Welfare and Distributional Effects of Road Pricing Schemes for Metropolitan Washington, DC

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Abstract

Economists have long advocated congestion pricing as an efficient way of allocating scarce roadway capacity. However, with a few exceptions, congestion tolls are rarely used in practice and strongly opposed by the public and elected officials. Although high implementation costs and privacy issues are alleviated as appropriate technologies are developed, the concerns that congestion pricing will adversely affect low-income travelers remain.

In this paper, we use a strategic transportation planning model calibrated for the Washington, DC, metropolitan area to compare the welfare and distributional effects of three pricing schemes: value pricing (HOT lanes), limited congestion pricing, and comprehensive congestion pricing. We find that social welfare gains from HOT lanes amount to three-quarters of those from the comprehensive road pricing. At the same time, a HOT lanes policy turns out to be much more equitable than other road pricing schemes, with all income groups strictly benefiting even before the toll revenue is recycled.

Key Words: traffic congestion, congestion pricing, value pricing, HOT lanes, HOV lanes

JEL Classification Numbers: R40, R41, R48, H23

Contents

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1 INTRODUCTION

Traffic congestion imposes substantial costs on society: the Texas Transportation Institute (2001) estimates that travel delays and the resulting extra fuel combustion cost the United States $68 billion in 2000. Congestion is likely to worsen in the future with continued growth in vehicle miles; for example, in the metropolitan Washington, DC, area, vehicle miles are projected to increase by more than 40% over the next 20 years (National Capital Region Transportation Planning Board 2002). Meanwhile, environmental constraints, neighborhood opposition, and budgetary limitations are making it ever more difficult to build new roads. Consequently, transportation planners and policy analysts are exploring novel approaches for bringing expanding demand for driving in line with available road capacity. One such approach is time-of-day congestion pricing, which economists have long advocated as an effective way of allocating scarce roadway capacity to the highest-valued users (Pigou 1920; Walters 1961; Vickrey 1969).

Yet, with a few exceptions, congestion tolls have been vigorously opposed by most local elected officials in the United States and by the public.[1] Among the major public concerns about congestion pricing are high implementation costs, privacy issues, and distributional effects. The development of electronic debiting from smart cards has made implementation easier, and it may

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[1] To date, there are only four examples of congestion pricing schemes in the entire United States. These operate on Route 91 linking Riverside to Orange County in Southern California; I-15 in San Diego; I-10 in Houston; and two bridges in Lee County, Florida. Pricing schemes are under discussion, however, in a number of other urban centers. Congestion pricing was first introduced in Singapore in 1975. The most important recent example is the area license scheme in the United Kingdom, covering eight square miles of central London.

help alleviate fears about privacy as well, since there is no need to record the license plates of vehicles with smart cards.

Distributional effects of congestion tolls, however, remain a major obstacle. Since everyone pays the same charge regardless of income, there are concerns that low-income motorists will suffer disproportionately. Compensation of potential losers, by appropriate spending or other recycling of toll revenues, may determine the overall political feasibility of congestion pricing. This has been confirmed by various surveys showing that support for congestion pricing increased with explicit proposals for using the revenues to reduce other taxes or invest in roads or public transit (Jones 1991; Ison 2000; Harrington et al. 2001; RAC Foundation for Motoring 2003). Designing such compensation packages requires information about the initial impact of tolls on different groups.

Prior literature has emphasized that the effect of congestion pricing on vertical equity is governed by two factors working in opposite directions (Small 1983): higher-income individuals have a greater propensity to use automobiles and therefore will pay more in tax dollars, but they also benefit disproportionately from congestion relief, not least because they have higher values of travel time. Indeed, under certain conditions higher-income groups may on balance be better off (i.e., they value the time savings more than the tax payments) while lower-income groups are made worse off (Small 1983; Cohen 1987). Nonetheless, a sufficiently progressive recycling of toll revenues could ensure that all income groups benefit overall (Small 1992a).

Previous studies of the distributional effects of congestion pricing have mainly been confined to highly aggregate models in which agents might choose among different modes but travel on a single route (Anderson and Mohring’s 1997 model of the Twin Cities is a notable exception). In contrast, this paper analyses distributional effects using a detailed transportation network model, representing metropolitan Washington, DC. The model, which disaggregates 40 travel zones and four income groups, offers several advantages over more aggregated models.

First, congestion pricing on a subset of links within a network will induce an array of substitution effects as people switch to unpriced routes, use public transit, travel at off-peak periods, and so forth. Consequently, the costs of traveling elsewhere can change; for example, congestion can increase on alternative roads but may fall in the downtown core if fewer people are driving in. The model used in this study is ideally suited to capturing these potentially important indirect effects, which have been neglected in prior incidence studies.[2]

Second, the model reveals the crucial importance of preexisting congestion policies for the welfare and distributional effects of congestion pricing. Major freeways in the DC area have restricted high-occupancy vehicle (HOV) lanes during peak periods; allowing single-occupancy vehicles to use these lanes in exchange for a fee would open up scarce road capacity. Many motorists would benefit from this policy, including those who would pay the fee and those who would enjoy less congestion on adjacent freeway lanes. Policies to convert HOV lanes into high-occupancy/toll, or HOT, lanes are gaining in political acceptability, yet there has been little formal analysis of their welfare and distributional effects.[3]

Third, the model can be used to analyze horizontal distributional effects, particularly the winners and losers across regional zones. Horizontal equity effects have been absent from previous studies but are important for political feasibility, since the greater the number of localities that stand to benefit from congestion pricing, the greater the likelihood of assembling a coalition of winners large enough to enact the measure.

This paper focuses on three main policies: (1) the conversion of existing HOV lanes into HOT lanes, (2) a "limited pricing" policy in which charges are applied to all lanes of freeway segments that currently have HOV lanes, and (3) a "comprehensive pricing" policy in which all lanes of all segments on all major freeways are covered by pricing. In principle, a more encompassing policy would also cover city streets, though this is not yet practical with current technology.

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[2] Previous studies have shown that substitution into alternative unpriced (and congested) routes can considerably diminish the efficiency gains from, and optimal levels of, congestion tolls applied to a single freeway or a single lane on a freeway (Van Dender 2001; Small and Yan 2001; Parry 2002; Verhoef 2002). However, the distributional implications of these substitution effects have not been explored, nor has much attention been paid to reduced congestion on complementary roads that feed into or out of the priced freeway.

[3] HOT lanes have recently been endorsed by the Federal Highway Administration under its Value Pricing Pilot Program. They have been formally modeled by Dahlgren (1999) and Kim (2000); however their focus was on travel delays modeled within a one-road bottleneck framework, rather than on welfare and distributional effects. HOT lanes are also discussed in Fielding and Klein (1993) and Poole and Orski (1999, 2002).

The results can be summarized as follows.

First, the aggregate annual social welfare gain from comprehensive freeway pricing is estimated at $220 million; however, 77% and 83% of this gain are achieved under the HOT lane and limited freeway pricing policies, respectively. Thus, just allowing single-occupant vehicles to pay to use HOV lanes achieves more than three-quarters of the gain from more comprehensive pricing. Pricing of additional lanes and freeway segments reduces congestion on those links further, but the gains are partly offset by added congestion elsewhere in the network, primarily on unpriced arterials.

Second, even when toll revenues are excluded, all household income quartiles are better off under the HOT lane policy, while for the most part all income groups are made worse off under other pricing policies. People pay HOT lane tolls only if they are more than compensated by the value of travel time savings, and drivers remaining in adjacent unpriced lanes benefit from reduced congestion. Under other policies drivers must pay tolls, whether they are compensated by time savings or not, unless they make (costly) adjustments in travel behavior, such as driving on other routes or at off-peak hours. Across jurisdictions or zones within the region, the coalition of winners is much broader under the HOT lane policy; to build as wide a geographic coalition of winners under the other policies would require a complex system of inter-jurisdictional transfers. These considerations suggest that political opposition should be less of an obstacle for HOT lanes than for more comprehensive pricing.

Third, in relative terms the regressive tendencies of congestion pricing are less severe under HOT lanes: all income groups benefit under this policy (prior to revenue recycling), and the top-income quartile gains less as a fraction of income than households in the third-income quartile, who have longer average commute times. Under other pricing policies, welfare losses as a proportion of income are significantly larger for lower-income groups.

In short, the results of this paper suggest a strong case—on the grounds of efficiency, equity, and political feasibility—for converting existing HOV lanes into HOT lanes as a first step in addressing the region's congestion problems. An initial jump toward more comprehensive pricing raises some troublesome issues of equity and practicality, unless toll revenues can be credibly used in appropriate compensation schemes, for relatively modest additional welfare gains.

It should be emphasized, however, that much of the benefit from HOT lanes is due to correcting a large inefficiency created by existing HOV lanes—that is, underutilization of the premium lane and overuse of adjacent, unrestricted lanes. Single-lane tolls imposed on freeways with no prior HOV restrictions are far less attractive on welfare and distributional grounds, not least because they increase rather than reduce congestion in adjacent lanes (Small and Yan 2001).

Moreover, policy results should be taken with caution until a number of issues, discussed below, have been explored in future modeling efforts. These include fine-tuning prices to reflect real-time traffic flows within peak periods and across different links, incorporating non-recurrent congestion (e.g., from accidents), analyzing how pricing policies interact with the broader fiscal system under different scenarios for the use of toll revenues, and taking into account changes in land-use patterns caused by road pricing.

The rest of the paper is organized as follows. Section 2 provides a heuristic framework for understanding some basic determinants of the distributional effects of road pricing. Section 3 briefly describes the structure and calibration of the computational model. Section 4 discusses who currently bears the burden of congestion in the Washington, DC, region. Sections 5, 6, and 7 present the results from the policy simulations. The final section concludes and discusses model limitations.

2. CONCEPTUAL FRAMEWORK

This section discusses welfare and vertical equity effects of road pricing policies in single and multiple route settings and comments on the significance of existing HOV lanes and horizontal equity.

2.1. Single Route Framework

Consider a highly simplified model of automobile travel on a single route where individuals differ according to whether they have low (L) or high (H) income. Denote household income by I^i where i = L, H and $I^H > I^L$. Individual mileage is M^i, where $M^H > M^L$ as auto ownership and use tend to increase with income.[4]

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[4] Estimates of the elasticity of vehicle miles with respect to income are typically around 0.35–0.8, or higher (Pickrell and Schimek 1997).

The initial "full" cost per mile driven (in dollars) for household i is $f^i = c + \pi v^i$. Here c denotes gasoline and other money costs per mile, π is the average time it takes to drive a mile, and v^i is the value of travel time; therefore πv^i is the per-mile time cost in dollars. High-income agents have greater willingness to pay for time savings (Wardman 2001; Mackie et al. 2001); therefore $v^H > v^L$. Individuals perceive π as exogenous, though it increases with the total volume of traffic as congestion slows travel speeds.

Individuals as a group drive up to the point at which the marginal (private) benefit, or height of their group demand curve for vehicle miles, equals the full cost per mile; initial mileage for group i is therefore M_0^i in Figure 1. Consumer surplus from driving—that is, benefits of travel minus full travel costs—is triangle *abc.* The change in consumer surplus in response to pricing polices measures the group's change in welfare.

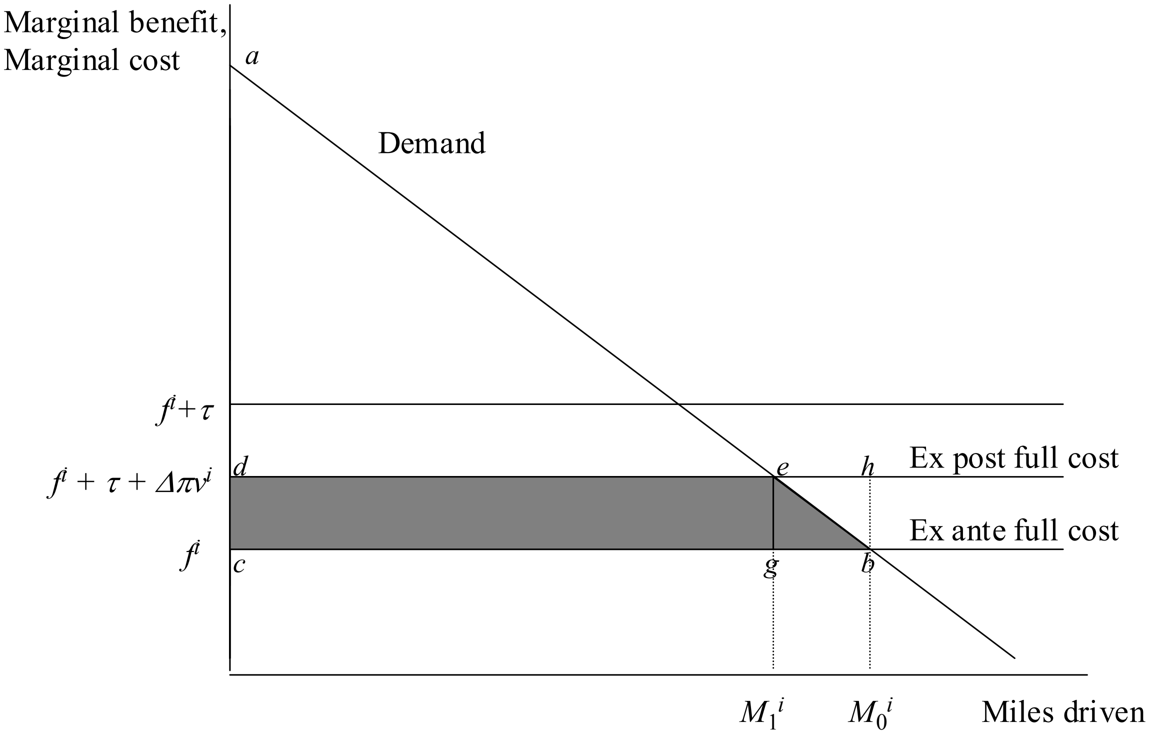

Figure 1. Welfare Effect of Congestion Tax

Suppose a toll of τ is levied for every mile driven by households and that the government keeps the revenues instead of recycling them. The demand for driving falls to M_1^i in

Figure 1, as individuals carpool, switch to public transit, or reduce trip frequency, and congestion is reduced; $\Delta\pi < 0$ denotes the change in time cost per mile. Thus, the change in the full cost of driving is $\tau + \Delta\pi v^i$ per mile.

The welfare loss for group *i* is the shaded trapezoid *debc* in Figure 1; it consists of a first-order income loss from the full cost increase (rectangle *dhbc*), less a second-order gain from reducing driving to its new (privately) optimal level (triangle *ehb*, equal to cost savings net of forgone driving benefits). As a proportion of income, the welfare loss (assuming linear demand) can be described by Equation (1):

$$\frac{(\tau + \Delta\pi v^i)M_0^i}{I^i}\left\{1 - \frac{1}{2}\frac{\Delta M^i}{M_0^i}\right\} \qquad (1)$$

where $\Delta M^i = M_0^i - M_1^i$.

If the proportionate reduction in driving $\Delta M^i / M_0^i$ is small, two main factors determine congestion toll incidence. The first factor is the increase in the full cost of driving per mile, $\tau + \Delta\pi v^i$, which is smaller for high-income agents because they have a greater value of time. Indeed, the full travel cost could fall for high-income groups, while that for low-income groups necessarily increases.[5] The second is the ratio of initial mileage to income, M_0^i / I^i. Normally, a policy is thought of as progressive if it imposes a burden that is a larger fraction of income for higher-income groups and regressive if it imposes a smaller burden. In this example, the welfare loss as a proportion of income is larger for higher-income households only under two stringent conditions: the change in the full cost for the high-income group is positive, and the mileage relative to income is not only larger for the high-income group, but also large enough to outweigh the effect of their smaller full cost per mile increase.

Opponents of congestion pricing often contend that it will drive poor people off the roads—that is, $\Delta M^i / M_0^i$ is substantial for low-income groups. From Figure 1 it is easy to see that for a given increase in the full cost of driving and a given initial mileage, the greater the

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[5] The full cost cannot fall for all income groups. Congestion tolls reduce aggregate vehicle miles and lower congestion; this implies that at least some individuals must face an increase in full driving costs, and that the reduction in their mileage must more than offset any increased mileage for individuals whose full driving cost falls.

reduction in mileage by the low-income group, the *smaller* must be their welfare loss. This is because the group demand curve must be flatter, implying a larger second-order gain from reduced driving (triangle *ehb*). In other words, if a large substitution away from tolled roads by low-income drivers occurs, this is not evidence of a large reduction in their welfare per se; instead it likely reflects indifference on their part between driving on the tolled road and other travel options, or not traveling.

2.2. Multiple Routes

Now suppose that individuals travel on two routes, denoted by superscripts A and B, both of which are congested but only one of which, route A, is subject to a toll. A and B might be substitute roads, such as different lanes on the same freeway, or spatially separated but competing routes into town. They could also be "complements"; for example, B might be roads feeding into and out of the freeway.

Suppose that as motorists are diverted off A in response to the toll, congestion increases on B ($\Delta\pi^B > 0$). This reduces consumer surplus for group *i* by the shaded trapezoid in Figure 2 (if congestion falls, there would be a gain in surplus). Combining effects from routes A and B (that is, the two trapezoids in Figures 1 and 2), the welfare loss to income ratio for group *i* is[6]

$$\frac{(\tau + \Delta\pi^A v^i) M_0^{iA}}{I^i} \left\{ 1 - \frac{1}{2} \frac{\Delta M^{iA}}{M_0^{iA}} \right\} + \frac{\Delta\pi^B v^i M_0^{iB}}{I^i} \left\{ 1 - \frac{1}{2} \frac{\Delta M^{iB}}{M_0^{iB}} \right\} \qquad (2)$$

The second component in Equation (2) may well be larger for low- than for high-income groups, since the former are more likely than wealthy motorists to avoid driving on toll roads. If so, an analysis that neglected welfare effects arising from changes in congestion on un-tolled routes might seriously understate the overall burden on lower-income groups. It should also be noted that the previous point about the welfare loss for the low-income group—that it diminishes with their willingness to substitute away from the tolled road—is less clear when congestion costs increase on alternative routes.

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[6] For clarity, shifts in demand curves in Figures 1 and 2 stemming from cross-price effects are not shown; nonetheless, the formula in (2) is still correct, so long as the *ΔM*s are interpreted as quantity changes taking into account price changes on both routes.

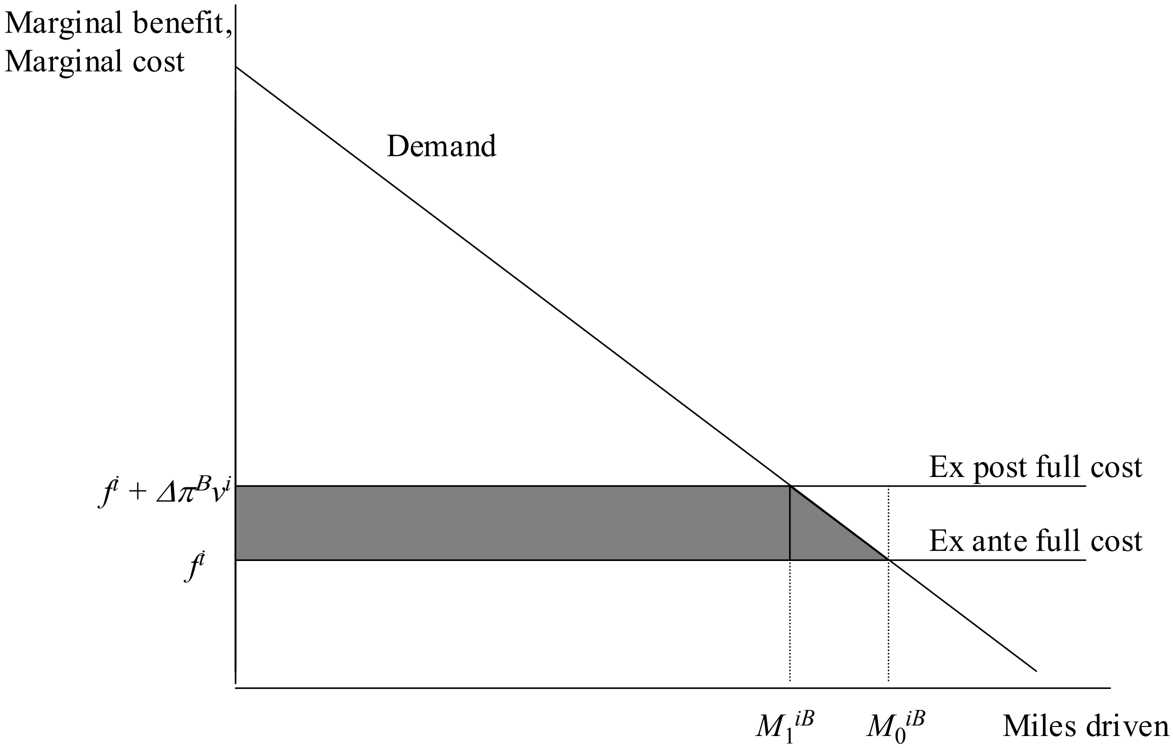

Figure 2. Welfare Effect of Change in Congestion on Related Route

The formula in (2) readily generalizes to the case of multiple tolled roads, denoted *j* = 1…*N*, and multiple un-tolled routes, denoted *k* = 1…*M*:

$$\sum_{j=1}^{N} \frac{(\tau^j + \Delta\pi^j v^i) M_0^{ij}}{I^i} \left\{1 - \frac{1}{2}\frac{\Delta M^{ij}}{M_0^{ij}}\right\} + \sum_{k=1}^{M} \frac{\Delta\pi^k v^i M_0^{ik}}{I^i} \left\{1 - \frac{1}{2}\frac{\Delta M^{ik}}{M_0^{ik}}\right\} \qquad (3)$$

It is difficult to judge how important indirect effects on other routes will be for the welfare effects of road pricing—that is, the relative magnitude of the second summation term in Equation (3)—without detailed modeling of the particular policy and the transportation network in question. It will depend on how comprehensive congestion pricing is (a broader policy reduces substitution possibilities onto other roads), the extent to which people reschedule trips to off-peak period, and the extent of initial congestion on other routes.

2.3. Importance of Existing HOV Lanes

Currently, major stretches of freeway lanes going into the District of Columbia are restricted to high-occupancy vehicles. As they are off-limits to single occupancy vehicles (SOVs), these lanes are underused relative to adjacent freeway lanes. Allowing single-occupancy vehicles (SOVs) to use existing HOV lanes in exchange for a fee would effectively open up underutilized road capacity. It should be noted that every SOV driver who switches to the premium lane must value the travel time savings by more than the fee; hence their welfare increases, even with no compensation for the tolls that they pay. Moreover, the diversion of drivers onto (rather than away from) the priced lane *reduces* rather than increases congestion on competing routes.

2.4. Horizontal Distribution

Horizontal distribution refers to the welfare impacts of policies across groups distinguished by some attribute other than income. The focus here is mostly on the geographic dimension—that is, how the welfare of households living in different regional zones may be differentially affected by pricing policies. One zone may have a congested freeway running through it, while in another the only links might be arterial roads. Thus, a policy that significantly reduced freeway congestion might benefit the first zone, while the resulting traffic diversion might harm the second. On the other hand, the downtown core might benefit from reduced traffic if suburban freeways leading into the city were priced. Identifying which zones gain and lose is important for designing inter-jurisdictional compensation packages that might widen the coalition of support for road pricing.[7]

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[7] Horizontal distribution has received very little attention in prior literature. Spatially disaggregated models usually assume that agents with identical preferences and income would relocate until their welfare is equated across locations; differential welfare impacts do not therefore persist in these models over the very long run. And theoretical models often focus on comprehensive congestion pricing of all links within a network; in practice, because it is very difficult to price streets and arterials with frequent intersections, pricing will create differential impacts on zones with different mixes of freeways, arterials, and streets.

3. DESCRIPTION OF THE WASHINGTON-START MODEL

The Washington-START model distinguishes 40 travel zones. Each zone contains three stylized links (inbound, outbound, and circumferential) that aggregate arterials and side streets; the model also incorporates various “special links,” which represent freeway segments and bridges.[8] Six main corridors, I-270, I-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, as shown in Figure 3. Existing HOV lanes on these freeways at peak period are taken into account.[9]

The rail network combines the Washington Metrorail system and the two suburban light rail systems, MARC and VRE. Bus travel is represented by a stylized route network, with bus accessibility in any zone determined by the density of stops, frequency of service, and reported bus travel times. Public transit crowding costs and parking search costs are included in the model; these are obtained from functions relating time penalties to excess demand for public transit and parking capacity. The value of time spent waiting for bus or rail and searching for parking is greater than the value of in-vehicle time.

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[8] The START (Strategic and Regional Transport) modeling suite was developed by MVA Consultancy and has been applied to a range of urban centers in the United Kingdom.

[9] The only exception is US-50, which operates a 24-hour HOV lane; this route is modeled off-peak as well.

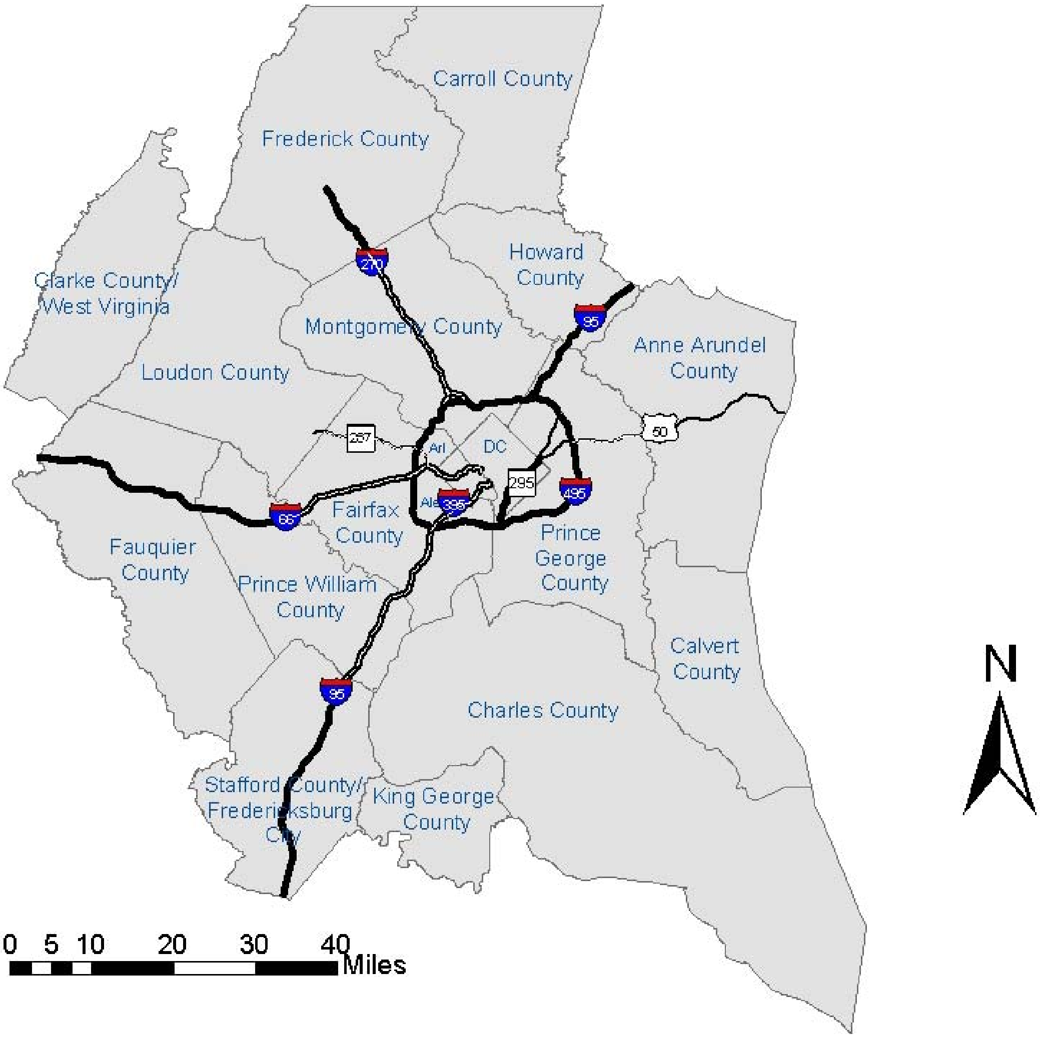

Figure 3. START Modeling Region with All Special Links

On the demand side, 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).

START takes the distribution of households by demographic segment and residential location as given. 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. 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. It should be emphasized that the model is well-suited to tackle issues related to HOV lanes, since solo driving and carpooling are choice variables for an individual traveler and therefore aggregate carpooling is endogenous as well.

The model was calibrated to the year 2000 by aggregating trip data (including freight) from the Metropolitan Washington Council of Governments (COG) Version 1 transportation planning model, which disaggregates more than 2,100 travel zones. The number of households from different income groups living and working in different zones was estimated using data from the Census Transportation Planning Package and 1994 Travel Survey; from this, total trips between any given origin–destination pair were allocated to different household groups. Data on wages and price indices were obtained from the Census and Bureau of Labor Statistics. Trip times on each link were computed from speed/flow curves generated from runs of the COG model and validated against estimates of rush-hour speeds developed from analysis of aerial photography (Council of Governments, 1999).

Travel demand response parameters were chosen to satisfy the hierarchical structure of the logit model and to be largely consistent with empirical literature. In particular, computed fuel price elasticities of vehicle-miles traveled varied across trip purposes between 0.013 for non-home-based, non-work-related travel and 0.055 for home-based shopping. It should be noted that those elasticity values are not model parameters, but the results obtained in 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. Although those values seem to be on the low end of the reported spectrum (Harvey and Deakin 1998; Johansson and Schipper 1997; de Jong and Gunn 2001), the underlying model parameters are in line with empirical evidence.

Washington-START offers an attractive compromise between the highly disaggregated planning models typically used by metropolitan planning organizations, such as the COG model for Washington, DC, and economic models that do not disaggregate travel zones, such as the Transport, Energy, and Environment (TRENEN) model that has been developed for Brussels and other European cities (de Borger and Proost 2001). Unlike the COG model, Washington-START is rigorously grounded in household optimization, computes welfare measures that take into account behavioral responses to policy changes, and has relatively quick run times, enabling a wide range of policy simulations and sensitivity analysis.[10] In addition, unlike the TRENEN model, the Washington-START model can be used to examine the impact of policies across different zones within the region.

4. CURRENT DISTRIBUTIONAL BURDEN OF CONGESTION

The metropolitan Washington, DC, area is consistently ranked as having some of the worst traffic congestion in the United States, behind only Los Angeles and San Francisco. Daily backups have now spread to vast stretches of the Washington area highway system, such as I-95 in Northern Virginia and the I-495 Beltway, where 10 years ago traffic was relatively free flowing (Council of Governments, 1999). This section briefly comments on how the costs of congestion are currently borne by different household groups and regional zones.

4.1. Characteristics of the Transportation System

Washington, DC, has a fairly well developed public transit system, including a Metrorail and a bus network. However, public transportation is predominantly located in the city proper, with few options in the outer suburbs. As shown in Table 1, public transit accounts for 22% of trips that terminate in the city core and only 3% of total trips in the metropolitan region as a whole. It can also be seen in the table that 90% of trips in the region are made in either SOVs or HOVs; moreover, 71% of work trips, which occur at peak periods, are in SOVs. This preponderance of SOV (and HOV) trips, combined with limited capacity of the region's road network, leads to considerable congestion.

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[10] Traditional welfare measures in the literature incorporate only changes in full costs associated with travel choices (e.g., Jara-Díaz and Farah 1988, Section 3.2). The measure used here is more comprehensive because it also includes utility changes from modal, time-of-day, and route adjustments.

Table 1. Trips by Mode

Trip purpose	*SOV*	*HOV*	*Public transit*	*Walk/bicycle*
All				
000s per day	10,300	10,337	591	1,683
%	45	45	3	7
Work only				
000s per day	3,722	896	439	173
%	71	17	8	3
Ending in DC				
000s per day	247	210	142	49
%	38	32	22	8

Table 2 provides some sense of how congestion currently slows travel speeds on selected highway segments and an aggregate of arterials in northwest Washington. Here, morning peak refers to the average travel speed between 6:30 and 9:30 a.m.; the evening peak, between 3:30 and 6:30 p.m.; and off-peak, the average at all other times during weekdays. Peak-period speeds are 10% to 44% slower than off-peak speeds.

Table 2. Average Speeds on Selected Congested Links (miles per hour)

Link	*Direction*	*Morning peak*	*Evening peak*	*Off-peak*
Wilson Bridge on I-495	West	38.9	41.5	56.4
	East	49.5	38.5	56.6
I-95 in Prince William Co.	North	39.1	32.7	58.7
	South	37.1	43.4	58.7
I-395 in Alexandria	North	36.2	42.7	50.4
	South	45.7	37.2	51.0
Northwest DC arterials		28.6	28.2	34.3

4.2. Burden of Congestion

As shown in Table 3, mean income across all households is $69,349, and average income for households in the bottom and top quartiles is $25,998 and $135,591 respectively.[11] Following Small (1992b), the value of travel time is set at 50% of the hourly market wage; values of time vary from $3.2 per hour for quartile 1 to $20.4 per hour for quartile 4. Hours of travel delay are computed by dividing mileage at peak period by the peak and off-peak travel speeds and aggregating the difference over links and households. In absolute terms, hours of travel delay increase with income because higher-income households own more vehicles and make more trips: annual travel delays are 42.6 and 24.4 hours for average households in the top and bottom income quartiles, respectively.

Table 3. Distribution of Burden of Congestion ($2000)

Quartile	*Average household income ($/year)*	*Value of travel time ($/hour)*	*Time delay (hours/year)*	*Average delay cost ($/year)*	*Total delay cost ($million /year)*	*Share in aggregate delay cost %*
1	25,998	3.2	24.4	78	48	4.1
2	45,196	6.7	28.2	189	116	9.9
3	70,620	11.3	39.7	449	355	30.3
4	135,591	20.4	42.6	869	653	55.7
All	69,349	10.4	38.1	396	1,172	100

Multiplying the time delay by the value of time yields annual delay costs in dollars. These increase by more than in proportion to income: delay costs for the top quartile are $869, about 11 times those for the bottom quartile, while their income is about 5 times as high. Total delay costs aggregated over all households in the region are $1.17 billion per year; of these costs 55.7% are borne by the top-income quartile and 4.1% by the bottom quartile.

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[11] Household income exceeds annual wages per worker due to non-labor income and secondary workers in many households. It should also be noted that the income quartiles are approximate: the percentage of households in quartiles 1–4 is: 22%, 23%, 28%, and 27% respectively.

These estimates are for recurrent congestion only; they exclude delays due to accidents, breakdowns, road maintenance, and bad weather. A widely cited study by the Texas Transportation Institute (2001) puts total congestion costs for the Washington metropolitan area in 2000 at $2.3 billion, roughly half of which is due to non-recurrent congestion; hence their estimates for recurrent congestion costs are similar to the ones presented here.[12]

4.3. Geographic Distribution of Current Congestion

Congestion is predominantly concentrated in the streets of the city core and surrounding urban highways, with generally decreasing costs of congestion as distance from the downtown increases. As shown in Table 4, the inner core, represented by the area inside the Beltway with around 666,000 households, has an average delay time across peak and off-peak periods of 0.21 minutes per mile. The inner suburbs, with around 728,000 households, and outer suburbs, with around 710,000 households, have average delay times of 0.18 and 0.13 minutes per mile, respectively.[13] It can also be seen from the table that arterials have higher delay costs per mile than freeways, underscoring the potential costs of policies that divert traffic onto them from freeways.[14]

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[12] However there are some methodological differences. The Texas Transportation Institute study uses the difference between observed speeds and a free-flow estimate of potential speeds, and they include extra fuel consumption costs; both these factors raise estimated congestion costs relative to the estimates reported in this section. On the other hand, they compute costs for a smaller geographic region with 3.2 million people, whereas the START modeling region encompasses around 5 million people.

[13] It should be noted that those delay times are experienced by all travelers using a particular part of the transport network and not necessarily by residents of a particular zone.

[14] Marginal congestion costs for individual links are not reported because they are difficult to compute in a network model. This is because adding an extra vehicle on one link affects congestion and travel costs on that link relative to other links, leading to a reallocation of driving that affects congestion on other links. However, as noted in the sensitivity analysis below, the exogenously specified tolls considered here do not appear to be too far off their second-best optimal levels.

Table 4. Average Delay by Region and Road Class (minutes/mile)

	DC core	*Inner suburbs*	*Outer suburbs*
Entire road network	0.21	0.18	0.13
Freeways	0.17	0.14	0.11
Arterials	0.24	0.21	0.13

5. HOT LANE POLICY

5.1. Policy Overview

The first policy considered converts all existing HOV lanes into HOT lanes; a fee of 20 cents per mile is applied to SOVs using the HOT lane during rush hours, while HOVs continue to use restricted lanes free of charge.[15] The toll level was chosen by roughly optimizing the comprehensive pricing policy described below and, to make policies comparable, applying (approximately) the same rate to other policies. In the sensitivity analysis it is shown that optimized toll rates for the HOT lane and limited pricing policies only moderately increase social welfare.

Table 5 illustrates the policy's effect for a typical special link, a 3.5-mile segment of I-395 in Alexandria (Northern Virginia) during evening rush hour; this stretch has two HOV lanes

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[15] The policy is implemented by lowering the effective price on SOVs in HOV lanes from a very high level, used to deter most solo drivers (currently, a small number of SOVs illegally use HOV lanes, and these drivers are included in the baseline calibration).

and three general-purpose lanes (GPLs). Initial travel speeds are 52.8 mph in the HOV lanes and 36.2 in the GPLs. By opening up lane capacity to SOV drivers, the HOT lane policy increases traffic flow in the restricted lanes by 68%. Because of the diversion of fee-paying SOV drivers, speed in the GPLs increases from 36.2 to 37 mph; this is a small increase but it applies to a large number of drivers.

Table 5. Effect of HOT Policy on Selected Link

	HOV/HOT lane		*Adjacent GPLs*	
	Before	*After*	*Before*	*After*
Average peak speed (mph)	52.8	51.9	36.2	37.0
Flow (passenger-cars/mile/hour)*	1,909	3,215	10,903	10,638
Average trip time per vehicle (minutes)	4.0	4.1	5.9	5.7

Notes. Results are for a 3.5-mile stretch of I-395 in Alexandria during evening peak.

* Flows are aggregated across two HOV/HOT lanes and across three GPLs.

A typical SOV commuter from zone 31 (Prince William County) to zone 1 (DC) who uses the I-395 freeway and other freeway segments with HOT lanes saves 3.6 minutes per day (16 hours per year) if she continues to use GPLs. But if she switches to the new HOT lanes, she saves 15.2 minutes a day (63 hours per year) at a cost of $7.40 in toll payments per day. A similar commuter who was initially driving in HOV lanes faces an increase in trip time of 1 minute per day (4 hours per year); thus carpoolers are worse off, but only moderately so.

5.2. Welfare and Distributional Effects

As shown in Table 6, the HOT lane policy produces a social welfare gain, aggregated over all households, of $105.9 million per year, before counting the value of toll revenues; thus, it easily passes a cost-benefit test on pure economic efficiency grounds.[16] This is not surprising, since people are not coerced to pay the toll; they pay it only if they are more than compensated by the value of reduced travel time. Most of those not paying the toll are either indirectly made better off through reduced congestion, or not affected. Adding the $65 million of annual toll revenues yields an after-revenue social welfare gain of $170.9 million.[17]

Table 6. Welfare Changes by Income Group under HOT Policy

Quartile	*Tolls paid by income group ($000/year)*	*Percentage of tolls paid by income group*	*Welfare change* ($000/year)*	*Percentage of welfare change accruing to quartile*	*Welfare change as percentage of income*
1	3,412	5.2	3,047	2.9	0.028
2	7,822	12.0	12,172	11.5	0.037
3	21,073	32.4	32,717	30.9	0.050
4	32,728	50.3	57,935	54.7	0.042
Total	65,035	100.0	105,870	100.0	0.045

* Before counting the value of toll revenues.

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[16] Welfare gains reflect the excess value of time savings over toll payments and account for a range of behavioral responses to take advantage of reduced travel costs (e.g., trip rescheduling, route substitution, reduced carpooling). Also included in the welfare measure are losses to people originally using the HOV lane and an increased congestion in the downtown core as more people are encouraged to drive.

[17] The HOT lane policy discourages use of public transportation and therefore also decreases fare collection. However, lost revenue ($1.2 million) is much smaller than the road toll collection and is ignored below. In principle, an alternative measure of aggregate social welfare could be obtained using distributional weights derived from a social welfare function (e.g., Mayeres and Proost 1997). This issue is left aside, however, given the difficulty of assessing society's preference for redistribution. For example, it is possible to infer a set of distributional weights by exploring how much economic efficiency the government is willing to sacrifice to have a progressive, distortionary income tax system. At the same time, the tax system is at least partly determined by the interplay of interest groups, rather than purely benevolent government behavior, implying that such estimates may be an unreliable indicator of society's true preferences.

The wealthiest quartile pays 50.3% of total toll revenues collected and receives 54.7% of the before-revenue social welfare gains; the bottom quartile pays only 5.2% of the tolls and receives 2.9% of the before-revenue welfare gains. In absolute terms, households in the wealthiest quartile are easily the biggest winners, gaining $57.9 million annually as a group, and the bottom quartile gains $3 million. However, relative to income, the third income quartile benefits the most because they are most likely to live in the outer suburbs and have long commutes; their before-revenue welfare gain is 0.05% of income, compared with 0.042% and 0.028% for the top and bottom quartiles, respectively. The most important point from Table 6, however, is that all income groups benefit from HOT lanes prior to any recycling of toll payments.

Figure 4 shows before-revenue welfare changes for households living in different regional zones. Zones with or near HOT lanes receive the greatest benefit; for example, northeast Prince George's County (zone 12) benefits the most (7-13 cents per trip), mainly because the US-50 corridor there is highly congested and has a 24-hour HOV lane that would be converted into a 24-hour HOT lane. Zones that show losses—for example, the DC core—suffer increased congestion and parking search costs as the total number of people driving into town increases; however, the losses are small in magnitude (less than 1 cent per trip).

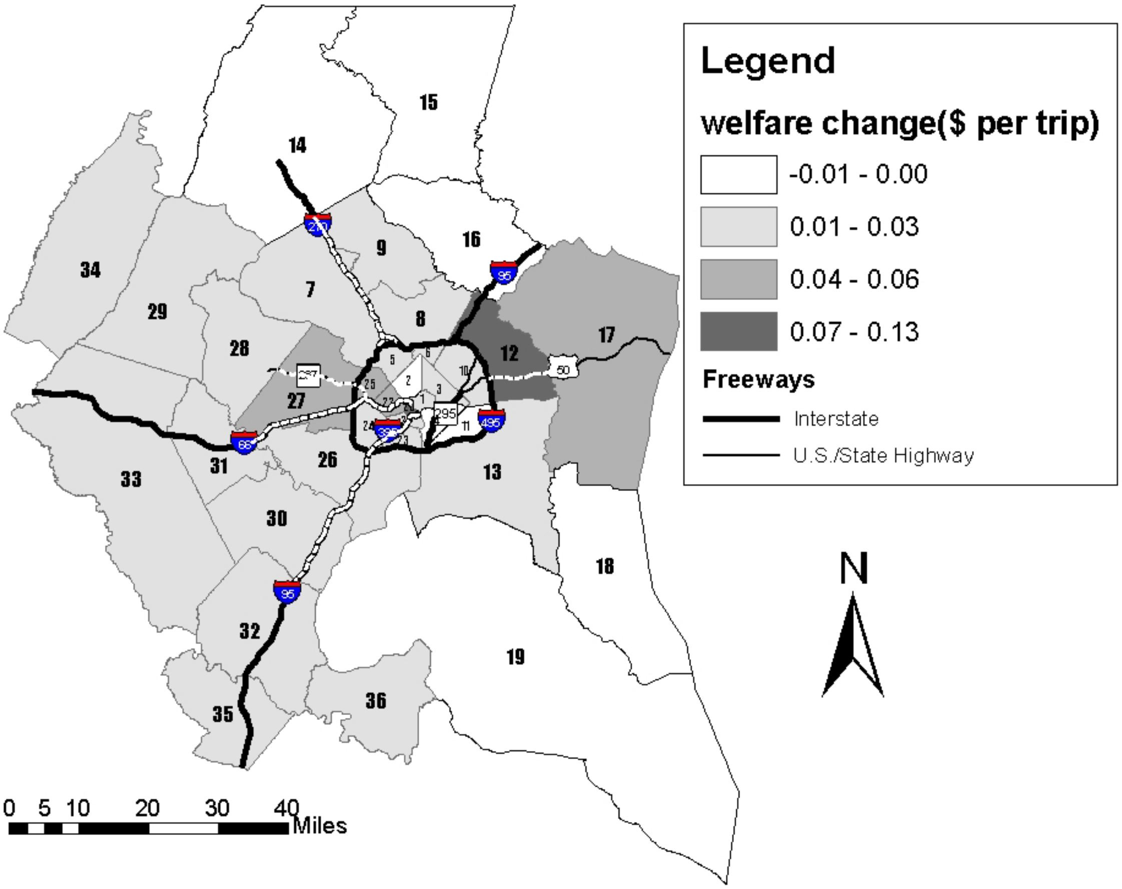

Figure 4. Before-Revenue Welfare Change by Zone under HOT Policy ($ per trip)

Other losing groups include those initially using HOV lanes, such as carpoolers and family members traveling together. In a typical example, a commuter using the I-66 HOV lanes to travel from northwest Fairfax County to downtown DC loses by just over 2 minutes a day, or 8.7 hours per year. Thus, two commuters who are identical except that one carpools on the HOV lane and the other does not, fare quite differently: the carpooler in the HOV lane faces increased congestion, but the single driver benefits from reduced congestion.

6. LIMITED PRICING

6.1. Policy Overview

The second policy considered involves a toll of 22 cents per mile for all users of current HOV lanes, and a toll of 7 cents per mile on all GPL segments adjacent to existing HOV lanes.[18] The policy combines elements of traditional congestion pricing—that is, charging people for road use that was previously free—with the opening of capacity in HOV lanes to new users. It is "limited" in the sense that it applies only to highway segments that currently have HOV lanes.

Table 7 illustrates impacts on travel speeds and flows for the same stretch of I-395 at evening peak as before. Traffic flows in the GPLs fall by around 10%, compared with a 3% reduction under the HOT lane policy, as the new charges on these lanes divert drivers onto other routes; travel speeds in these lanes increase from 36.2 mph to 38.6 mph. In the premium lane, traffic flows increase by 44%, noticeably less than the 68% increase under the HOT lane policy: some HOVs no longer use this lane because they now have to pay. Despite freeway pricing, there is a very slight reduction in traffic on nearby side roads: although some drivers are "tolled off" the freeway onto streets, this is offset by the diversion of drivers taking advantage of new capacity on the premium lane.

Table 7. Effect of Limited Pricing on Selected Link

	Premium lane		*Adjacent GPL*		*Nearby side roads*	
	Before	*After*	*Before*	*After*	*Before*	*After*
Average peak speed (mph)	52.8	52.1	36.2	38.6	28.0	28.1
Flow (passenger-cars/mile/hour)	1,909	2,752	10,903	9,780	18,012	17,778
Average peak time per trip (minutes)	4.01	4.07	5.85	5.49	7.71	7.69

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[18] Previous analytical work shows that optimal tolls differ across freeway lanes in order to sort out drivers with high and low time costs across faster and slower lanes (Small and Yan 2001).

Note: Results are for a 3.5-mile stretch of I-395 in Alexandria and slightly longer adjacent side roads during evening peak.

An average commuter using GPLs to go from zone 31 (Prince William County) to zone 1 (DC) will save more than 4.4 minutes (18 hours per year); if she originally drove in the GPLs and then switched to the new premium lane, she would save more than 20.2 minutes a day (84 hours per year). However, if the toll induced her to drive on side roads rather than the GPLs, trip time would increase by 3.9 minutes (16.3 hours per year).

6.2. Welfare and Distributional Effects

As shown in Table 8, the before-revenue social welfare change under the limited pricing policy is negative $70 million. Households are worse off in aggregate, mainly because for many drivers in GPL lanes and HOVs in premium lanes, the value of reduced travel time is insufficient to fully compensate them for the tolls. The after-revenue welfare change is plus $182 million, only 7% greater than that under the HOT lane policy. Annual revenues raised are $253 million, almost four times the amount raised under HOT lanes, since this policy charges for additional lanes and HOVs using premium lanes.

These findings differ sharply from those in some earlier studies of individual freeways where single-lane tolls capture only a minor portion of the welfare gains from pricing that covers all freeway lanes (Liu and MacDonald 1998; Small and Yan 2001; Parry 2002). In these models, which exclude existing HOV lanes, a single-lane toll compounds congestion in adjacent GPLs; this problem, however, is avoided as more freeway lanes are priced. Converting an HOV lane to a HOT lane reduces rather than increases congestion in adjacent GPLs; moreover, unlike in single-freeway models, welfare gains from more comprehensive pricing are offset to some extent in this case by greater congestion elsewhere in the network.

Table 8. Welfare Changes by Income Group under Limited Pricing

Quartile	*Tolls paid by income group ($000/year)*	*Percentage of tolls paid by income group*	*Welfare change* ($000/year)*	*Percentage of total welfare loss borne by quartile*	*Welfare change as percentage of income*
1	23,563	9.3	–26,555	37.8	–0.217
2	38,233	15.1	–23,474	33.4	–0.112

3	81,927	32.4	–24,301	34.6	–0.057
4	108,859	43.1	4,085	–5.8	0.005
Total	252,583	100.0	70,244	100.0	–0.048

* Before counting the value of toll revenues.

Although the share of the toll burden increases with income, in terms of before-revenue welfare effects, limited pricing is regressive throughout the income distribution. As shown in Table 8, the top quartile gains $4 million per year, but the other three income quartiles lose, $23 million to $26 million per year. Welfare losses as a portion of income are greatest for the bottom quartile, mainly because they value time savings the least.

The spatial dispersion of before-revenue welfare impacts is more striking under limited pricing than under HOT lanes, as Figure 5 shows. The few zones that gain under this policy are highly congested and reap the largest benefits from the conversion of the HOV lane to a premium lane, such as the northeast of Prince George’s County (zone 12) which contains US-50. Most other zones suffer a loss because of the burden of the toll and the diversion of traffic onto already congested side roads. Most negatively affected zones are located in the outer suburbs, where residents have relatively long commutes.

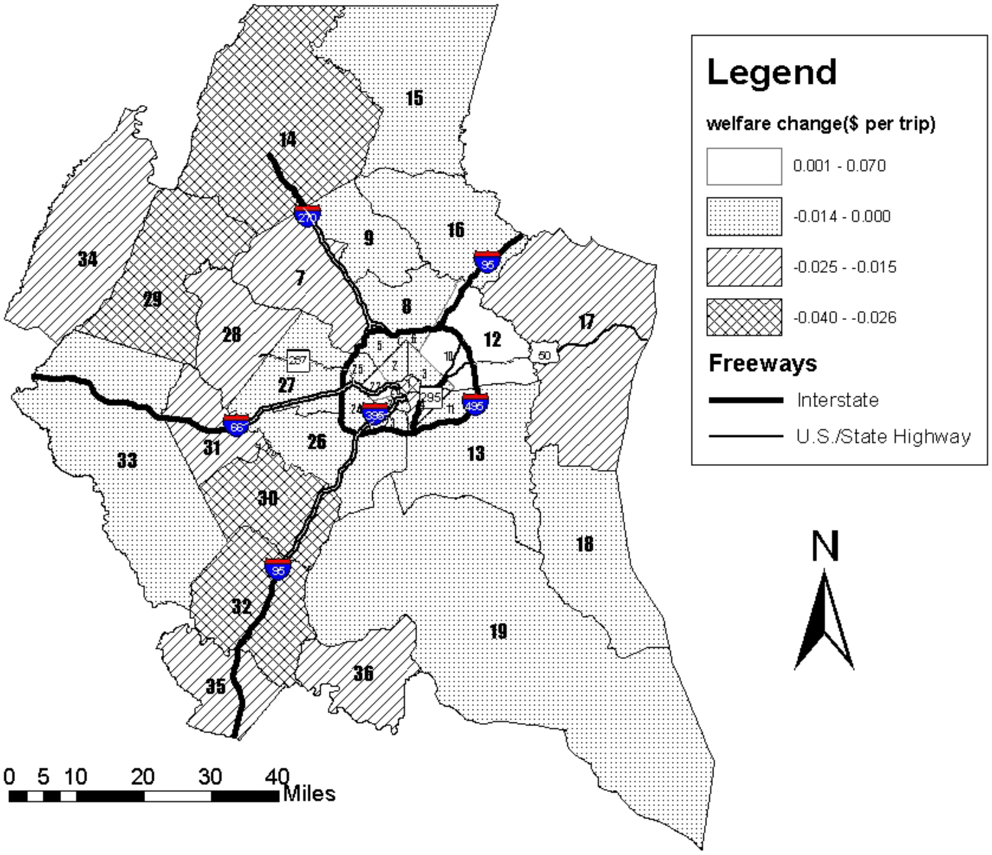

Figure 5. Before-Revenue Welfare Change by Zone under Limited Pricing ($ per trip)

7. COMPREHENSIVE PRICING

7.1. Policy Overview

The final policy considered extends the 7 cents per mile toll on all freeway segments throughout the region; tolls for any vehicle using existing HOV lanes remain at 22 cents. This policy covers considerably more of the road network than limited pricing, though it is not fully comprehensive because side streets and arterials remain unpriced.

The policy has essentially the same effect as limited congestion pricing on traffic flows and speeds on freeway segments with HOV lanes. On other freeway segments the main effect is some diversion of vehicles onto nearby side roads. Table 9 illustrates this for a 4-mile stretch of the Beltway between I-66 and US-267 in Fairfax County during the evening peak. Traffic flows on this Beltway segment decrease 9% and speeds increase from 36.4 to 40.6 mph, but travel flows on adjacent side roads increase by 4% and average speeds decline by 0.4 mph. Drivers who pay the toll benefit from an 11% reduction in travel time on this segment; those switching to side roads to avoid the toll suffer an increase in travel time of 51%. Because of increased speeds on all special links, an average commuter using a GPL from Prince William County to downtown DC saves nearly 5 minutes a day (21 hours per year); however, if that commuter switched to side roads to avoid tolls, she would lose 4.3 minutes a day.

Table 9. Effect of Comprehensive Pricing on Selected Link

	Beltway		*Nearby side roads*	
	Before	*After*	*Before*	*After*
Average peak speed (mph)	36.4	40.6	36.3	35.9
Flow (passenger-cars/mile/hour)	8,811	8,052	8,226	8,528
Average peak time per trip (minutes)	6.6	5.9	9.9	10.0

Note: Results are for the approximately 4-mile stretch of the Beltway between VA-267 and I-66 and 6 miles of adjacent side roads during evening peak.

7.2. Welfare and Distributional Effects

Comprehensive pricing produces an annual after-revenue social welfare gain of $220 million, 29% and 21% larger than under HOT lanes and limited pricing, respectively. As shown in Table 10, toll revenues are $446 million, 76% higher than under limited pricing, and almost seven times revenue under the HOT policy. Comprehensive pricing produces a before-revenue social welfare loss of $225.6 million, more than three times the loss under limited pricing.

It can also be seen from the table that all four quartiles suffer before-revenue welfare losses under this policy, but relative to income, losses are almost 12 times as large for the bottom quartile as for the top quartile. Thus, the policy is quite regressive, even though the top quartile pays 40% of the total toll revenues.

Table 10. Welfare Changes by Income Group under Comprehensive Pricing

Quartile	*Tolls paid by income group ($000/year)*	*Percentage of tolls paid by income group*	*Welfare change* ($000/year)*	*Percentage of welfare loss borne by quartile*	*Welfare change as percentage of income*
1	47,849	10.7	–55,815	24.7	–0.456
2	71,771	16.1	–60,510	26.8	–0.288
3	147,580	33.1	–79,009	35.0	–0.187
4	178,824	40.1	–30,312	13.4	–0.039
Total	446,026	100.0	–225,646	100.0	–0.155

* Before counting the value of toll revenues.

Geographic disparities in before-revenue welfare effects are more pronounced for some zones under comprehensive pricing than under limited pricing, while other zones fare about the same. For example, several zones including non-HOV freeways, such as zone 13, now suffer bigger losses because residents must choose between paying a toll on the Beltway or driving on more congested side roads. Several zones on the city outskirts that were affected the most under limited pricing (for example, zones 30, 31, 29, and 14) show similar levels of per-trip welfare losses but are now affected less relative to other zones. This is because residents of these suburbs now enjoy reduced congestion on the Beltway when they drive in.

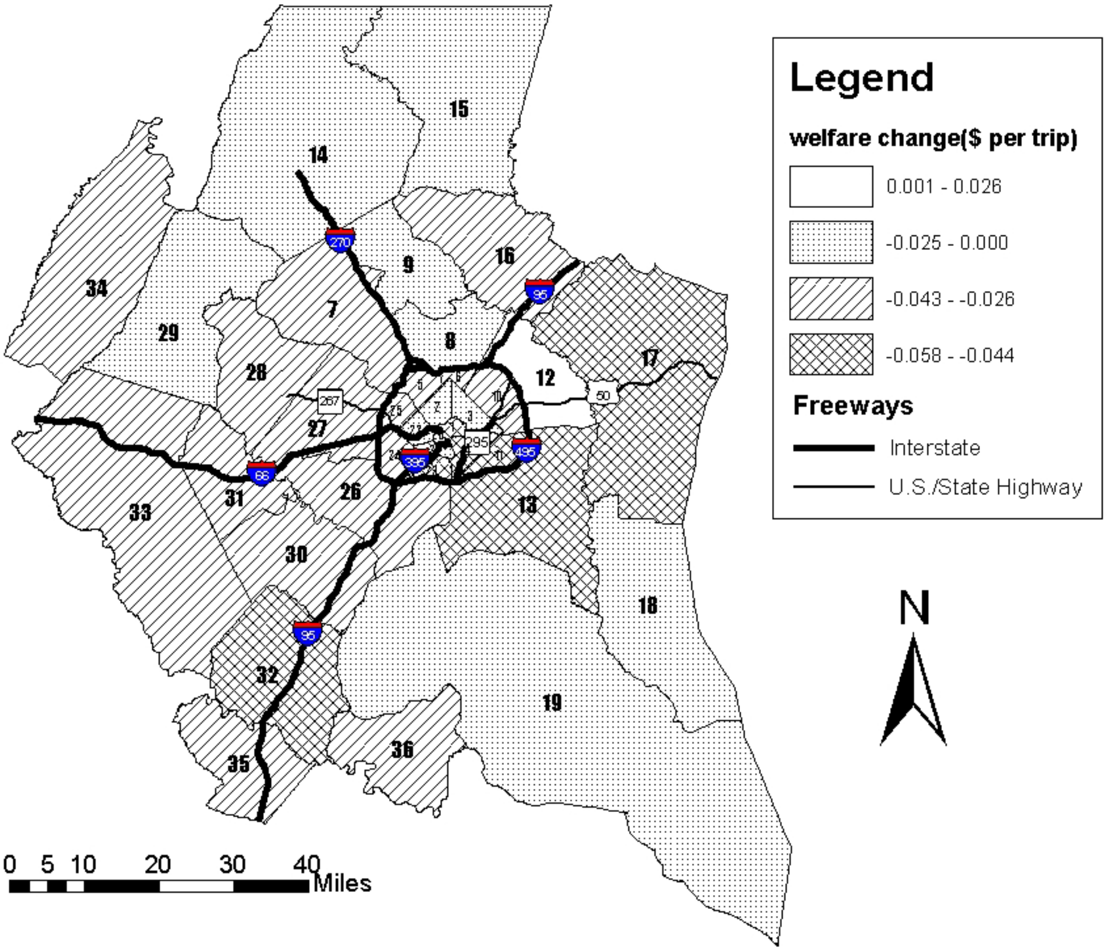

Figure 6. Before-Revenue Welfare Change by Zone under Comprehensive Pricing ($ per trip)

7.3. Sensitivity Analysis

Loosely speaking, the distributional impacts described above change in proportion as all tolls are varied by the same proportion. Here aggregate social welfare effects are briefly discussed.

As shown in the middle two rows of Table 11, increasing and decreasing all tolls by 50% moderately reduces welfare gains relative to those in the benchmark. The one exception is the HOT lane: higher tolls increase social welfare, but only moderately. As shown in the bottom row, doubling the toll on GPLs while keeping the premium lane toll fixed reduces welfare under comprehensive pricing but moderately increases welfare under limited pricing. This is because average congestion in GPLs affected by the limited pricing policy is greater than the average congestion across the (much wider) range of GPLs affected by comprehensive pricing.

Table 11. Sensitivity Analysis

Policy scenario		*HOT lane*	*Limited pricing*	*Comprehensive pricing*
Benchmark	Premium lane toll (cents/mile)	20	22	22
	Toll on other lanes (cents/mile)	0	7	7
	Social welfare gain ($million/year)	171	182	220
High tolls	Premium lane toll (cents/mile)	30	33	33
	Toll on other lanes (cents/mile)	0	10.5	10.5
	Social welfare gain ($ million/year)	181	180	216
Low tolls	Premium lane toll (cents/mile)	10	11	11
	Toll on other lanes (cents/mile)	0	3.5	3.5
	Social welfare gain ($million/year)	**149**	**162**	**193**
Reduced toll differential	Premium lane toll (cents/mile)		22	22
	Toll on other lanes (cents/mile)		15	15
	Social welfare gain ($		**191**	**188**

million/year)

8. CONCLUSIONS

The inability of enhanced road and public transit capacity to keep pace with relentless growth in vehicle miles has made urban centers ever more congested. Recent experiments with encouraging expansion of carpooling on high-occupancy vehicle lanes have failed to seriously dent congestion by encouraging the hoped-for expansion of carpooling (Poole and Orski 1999). Whatever the economic merits of road pricing, in the past policy stakeholders have regarded it as impractical, because of the apparent unwillingness of motorists to pay for something that they have previously used for free.

However, HOV lanes, which have disappointed their many advocates, may end up being a Trojan horse for congestion tolls, at least in a limited form. There is no coercion involved in opening HOV lanes up to single occupant vehicles in exchange for a fee: motorists can continue to use adjacent freeway lanes for free if the value of time savings is insufficient to compensate them for the toll. The policy creates a broad coalition of winners, both across different income groups and across local jurisdictions, even prior to recycling of toll revenues. And according to the results from the model presented in this paper for Washington, DC, the social welfare gain from HOT lanes can achieve around three-quarters of the welfare gains from substantially more comprehensive road pricing.

A major caveat 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, and degree of utilization of HOV lanes. It would be interesting to study whether the quantitative results reported here apply broadly to other urban centers. Nonetheless, the qualitative result that HOT lanes offer travelers more choices and therefore can produce better distributional outcomes compared with more general congestion pricing should be robust.

A number of other limitations to the analysis deserve mention. For computational reasons, the tolls are exogenously specified: they are constant across entire peak periods and they are the same for different freeways. More precisely targeted tolls that varied across freeways and with real-time traffic flows within the peak period would yield greater welfare gains.

Only recurrent congestion is considered; welfare gains from improving travel flows would be significantly larger if reduced non-recurrent congestion (due to accidents, bad weather, breakdowns, and so on) were also taken into account. Welfare gains would also be larger if additional heterogeneity in values of time due to factors beyond differences in wages were accounted for (Small and Yan 2001; Small et al. 2003).

The interactions between congestion charges and other motor vehicle externalities, such as pollution and accidents, are beyond the scope of this paper. Parry and Bento (2002) discuss the welfare effects of congestion charges in the framework of other distortions within the transportation system. The interactions between policies and the broader fiscal system are also ignored. If policy revenues are used to improve economic efficiency—for example by reducing income taxes that distort labor and capital markets—welfare gains could be substantially higher than those computed here. But there is an offsetting effect that should be included in a more general analysis: by raising the costs of commuting to work and discouraging labor force participation, congestion pricing can also reduce efficiency in the labor market, which is badly distorted at the margin by the tax system (Parry and Bento 2001; Mayeres 2001).

Finally, only the direct short-term effect of congestion policies is considered; over the long haul, distributional incidence will change as people respond to road charges by changing residential location or place of work and demanding higher wages or travel allowances from employers to compensate for tolls (Boyd 1976).

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