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Measuring Marginal Congestion Costs of Urban Transportation: Do Networks Matter?

Elena Safirova and Kenneth Gillingham

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Abstract

In determining the marginal cost of congestion, economists have traditionally relied upon directly measuring traffic congestion on network links, disregarding any “network effects,” since the latter are difficult to estimate. While for simple networks the comparison can be done within a theoretical framework, it is important to know whether such network effects in real large-scale networks are quantitatively significant.

In this paper we use a strategic transportation planning model (START) to compare marginal congestion costs computed link-by-link with measures taking into account network effects. We find that while in aggregate network effects are not significant, congestion measured on a single link is a poor predictor of total congestion costs imposed by travel on that link. Also, we analyze the congestion proliferation effect on the network to see how congestion is distributed within an urban area.

Key Words: marginal congestion costs, congestion pricing, urban networks

JEL Classification Numbers: R41, R48

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Measuring Marginal Congestion Costs of Urban Transportation: Do Networks Matter?

Elena Safirova and Kenneth Gillingham*

1. INTRODUCTION

The principle of marginal cost pricing of urban transportation infrastructure has become increasingly politically acceptable. Recent studies have made great strides forward towards developing more detailed and realistic urban transportation network models and more accurate empirical estimates of marginal congestion costs (MCC). Precise estimation of congestion costs is important and policy-relevant for several reasons. First, they serve as status indicators that describe the current state and trends of congestion. Second, congestion costs provide a basis for cost-benefit analysis that assesses whether individual projects and programs are worthwhile investments. Finally and possibly most importantly, obtaining accurate marginal congestion costs is crucial for designing efficient transportation infrastructure pricing schemes, as is discussed by Lee (1).

Traditionally, people have thought about average costs when considering costs of transportation and therefore disregarded the negative externality each traveler imposes on others on a congested road. Using average costs tends to underestimate the true costs of congestion since this externality is not taken into account. More recently, a popular way to define the costs of urban congestion is based on costs of delay, that is, the difference in travel costs computed on the basis of the difference between actual speeds and free-flow speeds (2,3). While the costs of delay are an acceptable benchmark, especially for comparing congestion levels across different metro areas, they are not particularly instructive either since bringing all traffic to free-flow speeds at all times would constitute an inefficient overprovision of road space and therefore cannot serve as a meaningful policy goal. Only marginal costs of congestion capture the magnitude of congestion externalities and can be used in the design of transportation policies.

*Resources for the Future, Washington DC. The authors would like to thank Winston Harrington and Peter Nelson for helpful suggestions, all remaining errors are exclusively ours.

Currently, there exist several competing approaches to computing the marginal congestion costs of urban transportation that go beyond one-link static models. One approach emphasizes the connections between transportation and other sectors in the economy and focuses on analyzing the total impact of traffic congestion. Although presenting a rich picture of inter-sectoral relationships, such models tend to feature a relatively simple representation of the transportation system. For example, Mayeres and Proost (4) evaluate the efficiency effects of transportation charges in Belgium by computing the marginal welfare cost of public funds for a number of tax instruments; Parry and Bento (5) emphasize the interaction between congestion and labor supply and point out that congestion-pricing schemes are sensitive to the allocation of revenues. While these general-equilibrium effects are important, the simple treatment of the transportation system in this class of models prevents them from addressing complex network modeling issues.

Another approach assumes that marginal congestion costs obtained for each link on the network could be used as substitutes for the true system-wide marginal congestion costs. For instance, Anderson and Mohring (6) compute marginal congestion costs on the road network of the Twin Cities area using a link-by-link method and draw on obtained results to simulate a marginal congestion pricing policy. Ozbay et al. (7) use speed-flow relationships on each link to compute marginal costs along routes for a full network. They thus assume that any additional flow in the system does not disturb the existing flow patterns on the network. The latter authors recognize that this is an approximation: “We are aware of the fact that the resulting value will not be the same as the true system-wide marginal cost. This value can only be obtained by performing a new traffic equilibrium assignment, which will reflect the change in flow patterns due to the addition of an extra unit of demand. However, compared to the overall demand, because the additional demand is relatively small...we can assume that the resulting costs will be reasonable approximations of actual costs.” (p. 85). These changes in flow patterns due to the addition of an extra unit of demand are commonly referred to as “network effects,” and a full accounting of the impacts of these effects on the true system-wide marginal congestion costs remains an open research topic.

However, a branch of the literature has approached the issue of network effects in the context of optimal and second-best congestion tolls. In the traffic assignment literature it is well known that marginal-cost tolls are optimal on a network with fixed demands—see, for example, Sheffi (8). Yang and Huang (9) set up an optimization problem the solution of which determines optimal congestion tolls for each link on a general congested network. The solution suggests that

network interactions do matter, but it is impossible to quantify such effects using a theoretical model. Later, Hearn and Yildirim (10) developed an algorithm for finding congestion tolls on a network with elastic demands and used this algorithm for determining congestion tolls for a small network. They numerically solved for optimal congestion tolls for a theoretical 9-node network with elastic demands and conjectured that the same algorithm can successfully be applied to solving modest-sized urban networks. However, elastic-demand optimal toll problem has yet to be solved for a realistic transportation network.

Although elastic demands and route choice pose significant problems for transportation researchers, real networks feature an array of other complicating features—mode choice, different times of day, and heterogeneous agents. Each of these factors has the ability to complicate significantly the overall network equilibrium. While in the literature mode choice, time of the day differentiation and agent heterogeneity deserve and receive separate treatment (see 11, 12, 13), in this paper we analyze their *composite* effect on a real network. In particular, we attempt to determine whether in the presence of all the complicating factors, network effects can be significant enough to render calculations of marginal congestion costs using the common link-by link method inaccurate.

In order to achieve this research goal, we employ a strategic transportation planning model, START—or Strategic and Regional Transport—calibrated to the Washington, DC, metro area as an example of a sufficiently large network featuring mode choice, time periods, agent heterogeneity, and a realistic distribution of demand. While we do not claim that the results of this paper are general and applicable to other metropolitan areas, we intend our work to shed some light on the relationship between marginal congestion costs measured on individual links isolated from the network and marginal congestion costs measured on links in an integrated network.

The rest of the paper is structured as follows. In section 2, we provide an overview of the START Model and key facts about the Washington, DC, modeling region. In section 3, three methods of computing congestion costs are described and compared. Section 4 presents major results of this research and outlines the implications of these results for congestion pricing. Section 5 concludes and provides direction for future study.

2. START MODEL OVERVIEW

The START modeling suite was developed by MVA Consultancy and has been applied to a range of urban centers in the United Kingdom, including Birmingham, Edinburgh, Bristol, and South England (14,15).

Unlike traditional transportation models, START is designed to predict the outcomes of different transportation strategies, where strategies refer to the combinations of different transport elements, which in broad terms encompass changes in capacity (such as new infrastructure), operating conditions, and prices. Therefore while most of the components of the model are conventional, the suite features a limited number of zones and an aggregated representation of the supply side (transportation network and provision of public transportation) coupled with a rich and detailed demand side. An important advantage of the model is its relatively fast runtime, which provides the opportunity to conduct a number of simulations to better understand probable policy consequences.

Traffic congestion on highway links in START is modeled via speed/flow•distance curves specified for each highway link.¹ Unlike some other popular transportation models, congestion arising at intersections is not explicitly represented. Explicitly defined routes between each origin and destination pair determine the quantity of traffic and the distance traveled by that traffic on each of the START links. Thus, when the START demand model forecasts the number of trips between each origin and destination and accumulates these onto specific routes and consequently onto links, the “flow•distance” information allows the link speed to be calculated. The choice of route is determined endogenously and is influenced by the congestion on each link. Therefore, the model is very well positioned to address the question of the extent of congestion spillovers in the network.

The Washington-START model has 40 travel zones with three stylized transportation links in each zone (inbound, outbound, and circumferential) and a number of other “special” links that represent freeway segments and bridges. 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

¹ START differs from most traffic assignment models since it utilizes speed/flow•distance curves instead of speed/flow curves. This feature is required because in this modeling suite routes can contain portions of road links instead of entire links. The speed is in the units of miles per hour and flow•distance is in the units of PCU-miles, where PCU stands for passenger-car-unit (to account for buses and trucks requiring more road space than a typical passenger car).

central region within the circular I-495/I-95 known as the Beltway (see Figure 1). The rail network combines the Washington Metrorail system and suburban light rail systems (MARC, VRE). Bus travel is represented by a highly stylized route network, with bus accessibility in any zone determined by the density of stops, frequency of service, and reported bus travel times. Transit crowding costs and parking search costs are explicitly included in the model. We also account for existing high occupancy vehicles (HOV) lanes on I-95, I-395, I-66, and VA-267 in Northern Virginia, as well as I-70 and US-50 in Maryland.

This rather aggregated supply-side representation is combined with a detailed demand-side structure. The model features 8 household types differentiated by income and vehicle ownership levels. There are six trip purposes—home-based work (HBW), home-based shopping (HBS), home-based other (HBO), non-home-based work (NHBW), non-home-based other (NHBO), and freight. Home-based trips either originate or terminate at home. The model distinguishes four travel modes: single occupancy vehicle (SOV), high-occupancy vehicle (HOV), bus/rail, and non-motorized (walk/bike). It also contains three times of day: morning peak, afternoon peak, and off-peak (weekend travel is excluded). Table 2 contains an overview of the breakdown in travel demand in DC, by purpose and time of day.

START takes the distribution of households by demographic segment and residential location as exogenous. Travel decisionmaking is modeled as a nested logit tree. The utility functions at each nest are linear in generalized cost (the combined time and monetary costs of travel). The value of time is a fraction of the traveler's wage rate and this fraction varies according to trip purpose and mode.² In successive nests, households choose whether to take the trip, then destination, mode, time of day, and route.

These choices can be seen as a sequential process. First, the decision whether to make a trip at all is made. Then, conditional on that choice, a destination is chosen. After that, conditional on the choices made previously, mode is selected, and so forth.

Therefore, the probability that a consumer makes a trip i to destination j by mode m during period t using route r is

$$P_{ijmtr} = P_i P_{j|i} P_{m|ij} P_{t|ijm} P_{r|ijmt} \quad (1)$$

² Values of time in current application vary between \$3.24 and \$20.59.

The five choice levels are described by logit models. For example, the route choice (the lowest nest) is given by a logit demand form:

$$P_{r|ijmt} = \frac{\exp(A_{ijmtr} - \beta^r p_{ijmtr})}{\sum_{l=1}^{R_{ijmt}} \exp(A_{ijmtl} - \beta^r p_{ijmtl})}, r=1, \dots, R_{ijmt}, \quad (2)$$

where

$P_{r|ijmt}$:= the probability that a route r is chosen conditional on choice of generation, destination, mode and time of day

p_{ijmtr} := the generalized costs of route r

A_{ijmtr} := the constant term which includes all aspects of attractiveness of a travel option except the cost

β^r := the route choice elasticity parameter

R_{ijmt} := the number of routes in the nest

The parameter $0 \leq \beta^r < 1$ represents the elasticity of travel choices at the nest level. When $\beta^r \rightarrow 0$, the choice between routes is price-inelastic, and is hardly affected when generalized costs change. On the other hand, when $\beta^r \rightarrow 1$, travel choices are very sensitive to prices. Values of parameters used in the model are presented in Table 1.

To calibrate the model, we use data on how many trips occur on different links within zones by consolidating output from the Metropolitan Washington Council of Governments (COG) Version 1 transportation planning model (which disaggregates over 2,100 travel zones). Using data from the Census Transportation Planning Package and 1994 Travel Survey, we estimate how many households from different demographic groups live and work in different zones, and from this we are able to allocate total trips on any given link 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 are validated against estimates of rush-hour speeds developed from analysis of aerial photography (16). The model in its present form has also been used to conduct policy simulations of gasoline taxation, HOT lanes, and congestion pricing (17,18).

3. CONGESTION MEASUREMENT

As has been discussed in the introduction, one method of measuring marginal congestion costs is on a link-by-link basis with the assumption that proliferation of congestion on the network is relatively insignificant. Undoubtedly, it is the simplest method of measuring marginal congestion costs and this simplicity is quite appealing. In this paper we will call this approach method 1.

In order to take into account the redistribution of traffic flow over the network, we also developed methods 2 and 3. The attractiveness of method 2, like method 1, lies in its relative simplicity in application to our model. In particular, we are able to compute the MCC on all network links via method 2 by running the START model only once. On the other hand, method 3 seems to present the most theoretically correct results, but requires the highest level of effort—a separate run of the model is required for the computation of MCC on each link. Therefore, we apply method 3 only to a limited, but representative, set of links.³

Method 1

Method 1 simply utilizes the exogenous speed/flow•distance relationship governing congestion on each individual link. Suppose a speed/flow•distance relationship is denoted by $S_k = S(FD_k)$, where S_k is the speed on the link and FD_k is the flow•distance on that link. Then the marginal congestion costs per mile on link k would be equal to

$$MCC_k^1 = \left(\frac{1}{S_{k1}} - \frac{1}{S_{k0}} \right) \times FD_k \times VOT_k, \quad (3)$$

where S_{k0} and S_{k1} are correspondingly the initial and resulting speed levels on the link k after adding one unit of flow•distance to the link. Therefore, marginal congestion costs imposed by one extra vehicle mile traveled on a link k comes to an increase in travel time $\left(\frac{1}{S_{k1}} - \frac{1}{S_{k0}} \right)$ experienced by all other link k users FD_k multiplied by the average value of time VOT_k .

³ The links were chosen to represent different link types (inbound, outbound, circumferential, special) as well as different geographical parts of the metro area.

Since $S_{1k} = S_{0k} + \frac{\partial S}{\partial FD_k}$, we can rewrite equation (3) as follows:

$$MCC_k^1 = - \frac{\frac{\partial S}{\partial FD_k}}{S_{k0} \left(S_{k0} + \frac{\partial S}{\partial FD_k} \right)} \times FD_k \times VOT_k \quad (3')$$

where VOT_k is the average value of time of travelers on link k (for the sake of simplicity, we do not account for changes in monetary costs of travel due to decreased speeds since those are of much smaller magnitude than direct time losses).

In other words, the marginal congestion cost per mile of travel on a link is equal to the monetary value of time lost by all travelers on link k . This measure assumes that travel times on all other links except the link k are unchanged and there is no traffic reassignment.

Method 2

In order to account for the interaction between traffic congestion on different links on the network, one has to perform a new traffic assignment and compute marginal congestion costs on links resulting from changes in speeds on the entire network. In this study, we change (for example, decrease) the demand for travel between all origin-destination pairs by the same small percentage and run the START model with the new initial demand. Then, the marginal congestion costs per mile of travel are computed as follows:

$$MCC_k^2 = \left(\frac{1}{S_{k1}} - \frac{1}{S_{k0}} \right) \times \frac{(FD_{k0} + FD_{k1})}{2} \times VOT_k \times \left(\frac{1}{FD_{k1} - FD_{k0}} \right), \quad (4)$$

where subscripts 0 and 1 denote initial and resulting traffic assignments.

Equation (4) looks very similar to the equation (3) except for the fact that now changes in FD on each link can be much larger than unitary perturbations assumed in method 1. Therefore, we multiply the time losses experienced on link k by the average of the initial and resulting flow•distance on the link $\frac{(FD_{k0} + FD_{k1})}{2}$. Likewise, the value of MCC should be prorated to

reflect the impact of unitary increase in VMT on the link and therefore the result is multiplied by $\left(\frac{1}{FD_{k1} - FD_{k0}}\right)$.

As it stands, in this second method we tacitly attribute changes in a link's congestion level to additional PCUs (passenger-car-units) on the very same link. By adding more PCUs to every link, travel demand is decreased uniformly. However, the flow on different links varies to different degrees depending on redistribution of the traffic in the network.

An important advantage of method 2 is that, unlike method 1, it accounts for the interaction of the speeds and traffic flows on the network. In fact, it accounts for all the network effects and is very cost-effective since obtaining a full set of MCC using this method requires only one model run. Unfortunately, while method 2 still does take into account the effects of congestion on one link on congestion on other links of the network, it is not exact. For example, if we just consider two links on the network — k and n —then the overall network effect would include the changes in speeds on both links due to changes in flow on link k as well as changes in speeds on both links due to changes in flow on link n . However, this method attributes *all* changes in speed on link k to changes in flow on link k , and the same is true for link n . Furthermore, it is not possible to uncouple those effects using method 2. Therefore, to accurately account for all congestion redistribution, we have to turn to method 3.

Method 3

In order to simulate the overall network effects of a unitary change in flow on a single link, we need to be able to change demand on the link in question only and to keep all other demands intact. However, since travel demand is defined by origin-destination pairs, it is impossible to do so. Therefore, instead of changing demand, we simulate the impact of a unitary PCU-mile increase on a link by reducing the capacity on that link by one PCU-mile and rerunning START with the reduced supply. Suppose a network contains a total of N links. Then, the marginal congestion cost per mile on a link k correctly accounting for the full effects on all other links would be

$$MCC_k^3 = \sum_{n=1}^N \left(\frac{1}{S_{n1}} - \frac{1}{S_{n0}} \right) \times \left(\frac{FD_{n0} + FD_{n1}}{2} \right) \times VOT_n, \quad (5)$$

where S_{n1} and FD_{n1} are speeds and flows on a link n resulting from a decrease in road supply on link k by 1 PCU-mile. As we stated in the beginning of this section, although method 3 provides

the most accurate results, it is also the costliest of the three since a computation of MCC for each link requires an additional run. However, on average, methods 2 and 3 should produce the same results because both of them include own-link effects as well as network effects, but attribute them to different links. Therefore, since running model 3 for each link of the network is prohibitively costly, we will use the results obtained using method 2 as a proxy for the overall results that would be obtained by method 3.

At the same time, since method 2 is inexact in application to individual links, it is important to see to what extent the results yielded by the three methods differ quantitatively to judge if and under what conditions using methods 1 and 2 achieves satisfactory results.

4. RESULTS

Comparison of Methods

The quantitative results of this study suggest that under different circumstances it may be appropriate to use marginal congestion costs obtained using methods 1 and 2 when the goal is to obtain average marginal congestion costs. For example, if the policy options are limited to spatially uniform ones (a fuel tax, for example), policymakers only need to know an average value for the entire metro area. In our calculations, the average MCC weighted by link flow computed using methods 1 and 2 come out to be very similar. For the morning peak, the values are \$0.7940 and \$0.7613 correspondingly, and for the afternoon peak they are \$1.101 and \$1.170.

At the same time, individual links on the network may differ greatly. For example, on the inbound link of downtown DC, in the morning, MCC per mile of travel measured on the link without network effects seems to be quite high (\$0.931), but when network effects are factored in (method 2), the MCC per mile is reduced to much more modest \$0.207. On the other hand, on a segment of the Beltway's inner loop in Northern Prince George's County in the morning, the MCC computed on the link alone using method 1 comes out to only \$0.558, but when the network effects are included, it is greatly magnified to \$4.342 (see Tables 3 and 4). While we do not intend to explain in detail why methods 1 and 2 yield such different results in the case of each individual link, we do want to mention that it primarily depends on the structure of alternative routes available to travelers in a particular area and whether those alternatives are relatively cost-effective.

The degree of variation between the MCC computed using methods 1 and 2 can be clearly seen in the comparison between Figures 2 and 3, where congestion costs are averaged by zone. According to these figures, judged by method 1, the entire area inside the Beltway seems to be very congested, but according to method 2, DC, and the suburbs inside the Beltway face a comparatively lighter congestion burden.

Before we go on to compare the results of method 3 with those of two other methods, it is useful to decompose the MCC computed using method 3 into two components:

$$MCC_k^3 = \left(\frac{1}{S_{k1}} + \frac{1}{S_{k0}} \right) \times \left(\frac{FD_{k0} + FD_{k1}}{2} \right) \times VOT_k + \sum_{n \neq k} \left(\frac{1}{S_{n1}} - \frac{1}{S_{n0}} \right) \times \left(\frac{FD_{n0} + FD_{n1}}{2} \right) \times VOT_n \quad (5')$$

The first component represents the own-link effect, that is, the marginal congestion costs on the link k resulting from an initial unitary increase in flow on the same link. The second component is the sum of the effects of the initial unitary increase in flow on link k on all other links in the network. Cumulatively these effects can be viewed as the true network effects.

From Table 3 one can make several interesting observations regarding these two components. First, the MCC computed using method 2 and the own-link effect computed using method 3 show very close results. At the same time, for most links, the total effect computed using method 3 is smaller than the own-link effect alone. Therefore, although we have results based on method 3 only for selected number of links, we hypothesize that the results computed using method 3 would on aggregate show a lower average MCC than those computed by methods 1 and 2.

Congestion Spillovers over the Road Network

The results obtained using method 3 provide an opportunity to learn to what extent a real transportation network serves as a conductor of congestion. In particular, it is interesting to see how strong the effects on other links are and how far from the point of impact they can be felt.

Looking at the Table 5, we conclude that the degree to which travel conditions on one link affect others greatly depends on whether the affected link turns out to be a “bottleneck” on the network. In other words, if a link happens to be more heavily used by travelers along a large number of routes (such as links 65 and 244), a shock to that link would result in impact on

numerous other links. On the other hand, if a link primarily serves local travelers and is not very congested initially (link 126), only a limited number of other links turn out to be affected.

At first it might seem counterintuitive that an increase in the costs of travel on one link leads to a *decrease* in the level of congestion on a number of other links. Perhaps, the major factor contributing to this is the *bundling effect*. By bundling effect we mean the effect resulting from the fact that when travelers make their transportation decisions, they choose entire routes rather than individual links. Therefore, transportation links that are often used as parts of the same route become closely related. In this example, after the initial increase in MCC on the impacted link, some travelers will switch to other routes. Therefore, the number of travelers on routes containing the impacted link would have decreased and, consequently, other links along those routes would become less congested.

It is quite interesting to see how far an initial impact on one link can travel along the urban transportation network. On Figure 4, one can observe that the adjacent areas tend to experience a slight congestion relief, while nonnegligible effects of initial increase in congestion in the northern part of Montgomery County can be felt as far away as in the areas south of the Beltway.

Implications for Congestion Pricing

The results presented above provide a few lessons on design of congestion pricing schemes. First of all, using non-network marginal congestion costs as a basis for estimating appropriate levels of congestion tolls may be very inaccurate since they are not highly correlated with network-based marginal congestion costs. Secondly, marginal congestion costs vary considerably link-by-link and therefore setting uniform tolls for all roads during rush hour would result in an outcome significantly different from the first-best. Another conjecture is that pricing individual links on the network, while keeping the rest of the network un-priced would result in significant congestion spillovers in a large part of the metro area.

5. CONCLUSIONS

This paper investigates the question of whether marginal congestion costs computed on a network using a realistic urban-scale model significantly differ from the marginal congestion costs computed based on individual congestion functions on each link. The strategic

transportation planning model START was calibrated for the Washington, DC, metropolitan area and used to simulate the impact of changes in flow on network links.

We have concluded that a straightforward link-by-link method can be utilized to compute the region-wide average levels of marginal congestion costs. Such average values could be applied to estimate spatially aggregate policies—such as fuel tax or even cordon toll (19). However, this method may not be appropriate for designing finer policies such as geographically differentiated congestion tolls. Also, we observe that the DC area urban network is a good conductor of traffic congestion. Therefore, policymakers should be careful with implementation of transportation pricing policies in one part of the urban area without taking into account probable changes in congestion in its other parts.

In the future it would be interesting to see if the results of this paper can be corroborated by either using different models or applying START to other urban areas. In addition, theoretically appealing marginal congestion costs containing networks effects could potentially be applied to design first-best marginal pricing schemes on urban transportation networks.

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TABLE 1. Beta Coefficient Values

	<i>HBW</i>	<i>HBS</i>	<i>HBO</i>	<i>NHBW</i>	<i>NHBO</i>
Trip generation	−0.0045	−0.005	−0.0045	−0.0045	−0.0045
Destination choice	−0.02	−0.05	−0.02	−0.02	−0.02
Mode choice	−0.05	−0.05	−0.05	−0.05	−0.05
Time choice	−0.05	−0.1	−0.09	−0.1	−0.1
Route choice	−0.185	−0.185	−0.185	−0.185	−0.185

TABLE 2. DC, Region Trips Demand by Purpose and Time Period

	<i>HBW</i>	<i>HBS</i>	<i>HBO</i>	<i>NHBW</i>	<i>NHBO</i>
Morning peak	1,810.56	636.68	2,660.08	61.83	97.33
Afternoon peak	1,830.41	1,374.02	3,868.36	61.83	156.69
Off-peak	1,588.77	2,314.05	4,171.04	30.92	1,017.99
Note: Units in thousands of trips.					

TABLE 3. Morning Marginal Congestion Costs from 3 Methods on Selected Links

<i>Selected link</i>	<i>Zone</i>	<i>Method 1</i>	<i>Method 2</i>	<i>Method 3</i>		
				<i>Own-link</i>	<i>Total</i>	<i>Percentage</i>
D.C. downtown	1	\$0.931	\$0.207	\$0.204	\$0.3042	114.9%
I-270 Montgomery Co. S-bound	7	5.938	5.663	4.592	4.1301	89.9%
Inner Beltway Montgomery Co.	8	0.136	1.291	1.305	1.2935	99.1%
Northeast Montgomery Co.	9	0.137	1.716	1.779	1.7043	95.8%
Inner Beltway N. Prince George's	10	0.558	4.342	3.733	3.9364	105.4%
US-50 Prince George's W-bound	12	0.311	0.391	2.079	0.1586	7.6%
Anne Arundel Co.	17	0.190	0.387	0.378	0.3822	101.0%
Eastern Fairfax Co.	24	0.764	0.349	0.353	0.3419	96.8%
Outer Beltway NE Fairfax Co.	25	0.367	0.140	0.141	0.1755	124.1%
Stafford/Fredericksburg North	32	0.229	1.278	1.228	1.0309	84.0%
I-95 in Zone 32 N-bound	32	0.360	0.196	0.198	0.2405	121.7%
Note: Marginal cost values in 2000 dollars.						

TABLE 4. Evening Marginal Congestion Costs from 3 Methods on Selected Links

<i>Selected link</i>	<i>Zone</i>	<i>Method 1</i>	<i>Method 2</i>	<i>Method 3</i>		
				<i>Own-link</i>	<i>Total</i>	<i>Percentage</i>
D.C. downtown	1	\$1.263	\$0.283	\$0.279	0.290	104.1%
I-270 Montgomery Co. S-bound	7	1.491	2.235	3.365	2.773	82.4%
Inner Beltway Montgomery Co.	8	0.151	1.652	1.659	1.574	94.9%
Northeast Montgomery Co.	9	0.331	2.520	2.612	0.325	12.4%
Inner Beltway N. Prince George's	10	0.490	3.954	4.175	3.956	94.8%
US-50 Prince George's W-bound	12	0.166	0.175	0.539	0.027	5.1%
Anne Arundel Co.	17	0.183	0.373	0.359	0.325	90.5%
Eastern Fairfax Co.	24	0.761	0.347	0.352	0.339	96.4%
Outer Beltway NE Fairfax Co.	25	0.347	0.129	0.130	0.129	99.4%
Stafford/Fredericksburg North	32	0.239	1.493	1.502	1.500	99.9%
I-95 in Zone 32 N-bound	32	0.300	0.161	0.158	0.135	85.5%
Note: Marginal cost values in 2000 dollars.						

TABLE 5. Distribution of Marginal Congestion Costs Using Method 3

<i>Link Name</i>	<i>Zone</i>	<i>Link</i>	<i>Montgomery Northeast (zone 9, link 65)</i>	<i>Anne Arundel (zone 17, link 126)</i>	<i>Stafford North (zone 32, link 244)</i>
Inner Beltway Montgomery SW	5	32	0.001		
Outer Beltway Montgomery SW	5	33	0.002		
West Montgomery Co. arterials	7	45	-0.002		
I-270 Montgomery Co.	7	46	-0.006		-0.004
I-270 Montgomery Co.	7	47	-0.020	-0.007	
East Montgomery Co. inbound	8	52	-0.028	0.005	
East Montgomery Co. outbound	8	53	-0.005		
East Montgomery Co. arterials	8	54	-0.002	0.002	
Inner Beltway E Montgomery	8	57	0.001		
Outer Beltway E Montgomery	8	58	0.003		
NE Montgomery Co. inbound	9	63	-0.002		
NE Montgomery Co. outbound	9	64	-0.005		
NE Montgomery Co. arterials	9	65	1.368		
NW Prince George's arterials	10	71			0.001
Inner Beltway Prince George's	10	82	0.003		
I-95 north of Beltway	12	101	0.008		0.001
SE Prince George's arterials	13	110	0.003		
Frederick Co. inbound	14	113	-0.011	-0.006	
Frederick Co. outbound	14	114		0.005	0.005
Frederick Co. arterials	14	115	0.007		
Anne Arundel Co. inbound	17	126		0.291	
Charles Co. inbound	19	134			-0.003
Charles Co. outbound	19	135			-0.002
Inner Beltway NE Fairfax Co.	25	190			-0.001
S Fairfax Co. inbound	26	194	0.003		-0.005
Inner I-95 S Fairfax Co.	26	197			-0.005
Outer I-95 S Fairfax Co.	26	198			0.003
NW Fairfax Co. inbound	27	207	-0.002		
I-66 NW Fairfax Co. W-bound	27	213			0.001
E Loudon Co. inbound	28	222	0.001	0.001	
W Loudon Co. arterials	29	231	-0.002		
S Prince William Co. inbound	30	232			-0.141
S Prince William Co. arterials	30	234			-0.027
I-95 S Prince William Co. N-bound	30	235		0.002	0.061
I-95 S Prince William Co. S-bound	30	236	-0.003		-0.003
N. Stafford Co. inbound	32	244			0.944
N. Stafford Co. outbound	32	245			-0.008
N. Stafford Co. arterials	32	246			-0.021

<i>Link Name</i>	<i>Zone</i>	<i>Link</i>	<i>Montgomery Northeast (zone 9, link 65)</i>	<i>Anne Arundel (zone 17, link 126)</i>	<i>Stafford North (zone 32, link 244)</i>
I-95 Stafford Co. N-bound	32	247			0.004
Fauquier Co. arterials	33	251			−0.003
S. Stafford Co. inbound	35	257			−0.002
S. Stafford Co. arterials	35	259			−0.002
<i>Total marginal congestion cost</i>			<i>1.311</i>	<i>0.294</i>	<i>0.793</i>

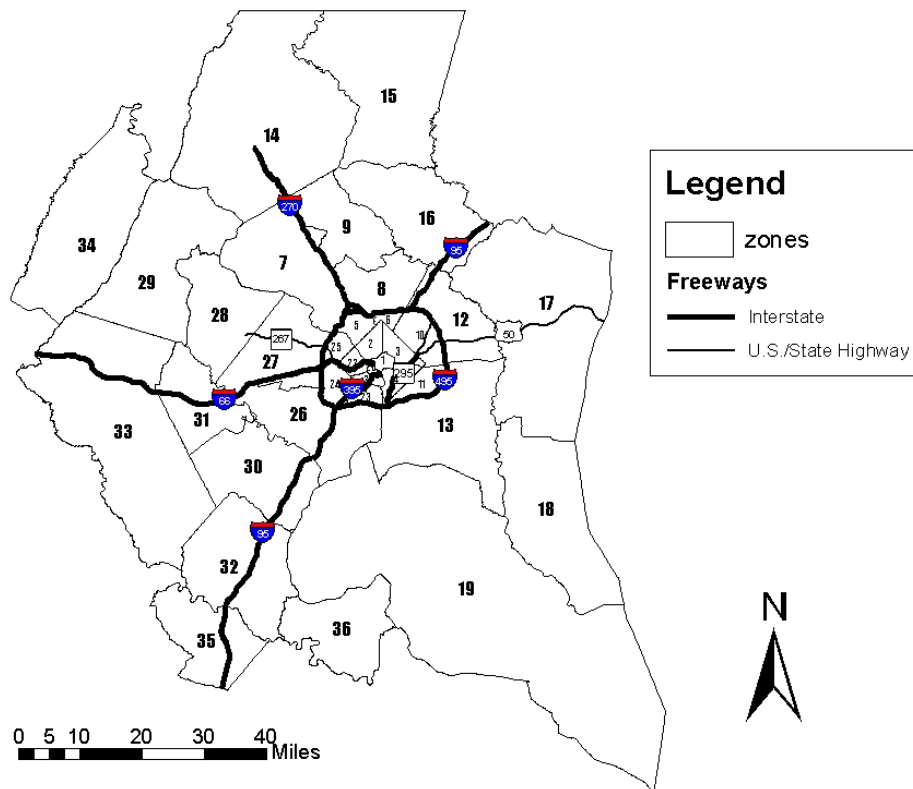
FIGURE 1. START Modeling Region with All Special Links

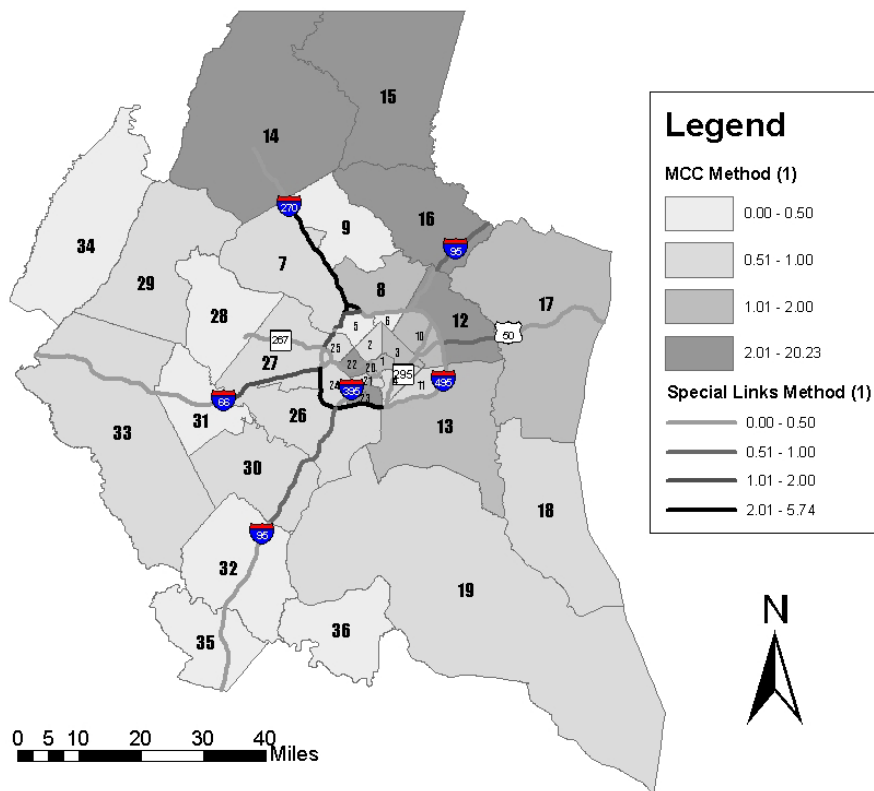
FIGURE 2. Zonal Average Marginal Congestion Cost Calculated Using Method 1

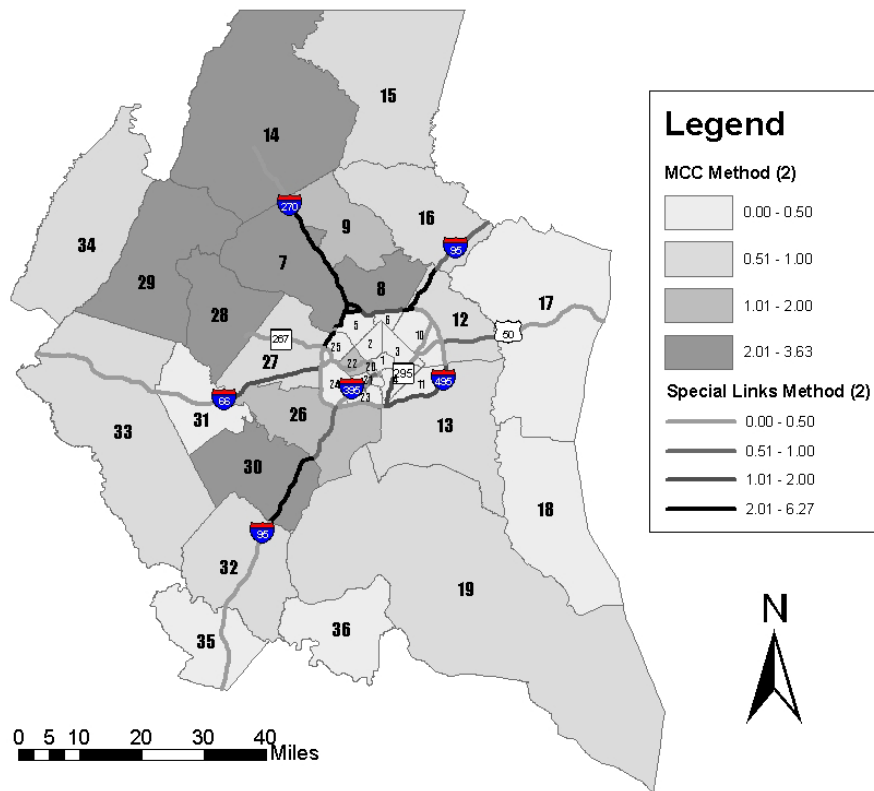
FIGURE 3. Zonal Average Marginal Congestion Cost Calculated Using Method 2

FIGURE 4. Geographic Distribution of Method 3 Marginal Congestion Costs for Link 65