual financial reports. With a simplified assumption (in reality the capital stock would depreciate with use) that the capital cost savings from reducing system size are symmetrical to the capital costs of increasing system size, we find the optimal supply in terms of capacity and frequency is about 25 percent lower than current levels. The potential gain from moving to this optimum is only about $20 million a year, or about one percent of the total net benefits of the transit system. This figure illustrates how flat the net benefit curve is near the optimum.

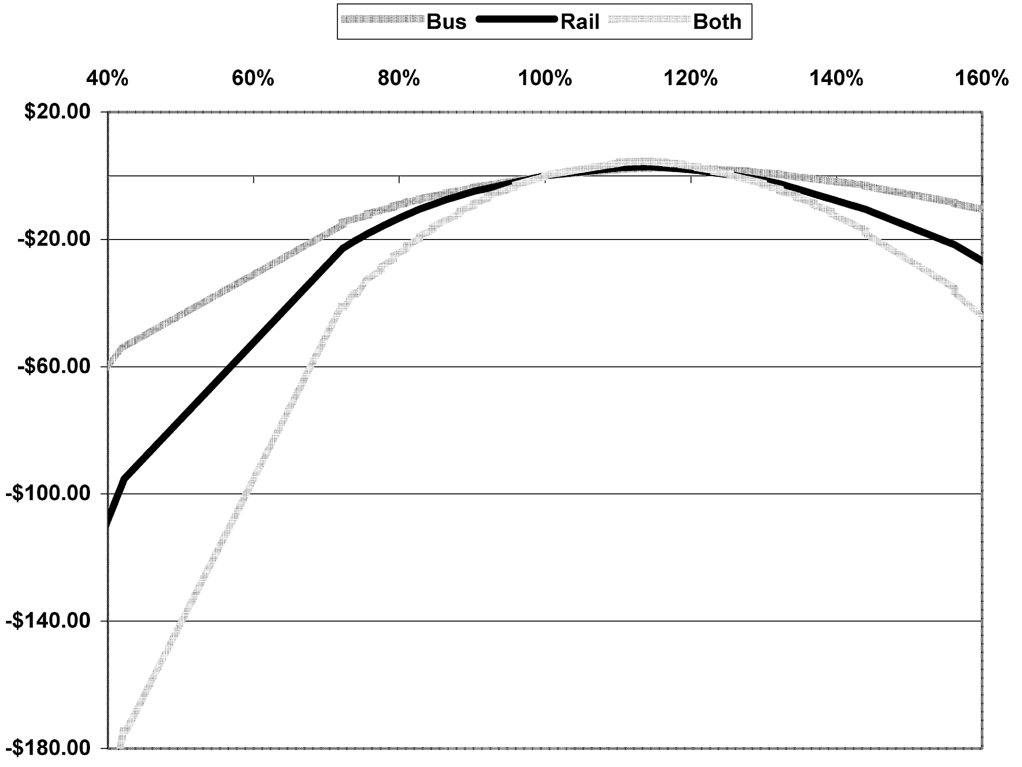

Fig. 5. Optimal transit provision.

In addition, we test the relative attractiveness of bus and rail investment by changing the level of one while holding the other constant. When ignoring capital costs, we find that both bus and rail are underprovided. Bus should be increased by 16.6% if rail is held fixed. Holding bus fixed, we find that rail should be increased by over 14%. The two modes differ much in the composition of their net benefits, however. Increasing bus supply alone brings more marginal benefits to travelers and higher marginal costs to the transit agency than do changes in rail alone. This is intuitive; bus is subsidized almost twice as much as rail per passenger and rail trips are very frequent during the rush hour in Washington (every 2.5–3 min whereas busses run every 5–10 min), so the time benefits of additional rail frequency are proportionately lower than additional bus frequency.

6. Discussion

An obvious limitation of this study is that the results reflect specific features of the Washington metropolitan area, including the geography of income distribution, relative importance of public transit, level of carpooling, degree of utilization of HOV lanes and the Federal Government's placement as a fixed central economic activity. As Baum-Snow and Kahn [2,3] argue, the DC region is one of the most promising settings for a major transit system in the country. The large benefits found here should not be taken as evidence in support of transit investment in dissimilar locations.

In addition, the decision to have a major transit system represents a non-marginal choice about overall urban form. Without WMATA, DC's economic geography of development patterns and road networks would look very different. Care should be taken in interpreting the overall benefit number because estimating the true benefit requires an ad hoc counterfactual speculation about the region's alternative development path. Still, this test can shed light on the benefits of the system across various income classes and geographic regions, under current conditions.

The test of optimal provision presented here shifted the level but not the spatial pattern of investment. There is reason to believe that the current geographic distribution of transportation services is inefficient, given that transit operates at low capacity levels in the outlying areas. If transit routes were rationalized, the optimal level of investment could be higher or lower than the current amount. In other words, our optimum is highly constrained.

The benefits measured here include reduced congestion and increased travel options. Other benefits such as reduced air pollution and accidents are ignored in the analysis. However, numerous studies show the benefits from reduced pollution are very small, especially when compared to those from congestion reduction. The benefits from reduced accidents, on the other hand, are significant and therefore the benefit numbers reported here are probably an understatement [36].

Finally, efficiency is but one of the rationales for transit investment, while serving low-income communities is another. With the approach taken here, improved service to lower income travelers will be weighted lower based on their assigned value of time. This may not be appropriate, given societal desires for ensuring access to employment, health care and other goods. A related point is that people's value of time as they travel may not be as closely connected to wage levels as this study assumes.

In spite of these caveats, several conclusions can be drawn. First, it is clear that under a wide range of assumptions, the transit system delivers large benefits to travelers, transit users and drivers alike. These benefits dwarf the region's operating subsidies and are still significantly large when capital outlays are taken into account.

Second, against conventional wisdom, the benefits of DC's transit system accrue disproportionately to wealthy travelers, both in terms of economic welfare measures and raw minutes saved while traveling. This observation lends support to the proposition that transit provision should be financed through progressive revenue instruments.

Third, although the current level of investment in transit in the Washington area is not optimal, it is reasonably close. Furthermore, although the value of the system as a whole is unquestionable, the net gains from moving from baseline to the optimum (assuming no other concurrent instruments, like road pricing) are trivial when compared to the net benefits of the system. Similarly, moving from the optimum to a point of lower provision results in trivial losses. This large range of near-optimal transit provision suggests that political concerns can shift transit provision levels within the current road and transit network framework without large reductions in aggregate social welfare.

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Appendix A. Transit trip cost calculation

Transit users face monetary costs as follows:
Bus:

$$P = f + 2v^*(1 + 2\pi)w + v^*(1 + \rho)t \tag{A.1}$$

Rail:

$$P = f + 2v^*w + v^*(1 + \rho)t + \tilde{d} + \tilde{f} + v^*\tilde{t} + 2v^*(\tilde{s} + \tilde{e}). \tag{A.2}$$

Where:

- f is the transit fare
- v^* denotes value of time, set at 40% of the wage rate for all purposes except non-home-based work trips. For non-home-based work trips, it is assumed that the traveler is "on the clock," and the value of time is therefore set at the wage rate. For waiting time, parking egress time, and parking search time the value of time is doubled, as time spent in these activities is considered more unpleasant than time spent in-vehicle
- π denotes the probability of missing a bus and having to wait for the next one (this constant also helps to address the bunching effect often seen on bus routes), and is a function of the fullness of the bus
- w denotes the waiting time
- ρ denotes an increase in perceived time resulting from crowding (to be explained in the next section). This perceived crowding penalty is purely psychological; it does not represent any real factor contributing to trip time
- t denotes the travel time, including transfers between bus/rail lines

The following variables pertain to the park-and-ride leg of rail routes. The park-and-ride leg is weighted to accurately represent the tendency of rail users to drive and park at the origin rail station.

- $\tilde{d}$ denotes the monetary driving costs for the drive from home to the rail station
- $\tilde{f}$ denotes the parking fee associated with the route
- $\tilde{t}$ denotes the time required to drive from home to the rail station
- $\tilde{s}$ denotes the time required to find a parking space, and is a function of the fullness of the parking area and of one's parking category (reserved versus unreserved space), as well as of the physical details of the parking area, such as lot size
- $\tilde{e}$ denotes the time required to egress from one's car to the rail station entrance

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