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The Optimal Supply and Demand for Urban Transit in the United States

HDR|HLB Decision Economics

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THE OPTIMAL SUPPLY AND DEMAND FOR URBAN TRANSIT IN THE UNITED STATES

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Disclaimer

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EXECUTIVE SUMMARY

The United States is sharply underinvested in urban transit. Capital investment of $111.0-$259.0 billion over the amount actually spent in 2004 would have been required to bring the supply of transit into line with the optimal conditions of supply in that year. While an investment and collateral increase in running costs of such a magnitude in a single year was, and is, infeasible (fiscally or operationally), the $111.0-$259.0 billion does represent the amount by which actual transit supply currently falls short of the economically appropriate level. At the optimal level of service, transit ridership would be an estimated 84 percent greater than it is today. Automobile travel would be less by an estimated 2.8 percent with much of this reduction in some of the most congested corridors in the country.

The economic and social benefits of bringing transit to the optimal level of supply would be significant, in the order of $2,359 billion over 30 years. More than two-thirds of these benefits constitute the economic value of reduced roadway congestion. Since congestion represents a widely acknowledged drain on national economic productivity and performance, this finding gives transit investment national strategic significance. Thus, while the $259.0 billion capital cost and corresponding increase in operating support needed to optimize the provision of transit might be beyond the fiscal capacity of local and state governments, there exists a powerful rationale for federal financial involvement.

The United States does not rely on market-based (full cost-based) prices to bring about the optimal allocation of resources between urban roadway infrastructure and urban transit. Although congestion pricing in various forms is the subject of vigorous policy debate, and while a handful of toll roads and “High-Occupancy Vehicle Lanes” are under development, congestion pricing is occurring to a very minor extent and almost exclusively for newly constructed roads. Thus there are no prices, for the most part, to signal consumers about the massive resource costs of using their cars during congested periods, costs that are estimated to exceed $78 billion a year in lost time and wasted fuel. As a result, city streets, roads and highways are regularly in “short supply,” choked with long queues of cars and trucks. If “congestion tolls” were in place, fewer people would use cars and more would use transit. Travelers would signal a different allocation of resources between roadway and transit infrastructure than that in place today.

In the absence of ubiquitous congestion tolls, a “second-best” optimal allocation of urban transportation resources can be achieved by holding transit fares below their full cost and providing sufficient transit service to induce some car users to switch to bus or rail. Using the appropriate economic analysis tools, this study finds that the current provision of transit service (4.5 billion vehicle-miles in 2004) is too little to optimize the provision of urban transportation in the United States. As shown in Summary Table 1, the economically and socially optimal level of transit supply in 2004 would have required an estimated 10.7 billion vehicle-miles of transit service, or 139 percent more service than actually supplied.

Summary Table 1: Optimal Demand and Supply Conditions of Urban Transit and Road Infrastructure, 2004 (in 2004 dollars)

Optimal Demand and Supply, by Mode	2004 Actual	2004 Optimal	Optimal versus Actual (Percent)
TRANSIT			
Supply **(Millions of Vehicle-Miles)**	**4,471**	**10,690**	**139.1%**
Demand **(Millions of Passenger-Miles)**	**49,073**	**90,033**	**83.5%**
AUTO			
Demand **(Millions of Passenger-Miles)**	**1,427,894**	**1,387,467**	**-2.8%**
AUTO & TRANSIT			
Demand **(Millions of Passenger-Miles)**	**1,476,967**	**1,477,500**	**0.04%**

CATCHING UP

Recognizing that the gap between actual and optimal transit supply increases continuously as traffic congestion continues to mount, what might a budgetary plan look like that seeks to close the gap in transit supply as it stood in 2004? Summary Table 2 shows the effect of spreading a $259.0 billion investment over a period of ten years, and allowing for a rate of price inflation of two percent annually. This gives an average annual expenditure of $30.7 billion. It should be noted that the annual expenditure of $30.7 billion does not include funding for renewal and rehabilitation. Government contributions to operating revenue support would reach $65.0 billion by 2017.

Summary Table 2: A Ten Year Transit Capital and Operating Program to Reach Optimal Conditions of Supply by 2017 (in billions of current year dollars)

INVESTMENT CATEGORY	2008	2009	2010	2011	2012
CAPTIAL INVESTMENT					
Capital Investment in Service Expansion	$28.0	$28.6	$29.2	$29.7	$30.3
OPERATING REVENUE SUPPORT					
Operating Revenue Support	$19.0	$23.4	$26.6	$30.2	$34.3
INVESTMENT CATEGORY	**2013**	**2014**	**2015**	**2016**	**2017**
CAPTIAL INVESTMENT					
Capital Investment in Service Expansion	$30.9	$31.6	$32.2	$32.8	$33.5
OPERATING REVENUE SUPPORT					
Operating Revenue Support	$39.0	$44.3	$50.3	$57.2	$65.0

ECONOMIC RATE OF RETURN

The study finds that the economically and socially optimal investment program outlined above would generate significant economic and social benefits relative to the costs of achieving them. The present-day value of the program's total life-cycle benefits between 2008 and 2038 would total an estimated $2,359 billion. Total life-cycle costs over the same period (capital and operating expenses) would be $529 billion, for a net benefit of just under $1,830 billion – an economic rate of return of 23 percent. Of the $2,359 billion in total benefits, just under $1,675 billion, 70 percent, result from improved roadway congestion and associated gains in economic productivity and environmental conditions. The balance of benefit, fully $684 billion, reflects improvements in affordable mobility and urban economic development. The mobility and development benefits alone exceed the costs of the optimal program by almost $1.29 for each $1.00 of expenditure.

Macro-Economic Outcomes

The investment of $259.0 billion in new transit assets would bring with it significant macro-economic outcomes. Over a ten year period to achieve the needed optimal capital investment levels, the nation could expect to see 11 million associated construction-related jobs. And once transit systems were operating at the new, optimized level of service, permanent jobs in the transit sector, plus the multiplier effect of those jobs, would exceed 770,000 new full-time equivalent positions.

1: INTRODUCTION

Is the United States' present commitment to transit about right? Should cities be providing more transit? Less? In 2004, the most recent year for which official statistics are available, U.S. cities supplied 4.5 billion vehicle-miles of transit service (bus, rail and streetcars). A total of 49.1 billion passenger-miles were made in that year. Transit agencies spent $28.5 billion to operate the vehicles, facilities and equipment of which fare-paying passengers covered just over 34 percent[1]; taxes levied directly by transit agencies and other subsidies from local government such as bridge and tunnel tolls and non-transit parking lot funds covered 17%; governments (mainly state and local) made up the balance with operating support of $14.9 billion, or approximately 50%.

This study uses conventional and peer-reviewed methods of economic analysis to ascertain whether the provision of 4.5 billion vehicle-miles is too much or too little to optimize the performance of urban transportation in the United State. The optimal allocation of investment and operating dollars between transit and roadway infrastructure (streets, arterial roads, highways) is reached when the net benefits (benefits minus costs) people obtain from the urban transportation are maximized. The costs of urban transportation include the capital investment for facilities and equipment; the expense of operating and maintaining such facilities and equipment; and the costs associated with use of the facilities and equipment, such as accidents, congestion, environmental pollution, and greenhouse gases. The benefits of urban transportation arise in the form of mobility; accessibility; productivity; economic development; and reductions in vehicle operating costs (such as fuel and oil) brought about by improved facilities and equipment. Taking all these factors into account, this study quantifies:

- The optimal level of transit service;
- The level of transit capital investment and operating support needed to support optimal levels of service;
- The effect of optimizing transit levels of service ridership, automobile travel and roadway congestion; and
- The fiscal implications of aligning transit with the optimal conditions of supply.

A NATIONAL-LEVEL POLICY PERSPECTIVE

This study gives a national perspective on optimal transportation investment. The manner in which such investments should be allocated among regions, cities and types of transit (bus, light rail and so on) is not addressed. The study's conclusions do comment, however, on the local planning implications of the findings.

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[1] Estimated based on data from the American Public Transportation Association's Public Transportation Fact Book (April 2006).

PLAN OF THE PAPER

Section 2 presents the framework within which the “optimal” amount of transit can logically and reasonably be ascertained. Sections 3 and 4 apply the framework. These sections provide estimates of the optimal level of transit demand and supply; the volume of capital investment and operating support needed to achieve optimal conditions; the corresponding impact on the demand for automobile transportation and roadway investment; and the net economic rate of return that would follow from an optimization of urban transportation resources. Section 5 translates the findings into an optimal budgetary program for transit. Conclusions are presented in Section 6.

The report includes three technical Appendices. Appendix A describes the economic model used to estimate the level of optimal transit supply and investment, and the corresponding changes in transit ridership and auto demand. Appendices B and C report the assumptions and sources used in the analysis process. Appendix B gives assumptions and sources pertaining to the analysis of optimal transit investment while Appendix C provides the technical assumptions underlying the Cost-Benefit Analysis presented in Section 5.

2: FRAMEWORK FOR DETERMINING THE OPTIMAL SUPPLY OF URBAN TRANSIT

The economic benefits of transit stem from its effects on congestion, environment and health, mobility, and economic development.

- *Congestion.* Increased use of transit in lieu of automobiles leads to improved highway travel times and travel time reliability. Benefits accrue to both the passenger and freight sectors.
- *Environment and health.* Increased use of transit in lieu of automobiles reduces auto emissions and greenhouse gases and associated health damage.
- *Mobility*. Increased use of transit saves people valuable time and, for low income passengers, releases household budget funds for other high-valued uses such as shelter, nutrition and childcare.
- *Economic development.* Well designed transit facilities create increased property values and higher densities. Although a portion of the increased value is attributable to capitalization of time savings in the value of land, transit facilities also give rise to "non-use" benefits in the form of amenity value and agglomeration (values associated with higher density urbanized living arrangements). These non-use benefits are additive to those listed above.

The analytical framework within which the "optimal" amount of transit can be ascertained falls logically into two parts. The first addresses optimal supply in relation to congestion, environmental and health factors. The second addresses optimal supply in relation to mobility and economic development.

PART I: OPTIMAL TRANSIT SUPPLY IN RELATION TO CONGESTION, ENVIRONMENT AND HEALTH

The economy has a rich though finite endowment of resources (capital, labor) for use in producing the goods and services Americans need and want. Prices play an important role in establishing the mix of goods and services available to people at any given time. While some goods and services are delivered privately and some publicly, the role of prices is central to the realization of an efficient and effective use of our limited resources.

How Prices Help Lead to Maximum Well-Being

In the competitive market economy, prices have the effect of optimizing the allocation of resources. Prices serve this role because they present consumers with the true economic cost of using up the capital, labor and other scarce resources required to supply a given good or service. Based on personal tastes and preferences, and within the limits of their disposable income, people determine their willingness, or not, to pay the true cost of a good or service (a washing machine, say) by sizing up whether or not the benefits to be enjoyed make paying the price worthwhile. If people are not willing to pay for all the washing machines being produced, suppliers get the message in the form of un-used inventory: Resources are quickly shifted away from washing machines and into other goods and services for which people are willing to pay. In this way, prices guide consumers to make millions of individual cost-benefit decisions every day and thereby bring about the allocation of resources that achieves, more or less, maximum economic and social well-being. Economists call this process "signalling" wherein prices send cost signals to consumers who, through the benefit-cost choices they make of what to buy and what not to buy, signal producers as to how to deploy resources in such a way as to maximize their (consumers) well-being while averting persistent shortages, queues and surpluses.

The Role of Prices in the Supply of Government-Provided Urban Transportation Services

If prices serve to avoid persistent shortages and queues, why is it that city streets, roads and highways are routinely in "short supply," namely, choked with long queues of cars and trucks? The Texas Transportation Institute reports that urban congestion costs the United States over $78 billion a year in lost time and wasted fuel.[2] In point of fact, an important reason for chronically congested city streets, arterials and highways is that the price charged for using roadway infrastructure does not reflect the full cost of the resources consumed in its provision and use. In deciding how and when to travel, most travelers take into account their "private marginal costs" -- gas, oil and vehicle depreciation. They also consider the congestion they expect to encounter. No one, however, considers the costs their trips impose on <u>others</u> when they add to congestion – on other roadway users, on the economy, on the environment, on human health. The costs that travelers impose on others includes the value of time wasted in delayed and unreliable conditions; the extra gas and other vehicle operating costs of stop-and-go driving that drivers cause for others in the queue; and the environmental damage and related costs to human health resulting from extra noise, chemical emissions and greenhouse gases.

Economists have long recognized that charging prices (tolls) equal to the full costs travelers impose on others would optimize the use of existing transportation facilities in the short-run and provide information vital to optimizing the characteristics of these facilities in the long run.[3] Fewer trips would be made by car, more people would use transit and the allocation of investment resources between transit and roadways would better reflect the true transportation needs and preferences of travelers relative to the costs of satisfying those needs. However, while interest in congestion pricing is beginning to grow in relation to the construction of new highways, its imposition on existing streets, arterials and highways is fraught with a combination of technical, social and political barriers.

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[2] Texas Transportation Institute, <u>2007 Urban Mobility Report</u>, September, 2007

[3] Early 20th century economist Arthur Pigou was among the first to identify the prospective role of prices in obtaining efficiency from roads and bridges.

The Alternate Path to an Optimal Allocation of Urban Transportation Resources

Because the concept of congestion tolls mimics the way prices work in the competitive market economy (i.e., they send full cost signals), economists call congestion pricing the "first-best" approach to finding the optimal allocation of urban transportation resources. When technical, social and political barriers prevent the first-best approach, economic theory gives a "second-best" solution to securing an optimal allocation. In the case of urban transportation, the second-best approach is that of holding transit fares below their full cost and providing enough transit service so as to encourage "marginal" car users to switch to bus or rail. "Marginal" car users are those who would voluntarily elect to use transit if they faced the true congestion and environmental costs of using streets, roads and highways. The second-best solution is that of achieving the economically optimal balance of transit supply and auto demand by providing just enough transit so as to compensate for the effect of below-cost road user charges.[4]

From an analytical perspective, discovering the fare and service levels needed to achieve an optimal allocation of urban transportation resources turns principally on four factors:

1. The magnitude of the social marginal cost of congestion (the costs of the delay, travel time unreliability, chemical emissions and greenhouse gases) that drivers impose on others (in other words, on the economy);

2. The capital and operating cost per vehicle-mile of supplying transit services;

3. The cross-elasticities of demand between modes (the percentage amount by which auto travel declines for each one-percent reduction in transit fares, and for each one percent increase transit service levels); and

4. The micro-economic framework within which the factors listed above should be used in calculating the optimum transit fare structure and optimal level of service.

These factors and their application are addressed in Section 3.

PART II: OPTIMAL TRANSIT SUPPLY IN RELATION TO MOBILITY AND ECONOMIC DEVELOPMENT

The framework outlined above gives the optimal level of transit demand and the associated conditions of transit supply (fares, service levels) in relation to the effect of transit on congestion and associated environmental and health outcomes.

Even in the absence of roadway congestion, however, the mobility and economic development benefits of transit create economic value which in turn justifies the provision of service. How much service, and at what fare levels, hinges foremost on five factors:

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[4] As shown in Appendix A, the second-best solution relies on the actual effect of increased transit to draw marginal auto users to switch modes, not the simulated effect of road prices, automobile and transit demand will not be the same under first-best and second-best conditions.

1. The capital and operating cost per vehicle-mile of supplying transit services;

2. The own elasticities of demand for transit (the percentage amount by which the use of transit increases for each one-percent reduction in transit fares, and for each one percent increase in transit service levels);

3. The value of passengers' time in work and non-work purposes;

4. The extent to which transit facilities create economic development value over and above the capitalization of such value associated with time savings; and,

5. The appropriate Cost-Benefit Analysis framework within which the factors listed above should be combined.

3: OPTIMAL TRANSIT SUPPLY IN RELATION TO CONGESTION, ENVIRONMENT AND HEALTH

Ubiquitous congestion pricing on the United States' congested city streets, arterial roads and urban highways would help ensure that roads are used only by those who regard the benefits of auto travel worth enough to them to warrant paying the full economic and environmental cost of so doing. The balance would make fewer trips or switch to transit (or both), revealing the economic level of transit supply accordingly. In the absence of ubiquitous congestion pricing, a "second-best" optimal allocation of urban transportation resources can be achieved by holding transit fares below their full cost and providing extra transit service so as to encourage some car users to switch to bus or rail. "External" costs are the costs auto users impose on others when electing to travel during congested periods (i.e., costs external to those that enter peoples' normal decision making process -- gas, oil, their own time).

MICRO-ECONOMIC ANALYSIS FRAMEWORK

A framework of peer-reviewed and long-accepted micro-economic equations provides the basis for ascertaining the amount of transit needed to counter the economic costs of congestion in the manner outlined above. While mathematically complicated, the idea behind the equations is simple. Using accepted micro-economic principles, the equations combine the external costs of congestion (due to autos, but also buses), the cross-elasticities of demand between modes, and the costs of operating and expanding transit services to ascertain the conditions of transit supply that maximize passenger and automobile use net benefits from the transportation system (benefits minus costs). The mathematical model is explained in Appendix A. The following text presents the key assumptions, followed by the results of the analysis. Key assumptions are reported below for the most critical factors; other assumptions are listed in Appendix B. The three most critical factors are:

- The economic costs of congestion;
- Elasticities of demand; and,
- The costs of transit supply.

Economic Costs of Congestion

Measures of the marginal social costs of auto and transit exist for both the congestion and environmental damages of automobile and bus traffic.

Congestion Costs Due to Operating and Maintenance, Vehicle Capital, Travel Time and Schedule Delay and Unreliability

According to national statistics, 48 percent of urban vehicle miles of travel occur during congested conditions.[5] Small and Verhoef (2007) provides estimates of the marginal social costs

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[5] "Congested conditions" is defined here as travel on roadways on which the ratio of volume to capacity exceeds 0.70.

borne mainly by highway users for an additional vehicle-mile. Adjusting these estimates to measure the marginal cost on a passenger-mile basis in 2004 prices yields an operating and maintenance cost of $0.13; vehicle capital cost of $0.15; travel time costs of $0.35 and schedule delay and unreliability cost of $0.15. Combining these estimates guides us to an overall marginal social cost borne mainly by highway users of $0.78.

Congestion Costs Due to Accidents, Government Services and Environmental Externalities

Marginal accident, government services and environmental externality costs caused by automobile travel by urban commuters are borne largely by non-users. These costs are $0.16, $0.02 and $0.01 per passenger-mile for accidents, government services and environmental externalities, respectively. These estimates combine to a marginal cost, which will be borne substantially by non-users, of $0.19 per passenger-mile.

Overall Marginal Social Costs

The final row of Table 1 combines the marginal social costs borne mainly by highway users with the costs substantially borne by non-users. This gives an overall marginal social cost of $0.97 per passenger-mile for automobiles. This figure lies at the higher end of the evidentiary range of the last decade and it is indeed possible that a portion of the operating and maintenance and vehicle capital costs shown under the third column (social marginal cost) of Table 1 are borne privately. On the other hand, drivers entering a congested traffic stream do impose additional operating, maintenance and vehicle capital costs on others, so that some portion of these costs are indeed external to privately borne expenses. We use the full $0.97 per passenger-mile for our baseline optimizing computations but apply and report vigorous sensitivity analysis to the results in order to test their robustness to uncertainty in the evidence.

Analysts estimate that the marginal social cost per passenger-mile for transit is $0.32[6].

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[6] Litman, T. 2006. *Evaluating Public Transit Benefits and Costs: Best Practices Guidebook.* Victoria Transport Policy Institute.

Table 1: The External Marginal Social Costs of Congestion (in 2004 dollars per passenger-mile)

COST ELEMENT	Private Average	Social Average	Social Marginal
Variable Costs			
Costs Borne Mainly by Highway Users in Aggregate			
Operating & Maintenance	$0.13	$0.13	$0.13
Vehicle Capital	$0.15	$0.15	$0.15
Travel Time	$0.27	$0.27	$0.35
Schedule Delay & Unreliability	$0.08	$0.08	$0.15
Costs Borne Substantially by Non-Users			
Accidents	$0.10	$0.12	$0.16
Government Services	$0.00	$0.02	$0.02
Environmental Externalities	$0.00	$0.01	$0.01
Fixed Costs			
Roadway	$0.01	$0.05	
Parking	$0.01	$0.25	
Total Costs	**$0.76**	**$1.09**	**$0.97**

Source: Small, K and E. Verhoef. 2007. *Economics of Urban Transportation.* Routledge.

Note: Estimates from Small and Verhoef (2007) have been adjusted from vehicle-miles to passenger-miles by dividing by average occupancy per vehicle, and to 2004 prices from 2005 prices.

Elasticities of Demand

"Elasticity of demand" is a yardstick used to express the responsiveness of travelers to changes in the price, quantity and quality of transportation. *Elasticity of demand is the percentage change in travel following a one-percent change in the price, quantity or quality of travel.* An elasticity of transit demand with respect to transit fare of -1.0 would mean that each reduction in fare of one percent would result in one percent higher ridership. An elasticity of -0.33 would mean that each reduction in fare of one percent would result increased ridership of one-third of one percent.

As a measure of peoples' willingness to pay for cheaper or better transportation, elasticity is a core benchmark of the *value*, or benefit to them of consuming it. As such, elasticities of demand represent an important element in the calculation of optimal transit prices and levels of service from the perspective of maximizing traveler net benefits. Appendix A gives the specific, mathematical way in which elasticities are brought to bear in calculating the optimal condition.

The values of the elasticities used in the calculation of optimal transit supply, and the sources from which the evidence is drawn, are listed in Table 2 and Table 3. Table 2 gives elasticities with respect to fares: Table 3 gives elasticities with respect to level of service, measured as the quantity of vehicle-miles supplied.

Table 2: Auto and Transit Elasticities of Demand with Respect to Transit Fare in Peak and Off-Peak

Elasticity	Median Estimate
Elasticity of Peak Auto Demand with respect to Peak Transit Price	0.0066
Elasticity of Off-Peak Auto Demand with respect to Peak Transit Price	0.0000
Elasticity of Peak Transit Demand with respect to Peak Transit Price	-0.3000
Elasticity of Off-Peak Transit Demand with Respect to Peak Transit Price	0.0300
Elasticity of Peak Auto Demand with respect to Off-Peak Transit Price	0.0016
Elasticity of Off-Peak Auto Demand with respect to Off-Peak Transit Price	0.0200
Elasticity of Peak Transit Demand with respect to Off-Peak Transit Price	0.0300
Elasticity of Off-Peak Transit Demand with Respect to Off-Peak Transit Price	-0.5000

De Borger & Wouters (1998) cite the following articles for their price elasticity estimates: Oum, Waters & Yong (1992), Goodwin (1992),‘t Hoen, Kuik and Poppelaars (1991), Webster (1997), Ruitenberg (1983) and Glaister and Lewis (1978).

The values listed in Tables 2 and 3 reflect a meta-analysis of all available evidence. Meta-analysis is a formal method of evidentiary review (or literature review) and synthesis, and only published and peer reviewed evidence was used.

Table 3: Auto and Transit Elasticities of Demand with Respect to Transit Level of Service

Elasticity	Median Estimate
Elasticity of Peak Auto Demand with respect to Peak Transit Level of Service	-0.0300
Elasticity of Off-Peak Auto Demand with respect to Peak Transit Level of Service	0.0000
Elasticity of Peak Transit Demand with respect to Peak Transit Level of Service	0.6000
Elasticity of Off-Peak Transit Demand with Respect to Peak Transit Level of Service	0.0000
Elasticity of Peak Auto Demand with respect to Off-Peak Transit Level of Service	0.0000
Elasticity of Off-Peak Auto Demand with respect to Off-Peak Transit Level of Service	-0.0050
Elasticity of Peak Transit Demand with respect to Off-Peak Transit Level of Service	0.0000
Elasticity of Off-Peak Transit Demand with Respect to Off-Peak Transit Level of Service	0.2000

De Borger & Wouters (1998) cite the following articles for their price elasticity estimates: Webster (1977), Ruitenberg (1983), Varii Auctores (1980), Lago, Mayworm & McEnroe (1981) and Van DeVoodre (1981).

Although each of the elasticities reported in Tables 2 and 3 enters into the calculation of optimal conditions of transit supply, the results are most sensitive to three values in particular, namely:

- The elasticity of peak auto demand with respect to peak transit fare;
- The elasticity of peak auto demand with respect to peak transit level of service; and,
- The elasticity of peak transit demand with respect to peak transit level of service

The values attaching to the first two of these elasticities are given in the first row of Table 2 (for fares) and the first row of Table 3 (for level of service). The quantitative significance of the values can only be substantively revealed through their use in the equation system of Appendix A. By direct inspection, the elasticities seem low. For example, a 10 percent reduction in transit fare during congested (i.e. peak) conditions reduces auto traffic by only 0.066 percent; and a ten percent increase in transit service reduces auto traffic during congested conditions by 0.3 percent. On the other hand, diverting even one percent of the traffic volume along a busy and congested city corridor can be enough to noticeably speed up traffic.

The value attaching to the third elasticity listed above (given in the third row of Table 2) is significantly greater than the first two; At 0.6, it means that the percentage amount by which transit ridership increases following a 10 percent increase in the provision of vehicle-miles is six percent. Again, the implications for the bottom-line can only be ascertained after all values have been introduced into the equation system (see Results below).

The Costs of Transit Supply

From data for 2004 for all transit modes, and allowing for expenditures on vehicle and collateral investments in right of way, track, facilities and so on, we obtain a probability range of total average capital acquisition expenditures of about $2.5 million per new vehicle (for all transit modes, and including collateral land, structures, facilities and equipment.[7] Since the total capital expenditure data includes both new capacity, additions to existing capacity and asset renewal, there is a risk that the $2.5 million figure overstates the costs of investment in solely new capacity. Based on discussions with industry experts, we have thus taken 50 percent of the $2.5 million value. Treating this value ($1.2 million per vehicle) as a median, we adopt a range of plus-or-minus 40 percent to reflect the variance of unit capital costs associated with bus versus rail expenditure, bus of course costing less.

Operating cost was $0.58 per passenger-mile in 2004.

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[7] *2004 Fact Book of the American Public Transportation Association.* We translate vehicle-miles to vehicles for the purpose estimating capital expenditures because historical data on total capital transit outlays do not distinguish between outlays for new capacity versus outlays for increased service levels using existing capacity. Capital outlay on a per-vehicle basis thus gives a closer approximation to capacity expansion than on a per vehicle-mile basis. We convert vehicle-miles to vehicles with the formula:

$$Vehicles = \frac{\text{Peak Period Supply of Transit per Day}\left(\text{veh - mile}\right)}{\text{Average Transit Speed}\left(\text{miles}/_{\text{hour}}\right)\times\text{Hours in the Peak Period}\left(\text{hours}\right)}$$

RESULTS

Achieving the optimal level of supply reported above would require both significant capital expenditures and increased revenue support.

Capital Investment to Achieve Optimal Transit Supply

Capital investment of between $111.0 billion and $259.0 billion over the amount actually spent in 2004 would have been required to bring the supply of transit into line with the optimal conditions of supply in that year (Table 4). This in turn would have meant a significant increase in transit operating revenue support (of more than 185 percent) going forward. Investment on this scale cannot of course be contemplated in a single year and the $111.0-$259.0 billion would need to be invested over a multi-year period. The longer that period is, however, the more traffic congestion will continue to grow and the greater will be the amount of transit needed to realize economically optimal urban transportation conditions.

The $111.0-$259.0 billion range reflects different possibilities with regard to the mix of bus and rail service to be added in lifting total supply to 10.7 billion vehicle-miles. As shown in Table 4, investment costs (on a per-vehicle basis) are lower for bus systems than for rail systems. This is due, among other things, to the smaller level of ancillary outlays for land, facilities and equipment necessitated by bus transit.

The capital investment cost to realize optimal supply thus depends on the mix of bus and rail investment going forward. As shown in Table 4, if bus expansion were to dominate, the cost would be closer to the $111.0 billion end of the range. Greater rail investment in the mix would drive expenditures towards the $259.0 billion level. Depending upon local circumstances the higher costs of rail systems can be justified by proportionately higher benefits. In other cases, bus investment generates greater value for money. Only careful Cost-Benefit Analysis of bus versus rail alternatives in each city can reveal the appropriate mix of transit investment.

Table 4: Capital Investment Required to Raise Transit Service to Optimal Level

	CAPITAL COST PER NEW VEHICLE, INCLUDING ANCILLARY REQUIREMENTS IN LAND, FACILITIES AND EQUIPMENT		
	Low Range Unit Capital Costs	**Median Unit Capital Costs**	**Higher Range Unit Capital Costs**
	$0.7 million per vehicle	**$1.2 million per vehicle**	**$1.7 million per vehicle**
Total Capital Investment Required to Raise Transit Service to Optimal Level	**$111.0 billion**	**$185.0 billion**	**$259.0 billion**

Note: Calculations based on a requirement of 149,337 new transit vehicles and ancillary land, facilities and equipment. See footnote 10 for relationship between the addition of vehicle-miles of service and the corresponding number of vehicles required**.**

It is noteworthy that, as shown in Figures 1B and 2B above, increased capital outlays would be higher than $111.0-$259.0 billion if the demand elasticities and marginal costs of congestion assumed in our estimates prove to be conservative.

Operating Support

At 10.7 billion vehicle-miles of service, annual operating support would rise from the $17.5 billion level under 2004 conditions to $50.2 billion under optimal conditions (186 percent).

Demand and Mobility

At the optimal level of service given above, transit ridership would be greater by approximately 84 percent. Automobile travel would be less by an estimated 2.8 percent. Whereas on a percentage basis the decline in automobile travel seems small in comparison to the increase in transit ridership, it is important to compare the effects on mobility in terms of trip making, not percentages. Thus, from Table 5 it can be seen that, under conditions of optimal transit supply, people would reduce the amount auto travel by 40.4 billion passenger-miles. Transit travel would increase by 41.0 billion passenger-miles. This gives a net increase in total travel of 0.5 billion passenger-miles (0.04 percent on total auto-plus transit passenger miles in 2004 – see Table 5). Mobility increases because the additional transit service would not only attract some existing auto users to switch, but would also generate more transit demand among existing users of public transportation.

Table 5: Optimal Demand and Supply Conditions of Urban Transit and Road Infrastructure, 2004 (in 2004 dollars)

Optimal Demand and Supply, by Mode	2004 Actual	2004 Optimal	Optimal versus Actual (Percent)
TRANSIT			
Supply (Millions of Vehicle-Miles)	**4,471**	**10,690**	**139.1%**
Demand (Millions of Passenger-Miles)	**49,073**	**90,033**	**83.5%**
AUTO			
Demand (Millions of Passenger-Miles)	**1,427,894**	**1,387,467**	**-2.8%**
AUTO & TRANSIT			
Demand (Millions of Passenger-Miles)	**1,476,967**	**1,477,500**	**0.04%**

Sensitivity Analysis

The results given above reflect a large number of assumptions, all of which are uncertain and subject to error. What are the implications of such uncertainty for the major finding of this study, namely that the nation is seriously under-invested in transit. Sensitivity analysis of key assumptions indicates that, although the results reported are subject to a wide range of uncertainty, the central finding holds.

The results are especially sensitive to two factors, namely the responsiveness of auto users to improved conditions of transit supply; and the external costs, or social marginal costs of congestion. Sensitivity analysis in relation to these two factors is given in Figures 1 (A and B) and 2 (A and B), respectively. The results of the sensitivity analysis indicate that the findings reported in Table 5 are conservative – that optimal service levels, and the investment required to achieve such levels of service, are higher than shown.

Sensitivity to Elasticity of Demand Assumptions. Figure 1A indicates that the elasticity of demand for auto travel with respect to transit fare would need to be lower than 0.001 before existing conditions of supply could be considered economically appropriate. If the elasticity in reality rises to 0.03 (the result of climbing gas prices, perhaps), optimal supply would rise from 4.5 billion vehicle-miles to more than 35.2 billion vehicle-miles, indicating a capital shortfall not of $259.0 billion but more than $1,278 billion (see Figure 1B).

Sensitivity analysis with respect to the elasticity of demand for auto travel with respect to transit service, which empirical evidence indicates is materially greater than the elasticity of demand for auto travel with respect to transit fares (i.e., auto travelers are more responsive to better transit service than lower transit fares), yields similar findings. That is, the sensitivity of auto travel to improved transit service would need to fall significantly below measured elasticities in order to diminish our findings with regard to optimal investment.

Sensitivity to Assumptions Regarding the Marginal Costs of Congestion. Figure 2A indicates that our estimates of the external costs of congestion would need to be too high by a factor of more than four before existing conditions of supply could be considered economically appropriate. As shown in Figure 2B, new capital investment required in order to realize optimal conditions of supply would rise significantly above the $259.0 billion if the marginal costs of congestion are understated, or rise over time with increasing levels of congestion.

Figure 1A: Optimal Supply of Urban Transit Under Alternative Price Cross-Elasticities of Demand

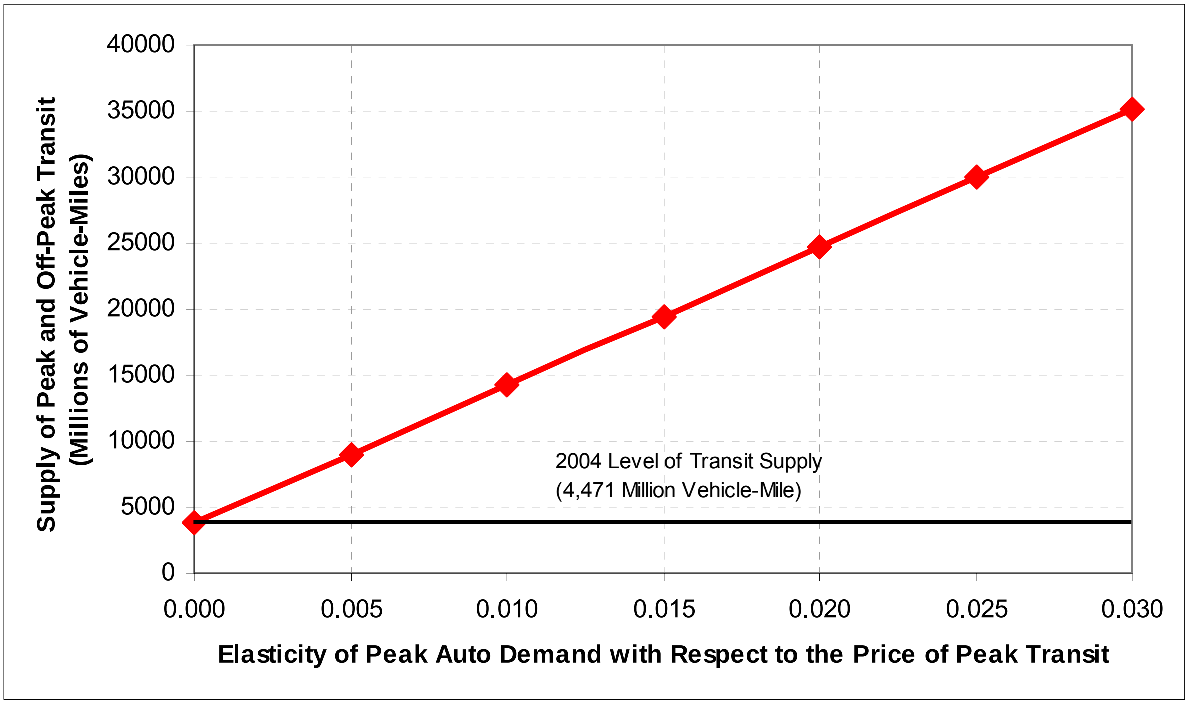


Figure 1B: Capital Expenditure to Achieve Optimal Supply of Urban Transit Under Alternative Price Cross-Elasticities of Demand

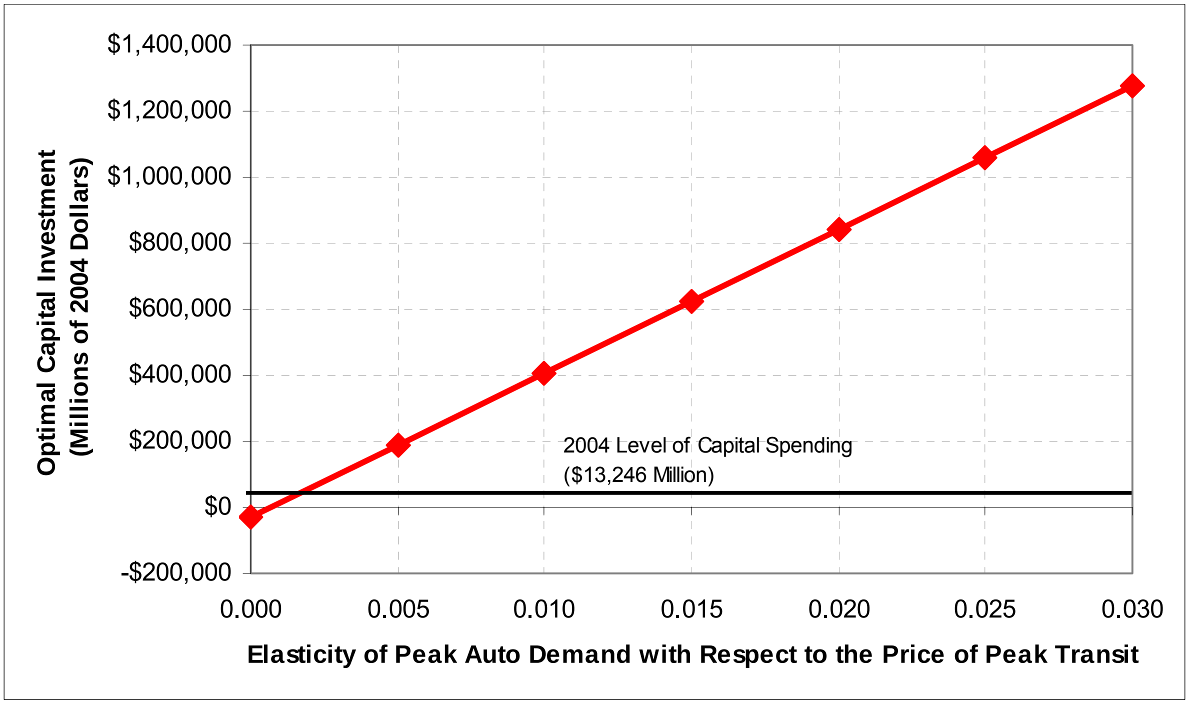


Figure 2A: Optimal Supply of Urban Transit with Alternative Levels of Automobile Congestion Costs

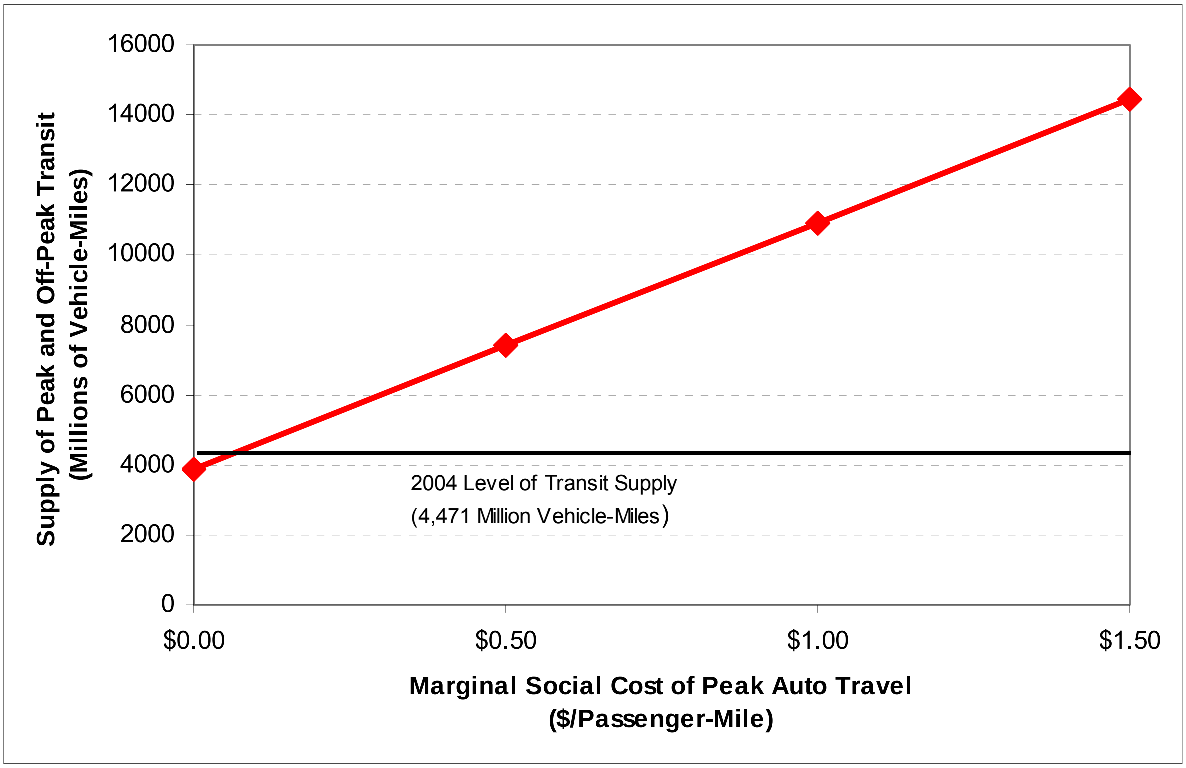
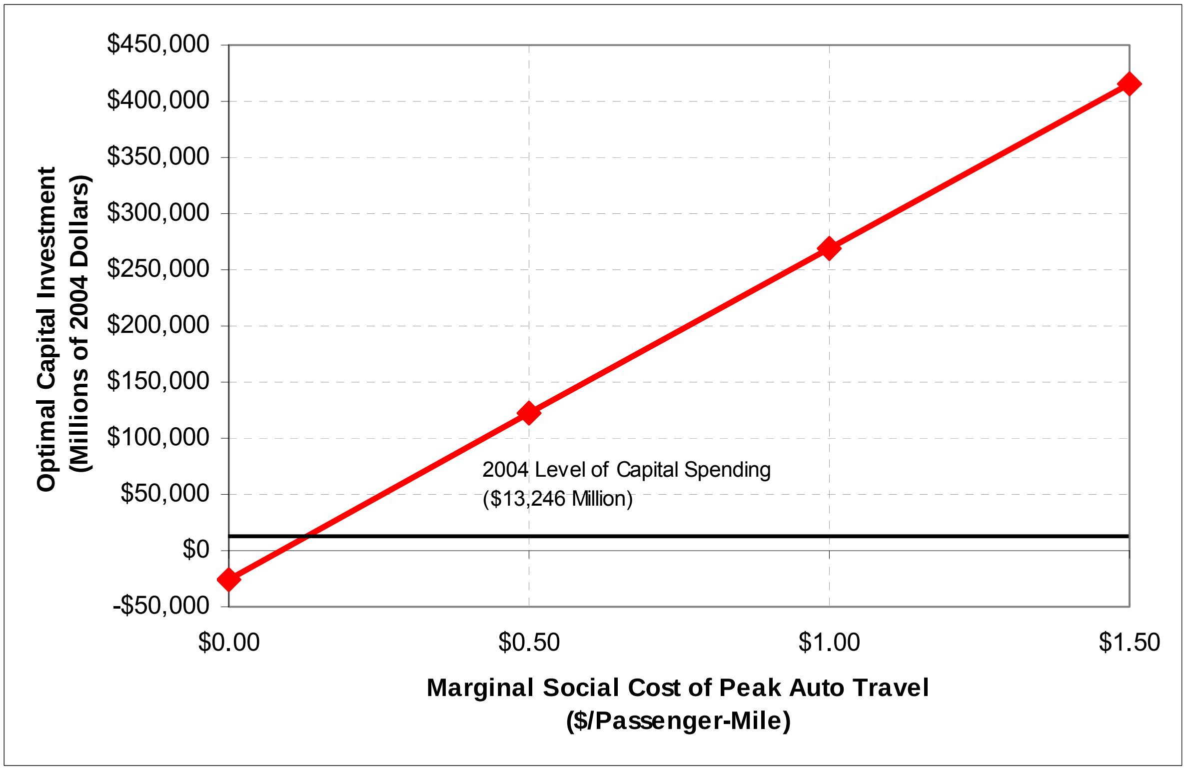


Figure 2B: Capital Expenditure to Achieve Optimal Supply of Urban Transit with Alternative Levels of Automobile Congestion Costs



4: OPTIMAL TRANSIT SUPPLY IN RELATION TO MOBILITY AND ECONOMIC DEVELOPMENT

To assess the economic value of the optimal investment levels given in Section 3, we have used the Cost-Benefit and Risk Analysis model called TransDEC.[8]

Based on the ridership and investment levels in Table 5, along with core assumptions for the value of time (weighted for work and non-work activities), safety, environmental emissions, greenhouse gases and economic development given in Appendix B, the TransDEC model assigns life-cycle economic value, or benefits, to the mobility, economic development and congestion management effects (including delay reduction and environmental effects) of a given investment package. It compares these benefits with the life-cycle capital and full incremental operating costs of the investment and computes the investment's net benefit (net present value) and economic rate of return accordingly. The TransDEC model also performs a risk analysis to account for uncertainty in underlying assumptions.

The results of the TransDEC analysis are given in Table 6. Over a thirty-year period, the present-day value of $259.0 billion in new transit investment plus the full incremental operating expenses associated new services totals to $529 billion. The present-day value of total economic benefits is an estimated $2,359 billion, giving a net benefit of $1,830 billion and an economic rate of return of 23 percent.

It can be seen in Table 6 that fully 70 percent of the total economic benefits stem from the congestion benefits and congestion-related effects (reduced delay, vehicle operating costs, accidents and environmental emissions) of the optimal investment package. However, the increase in transit services associated with optimal conditions of supply also leads to benefits in the form of mobility and economic development. From Table 6 it can be seen that, taken together, these two categories of value represent $684 billion of economic benefit over the 30-year timeframe of the analysis. At $684 billion, the mobility and economic development benefits alone, absent benefits associated with congestion, are thus sufficient to fully justify the $259.0 billion investment level and associated increase in operating costs.

Table 7 gives the macro-economic impact of the additional capital and operating expenses associated with the optimal conditions of supply. As the Table shows, the investment of $259.0 billion can be expected to generate 11 million full-time equivalent construction jobs; incremental operating expenditures would create an additional 770,000 jobs in the transit industry.

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[8] HDR|HLB Decision Economics TransDEC software.

Table 6: Cost-Benefit and Risk Analysis of Transit Under Optimal Conditions of Supply – 2008 to 2038 (in millions of 2004 dollars; Present Values reflect a discount rate of 5 percent)

CATEGORY	Mean	90% Probability of Exceeding	10% Probability of Exceeding
BENEFITS	Millions of $		
CONGESTION MANAGEMENT			
Times Savings	$1,253,290	$928,421	$1,620,614
Savings in Vehicle Operating Costs	$261,775	$216,039	$310,800
Emission Savings	$9,054	$3,712	$17,315
Accident Cost Savings	$150,628	$58,932	$290,586
Total Congestion Management	*$1,674,747*	*$1,207,105*	*$2,239,315*
AFFORDABLE MOBILITY			
Value to Low-Income Travelers	$333,067	$288,793	$380,709
Cross Sector Benefits	$9,127	$5,071	$13,580
Total Affordable Mobility	*$342,194*	*$293,865*	*$394,290*
COMMUNITY DEVELOPMENT			
Residential Development	$259,537	$149,498	$365,285
Commercial Development	$82,620	$42,704	$136,849
Total Community Development	*$342,157*	*$192,201*	*$502,134*
ALL BENEFITS	**$2,359,098**	**$1,693,171**	**$3,135,738**
COSTS			
Capital Expenditures	$210,224	$203,182	$217,237
Operating and Maintenance Costs	$318,744	$310,336	$327,216
ALL COSTS	**$528,969**	**$513,518**	**$544,453**
BENEFIT-COST ANALYSIS			
Net Benefits	**$1,830,129**	**$1,179,653**	**$2,591,285**
Rate of Return	**23%**	**20%**	**25%**

Note: Present-day values are calculated based on a five percent discount rate

Table 7: Macro-Economic Impact Analysis of Transit Under Optimal Conditions of Supply (in 2004 dollars)

CATEGORY	Mean	90% Probability of Exceeding	10% Probability of Exceeding
CONSTRUCTION (One-Time Expenditures)			
Total Spending			
Total (millions)	$258,965	$246,017	$272,595
Total Effects			
Output (millions)	$952,024	$904,423	$1,002,130
Employment	10,902,436	10,357,314	11,476,248
Wage and Salary Income (millions)	$344,834	$327,592	$362,983
Tax Revenue	$13,420	$12,749	$14,126
OPERATION (Recurring Annual Expenditures)			
Total Spending			
Total (millions)	$39,655	$37,672	$41,742
Total Effects			
Output (millions)	$80,462	$76,439	$84,696
Employment	773,182	734,523	813,876
Wage and Salary Income (millions)	$41,131	$39,074	$43,295
Tax Revenue (millions)	$1,601	$1,521	$1,686

5: BUDGETING FOR OPTIMAL TRANSIT SUPPLY OVER A TEN-YEAR CAPITAL AND OPERATING PROGRAM

Capital investment of up to $259.0 billion over the amount actually spent in 2004 would have been required to bring the supply of transit into line with the optimal conditions of supply in that year. This in turn would have meant a significant increase in transit operating expenses. The investment and collateral increase in running costs of such a magnitude in a single year was of course infeasible, both fiscally and operationally. This section presents a possible ten-year national transit plan that would achieve the economically optimal conditions of supply given in Section 3.

Transit capital is made up of spending to keep existing assets in good shape (renewal and rehabilitation) plus additional spending to expand the volume of transit services available. The illustrative program in Table 8 spreads the *new* investment needed to optimize the supply of vehicle-miles (of $259.0 billion) over a ten year period. For the purpose of this study, the amount of additional capital required for renewal and rehabilitation has not been estimated.

INVESTMENT FOR SERVICE EXPANSION: 2008 - 2017

The budget program in Table 8 spreads the investment needed to expand the supply of vehicle-miles to catch-up with optimal 2004 conditions, $259.0 billion, over the ten years from 2008 to 2017. An allowance for the effects of general price inflation of two percent annually is also included.

Following the catch-up period there will still be further expansion requirements but on a much smaller scale. This will be largely to accommodate natural population growth and other demographic and economic factors. More dollars will be required for renewal and rehabilitation as mid-life and replacement requirements emerge in relation to new equipment and facilities brought on-line in the 2008 to 2017 period.

TOTAL CAPITAL SPENDING: 2008 - 2017

Under the ten-year program on Table 8, average annual capital expenditure between 2008 and 2017 would be $30.7 billion.

Table 8: A Ten Year Transit Capital and Operating Program to Reach Optimal Conditions of Supply by 2017 (in billions of current year dollars)

INVESTMENT CATEGORY	2008	2009	2010	2011	2012
CAPTIAL INVESTMENT					
Capital Investment in Service Expansion	$28.0	$28.6	$29.2	$29.7	$30.3
OPERATING REVENUE SUPPORT					
Operating Revenue Support	$19.0	$23.4	$26.6	$30.2	$34.3
INVESTMENT CATEGORY	**2013**	**2014**	**2015**	**2016**	**2017**
CAPTIAL INVESTMENT					
Capital Investment in Service Expansion	$30.9	$31.6	$32.2	$32.8	$33.5
OPERATING REVENUE SUPPORT					
Operating Revenue Support	$39.0	$44.3	$50.3	$57.2	$65.0

REVENUE SUPPORT

As shown in Table 8, total government outlays to make up the difference between transit operating costs and revenue from passenger fares would be an estimated $65.0 billion by 2017. Compared with revenue support in 2004 -- $17.6 billion -- the sharp increase stems from the provision of more transit service and the maintenance of real (constant dollar) fares at the current level).

Since, under optimal conditions of supply, transit operating costs would rise proportionately more than transit demand, the rate of fare box recovery would fall -- from today's average of 34 percent to a new average of 26 percent. This is a worst-case outcome, however, since some operating efficiencies are likely to follow from a significant increase in the level of service.

6: CONCLUSIONS

The United States is sharply underinvested in urban transit. Capital investment of $111.0-$259.0 billion over the amount actually spent in 2004 would have been required to bring the supply of transit into line with the optimal conditions of supply in that year. While an investment and collateral increase in running costs of such a magnitude in a single year was, and is, infeasible (fiscally or operationally), the $111.0-$259.0 billion does represent the amount by which actual transit supply currently falls short of the economically appropriate level.

At the optimal level of service, transit ridership would be an estimated 84 percent greater than it is today. Automobile travel would be less by an estimated 2.8 percent with much of this reduction in some of the most congested corridors in the country.

The economic and social benefits of bringing transit to the optimal level of supply would be significant, in the order of $2,359 billion over 30 years. More than two-thirds of these benefits constitute the economic value of reduced roadway congestion. Since congestion represents a widely acknowledged drain on national economic productivity and performance, this finding gives transit investment national strategic significance. Thus, while the $259.0 billion capital cost and corresponding increase in operating support needed to optimize the provision of transit might be beyond the fiscal capacity of local and state governments, there exists a powerful rationale for federal financial involvement.

The optimal supply, demand and investment levels reported in this study represent estimates of what adopting a “second-best” investment strategy would imply for the allocation of urban surface transportation resources. What would a first-best policy mean for transit investment? Since the second-best approach relies on the extent to which more and better bus and rail service induces auto users to switch to transit, optimal transit supply and demand under first-best conditions (i.e. ubiquitous congestion pricing) would be greater than that presented in this study. This is because more people can be expected to switch from autos to transit under a strategy of direct road pricing than under a strategy that relies solely on transit as an inducement to switch.

RECOMMENDATIONS

We offer two recommendations. The first pertains to the pace at which the United States might wish to proceed to the optimal supply of transit service. The second recommendation goes to the need for sound planning in order to achieve the appropriate regional and modal mix of new investment.

A Ten-Year Catch-up Program

A fiscally viable approach would be to “catch-up” on the gap in transit supply over a period of time. Spreading the $259.0 billion requirement over a period of ten years, and allowing for a rate of price inflation of two percent annually, gives an average annual expenditure in new capital of $30.7 billion, something the fiscal framework and world-wide transit supply market could absorb. Government contributions to revenue support would reach $65.0 billion by 2017.

Regional and Modal Allocation

This study takes a national perspective: As such, it offers no information as to how $111.0-$259.0 billion in new transit investment should optimally be divided among regions and cities, and between different modes of transit, such as buses, bus rapid transit, light rail, streetcars, commuter rail and heavy rail. The key is good investment planning. State and local governments should be engaged in a coordinated and continuous process of identifying alternatives at the regional and local level, rigorously analyzing such alternatives in relation to their economic and social benefits and costs, and selecting projects on the basis of economic and social merit. In addition to its funding role, the federal government should promote research and development, on-going provision of economic evaluation tools, and due diligence in relation to its strategic financial commitment to the investment program.

APPENDIX A: MICRO-ECONOMIC FRAMEWORK FOR DETERMINING OPTIMAL TRANSIT SUPPLY IN RELATION TO CONGESTION, ENVIRONMENT AND HEALTH

The optimizing procedure used in this study represents the synthesis of three peer reviewed models, as follows:

- De Borger, B. and S. Wouters. 1998. Transport Externalities and Optimal Pricing and Supply Decisions in Urban Transportation: A Simulation Analysis for Belgium. *Regional Science and Urban Economics.* 28: 163-197.

- De Borger, B., I. Mayeres, S. Proost and S. Wouters. 1996. Optimal Pricing of Urban Passenger Transport: A Simulation Exercise for Belgium. *Journal of Transport Economics and Policy.* 31-54.

- Glaister, S. and D. Lewis. 1978. An Integrated Fares Policy for Transport in London. *Journal of Public Economics.* 9: 341-355.

Throughout the model the following indices denote mode:

Index	Transport Mode
1	peak auto
2	off-peak auto
3	peak transit
4	off-peak transit

Elasticity

Elasticity is a measure of the ratio a percentage change in one variable has on the percentage change in another variable. The elasticity below will be the percentage change in the demand for mode i given a percentage increase in the price for mode j

$$\eta_j^i = \frac{p_j}{X^i}\frac{\partial X^i}{\partial p_j} = \frac{p_j}{X^i}X_j^i \text{ for } i, j = 1, 2, 3, 4 \tag{1}$$

where p_j represents the price for mode j measured in dollars per passenger-mile, and X^i is demand for mode i measured in passenger-miles. For example, if the price elasticity of peak auto demand with respect to peak transit prices is 0.02, then for 50 percent drop in fares, auto demand will fall by 1 percent.

The Objective Function

The objective function is as follows:

$$\begin{aligned} \max_{p_3, p_4} \quad & \left\{ G\left(\alpha_3, \alpha_4, X^1(\alpha_3, \alpha_4), X^3(\alpha_3, \alpha_4), \hat{p}, u\right) \right. \\ & - G\left(p_3, p_{4,} X^1(p_3, p_4), X^3(p_3, p_4), \hat{p}, u\right) \\ & \left. - \left[C^3\left(X^1, X^3\right) - p_3 X^3\right] - \left[C^4\left(X^4\right) - p_4 X^4\right] \right\} \end{aligned} \qquad (2)$$

where $G\left(p_3, p_{4,} X^1, X^3, \hat{p}, u\right)$ is the expenditure function aggregated across individuals, $\hat{p}$ is a vector of all other prices (including p_1 and p_2), u is vector of constant utility levels, C^3 and C^4 represent the total operating costs of the public transit modes, and α_3 and α_4 are prices higher than p_1 and p_2.

The expenditure functions measures the minimum amount of money necessary to maintain a given level of utility for a given set of prices. Utility is measure of satisfaction that a bundle of goods provides an individual. The difference between the two expenditure functions, $G\left(\alpha_3, \alpha_4, X^1, X^3, \hat{p}, u\right) - G\left(p_3, p_{4,} X^1, X^3, \hat{p}, u\right)$, is known as the compensating variation. In other words, it is the amount of money necessary to compensate an individual for a fare increase from p_3 and p_4 to α_3 and α_4 in order to maintain the same utility level.

The final two components in Equation (2), $-\left[C^3\left(X^1, X^3\right) - p_3 X^3\right] - \left[C^4\left(X^4\right) - p_4 X^4\right]$, measure the total operating revenue and total operating costs of transit.

Differentiating the objective with respect to p_3 yields the following first order condition:

$$\begin{aligned} & -\left(\frac{\partial G}{\partial p_3} + \frac{\partial G}{\partial X^1}\frac{\partial X^1}{\partial p_3} + \frac{\partial G}{\partial X^3}\frac{\partial X^3}{\partial p_3}\right) - \left(\frac{\partial C^3}{\partial X^1}\frac{\partial X^1}{\partial p_3} + \frac{\partial C^3}{\partial X^3}\frac{\partial X^3}{\partial p_3} - X^3 - p_3\frac{\partial X^3}{\partial p_3}\right) \\ & -\left(\frac{\partial C^4}{\partial X^4}\frac{\partial X^4}{\partial p_3} - p_4\frac{\partial X^4}{\partial p_3}\right) = 0 \end{aligned} \qquad (3)$$

To put it simply, differentiating Equation 2 with respect to the price will allow us to determine the conditions of supply necessary to maximize the economic well-being of transit users.

A simplifying property of an expenditure function is that

$$\frac{\partial G}{\partial p_i} = \sum_h \frac{\partial g_h}{\partial p_i} = \sum_h x_h^i = X^i \qquad (4)$$

where X^i is the demand for mode i.

Additionally, the peak period marginal social cost of auto and off-peak marginal social cost of transit are defined as follows:

$$S_1 = \frac{\partial G}{\partial X^1} + \frac{\partial C^3}{\partial X^1} \text{ and } S_3 = \frac{\partial G}{\partial X^3} + \frac{\partial C^3}{\partial X^3} \tag{5}$$

Note that both marginal social costs are in units of dollars per passenger-mile. Marginal costs represent the addition to total cost for an added passenger-mile

Collecting terms, and utilizing the aforementioned properties, the first order condition can be simplified to the equation below:

$$S_1 X_3^1 = X_3^3\left(p_3 - S_3\right) + X_3^4\left(p_4 - C_4^4\right) \tag{6}$$

An identical process can be used to differentiate the objective function with respect to p_4. This derivation would result in equation (7).

$$S_1 X_4^1 = X_4^3\left(p_3 - S_3\right) + X_4^4\left(p_4 - C_4^4\right) \tag{7}$$

Multiplying both sides of equations (6) and (7) by $\eta_3^1 \text{and} \eta_4^1$, respectively, yields equations (8) and (9).

$$\eta_3^1 = \frac{1}{S_1 X^1}\left[\eta_3^3\left(p_3 - S_3\right)X^3 + \eta_3^4\left(p_4 - C_4^4\right)X^4\right] \tag{8}$$

$$\eta_4^1 = \frac{1}{S_1 X^1}\left[\eta_4^3\left(p_3 - S_3\right)X^3 + \eta_4^4\left(p_4 - C_4^4\right)X^4\right] \tag{9}$$

Equations (8) and (9) can be expressed in matrix notation (see equation (10)). Equation (10) is a system of linear equations that can be solved, using Cramer's Rule, to determine the optimal prices of transit, p_3 and p_4. The resulting prices are what transit would need to charge in order to generate optimal demand in the presence of the congestion externality.

$$\begin{bmatrix} \eta_3^3 & \eta_3^4 \\ \eta_4^3 & \eta_4^4 \end{bmatrix} \begin{bmatrix} \left(p_3 - S_3\right)X^3 \\ \left(p_4 - C_4^4\right)X^4 \end{bmatrix} \frac{1}{S_1 X_1} = \begin{bmatrix} \eta_3^1 \\ \eta_4^1 \end{bmatrix} \tag{10}$$

Optimum Prices

The optimum price structure is as follows:

$$p_3 = \left[\frac{\eta_3^1 \eta_4^4 - \eta_4^1 \eta_3^4}{\eta_3^3 \eta_4^4 - \eta_4^3 \eta_3^4}\right] \frac{S_1 X^1}{X^3} + S_3 \tag{11}$$

$$p_4 = \left[\frac{\eta_3^3 \eta_4^1 - \eta_4^3 \eta_3^1}{\eta_3^3 \eta_4^4 - \eta_4^3 \eta_3^4} \right] \frac{S_1 X^1}{X^4} + C_4^4 \qquad (12)$$

Optimum Service Level

If optimum pricing implies negative fares a signal is recognized that the level of service (vehicle-miles supplied) is too low. Based on the elasticity of demand for transit with respect to level of service, the procedure is to calculate the additional volume of scheduled vehicle-miles of service required to attract the same volume of passenger-miles of demand that would otherwise be generated by negative fares.

Analysis

Using the assumptions listed in Appendix B, the framework was executed in two “rounds.” Round one of the analysis indicates that, the economically the optimal demand for urban transit is an estimated 90.0 billion passenger-miles, 84 percent more ridership than the 2004 level of 49.1 million passenger-miles. Roadway traffic would decline by 2.8 percent. Round one indicates that, in order to generate these volumes of demand, transit fares during peak periods would need to be reduced (through additional government operating support) from the 2004 average of $0.20/passenger-mile to *negative* $0.66/passenger-mile.

The economic signal in the round-one finding – which implies a payment to peak passengers of $0.66 per passenger-mile in order to induce people to reallocate their trips between roads and transit so as to optimally offset the congestion externality -- is that the level of service (vehicle-miles supplied) is too low. Based on the elasticity of demand for transit with respect to level of service, round-two of the analysis calculates the additional volume of scheduled vehicle-miles of service required to attract the same volume of passenger-miles of demand that would otherwise be generated by the “negative fares” implied in round one.

The results of round-two analysis are given in Table A1. Based on 2004 conditions, the table indicates that vehicle-miles supplied need be increased from 4.5 billion to 10.7 billion (139 percent) in order to optimize the conditions of transit supply and demand. Based on transit investment costs reported earlier, this would require an investment of $111.0-$259.0 billion (in 2004 dollars).

Because the achievement of optimal conditions through lowered fares results in the theoretically correct but pragmatically infeasible application of negative fares, the analysis fails to give a definitively optimal level of revenue support. Implied in the analysis is that economic optimality represents some combination of lower fares than in place today and higher service levels. The combination of capital investment and operating support given in Table A1 is that of the higher service level shown (7.3 billion vehicle-miles) at existing real fare levels,(the latter resulting in a reduction in the farebox recovery ratio from an average of 34 percent to an average of 26 percent.) Annual operating subsidy would rise from the $17.6 billion level under 2004 conditions to $50.2 billion (186 percent).

Table A1: Optimal Demand and Supply Conditions of Urban Transit and Road Infrastructure, 2004 (in 2004 dollars)

Optimal Demand and Supply, by Mode	**2004 Actual**	**2004 Optimal**	**Optimal versus Actual (Percent)**
TRANSIT			
Supply **(Millions of Vehicle-Miles)**	**4,471**	**10,690**	**139.1%**
Demand **(Millions of Passenger-Miles)**	**49,073**	**90,033**	**83.5%**
AUTO			
Demand **(Millions of Passenger-Miles)**	**1,427,894**	**1,387,467**	**-2.8%**
AUTO & TRANSIT			
Demand **(Millions of Passenger-Miles)**	**1,476,967**	**1,477,500**	**0.04%**

APPENDIX B: ASSUMPTIONS USED IN OPTIMAL SUPPLY MODEL

A. Demand (Millions of Passenger-Miles)

Variable Name	Median Estimate	Source/Comment
Peak Urban Automobile Demanded	1,427,894	**Source:** FHWA vehicle-mile estimates based on State provided HPMS data. **Comment:** See Structure and Logic below for how HDR adjusted the vehicle-mile estimate to reflect passenger-miles in the peak and off-peak periods.
Off-Peak Urban Automobile Demand	1,186,995	
Peak Urban Transit Demand	31,518	**Source:** American Public Transit Association. 2006. Public Transit Fact Book. **Comment:** Peak and off-peak have been separated based on a 64%, 36% split, respectively.
Off-Peak Urban Transit Demand	17,555	

Peak Urban Automobile Demand = Urban Vehicle-Miles X Passengers per Vehicle X Percent of Trips in the Peak Period X Percent of Peak Auto Travel that is Congested

Off-Peak Urban Automobile Demand = Urban Vehicle-Miles X Passengers per Vehicle X Percent of Trips in the Off-Peak Period

B. Supply (Millions of Vehicle-Miles)

Variable Name	Median Estimate	Source/Comment
Total Transit Supplied	4,471	**Source:** American Public Transit Association. 2006. Public Transit Fact Book. **Comment:** Peak and off-peak have been separated based on a 64%, 36% split, respectively.
Peak Transit Supplied	2,871	
Off-Peak Transit Supplied	1,599	

C. Transit Fares (Dollars per Passenger-Mile)

Variable Name	Median Estimate	Source/Comment
Peak Transit Fare	$0.20	**Source:** American Public Transit Association. 2006. Public Transit Fact Book. **Comment:** HDR estimated this variable by dividing Total Passenger Fares by Total Passenger-Miles.
Off-Peak Transit Fare	$0.20	

D. Operating Cost (Dollars per Passenger-Mile)

Variable Name	Median Estimate	Source/Comment
Operating Cost Per Passenger-Mile	$0.58	**Source:** American Public Transit Association. 2006. Public Transit Fact Book. **Comment:** HDR estimated this variable by dividing Total Operating Expenses by Total Passenger-Miles.
Operating Cost Per Vehicle-Mile	$6.38	**Source:** American Public Transit Association. 2006. Public Transit Fact Book. **Comment:** HDR estimated this variable by dividing Total Direct Operating Expenses by Total Vehicle-Miles.

E. Marginal Social Costs (Dollars per Passenger-Mile)

Variable Name	Median Estimate	Source/Comment
Social Cost of Peak Auto	$0.97	**Sources:** Small, K and E. Verhoef. 2007. *Economics of Urban Transportation.* Routledge. **Comment:** Estimates have been adjusted from vehicle-miles to passenger-miles by dividing by average occupancy per vehicle, and to 2004 prices from 2005 prices.
Social Cost of Peak Transit	$0.32	**Sources:** Litman, T. 2006. Evaluating Public Transit Benefits and Costs: Best Practices Guidebook. *Victoria Transport Policy Institute.*

F. Capital Cost (Dollars per Vehicle)

Variable Name	Median Estimate	Source/Comment
Average Capital Cost Per Vehicle	$2,477,277	**Source:** American Public Transit Association. 2006. Public Transit Fact Book. **Comment:** HDR estimated this variable by dividing Total Capital Expenditures by Total Vehicles Purchased.

G. Price Elasticities

Elasticity	Median Estimate
Elasticity of Peak Auto Demand with respect to Peak Transit Price	0.0066
Elasticity of Off-Peak Auto Demand with respect to Peak Transit Price	0.0000
Elasticity of Peak Transit Demand with respect to Peak Transit Price	-0.3000
Elasticity of Off-Peak Transit Demand with Respect to Peak Transit Price	0.0300
Elasticity of Peak Auto Demand with respect to Off-Peak Transit Price	0.0016
Elasticity of Off-Peak Auto Demand with respect to Off-Peak Transit Price	0.0200
Elasticity of Peak Transit Demand with respect to Off-Peak Transit Price	0.0300
Elasticity of Off-Peak Transit Demand with Respect to Off-Peak Transit Price	-0.5000

De Borger & Wouters (1998) cite the following articles for their price elasticity estimates: Oum, Waters & Yong (1992), Goodwin (1992),‘t Hoen, Kuik and Poppelaars (1991), Webster (1997), Ruitenberg (1983) and Glaister and Lewis (1978).

H. Supply Elasticities

Elasticity	Median Estimate
Elasticity of Peak Auto Demand with respect to Peak Transit Level of Service	-0.0300
Elasticity of Off-Peak Auto Demand with respect to Peak Transit Level of Service	0.0000
Elasticity of Peak Transit Demand with respect to Peak Transit Level of Service	0.6000
Elasticity of Off-Peak Transit Demand with Respect to Peak Transit Level of Service	0.0000
Elasticity of Peak Auto Demand with respect to Off-Peak Transit Level of Service	0.0000
Elasticity of Off-Peak Auto Demand with respect to Off-Peak Transit Level of Service	-0.0050
Elasticity of Peak Transit Demand with respect to Off-Peak Transit Level of Service	0.0000
Elasticity of Off-Peak Transit Demand with Respect to Off-Peak Transit Level of Service	0.2000

De Borger & Wouters (1998) cite the following articles for their price elasticity estimates: Webster (1977), Ruitenberg (1983), Varii Auctores (1980), Lago, Mayworm & McEnroe (1981) and Van DeVoodre (1981).

APPENDIX C: ASSUMPTIONS USED IN COST-BENEFIT ANALYSIS MODEL

A. Base Assumptions

A	Variable Name	Median Estimate	Source/Notes
A1	First year of capital investment	2008	HDR assumption
A2	Opening year of transit expansion	2018	HDR assumption
A3	Period of analysis	30 years	TransDEC default
A4	Discount rate	5%	Ran sensitivity at 10%

B. Value of Time

B	Variable Name	Median Estimate	Source/Notes
B1	Value of time (VOT)	$15	TransDEC default

C. Transit Ridership

C	Variable Name	Median Estimate	Source/Notes
C1	Daily subway ridership in opening year	20,066,399	HDR model output
C2	Subway ridership annual growth - Years 1-5: - Years 6-10: - Years 10+:	 2.5% 2.5% 2.5%	HDR assumption

D. Corridor Roadway Traffic Conditions

D	Variable Name	Median Estimate	Source/Notes
D1	Average Daily Traffic (ADT) in catchment area – AM peak hour	715,433,000	Source: HDR calculation based on data from the FHWA and the HPMS database.
D2	ADT annual growth - 2007+:	1.5%	HDR assumption
D3	2007 peak-period congestion index	0.90	TransDEC default

E. Affordable Mobility & Economic Development

E	Variable Name	Median Estimate	Source/Notes
E1	Affordable Mobility Benefits - Value to low-income travelers - Cross sector benefits	15%	Affordable mobility benefits represent approximately 15% of total benefits
E2	Community Development Benefits - Residential development - Commercial development	15%	Community development benefits represent approximately 15% of total benefits

F. Capital and Operating Costs

F	Variable Name	Median Estimate	Source/Notes
F1	Capital Cost – 2008	$36,995 M	HDR model output
F2	Capital Cost – 2009	$36,995 M	HDR model output
F3	Capital Cost – 2010	$36,995 M	HDR model output
F4	Capital Cost – 2011	$36,995 M	HDR model output
F5	Capital Cost – 2012	$36,995 M	HDR model output
F6	Capital Cost – 2013	$36,995 M	HDR model output
F7	Capital Cost – 2014	$36,995 M	HDR model output
F8	Capital Cost – 2015	$36,995 M	HDR model output
F9	Capital Cost – 2016	$36,995 M	HDR model output
F10	Capital Cost – 2017	$36,995 M	HDR model output
F11	Annual incremental O&M costs – 2018+	$39,655 M	HDR model output

G. Employment Impact

G	Variable Name	Median Estimate	Source/Notes
G1	Jobs supported Per $1 billion Federal Spending	42,100	Federal Highway Administration. 1996. Highway Infrastructure Investment and Job Generation: A Look at the Positive Employment Impacts of Highway Investment. *US Department of Transportation.*

APPENDIX D: BIBLIOGRAPHY

American Public Transportation Association. 2006. *Public Transportation Fact Book.* 57th Edition.

Cambridge Systematics, Inc. and Economic Development Research Group. 1999. Public Transportation and the Nation's Economy: A Quantitative Analysis of Public Transportation's Economic Impact. *American Public Transit Association.*

Cromwell, B. 1989. Capital Subsidies and the Infrastructure Crisis: Evidence from the Local Mass-Transit Industry. *Economic Review – Federal Reserve Bank of Cleveland.*

De Borger, B., I. Mayeres, S. Proost and S. Wouters. 1996. Optimal Pricing of Urban Passenger Transport: A Simulation Exercise for Belgium. *Journal of Transport Economics and Policy.* 31-54.

De Borger, B. and S. Wouters. 1998. Transport Externalities and Optimal Pricing and Supply Decisions in Urban Transportation: A Simulation Analysis for Belgium. *Regional Science and Urban Economics.* 28: 163-197.

Dodgson, J.S. 1986. Benefits of Changes in Urban Public Transport Subsidies in the Major Australian Cities. *Economic Record.* 62: 224-235.

Dodgson, J.S., and N. Topham. 1987. Benefit-Cost Rules for Urban Transit Subsidies: An Integration of Allocational, Distributional and Public Finance Issues. *Journal of Transport Economics and Policy.* 57-71.

Dunne, J.P. 1984. Elasticity Measures and Disaggregate Choice Models. *Journal of Transport Economics and Policy.* 189-197.

Elgar, I. and C. Kennedy. 2005. Review of Optimal Transit Subsidies: Comparison Between Models. *Journal of Urban Planning and Development.* 71-78.

Federal Highway Administration. 1996. Highway Infrastructure Investment and Job Generation: A Look at the Positive Employment Impacts of Highway Investment. *US Department of Transportation.*

Frankena, M. 1983. The Efficiency of Public Transport Objectives and Subsidy Formulas. *The Journal of Transport Economics and Policy.* 67-76.

Glaister, S. and D. Lewis. 1978. An Integrated Fares Policy for Transport in London. *Journal of Public Economics.* 9: 341-355.

Goodwin, P.B. 1992. A Review of New Demand Elasticities with Special Reference to Short and Long Run Effects of Price Changes. *Journal of Transport Economics and Policy.* 155-169.

HLB Decision Economics. 2001. The Value Proposition for Transit Investment, Subsidy and Federal Involvement. *Canada Transportation Act Review.*

HLB Decision Economics, IBI Group and Morrison Hershfield Limited. 2003. Estimating the Welfare Costs of Measures to Reduce Greenhouse Gas Emissions in the Passenger and Freight Sectors. Volume III: Estimating Canadian Transit Elasticity Measures and the Impact of Alternative Levels and Distribution of Transit Capital Resources on Greenhouse Gas Emissions. *Transport Canada.*

Jansson, K. 1993. Optimal Public Transport Price and Service Frequency. *Journal of Transport Economics and Policy.* 33-50.

Lago, A., P. Mayworm and J.M. McEnroe. 1981. Transit Service Elasticities: Evidence from Demonstrations and Demand Models. *Journal of Transport Economics and Policy.* 99-119.

Lewis, D. 1977. Estimating the Influence of Public Policy on Road Traffic Levels in Greater London. *Journal of Transport Economics and Policy.* 155-168.

Litman, T. 2004. Transit Price Elasticities and Cross-Elasticities. *Journal of Public Transportation.* 7: 37-58.

Litman, T. 2006. *Evaluating Public Transit Benefits and Costs: Best Practices Guidebook.* Victoria Transport Policy Institute.

Mohring, H. 1972. Optimization and Scale Economies in Urban Bus Transportation. *The American Economic Review.* 62: 591-604.

Oum, T.H. 1989. Alternative Demand Models and Their Elasticity Estimates. *Journal of Transport Economics and Policy.* 163-187.

Oum, T.H., W.G. Waters, II, and J.S. Yong. 1990. A Survey of Recent Estimates of Price Elasticities of Demand for Transport. *Infrastructure and Urban Development – The World Bank.*

Oum, T.H., W.G. Waters, II, and J.S. Yong. 1992. Concepts of Price Elasticities of Transport Demand and Recent Empirical Estimates: An Interpretive Survey. *Journal of Transport Economics and Policy.* 139-154.

Ruitenberg, L.W. 1983. Openbaar Personenvervoer – Beïnvloedende factoren en verdelingsnormen. Tijdschrift voor Vervoerswetenschap. 19: 327-338

de Rus, Gines. 1990. Public Transport Demand Elasticities in Spain. *Journal of Transport Economics and Policy.* 189-201.

Schrank, D. and T. Lomax. 2007. *The 2007 Urban Mobility Report.* Texas Transportation Institute – The Texas A&M University System.

Small, K and E. Verhoef. 2007. *Economics of Urban Transportation.* Routledge.

Taplin, J., D. Hensher and B. Smith. 1999. Preserving the Symmetry of Estimated Commuter Travel Elasticities. *Transportation Research Part B.* 33: 215-232.

‘t Hoen, A.L. F.C. Kuik, and J.A.A. Poppelaars. 1991. Vervoerselasticiteiten: een basis voor differentiatie. Insituut voor Onderzoek van Overheidsuitgaven, Reeks nr. 30, Den Haag, 113.

US Department of Energy. 2007. *Transportation Energy Data Book.* Download Edition 26.

Van de Voodre, E. 1981. De Invloed van de Tijdsfactor op de Vraag naar Stedelijk Openbaar Vervoer, Tooepassing op het Intercommunaal Vervoer te Brussel. Tijdschrift voor Economie en Management. 16: 49-71.

Varii Auctores. 1980. The Demand for Public Transport: Report of the International Collaborative Study of the Factors Affecting Public Transport Patronage. *Transport and Road Research Laboratory, Crowthorne.*

Webster, F.V. 1977. Urban Passenger Transport: Some Trends and Prospects. *Transport and Road Research Laboratory, Crowthorne.*

Williams, F. and D. Lewis. 1999. *Policy and Planning as Public Choice: Mass Transit in the United States*. Ashgate Publishing.