DEPARTMENT OF TRANSPORTATION
UNITED STATES OF AMERICA

Assessing the Full Costs of Congestion on Surface Transportation Systems and Reducing Them through Pricing

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Prepared by HDR for the Office of Economic and Strategic Analysis, U.S. Department of Transportation

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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EXECUTIVE SUMMARY

The nation's transportation network is an essential component of economic growth and prosperity. In particular, roads and highways represent a vital element for automobile and freight truck transportation. Consequently, keeping traffic moving as efficiently as possible is an important contributor to the health of the economy. However, with demand for the existing surface transportation infrastructure exceeding capacity, delays in travel time is only one of the many symptoms of congestion. The effects of congestion are widespread and in addition to delays in travel time, stop-and-go traffic results in increased fuel consumption and to lost productivity and efficiency.

It is therefore important to understand the magnitude of the congestion problem and its implications on the national economy as a first step toward identifying possible remedies. In order to allocate the limited roadway capacity among users, congestion pricing is frequently considered an efficient management technique, whereby roadway users are forced to choose between their need to travel and their willingness to pay to travel on certain portions of the road or at certain, high-demand times.

While a number of studies have investigated the costs associated with road congestion, most have focused on two main issues, namely increased travel time and added fuel costs. While these two direct costs are understandably significant components, congestion generates a host of other costs that add to the extent of problem. Potential costs of congestion that have received much less attention are those related to increased unreliability, emissions and environmental damage, excess vehicle operating costs, loss of productivity, increased inventory costs as well as higher frequency of cargo delays.

Even for the more commonly measured costs, considerable uncertainty surrounds their magnitudes. In measuring the value of time, for example, it is important to differentiate among the many regions and urban centers being considered, for the value of time varies considerably across different areas. Furthermore, when accounting for congestion delay to truck movements, the inclusion of cargo costs in addition to labor and vehicle operating costs is important. Additionally, while the time cost component is a major factor in determining congestion pricing levels, the inclusion of additional factors such as vehicle operating costs and reliability could enhance the accuracy of pricing and consequently maximizing social welfare.

Figure ES1: Total Annual Congestion Costs by Urban Area Size ($b) (Total: $85.4 billion)

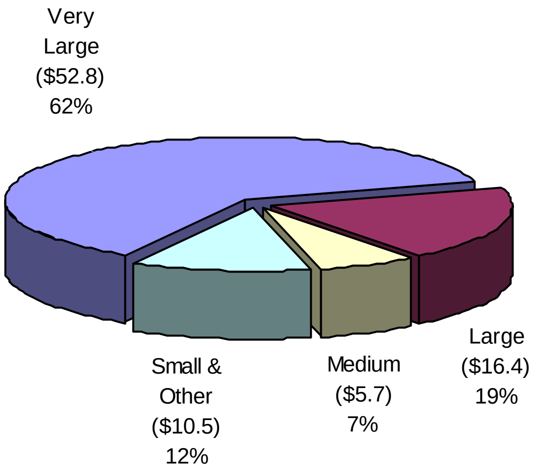
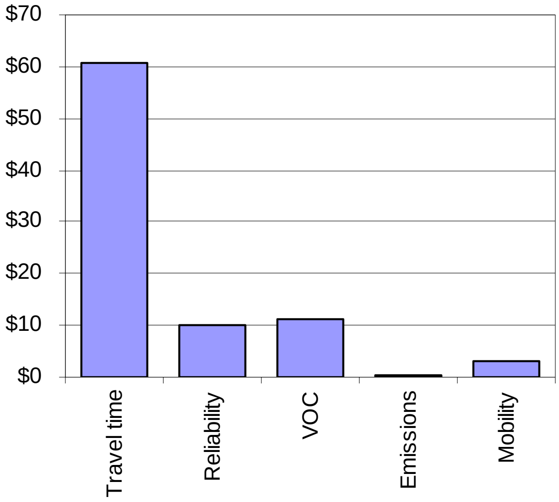
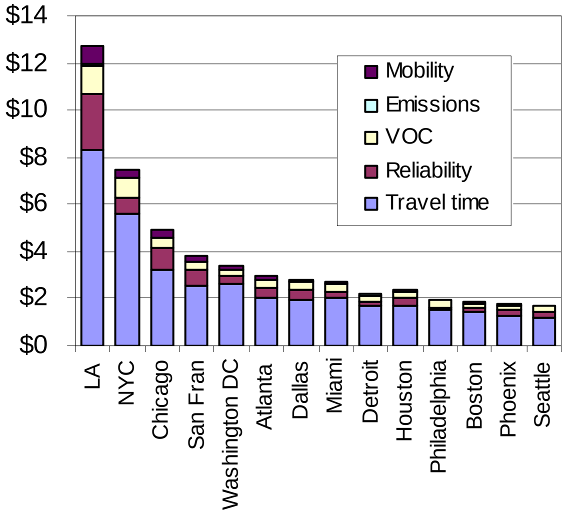


Figure ES2: Annual Total Congestion Costs by Component ($b)



In this regard, HDR was tasked to review the extensive literature on congestion and examine the costs associated with surface transportation congestion, mainly on roads and highways, in addition to estimating the welfare gains from a comprehensive congestion pricing scheme on the nation's urban roadways. Congestion on the urban road network in the United States is estimated to cost the nation about $85 billion per year, the equivalent of $763 per commuter annually. To put this number in perspective, a saving of that amount in what Americans spent at the pump on gasoline in 2005 would have reduced the total national gasoline bill by over 40 percent. In addition, the 14 largest metropolitan areas investigated in this report bore over 62 percent of costs associated with road congestion (Figure ES1).

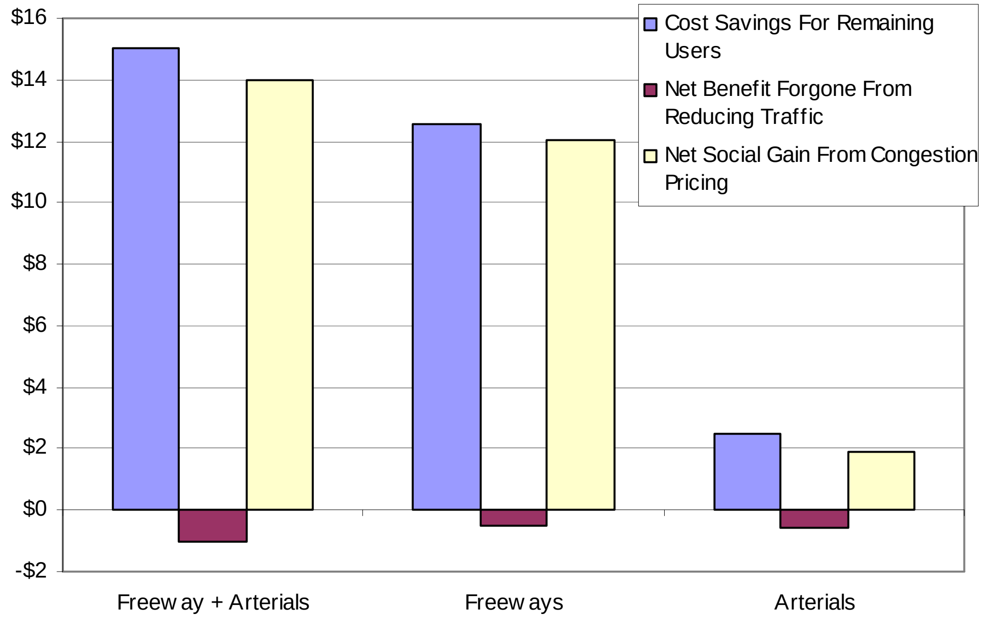
Figure ES3: Annual Congestion Costs Breakdown by Major Urban Area and Cost Component ($b)



Travel time costs, which represent the opportunity costs of wasted time on congested roads, is the major contributor to the overall cost of congestion, accounting for 71 percent of the total ($60.6 billion annually). Meanwhile, reliability costs are estimated to contribute about $10.1 billion to the overall cost of congestion. Vehicle operating costs are estimated to add $11.2 billion annually based on the assumption of a $2 per gallon gasoline price. Other contributors to the costs of congestions include the loss of mobility resulting from some road users opting not to drive during peak periods in addition to vehicle emissions, which have a much smaller impact on the overall cost of congestion (Figures ES2 & ES3).

In the very large urban areas (population over one million), congestion pricing has the potential to increase the average freeway speed during peak congested periods by over 47 percent. Even for the urban areas that are simply large, the increase in average freeway speed is predicted to be 31 percent. These increases in speed would stem from an estimated 8.9 percent decline in freeway VMT during congested peak periods, for large and very large urban areas combined. For arterials, the results are likewise encouraging. Furthermore, congestion pricing on the freeways and arterials of large and very large urban areas would produce an annual welfare gain estimated at $17.6 billion or an annual average social gain of $620 and $255 per commuter in very large and large cities, respectively.

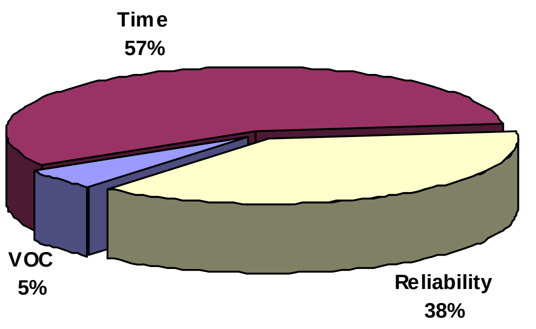
Figure ES4: Net Social Gain From Congestion Pricing, ($b)



In addition to congestion on the nation's roads and highways, other modes of surface transportation are also faced with similar limited capacity issues. Congestion problems also exist on public transit, freight rail, inland waterways and sea ports. Studying the costs of congestion and the benefit of congestion pricing on these modes of transportation is more complex due to the nature of these networks and the scarcity of data compared to the road network.

Figure ES4 displays the net social gain from congestion pricing or the difference between the total social welfare saved and the benefit forgone from the reduction in trips in the 14 largest areas. Congestion pricing on freeways and arterials results in a net social gain of almost 14 billion dollars. Of this saving, about 86 percent would arise from congestion reduction on the freeways and the rest from congestion reduction on the arterials. Although not modeled in this study, limited evidence from other studies suggests that congestion pricing confined to freeways would produce substantially smaller welfare gains. In part, this reflects that congestion would worsen on

Figure ES5: Annual Social Cost Saved From Congestion in Freeways and Arterials By Categories



some arterials, to which some motorists would divert to avoid congestion charges on the freeways. These findings underscore that policies to effectively combat road congestion should be comprehensive in their network coverage. Likewise, public policies comprehensively address congestion on the various surface transportation modes – including transit, rail, and water transportation – will be more effective than policies that only address road congestion.

Figure ES5 shows the breakdown of cost saving for remaining users by category. For both freeways and arterials travel time is largest saving realized, accounting for 57% of the cost saved on freeways and arterials by the remaining road users.

1 INTRODUCTION

The Office of the Secretary of Transportation (OST) at the United States Department of Transportation has commissioned this study to assess the cost of surface transportation congestion from a national perspective. For road travel, a number of previous reports have assessed the cost of congestion nationally or for particular areas. For the most part, however, these reports measure a circumscribed range of costs. The most widely recognized national study of road congestion costs, the Texas Transportation Institute's (TTI) Urban Mobility Report (UMR), measures only the costs in wasted time and fuel.

Potential costs of congestion that have received much less study are those relating to safety, pollution from vehicle emissions, indirect costs in reduced business productivity, vehicle operating costs other than fuel cost, and reliability of travel time. Moreover, even for the more commonly measured costs, considerable uncertainty surrounds their magnitudes. For estimating the cost of wasted time, a particular challenge is valuing the cost of an increase in time required for freight delivery. For congestion delay to truck movements, the UMR measures the resulting cost in driver labor and vehicle operation, but make no allowance for cargo-related cost.

One of the objectives of this study is to estimate the national costs of road congestion including the above-mentioned costs omitted from the UMR. That these costs are quite large is apparent from previous statistics, such as the UMR estimate for 2007 that congestion on U.S. roads consumed $78 billion in wasted time and fuel. But even without statistics, Americans understand from their everyday experiences the toll congestion is taking on their economy and society. Examples of these experiences in the Washington, D.C. area, taken from a recent newspaper article,[1] include the following:

- A Virginia-based company found that increasing congestion was making it impossible to cross the Potomac River during the workday and meet delivery deadlines. The company's owner observed that on some routes that previously accommodated 50 deliveries a day, the growth in congestion had reduced the number to 40. To deal with this problem, the company built a new $5 million warehouse in Maryland, which receives shipments from Virginia in the middle of the night for delivery to Maryland and District customers the next day.

- Fairfax County adds 20 to 30 vehicles a year to its fleet of school buses, which currently number 1,800, even during times of flat enrollment. The chief operating officer of the school system attributes this to increasing congestion on the county's roads, with routes that used to take 30 minutes now taking 50 minutes. Bus runs are scheduled increasingly early to avoid the peak morning traffic, which means high school students being dropped off as early as 6:45 a.m. for classes that start at 7:20 a.m.

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[1] Weiss, E. 2008, "Traffic Cure Worsens the Pain**:** Fleets Expand to Beat Jams but Cause Some of Their Own" Washington Post, October 6, Section A.

- For its crew of 250 technicians who travel the area's roads each day, Cox Cable uses 30 more trucks than in similar-size markets elsewhere in the country. The company's other adjustments to the Washington area's relatively severe congestion include more flexible work arrangements, such as having technicians start their work day from home, telecommuting, and alternate hours.

In other urban areas as well, road congestion has been worsening over recent decades. On a national basis, the amount of delay per peak-period traveler on urban roads jumped from 14 hours in 1990 to 38 hours in 2005. This worsening of an already serious problem has generated interest in potential solutions, including that of congestion pricing. Also contributing to the interest in congestion pricing are fiscal and environmental concerns:

- Public funding for transportation infrastructure has been squeezed by erosion of the revenue base and rapidly escalating construction costs. Federal and state motor fuel taxes supply most of the funding for highways and some for transit, but tax rates have not kept pace with inflation. Indeed, federal taxes have remained at a little over18 cents per gallon on gasoline and 24 cents on diesel fuel since 1993. Further eroding fuel tax revenues, recent increases in the motor fuel prices have curtailed demand. As a potential source of transportation funding, congestion pricing may be politically more palatable than raising fuel taxes.

- Pressure is mounting in the U.S. for concerted action to curb greenhouse gas emissions, including measures to reduce motor vehicle emissions. Heavy congestion makes vehicle speeds more variable, which leads to higher levels of fuel consumption and emissions of greenhouse gases as well as some noxious pollutants.

Prediction of the welfare gains from comprehensive congestion pricing on our nation's urban roads is the other principal objective of this study. Actual experience of congestion pricing in the U.S. has been quite limited, but a few other countries have implemented a form of congestion pricing—cordon pricing—in their national capitals. In addition to summarizing the various schemes, Chapter 2 of this report reviews evidence from previous studies on the costs of road congestion and the impacts of road congestion pricing. The review informed our decisions on which components of congestion cost are feasible to estimate within the parameters of this study as well as our estimation approach, detailed in Chapter 3.

The estimation results are discussed in Chapter 4, where the national results are the sum of estimates for individual urban areas plus an aggregation of the smaller urban areas. The traffic data for the analysis came from the UMR, which in turn relied on urban area summary information from the Highway Performance Monitoring System. In principle, simulations based on detailed travel demand models for individual urban areas would produce more reliable results. Although this was not feasible for the present study, our literature review in Chapter 2 discusses the results of studies that have taken this approach. Chapter 5 examines the evidence relating to congestion pricing on the surface transportation modes besides roads such as transit, freight rail, and water transportation.

2 LITERATURE REVIEW

This study has reviewed the extensive literature on various aspects of congestion, congestion costs, methods of cost evaluation, and congestion pricing. The available literature covers a variety of modes, but focuses in particular on roadway travel (both passenger vehicles and commercial trucks). The literature assessing congestion and congestion costs for other modes of transportation is comparatively scarce. Available literature describes approaches to estimating a variety of costs of delay, much of which focuses on time costs, fuel costs, and to a lesser extent other vehicle operating costs.

In addition to the literature on congestion costs, this review also encompasses studies seeking to identify the effect of pricing policies on congestion levels and associated cost effects. Furthermore, this chapter attempts to identify studies that provide data and assess their quality in order to determine if they might be used in this study to comprehensively measure the effects of congestion. The chapter also assesses the characteristics and limitations of the Texas Transportation Institute's (TTI) Urban Mobility Report (UMR) and the associated data sets. The goal of the literature review is the identification of effective, replicable approaches to comprehensively assess the level and cost of congestion nationwide as well as pricing methods.

2.1 Studies of Congestion Costs

This section contains a review of past studies, reports, and other sources that have examined the inefficiencies in the national economy resulting from congestion. The objective is to discuss and recommend the full range of costs that will be analyzed and estimated in this project. Most estimates of congestion costs (both nationwide and for individual metropolitan regions) have focused on direct costs, such as loss of time and excess fuel costs accruing to auto users. However, these direct costs are only a subset of the total costs associated with traffic congestion that this report will attempt to quantify.

2.1.1 Cost Categories

The costs of traffic congestion have received increasing attention in recent years. Of primary concern are the marginal costs of congestion above and beyond the "optimal level" of travel where the social marginal cost intersects with the demand curve. These costs comprise the deadweight loss (DWL) associated with a socially inefficient level of traffic and the concomitant congestion. As such, these costs could be mitigated by implementing marginal cost pricing. A study by Small and Verhoef (2007) contains recent estimates of such private and social average and marginal costs of travel (O&M, vehicle capital, travel time, schedule delay and unreliability, accidents, government services, and environmental externalities) on a per vehicle-mile basis.

In considering congestion, there are three aspects of delays to consider:

- Expected delays: delays that factor *a priori* into trip makers' decision process;
- Unexpected delays: delays that, by definition, do not enter the decision making process (and are thus more costly than expected delays); and
- Variability in delays: due to variance in the duration/frequency of both expected and unexpected delays.

The most widely cited estimates of the cost of congestion are from the UMR. The methodology and results of this report are reviewed separately in section 2.1.2. Meanwhile, the literature review has identified ten cost components associated with traffic congestion:

1. Increased travel time

The most prominent cost of traffic congestion is the delay associated with lower travel speeds, start-and-stop traffic flow, and in extreme cases, gridlock. These delays represent an opportunity cost of time, time that could be spent both at work and for leisure. Overall, this cost category has been the most studied and the greatest consensus has been reached. An estimate of excess passenger/vehicle-hours is required, and an hourly value can be applied to estimate the cost of increased travel time.

2. Greater travel time unreliability

In addition to the increased expected duration of travel in the presence of congestion, there is also a cost to trip makers in having to leave early for a destination to account for anticipated congestion. This increased variance (i.e. unreliability) of trip times is due to the inherent uncertainty of travel times, insofar as the level of congestion is not known prior to the trip start and to the "bullwhip effect" associated with traffic queues. There is also a psychological effect associated with uncertain trip times. The cost associated with this uncertainty is often found to outweigh the direct increase in travel time associated with congestion. The uncertainty of travel times also factors into schedule delays and alternative routing requirements.

There are several types of measures of reliability:

- Statistical range methods;
- Buffer time methods;
- ''Tardy-trip'' measures; and
- Probabilistic measures.

The value of travel time reliability has received less attention than overall travel times, although literature covering this issue has increased in recent years. There is less of a consensus in valuing reliability than the magnitude of travel times. Typically this cost is indexed relative to the value of travel time.

3. Excess fuel usage

Traffic congestion leads to excess fuel usage due to two effects: 1) time spent idling in gridlock, and 2) the start-and-stop nature of travel in congested conditions, as travel at a steady speed uses fuel at a lower rate. Qualitatively there is a consistent recognition of this effect, but there are not very many empirical estimates of its effect. This cost has increased in importance during the recent rise in gasoline prices. HDR's Strategic Highway Decision Support Tool (HighwayDEC) model illustrates the typical relation between fuel consumption and travel speeds. Since congestion occurs primarily in urban regions (where the curve is downward sloping), increased congestion results in increased fuel costs. Estimates of congested vs. "optimal" speeds are thus required, which can then be used to compute the excess volume of fuel consumed and the resulting excess cost.

4. Increased emissions and environmental damage

The more time spent on the road, the greater are the vehicle emissions and other negative environmental externalities, such as fuel run-off into water sources, with vehicle emissions increasing due to excessive delays, queue formation, and speed change cycles. At the local level, emissions from motor vehicles damage buildings, and in high concentrations, emissions are injurious to health. At the regional and global level, vehicle exhausts contribute to acid rain and global warming. Furthermore, emissions seem to be proportional to fuel usage, and are often measured on the basis of fuel volume consumed. It is assumed that the amount of pollutant released during motor vehicle operation is proportional with the amount of fuel consumed.

5. Higher accident rates and safety cost

Our literature review revealed the effect of congestion on road safety to be empirically hard to determine, even whether the effect is positive or negative. Overall, evidence suggests that crashes are more frequent, but less severe under congested conditions. The latter effect reflects that crash severity increases exponentially with vehicle speed. One indication of this is that the high gas prices through the first half of 2008 were reducing accidents, in part because drivers are reducing speed to save on gas.[2] Another indication comes from studies of the effects of changes in speed limits on road accident rates. Following 1987 federal legislation that permitted states to raise the speed limit on rural Interstate highways from 55 to 65 miles per hour (mph), states that exercised this option saw the fatality rates on these facilities increase by 35 percent on average (Ashenfelter and Greenstone 2004). For urban roads, evidence from other studies suggests that higher speed limits also increase road fatality rates (Keeler 1994).

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[2] http://www.statesman.com/search/content/shared-gen/ap/Health_Medical/Auto_Deaths_Gas_Prices.html

McFarland and Chui, back in 1987, noted that data on accident frequency at various speeds are "practically non-existent", apart from the data on fatal accidents on rural highways from Solomon (1964). In view of the tremendous strides in vehicle safety technology in the decades following their collection, those data are clearly obsolete by now and we have uncovered little in the way of more recent data that could be used for the present study.

The benefit-cost models developed thus far, including Highway DEC and Surface Transportation Efficiency Analysis Model (STEAM), do not include relationships between average speed and accident rates, such as would be needed to estimate the impacts of congestion. The Highway Economic Requirements System (HERS) model contains equations predicting the frequency of crashes by type of road, and the equation for urban freeways predicts frequency to increase with the volume-to-capacity ratio, which means that more congestion leads to more crashes. On the other hand, the numbers of fatalities and non-fatal injuries per crash are treated as constant, contrary to the reality that high-speed collisions are more likely to be fatal. Thus, the HERS model does not provide a basis for estimating the impact of congestion on accidents, even for urban expressways.

A recent review of the evidence on the relationship between road congestion and crashes found that:

> "Little research is available on the relationship between crashes and congestion as it relates to the performance of the transportation system….Although the evidence is mixed, less congested roadways appear to lead to fewer, but more severe, crashes. This relationship is especially strong in the case of crash severity; that is, more severe crashes occur on less congested roadways due in large part to faster speeds. On more congested roadways, the number of crashes may increase, but they may be primarily minor crashes reflecting the increased weaving and access/egress movements that often occur on congested road segments. *(Cambridge Systematics 2008, pp. 2-2 and 2-3).*

Moreover, with respect to the significant portion of congestion that has non-recurrent causes, to think of accident costs as a product of congestion is clearly problematic, since traffic accidents are more the cause than the result. In view of this and other limitations of the available evidence, the costs of road congestion in accidents are not measured in this report.

6. More wear and tear on vehicles and higher maintenance costs

In addition to time costs and excess fuel consumption, congestion also increases the wear-and-tear on vehicles. The start-and-stop nature of travel in congested conditions entails more strain on vehicles, primarily braking and engine systems. However, it is difficult to find empirical estimates of this cost in the literature. In this regard, this study calculated the effects of delay on other components of vehicle operating costs: motor oil, tires, maintenance, and depreciation.

7. Excess vehicle operating costs

This cost category – for non-commercial vehicles – is difficult to disentangle from wear and tear on vehicles and higher maintenance costs (i.e. to avoid double-counting). For commercial vehicles, these costs are outlined below.

8. Loss of productivity

The impact of traffic congestion on productivity – an indirect cost – has received relatively little attention compared to direct costs. Some of these impacts can be modeled within standard benefit-cost frameworks, which largely rely on the paradigm of an economy featuring perfect competition. An example is the cost to businesses from being induced by congestion to alter their choices of input suppliers—costs such as these can be captured by the induced traffic component in standard calculations of consumer surplus (the approach taken in this report, Chapter 3). Other potential productivity impacts of congestion that have been mentioned, such as loss of positive externalities from agglomeration, can only be analyzed within a framework that models imperfect competition (Luskin 1999). Within this category, the impact that has attracted the most attention is the potential erosion of quasi-monopoly power that occurs when transport costs fall, exposing local producers to greater competition from outside. Unfortunately, modeling of such effects has not advanced to a stage where results can inform the estimation of the costs of road congestion; hence, the effects associated with imperfect competition are not considered in this report.

Studies that use conventional frameworks (without modeling imperfect competition) to estimate the productivity costs of congestion are likely to produce estimates that are small compared to the direct costs of congestion. Prominent among these studies is the National Cooperative Highway Research Program (NCHRP) report by Weissbrod, Vary, and Treyz (2001). Using the Chicago and Philadelphia metropolitan areas for case study, the researchers estimated the productivity gains that would result from several hypothetical scenarios where road travel times are reduced. One of the focuses of this study was the impacts of such reductions on labor cost. First, the study estimated the direct reduction in labor cost assuming no change in the pattern of commuting by place of work and place of residence. For a 10 percent across-the-board reduction in travel times in the Chicago area, that estimate turned out at 0.419 percent, assuming that half of any reduction in commuting cost gets passed on to employers through wage reductions (from Table 6.3 in the NCHRP report). This pass-through assumption was based on a review of relevant evidence.

Next, the study estimated the gain in labor productivity that would result from better matches of employers and workers: The idea is that some workers previously deterred by the travel time to workplaces that would otherwise be a good match for them now take advantage of these job opportunities. Assuming that half of the gain in labor productivity is retained by the employers (rather than passed on to the workers through higher wages), inclusion of this productivity gain increased the overall reduction in labor cost to an estimated 0.423 percent. Thus, allowing for the productivity effect increases the estimated cost savings by slightly under 1.0 percent (≈ .0419/0.423).

The other focus of the NCHRP study was on the costs of freight movements and business travel. Again, they estimated the direct cost savings from the hypothetical reductions in road travel times, and then the additional cost savings from the productivity gain. Analogously to the commuting scenario, the productivity gain results from better matches between customers and suppliers – for example, a business switching to a more distant, but now more accessible, supplier of some commodity. As in the results for the commuting scenarios, however, the productivity gain is quite small compared to the direct cost savings. For the assumed 10 percent across-the-board reduction in travel times in the Chicago area, the estimated impacts are cost declines of 0.0385 percent and 0.0383 percent, respectively (NCHRP report Table 5.4). Thus, the productivity gain accounted for less than 1.0 percent of the total savings.

9. Increased inventory costs

In order to accommodate for longer travel times, larger stocks of inventory are required, and larger buffer stocks are also necessary to accommodate increased variability of travel time. This unreliability is often found to entail a higher cost than the total travel time itself; primarily due to the requirement of buffer stock and the incidence of "stock out" costs. Along with the impact of congestion on productivity, relatively little attention has been paid to the impact on inventory costs, though this has increased in recent years with an increased focus on efficient supply chain management. One difficulty may be avoiding double-counting the cost of inventory with loss of productivity and cargo delays.

10. Higher frequency of cargo delays

Compared to the value of time for passenger travel, relatively little attention has been paid to the value of time of freight movement. These costs are directly intertwined with the costs of inventory. Furthermore, there are costs associated with uncertainty of shipment arrivals, which can have severe repercussions for supply chain management (which again leads to lower productivity). An additional cost is for perishable goods. As with the other "business-related" indirect costs of congestion, there are relatively few empirical valuations to use as a reference point. Chapter 3 of this report reviews this evidence in deriving an average value of time for truck travel time.

Among these relative few are the valuations in Winston and Langer (2006), which estimated the national cost of congestion on U.S. roads. The estimation of the cost from slower delivery of cargo, or the "cost to firms" as the study termed it, depended on daily discount rates derived from a quite dated econometric analysis of freight mode choice (Winston 1981). The cargo-related cost was calculated for each broad category of cargo as the daily discount rate times the average value per truck payloads. At the daily discount rates used—15 percent for perishable commodities, 5 percent for bulk commodities, and 10 percent for other commodities— these costs are on the high side.

Based on information provided in the technical documentation for the HERS-ST model (FHWA 2005), the payloads of five-axle combination trucks had an average value of about $61,000 in 2005. At this value, the daily discount rates used by Winston and

Langer imply that each vehicle hour of congestion delay imposes cargo-related costs of between $128 (bulk cargo) and $384 (perishables). As will emerge from Chapter 4, these estimates are quite high compared to those used in most other studies and models, even compared to estimates that include the costs of truck labor and vehicle operation. To some extent, the difference could be attributed to the cost of unexpected delay, which Winston and Langer see their discount rates as including. We prefer, however, to clearly separate the cost of expected delay from the cost of unreliability.

2.1.2 Review of the Urban Mobility Report (UMR)

The Texas Transportation Institute (TTI) publishes the Urban Mobility Report (UMR) which profiles road congestion for 85 urbanized areas. The latest report (Schrank & Lomax 2007) also includes aggregate estimates for additional 352 urbanized areas that are mostly smaller with lower levels of congestion. The UMR's usage of the "urbanized area" as the unit of analysis stems from its reliance on data from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System (HPMS) that are provided for urbanized areas rather than metropolitan areas. An "urbanized area" is a U.S. Population census construct that delimits a relatively densely populated core within a metropolitan area. In Chicago, for example, the urbanized area covers 2,730 square miles and had 7.7 million residents in 2000, while the metropolitan area covers 3,749 square miles in Northeastern Illinois and had 8.15 million residents in 2000. Because the urbanized area contains the vast majority of the population and roads in the outlying areas are relatively uncongested, total hours of congestion delay would be only slightly larger for the metropolitan than for the urbanized area.

The network coverage of the UMR is based on the FHWA highway classification, and excludes collectors and local roads. The report analyzes congestion that occurs on arterial highways, which it differentiates between "freeways" – the Interstate system and functionally similar highways – and "arterials", which comprise all arterials other than freeways. Although the proportion of congestion delay that occurs on the arterials would vary among urbanized areas, the proportion can be assumed quite high as a rule. The Metropolitan Planning Organization (MPO) for New York City and the outlying counties estimated that of the congestion delay on the roads in its jurisdiction, 94 percent occurs on the arterials.

2.1.2.1 Data Sources

The HPMS is the primary source of data for the UMR. The HPMS includes data on traffic volumes and highway geometry, among other things, for a large sample of highway sections for each state. The sampling procedures that the FHWA requires the states to follow are designed to produce statistically valid estimates for each urbanized area, with a somewhat level of precision for larger areas (populations over 200,000). From the target levels of precision, it is not possible to calculate standard errors on the particular statistics that the UMR derives from the HPMS data.

The use of stratified random sampling for the HPMS helps ensure that the sample for each stratum (e.g., traffic volume band) is representative. On the other hand, this report's analysis of HPMS sample data for Minnesota revealed a substantial under-representation of off-system highway sections. Since this does not appear to be explained by the stratified design, it suggests that the Minnesota Department of Transportation may be over-sampling the on-system sections, perhaps because data are easier to obtain for them than for sections under local government control. In addition, the chief modeler at the Chicago MPO expressed concerns about the representativeness of the HPMS sample for the Chicago urbanized area.

At least in the larger metropolitan areas, the MPO databases provide more information on the road network than does the HPMS sample and thus should be able to support a more accurate analysis of the congestion problem. However, the advantage of the UMR estimates based on the HPMS sample is a consistent measurement across areas.

2.1.2.2 Estimation of the Amount of Congestion Delay

The UMR includes in its estimate of congestion delay the loss of travel time due to traffic incidents (collisions or disabled vehicles). The approach is to first estimate the amount of recurrent delay which occurs in the absence of such incidents – this delay simply results from traffic volume straining the capacity of the road network. The amount of recurrent delay is then multiplied by a ratio to factor in incident delay. For arterials, the ratio equals 1.1; for freeways, it varies across urbanized areas from 0.7 to 2.5, with a tendency to be higher in smaller cities. The UMR uses a methodology developed by the FHWA to derive these factors. Overall, FHWA estimates that 25 percent of highway congestion is incident-related.

The UMR analysis of congestion focuses on the peak morning and afternoon periods during the workweek (Monday through Friday). Estimates per workday are annualized assuming 250 working days per year, which allows for holidays. The morning and afternoon peak periods are defined as 6-10 a.m. and 3-7 p.m., and are combined in the analysis into an eight hour "peak period".

Based on an estimate for which no source is provided, the UMR assumes that the peak period accounts for 50% of daily VMT in each urbanized area. The UMR methodology recognizes, however, that recurrent congestion may be limited to a portion of this period, and that this portion varies across areas. To predict this portion of the day, the UMR uses a Roadway Congestion Index (RCI) that reflects peak-period traffic volume relative to network capacity in lane-miles. For the two most severely congested areas, Los Angeles and Riverside-San Bernardino, CA, the 2007 Report estimates that recurrent congestion could potentially occur over the entire eight hours – thus, that 50 percent of the daily traffic might experience recurrent congestion. For less congested urbanized areas, the proportion of daily traffic estimated to be on the road at times when recurrent congestion may occur is lower, as low as 25 percent in Buffalo, NY.

For travel during the congested portion of the day, the UMR also uses equations to predict average freeway and arterial speeds. For the estimated volume of traffic during these hours, the UMR develops a distribution of VMT by congestion level: uncongested, medium, heavy, severe, and extreme. The estimation procedure utilizes data on average daily traffic volume, section length, and the number of lanes for each highway section in the HPMS sample for each urbanized area. The "uncongested" category is included because even during the hours when recurrent congestion occurs, some sections of the highway network will remain uncongested. For these sections, the UMR assigns average speeds of 60 mph for freeways and 35 mph for arterials, which are the assumed average free-flow speeds.

For each higher congestion level, the UMR equations predict average speeds as a function of the average daily traffic per lane. Speeds are predicted separately for freeways and arterials and for the peak and off-peak directions of traffic. Speed equations in the 2007 UMR were modified substantially. In particular, the assumption was added that even under extreme congestion, peak-period freeway speeds will average at least 35 mph in the peak traffic direction and 40 mph in the off-peak direction. In the 2005 report (the latest one before the 2007 release), the equations did not include these minimums and predicted average freeway speeds as low as 20 mph at very high volumes of traffic.

The modifications to the speed equations were based on analysis of data from freeway traffic control centers, which have become much more available over the past few years, in addition to computer simulation modeling. More importantly, the UMR notes that the new equations give higher estimates of speeds, and hence lower estimates of delay, than do available planning models. This would partly explain why some MPOs obtain larger estimates of congestion delay from their models compared to what the UMR reports.

A potential refinement to the UMR speed equations would be the incorporation of inter-area variation in the average uncongested speeds. One might expect some variation only because of differences among states in speed limits; for urban Interstate highways, speed limits range from 55 mph to 75 mph.

2.1.2.3 Estimation of Fuel Consumption

The UMR estimates the cost of congestion in increased fuel consumption separately for cars and trucks. For trucks, the cost is subsumed within an estimated overall cost per hour of truck operation (see discussion of value of time below). For cars, the UMR uses the following equation to predict average miles-per-gallon (mpg) for travel during the potentially congested portion of the peak period:

$$\textit{Average MPG} = 8.8 + 0.25 * \textit{Average Speed} \qquad \textbf{(EQ 1)}$$

The methodological appendix to the UMR indicates that on the right-hand side of this equation, the average speed is measured exclusive of incident delay and for the entire eight hours of the peak period. Fuel economy, on the left of the equation, is measured for potentially congested portion of the peak period, a span of less than eight hours as determined by the Roadway Congestion Index. Since the basis for this equation is unclear, assessment and interpretation are difficult. The UMR notes only that they derived the equation through linear regression applied to fuel consumption data from (Raus 1981). For passenger cars, Raus relied on an equation estimated by General

Motors Research Laboratory using field data collected by driving instrumented vehicles in the Detroit metropolitan area. The vehicles used for these tests were 1973 through 1976 models, which would then have been new or near new. The equation relates fuel economy to a vehicle's weight, idle fuel flow rate, and average speed over the variety of driving conditions encountered in the tests. Raus stresses two points about this equation:

- "The speed [used in] the above relationship is not a steady state or uniform speed, but a transient speed reflecting stops and speed changes. Most previously published references on fuel consumption give values based on uniform speed. This is not the case here, and the two data sets are not comparable" (p.6).

- The equation is valid only for speeds up to about 35 mph, and that for higher speeds "air resistance (drag) assumes an increasingly dominant role" (p.6). He continues: "For the situation considered here, i.e. urban driving, the upper limit of 35 mph is quite adequate".

For trucks and buses, Raus used other sources of data to estimate relationships between fuel economy and average speed measured over a variety of driving conditions, but again only up to 35 mph. Presumably, the UMR has conducted some supplementary analysis to predict fuel economy at average speeds up to 60 mph, which is how equation (1) is used in their report. One could also presume that the UMR has updated the equations in Raus to at least roughly allow for changes over time in vehicle fuel economy. Possibly, this is done with some benchmark measure(s) such as the national aggregate figures that FHWA *Highway Statistics* reports by broad vehicle category.

In contrast with the monotonicity of the UMR equation – average mpg always increases with average speed – evidence at the individual vehicle level suggests a U-shaped relationship between mpg at any given moment and concurrent speed. For example, the evidence pertaining to freeways from Barth and Boriboonsomsin (2008) suggests that light-duty vehicles consume about 12 percent less fuel when traveling at 50 mph than when traveling at 60 mph. Since vehicles do not, however, all travel at the same speed, such evidence does not necessarily contradict a monotonic increasing relationship between average mpg and average speed.

2.1.2.4 Valuation of Travel Time

TTI provided the authors of this report with an unpublished memorandum that reviews the values of time used in the 2007 UMR and touches on the methodologies that underpin their development. The UMR calculates separate values of time for automobiles and commercial vehicles. For automobiles, values are derived from a 1986 vintage speed-choice model (Chiu and McFarland, 1987). Although the model is more than 20 years old, the authors suggest that the nature of traffic in Texas has not changed enough to cast doubt on the validity of its estimates. To corroborate the model results, the authors compare the speed-choice model's 1997 estimate of $11.97 with figures from other states. The UMR estimate is above average, but falls roughly in the middle of estimates used by Florida, Georgia, Virginia, and California. The authors conclude that this consistency, along with the independence of estimates provided by other states (although it is not clear how independent these other estimates really are) and the lack of "recent research that contradicts these data", obviates the need for any data adjustment.

The UMR estimates of the value of time for commercial data follow a different approach. In years prior to 2003, they were based on a vehicle cost-per-mile of $1.65 developed by the American Trucking Association (ATA). The base year for this figure is 1982, and subsequent years are the result of adjusting the 1982 estimate for inflation. This figure includes depreciation costs, maintenance, interest, and other costs with the notable exception of fuel. Although not mentioned explicitly, we assume that labor costs are also included.

The authors compare these figures with cost estimates from two sources: Transport Canada's *Operating Costs for Trucks, 2000* and FHWA's *An Evaluation of Expenses per Ton-Mile, Expenses per Mile and Expenses per Ton for major Commercial Carriers in Numerous Segments of For-Hire Trucking*. Transport Canada's figures are segregated by truck type (for example: 5 axle semi-unit, 5 axle bulk dry tanker, 2 axle straight truck, etc.) and include the drivers wage, fuel, and other operating costs for both the tractor and the trailer. Insurance, interest, and administration costs are also included. In all, Transport Canada reports on 15 truck classes and the UMR combined them into a composite hourly cost estimate of $68 in 2000 dollars using data from their own air quality model (details of this process were not reported).

The authors also compare the original cost per-mile figure with cost factors, published by the FHWA. To ensure that the comparison is valid, the cost of fuel per mile is added to the UMR estimates. The notable result from this comparison is that the FHWA figures are near constant over a 22-year period ($1.79 in 1982 and $1.83 in 2004); the UMR cost estimates are lower in 1982, but are adjusted for inflation and so are much higher after about 1988. Both the UMR (with fuel costs added) and the FHWA per-mile estimates are converted to a per-hour basis. This conversion may introduce biases into the estimate. This is because many vehicle operating costs are influenced more by speed or operating state than by time. For the year 2004, the UMR estimate is $129.06 per hour, while the FHWA figure is $68.70 hourly. After a brief discussion of factors that may explain the decline in the real cost of trucking (deregulation), the authors conclude that the FHWA costs are "a more reliable statistic" for truck values of time than the figures used in the UMR.

2.1.3 Federal Highway Cost Allocation Study Addendum 2000)

The United States Federal Highway Administration (FHWA) published a Cost Allocation study in 1997, which was later amended in 2000, addressing four main costs of highway use not borne directly by transportation agencies; crash costs, air pollution, congestion, and noise. Based on mid-range estimates, the FHWA estimated congestion costs to account for 14 percent of the total cost for those four impacts. The cost of congestion was estimated in the 2000 addendum to range between $16.35 billion on the low end and $181.64 billion on the high end with a mid-range estimate of $61.76 billion.

The FHWA contends that economic efficiency is enhanced if drivers had to pay for these marginal costs, which reflect changes in total costs associated with an additional increment of travel. Furthermore, since many marginal costs vary according to time and place, charges should also vary and not be limited to average costs. The report calculated congestion costs in 2000 for selected vehicles operating under different conditions based on the value of added travel time due to additional small increments of traffic. The costs varied from 0.78 cents per mile for an automobile on a rural interstate to as high as 32.64 cents per mile for a four-axel truck on an urban interstate.

2.1.4 Studies on Individual Urban Areas

HDR has conducted a number of studies pertaining to congestion costs, the latest of which was prepared for the Chicago Metropolitan Planning Council (see MPC 2008). The study investigated the impact of expressway and arterial road congestion on Chicago and its six surrounding counties and estimated its cost at around $7.3 billion a year in wasted time, fuel and environmental damage. The study estimates congestion to add 22 percent to peak period travel times, a cost of which is 19.5 times higher than that of wasted fuel. While the 2007 UMR estimates the cost of congestion in the Chicago area at $4 billion, HDR measured congestion over a longer portion of the day and a larger segment of the region's road network. In addition, HDR estimated lower average speeds based on 2005 data from the Chicago Metropolitan Agency for Planning.

The costs of congestion were also estimated for the New York metropolitan area in an HDR study conducted in 2006. The report investigated and quantified a number of cost impacts on the metropolitan area, covering New York and New Jersey. These costs included wasted time, wasted fuel, in addition to lost economic activity measured by the decrease in Gross Regional Product and the number of jobs lost. The study estimated that the annual costs of congestion amounted to $5 billion in terms of lost time and productivity in addition to $2 billion in wasted fuel and other vehicle operating costs.

2.1.5 Studies by Metropolitan Planning Organizations

This section assesses available evaluation approaches and sources of data produced by a variety of metropolitan planning organizations (MPOs) from around the United States, including studies produced by the San Diego Association of Governments (SANDAG), the North Central Texas Council of Governments (NCTCOG), the Atlanta Regional Commission (ARC), and the New York Metropolitan Transportation Council (NYMTC). This review assesses each MPO's approach, the publications they produce, the data they employ and compares their results to those generated by the UMR to assess the relative impact to the estimated effects of congestion of the application of alternative approaches.

2.1.5.1 San Diego Association of Governments (SANDAG)

SANDAG biennially analyzes roadway performance in their Congestion Management Program (CMP) and updates their Regional Transportation Plan (RTP) every four years. The CMP considers short-term congestion mitigation strategies and the RTP proposes potential long-term solutions. Because of this, they both differ from the UMR's estimation of the extent of congestion.

The CMP and RTP cover a much broader area than the UMR due to the jurisdiction of SANDAG. SANDAG is the planning agency for 19 different jurisdictions covering a total of 4,261 square miles and representing about 3.1 million people (2007 estimates). The UMR, on the other hand, accounts for 800 square miles and about 2.9 million people (2005 estimates). SANDAG covers a larger area while the UMR covers a more densely populated area. The CMP considers all state freeways, state highways, and principal arterials. All together, they account for 61% of daily VMT. The regional highway network analyzed in the RTP includes freeways, expressways, and the Regional Arterial System (RAS). The RAS includes all conventional state highways, prime arterials, selected major streets, and some local streets that connect various travel zones.

To measure freeway congestion in the CMP report, SANDAG uses observed average annual daily traffic data provided by the Caltrans District 11 Traffic Census Branch. They apply control data to find the average weekday traffic volume, determine the directional split, and calculate the peak hour percentage. To determine the severity of congestion, SANDAG analyzes traffic for the most congested peak hour of travel in the most congested direction. SANDAG then calculates traffic density (passenger cars per mile per lane) and compares it with congestion thresholds in the Highway Capacity Manual (HCM).

To determine the severity of congestion for arterial segments, local agencies collect traffic data using one of two methods. In the first method, known as the computation method, delay times are calculated for signalized intersections according to HCM recommendations and then added to segment running times based on lengths and posted speeds. In the floating car method, local agencies perform individual runs on roadways and calculate the running times and distances. In both methods, average speeds are calculated and compared with free-flow speeds to determine the congestion based on HCM thresholds.

The RTP looks at congestion performance measures for the entire peak periods of 6-9 a.m. and 3-6 p.m. Also, instead of using observed data, the RTP uses output from the San Diego Regional Transportation Model to determine the extent of current and forecasted congestion at the regional level. Due to limits in their transportation model, the RTP does not take into account incident delay or non-recurring congestion in their calculation of performance measures. Non-recurring congestion is too inconsistent to accurately model.

To measure performance in the CMP, SANDAG evaluates each roadway segment according to a Level of Service (LOS) standard. This standard, ranging from A (least congested) to F (most congested), is a qualitative measure describing the operational characteristics of a roadway. Speed estimates are determined based on the LOS designation for the highway section. Roadway segments operating at LOS "F" are required to be evaluated for congestion mitigating improvements. Since the CMP only reports the LOS, it is difficult to come up with some sort of measure of the total cost of congestion, but it could be used to estimate the percentage of roadways or lane miles that are congested.

In the RTP, speed is calculated as a function of travel time divided by VMT. Although the RTP does not include a measurement of the total amount or cost of congestion, there are numbers that can be used to infer such costs and compare with the UMR. Daily vehicle delay and daily hours of delay on the freight network are two reported performance measures that could be combined with population estimates and other information to calculate total delay and its cost. The RTP also includes measures for the congested percentage of peak period travel which can be compared to the UMR. Lastly, SANDAG provides estimates and future forecasts for smog forming pollutants per capita which is something most other MPOs do not.

According to SANDAG, the UMR is useful for determining trends in transportation conditions over time, but is not helpful for determining the performance of specific facilities. SANDAG also feels the HPMS data used for the UMR is not well reflective of the arterial system. Finally, since system delay is largely a function of speed, SANDAG is uncomfortable with the UMR's methods for calculating speeds. The report estimates speeds and takes a weighted average over an entire highway segment, whereas SANDAG prefers to use observed speeds at various points on the highway segment.

2.1.5.2 North Central Texas Council of Governments (NCTCOG)

NCTCOG produces two reports useful for this analysis. Their Congestion Management Process (CMP) looks at potential ways to mitigate specific congestion hotspots and the Metropolitan Transportation Plan (MTP) is established to provide long term transportation recommendations. The MTP produces a number of estimates for the total cost of congestion that are useful for drawing comparisons with the UMR.

The area and populations covered by the CMP and MTP are difficult to pinpoint precisely, but they are clearly larger than those covered in the UMR. The UMR represents 4.4 million people and 2,300 square miles in its analysis of the Dallas-Fort Worth-Arlington urbanized area. Looking at population data produced by NCTCOG and maps from the CMP report, it seems they analyze what they refer to as the nine county urban area representing 5.9 million people (2006 estimate). The MTP covers an area that represents 5.86 million people (2007 estimate), probably the most densely populated portions of the nine county urban area.

The CMP evaluates congestion on controlled-access highways, regional arterials, intermodal/ freight transportation, and passenger rail. The controlled-access highways include all freeways, expressways, and interstates in the region. Regional arterials include all roadways defined as principal arterials under federal law, all arterials on the National Highway System, and complementary local arterials.

NCTCOG uses the DFW Regional Travel Model to determine traffic densities on controlled-access highway segments. In addition, it supplements that data with low-level aerial photography to observe recurring congestion on the freeway system and help identify bottlenecks. The Council also uses their Transportation Intelligence System to identify highway sections with speeds less than 35 mph for a significant amount of time, allowing them to measure the impacts incident delay. To determine levels of congestion on the regional arterial system, the Council uses observed traffic counts to locate arterial segments where demand exceeds capacity. For the freight system, NCTCOG relies on their regional travel model and the Texas Department of Transportation (TxDOT) vehicle classification counts to identify potential congestion hotspots resulting from high volumes of freight truck and rail traffic.

The MTP predominantly looks at a measure similar to the travel time index that is the ratio of actual hours of travel to free-flow hours of travel. Light congestion begins with a ratio of 1.20 and severe congestion starts with a ratio of 1.50. Instead of looking at a peak period, their MTP considers delay over an entire 24-hour period. They also consider two types of delay: congestion delay and traffic control delay. Congestion delay results when vehicle demand exceeds capacity on a given segment. Traffic control delay is delay caused by traffic control devices such as signals and stop signs. Even on roadways without congestion, drivers may experience delay due to traffic control. Given the limitations of using a travel demand model, they are unable to account for non-recurring congestion in their MTP.

NCTCOG focuses on level of service (LOS) designations in their CMP report to identify controlled-access sections needing improvement. This LOS is used to determine average speeds according to the recommended highway capacity manual designations. For the regional arterial system, NCTCOG looks at intersections where volume demand exceeds capacity and for the freight system, NCTCOG determines which roadway segments have high levels of truck volumes.

2.1.5.3 Atlanta Regional Commission (ARC)

For their Congestion Management Process (CMP) and Regional Transportation Plan (RTP), the Atlanta Regional Commission (ARC) evaluates system performance for the 20-county area it represents. In 2005 the area had 4.7 million people, slightly more than the UMR estimate of 4.1 million. ARC considers all interstates, freeways, and HOV facilities in the 20-county region for the CMP. They also include all state routes and principal arterials as defined by the ARC Travel Demand Model, and any other roads previously identified as congested. It is not clear, however, what roadways the RTP considers.

For all of their congestion performance measures, ARC uses the ARC Travel Demand Model which only accounts for recurring congestion. Historically, ARC only accounted for passenger vehicles in their CMP, but they have recently begun using Passenger Car Equivalent (PCE) factors to estimate the impact trucks have on congestion. The PCE adjusts the weights of certain vehicles upwards by a predetermined factor to better reflect vehicle composition, significantly impacting the performance measurements.

The RTP considers congestion for an entire 24-hour period. This is divided into four times of day. The peak periods are 6-10 a.m. and 3-7 p.m. for the morning and afternoon respectively. ARC also considers congestion during the mid-day from 10 a.m. to 3 p.m. and nighttime from 7 p.m. to 6 a.m.

To measure congestion on roadway segments in the CMP, ARC uses a three dimensional process that considers the intensity, duration, and extent of congestion. Intensity is measured by the maximum travel time index for either the morning or afternoon peak period. The duration of congestion is defined as the number of hours roadway volume exceeds capacity. Demand exceeds capacity when the V/C ratio is greater than 0.9 for freeways and HOVs, and greater than 0.80 or 0.85 for other arterials (depending on size and location). The duration of congestion in each peak period is summed up to determine total duration. Extent is the percentage of vehicle delay for a given section divided by total vehicle delay for the entire system. Each of these measures is assigned a value based on its magnitude and sections with the highest scores are considered to be the most congested.

2.1.5.4 New York Metropolitan Transportation Council (NYMTC)

NYMTC produces thorough congestion estimates in their Congestion Management System (CMS) report. The NYMTC CMS report covers 10 New York counties that represent about 13 million people and 2,440 square miles. The UMR on the other hand represents about 17.8 million people and 4,780 square miles throughout the New York – New Jersey – Connecticut urbanized area. Also, the transportation model used by NYMTC lacks the ability to evaluate congestion on local roadways; it only analyzes controlled access highways, major arterial roadways, and minor arterial roadways.

To estimate congestion, NYMTC uses their Best Practices Model (BPM). Weekday recurring congestion is estimated for the four-hour a.m. and p.m. peak periods of 6-10 a.m. and 4-8 p.m. Although non-recurring congestion is expected to be significant, they find it too inconsistent to be accurately modeled. Implicit in their analysis and costs of congestion is an estimate that freight trucks account for 6% of travel demand.

The primary performance measure evaluated by NYMTC is intensity of congestion as measured by the V/C ratio. V/C ratios are calculated according to Highway Capacity Manual (HCM) techniques based on output data from the BPM. If control devices such as traffic signals are present, supplemental analysis is performed using the HCM signalized procedures. The V/C ratios are then used to determine average running speeds. Only sections that have an average V/C of 0.8 or higher for the entire four-hour peak period will be identified as congested. A V/C ratio exceeding 1.0 represents roadway sections that are severely congested.

NYMTC also calculates the Vehicle Hours of Delay, determined by the difference between the actual travel speed and the free-flow speed. Person Hours of Delay is simply Vehicle Hours of Delay times the average vehicle occupancy which varies by county. To determine average travel speed, NYMTC takes the weighted average of speeds for both freeways and arterials. Lane-miles of congestion are determined based on roadway segments with a level of service standard lower than "E" according to HCM requirements. The travel time index, like in the UMR, is a ratio of peak period travel time to free-flow travel times. The Roadway Congestion Index is calculated in the same methods as the UMR and measures the extent of congestion system-wide.

2.2 Studies of Congestion Pricing

Congestion pricing is a congestion management technique by which motorists are charged for driving on a particular roadway facility or in a particular area. It is sometimes called (road) value pricing to emphasize that motorists are thereby expressing their willingness to pay to drive in un-congested conditions.

The concept has been widely and successfully applied to other sectors of the economy (airfares, phone rates, hotel rates, etc.). The first example of congestion pricing is Singapore's Area License Scheme, which was put in place in 1975. Several countries in Europe (including Norway and England) have implemented similar techniques to curb congestion since then. In the United States, congestion pricing is a relatively late comer. The State Route 91 Express Lanes, the nation's first value-priced roadway, opened in December 1995 in Orange County, California.

Essentially, congestion pricing is a way to allocate limited roadway capacity among users by forcing them to choose between their need to travel and their willingness to pay to travel on certain portions of the roadway network, sometimes at certain times of the day (or the week). The primary goal of congestion pricing is to reduce traffic congestion by using the roadway network more efficiently.

Congestion pricing can take different forms, depending on the level of congestion or the area of implementation, among other factors. Generally speaking, congestion pricing schemes can be broken down into four main categories:

- **Variable Road Pricing**: A variable toll is charged to utilize a roadway facility (section of a highway, tunnel, or bridge); the toll increases or decreases depending on the (expected or actual) level of congestion.

- **Lane Pricing**: A variable toll is charged to drive on separated highway lanes; this type of congestion pricing scheme includes HOT (High Occupancy Toll) lanes.

- **Cordon Pricing**: A fixed or variable toll is charged to enter or drive within a particular area, usually a city or city center; this type of congestion pricing scheme includes urban toll rings.

- **Area-wide Pricing**: A per-mile toll is charged on the entire roadway network within a large area; area-wide pricing is relatively less popular than other congestion pricing schemes

2.2.1 Examples of Congestion Pricing

Singapore has more than thirty years of experience in congestion pricing. In 1975, the city-state implemented the first operational congestion pricing scheme in the world, the

Area License Scheme (ALS). Motorists were required to purchase and display a license before entering into the central business district's restricted zone during morning peak hours. Compliance was monitored manually at control points. The cost of the license was originally set at SGD3 per day or SGD60 per month ($1.30 and $27, respectively, at the time). Taxis, public buses, commercial vehicles, motorcycles and passenger cars with four or more passengers were exempted. Over time, a number of adjustments were made to the ALS. In particular, two major changes were made in June 1989: an afternoon peak charge was introduced; only public buses and emergency vehicles were eligible for exemption.

The ALS was replaced by the Electronic Road Pricing (ERP) system in 1998, in part to improve enforcement. Under the ERP, cars are fitted with in-vehicle units (or transponders) into which stored-value smart cards are inserted. Enforcement is handled using video cameras. Tolls apply on weekdays from 7:30 a.m. to 7:00 p.m., ranging from free (10:00 a.m. to 12:00 p.m.) to SGD5.00 (8:30 a.m. to 9:00 a.m. at most entry points) in the restricted zone, according to a fixed schedule keyed to the time of day. Unlike the ALS, which allowed multiple entries into the restricted zone during the day, the toll is charged for each entry. Pricing under the ERP covers not only more routes, with different prices along expressways according to location, but also more hours for restricted zone entry, than under the ALS.

Norway has been a pioneer in road tolling, especially with regard to urban toll rings. Since the mid-1980s, toll ring schemes have been implemented in seven cities, including the three largest: Oslo, Bergen, and Trondheim. These toll rings were designed primarily to finance transportation infrastructure projects, and, secondarily, to reduce roadway congestion. In Trondheim, however, the scheme incorporated some time-of-the-day differentiation into its pricing structure.

The world's first fully automated toll ring was implemented in Trondheim in October 1991. The toll ring surrounding the city center consisted of twelve toll stations equipped with the Q-Free® AutoPass system. In 1998 a zone-based tolling system was introduced to increase revenue and address equity concerns. In-going vehicles were charged a toll which varied by time of the day: a higher toll was charged during the morning peak period, from 6:00 a.m. to 10:00 a.m. No toll was charged after 6:00 p.m. and on weekends. Large vehicles were charged a double toll. A maximum of 60 crossings were charged per month. The scheme also offered the possibility to pay in advance by preset amount (NOK500, NOK2,500, or NOK5,000) which provided a discount. The scheme ceased to operate on December 31, 2005 as the agreed tolling period of fifteen years came to an end.

In the United States, contrary to the previous two examples, there are no congestion pricing projects where free lanes were transformed into toll lanes. All projects are either toll reductions during off-peak periods when tolls were already in place or transformations of underutilized high occupancy vehicle (HOV) lanes into high occupancy toll (HOT) lanes. An illustration of the latter case is the Interstate 15 (I-15) Express Lanes in San Diego County, California. Two barriers separated reversible lanes were built in the median of I-15 north of San Diego in 1988. During peak period the lanes were restricted to carpools with two or more passengers, as well as to motorcycles and emergency vehicles. In 1996, the HOV lanes were converted to HOT lanes, in part to improve air quality in the area. Pricing was introduced in two phases.

From December 1996 to March 1998, the permit ExpressPass program was put in place allowing a limited number of solo drivers to use the express lanes for a monthly fee, which was $50 at first and was raised to $70 two months after opening. In March 1998, the FasTrak program superseded the ExpressPass program. Monthly permits were replaced by transponders, which allow the flexibility of varying the toll. The toll is related to the quality of traffic flow in the express lanes and recalculated every six minutes to maintain Level of Service (LOS) "C" or better, with a refinement instituted in late 1998 emphasizing shoulder-of-the-peak discounting relative to the peak-of-the-peak. Under normal conditions, tolls vary from $0.50 to $4.00 per trip; in very severe congestion conditions, the maximum toll may go as high as $8.00. To provide an alternative to the toll lanes or the congested freeway, a new express bus service has been introduced as part of the FasTrak program.

2.2.2 Impacts of congestion pricing

In a study recently completed for the United States Department of Transportation (USDOT), HDR (2008) presented a sketch-planning for predicting the impacts of congestion pricing on urban freeway networks. Parameters of the model, TRUCE 3.0, were derived from careful review of the relevant research literature and initial applications were to the three urban areas of Los Angeles, Chicago, and Washington, D.C. Key findings from that effort, supplemented by literature review undertaken for the present study, are summarized below.

2.2.2.1 Traffic impacts

Since extensive congestion pricing on an urban road network has yet to be attempted in the United States and relevant international evidence relates mainly to cordon-type schemes (London and Stockholm), indications of the traffic impacts of comprehensive congestion pricing come largely from simulation studies. Overwhelmingly, these studies have used static travel demand models to predict average speed and total traffic volume over several hour spans of time, such as morning or evening peak periods. Although traffic volume and congestion vary substantially within these spans, and so should efficient congestion charges, static models lack the functionality to determine this variation. Moreover, traffic impacts predicted by static models can be substantial. For example, according to an analysis from the 1990s, quasi-optimal congestion pricing in the Minneapolis-St. Paul metro area would reduce peak-period traffic volume by 12 percent overall and 25 percent on the most heavily congested sections of freeway (Mohring and Anderson 1994). Results from another study suggest still larger impacts for more heavily congested urban Southern California (Wilbur Smith Associates 1997).

Results from emerging literature that simulates congestion pricing within dynamic frameworks suggest that such estimates from static frameworks are likely to be exaggerated. In the simplest dynamic model of vehicle queues at a traffic bottleneck, congestion pricing eliminates congestion without any reduction in peak traffic volume. The mechanism for achieving this result is fine time-of-day variation in congestion charges that encourages motorists to postpone arrival at the bottleneck, preventing queues from forming. Static models can also incorporate speed-flow relationships that have their grounding in dynamic paradigms, such as models of queuing, resulting in quasi-dynamic models.

2.2.2.2 Level of congestion charges

Estimates of the average charge under optimal or quasi-optimal congestion pricing are often fairly high, but vary considerably. Kockelman and Lemp (2008) note that welfare-maximizing congestion charges on particularly congested road corridors, such as heavily used bridges and other key bottlenecks, can reach $1 per mile or more during peak periods. This is based on a Bureau of Public Roads (BPR) speed-flow curve with standard parameter values in instances where demand-to-capacity ratios lie above 1.0 and values of time are on the order of $10 per vehicle-hour or more.

A complication in deriving such estimates is that imposing congestion charges on any one link of the network can affect congestion on other links through traffic generation and diversion. (In static frameworks, the typical result is that charges imposed on one link will aggravate congestion on other links to which traffic diverts). Because most of the analyses abstract from these cross-link effects when estimating the appropriate congestion charges, the charges they estimate are what Small and Verhoef (2007) call “quasi-first best”.

Quasi first-best prices are problematic particularly for simulations of pricing on only a portion of the congested road network. Indeed, the aforementioned study of congestion pricing in the Twin Cities of Minneapolis-St. Paul found that quasi first-best charges limited to freeways would divert so much traffic to arterials that congestion would worsen for the network overall. More generally, for a scenario where congestion pricing applies to only a portion of the network, quasi-first best prices will be excessive. When the study used instead congestion charges that were 20 to 40 percent of the calculated first-best charges, the overall welfare effect turned from negative to positive. The message from this and other studies is that to ensure welfare gains from congestion pricing on only a portion of the network requires careful calibration of the charges.[3]

For comprehensive congestion pricing on both freeways and arterials, the Twin Cities estimated quasi first-best charges for the morning peak that averaged 9 cents per mile overall and 21 cents per mile on the most heavily congested sections of freeway. These charges are predicated on average values of traveler time that reflect household income levels in 1990. Since then, the median income of Minnesota households has increased by 85 percent to just about $58,000 in 2007. Using this ratio to update the values of time in the Twin Cities study would push the estimates of average congestion charges from the Twin Cities study to about 28 cents overall and 39 cents for the most heavily congested

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[3] Likewise, Wilbur Smith Associates (1997) found that the congestion charges on Southern California freeways would, at the levels assumed in the study, reduce average network speed on freeways and arterials combined. For cordon pricing hypothetically applied to Washington, D.C. area,

sections of freeway. If the study's simulations were re-run with current traffic data, rather than data from 1990, the estimates of quasi first-best congestion charges would increase further, since congestion has worsened considerably over time. For average annual delay per peak-period traveler, the UMR shows about a doubling from 21 hours in 1990 to 43 hours in 2005.

The evaluation of potential congestion pricing on freeways in the Dallas Fort Worth area by Kockelman et al. (2005) is notable for using a conventional static travel demand model and, alternatively, a model including dynamic traffic assignment. Estimates of quasi first-best congestion charges were much lower in the results from the static modeling. For the peak periods as defined in the study (6-9 a.m. and 3:30-7 p.m.), charges averaged only \$0.03 per mile across the freeway network and about \$0.10 per mile for illustrative long-distance commutes from the suburbs to the Dallas Central Business District (CBD) (see Gulipalli and Kockelman 2006). Using dynamic modeling, the per mile charge varied over time and over the network from \$0.10 per mile all the way up to \$29 per mile. Although the study stressed the limitations of its dynamic modeling and considered the resulting estimates of congestion charges implausibly high, one of the authors contends that the estimates of congestion charges from the static analysis were biased in the opposite direction (downward) due to a problem with the speed-flow curve (see HDR Congestion Pricing Study, 2008, p. 27).

An evaluation of road pricing options for the Washington, D.C. metro area also produced estimates of quasi first-best congestion charges (Safirova, Houde, & Harrington 2007). The estimated charges were termed "second-best" because each of the modeled scenarios includes certain pricing distortions as fixed constraints. In the scenarios for cordon tolls, for example, such distortions include the absence of congestion charges for travel outside the cordon and the lack of differentiation of congestion charges inside the cordon according to how much a motorist travels. In the scenario of comprehensive congestion pricing across the entire road network, the congestion charge averaged about \$0.03 per mile over the entire day. Figures specifically for the peak period were not reported, but would have been higher.

Among the many factors that can contribute to the differences in estimates between studies, the treatment of heterogeneity in values of time probably ranks as one of the more important. The simpler frameworks recognize little or no heterogeneity, which may lead to over-prediction of the economically efficient level of congestion charges, as well as to under-estimation of the welfare gains from imposing these charges. This issue is discussed further in Chapter 4, when we discuss the findings from our congestion pricing analysis, which treats travelers as homogenous in their valuation of travel time.

2.2.2.3 Welfare gains

Studies that have used network models for individual urban areas have estimated large benefits from congestion pricing. For the Washington D.C. metro area, for example, Safirova, Houde & Harrington (2007) estimated an annual welfare gain of \$220 million from congestion pricing on freeways and \$558 million from comprehensive congestion pricing (under year 2000 conditions). For the Twin Cities region, Mohring and Anderson (1994) estimated that on-freeway pricing would realize at least 25-30 percent of the potential efficiency gain from pricing all congested roads. For the Wilmington, Delaware metro area, corresponding estimates based on Daniel and Bekka (2000) are higher (in the 40 to 70 percent range, depending on the assumptions), probably because the area is less congested than the Twin Cities region. Although these estimates are gross of toll collection costs, they are conservative in that they do not include the benefits from the reduction in incident delay that occurs with reductions in recurrent congestion.

2.2.2.4 Implementation costs

In its recent report on congestion pricing to the United States Department of Transportation (USDOT), HDR estimated the capital and operating costs of collecting congestion tolls on urban freeways in three case study urban areas: Chicago, Los Angeles, and Washington, D.C. For each area, the study considered a scenario for aggressive congestion pricing scenario, where the target was attaining the free-flow speed freeway speed of 60 mph, and another for moderate congestion pricing, where the target was eliminating severe-to-extreme congestion. The more relevant to the present analysis is the scenario for moderate congestion pricing, which ensures that average peak-period speeds on all sections of the freeway network of at least 50 mph (where the peak period is defined as in the UMR). For the three areas combined, the capital and operating costs of toll collection were predicted to consume 10 percent of the gross revenues from moderate congestion pricing compared to 13 percent from aggressive congestion pricing.

These estimates are based on electronic toll collection technology, with roadside readers interfacing with transponders installed on vehicles. Although this would be an economically efficient technology for congestion pricing limited to freeways, or for cordon pricing, comprehensive congestion pricing, which is what the present report considers, would call for a GPS-based system to track the movements of vehicles throughout the network and to charge based on the amount and location of travel. Currently, a GPS-based system is used in parts of Europe to collect mileage-based charges from operators of heavy trucks.

In a study just completed for USDOT, HDR examined the costs of key elements of a national GPS-based system for collecting mileage-based taxes for travel on U.S. roads and highways. The study assumed that the toll per mile would be independent of the time of travel, and hence omitted costs of some elements that would likely form part of a congestion pricing regime (e.g., variable message signs to convey the current level of the toll). The estimation of a GPS-based system for congestion pricing is beyond the scope of this report, and a number of technical issues would need to be resolved before such a system could be implemented on a large scale. In particular, closely placed parallel streets and service roads for large urban roads may create difficulty for some GPS systems to accurately measure exact entry and exit into a zone, especially if a vehicle’s route closely follows the zone perimeter. Future evaluations of the potential for comprehensive congestion pricing will need to consider the full range of other potential applications of the supporting GPS-based system, such as collection of traffic data and the imposition of a flat mileage-based tax.

2.2.2.5 Omissions

Of the common omissions from simulation modeling of congestion pricing, two have already been mentioned: the effect of recurrent delay on the amount of incident delay, and the costs of toll collection. The modeling undertaken for this report (Chapter 3) is unusual in including the effects of congestion pricing on incident delay, but does not measure the costs for toll collection. Other common omissions include the costs of congestion in:

- **Unreliability of travel time**. An evaluation of cordon pricing in Stockholm is the only study we know of that has included this cost, which added about 15 percent to the estimated savings in travel time. The analysis was undertaken by Transek and described in Prud'homme and Kopp (2006)
- **Fuel and other vehicle operating costs**. In their analysis of congestion pricing in the Twin Cities metro area, Mohring and Anderson (1994) found the estimated impacts to be insensitive to the inclusion of vehicle operating costs.
- **Accidents and pollution costs**. Safirova, Houde, and Harrington (2007) found that inclusion of accident and pollution costs only marginally affected their estimates of welfare-maximizing congestion charges. A major simplification that facilitated the inclusion of these costs was their assumption that the social cost of accidents and pollution are a linear function of aggregate VMT; by ignoring the effect on these costs of increases in average speed, this treatment rendered the impacts of congestion pricing on accident and pollution costs unambiguously beneficial. On the other hand, the modeling by HDR (2008) allowed both VMT and average speed to affect vehicle emissions of carbon dioxide. For the three studied urban areas (Chicago, Los Angeles, and Washington, D.C.), the results indicated that moderate congestion pricing would reduce peak-period emissions, with the largest decrease being the 7.3 percent estimated for Los Angeles. Likewise, Daniel and Bekka (2000) predicted that economically efficient congestion charges in the Wilmington, Delaware metro area would reduce vehicle emissions by as much as 10 percent in aggregate and 30 percent in highly congested areas. Benefits from reduced emissions were found to be 15-30 percent of those from reduced congestion.

On the other hand, congestion pricing to establish free-flow speeds, which will generally not be economically efficient, has no guarantee of environmentally friendly outcomes. In the HDR analysis of the three urban areas, the estimated impacts of aggressive congestion pricing on peak-period vehicle emissions of CO2 were speculative and ambiguous as to direction. Although a decrease was indicated for Los Angeles, the estimates for the other two urban areas, Washington, D.C. and Chicago, indicated that congestion pricing would slightly increase emissions.

3 ESTIMATING APPROACH

This chapter provides a detailed description of the methodologies utilized in this study to estimate the costs of congestion as well as the impact of congestion pricing on highways and arterials. The first section describes the different elements of congestion costs, their impact and the methodologies used to derive them. The second section conceptualizes congestion pricing by deriving appropriate congestion tolls and estimating the deadweight loss[4] (DWL) resulting from market inefficiencies.

3.1 Cost of Congestion

Congestion imposes significant costs on drivers, including wasted travel time, increased fuel consumption, added variability of trip times, and reduced mobility. Most estimates of congestion costs (both nationwide and for individual metropolitan regions) have focused on direct costs, including loss of time and excess fuel costs accrued to vehicle users. While the said costs are important, this study takes into account additional costs incurred due to unreliability as well as loss of mobility and excess emission costs. The principal categories of congestion cost considered in this study are:

- **Travel Time Cost:** The most prominent cost of traffic congestion is the delay associated with lower travel speeds, start-and-stop traffic flows, and in extreme cases, gridlock. These delays represent an opportunity cost of time -- time that could be spent both at work and for leisure.

- **Unreliability Cost:** This represents the cost assumed by drivers in having to deal with travel times made unpredictable by congestion. Travelers cope to some extent by leaving early for a destination in anticipation of delays, but they also sometimes suffer the inconveniences from arriving late.

- **Vehicle Operating Cost (VOC):** Traffic congestion leads to higher vehicle operating costs, primarily as a result of increased fuel use due to idling or start-and-stop traffic flows, both of which consume more fuel than driving at steady speeds.

- **Mobility Cost:** Congestion discourages the use of the road network for personal or business travel. This mobility cost captures the productivity lost due to foregone trips and is estimated as the consumer surplus derived from additional trips that would occur if congestion were eliminated.

- **Emission Cost:** The major environmental impact of vehicle use is exhaust emissions; an externality that imposes wide-ranging social costs on people. The negative effects of pollution depend not only on the quantity of pollution

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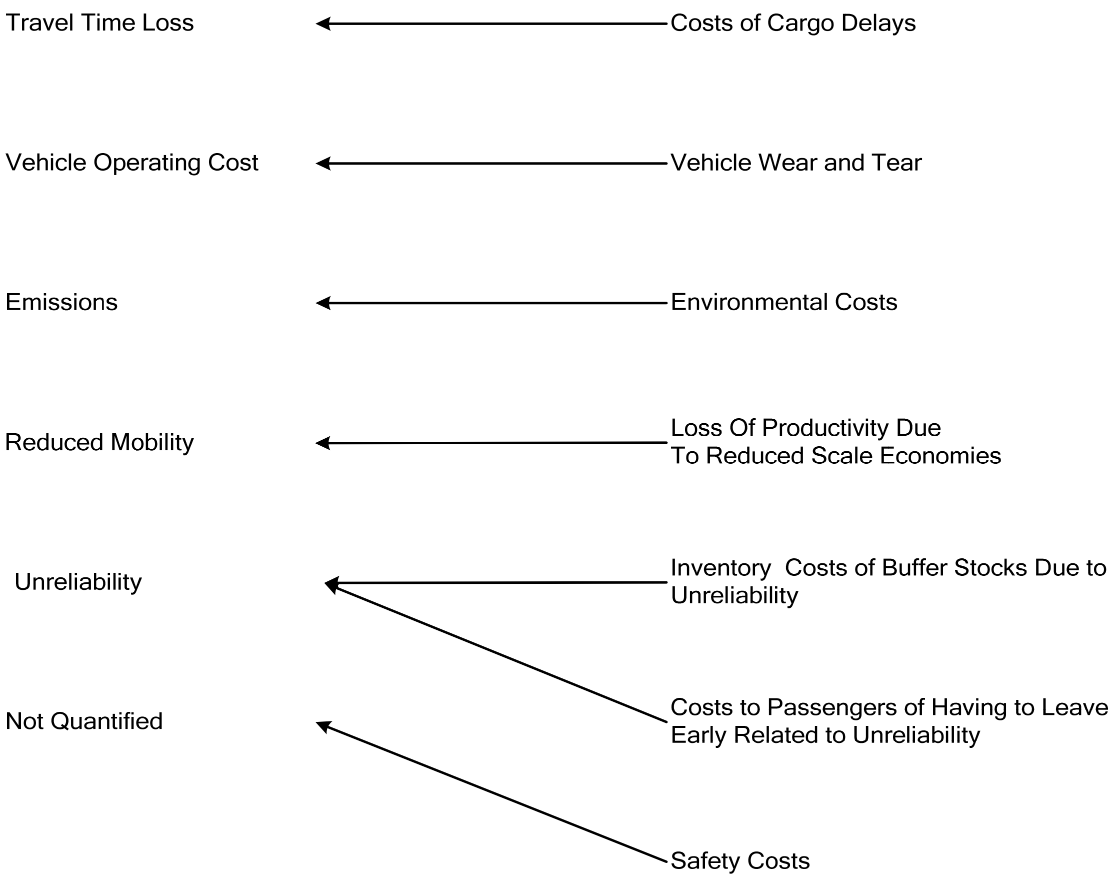
[4] Deadweight loss (DWL) is the net loss in social benefits or welfare that results because the benefit generated by an action is smaller than its cost.

produced, but on the types of pollutants emitted and the conditions into which pollution is released.

Figure 1: Mapping of Congestion Cost Categories

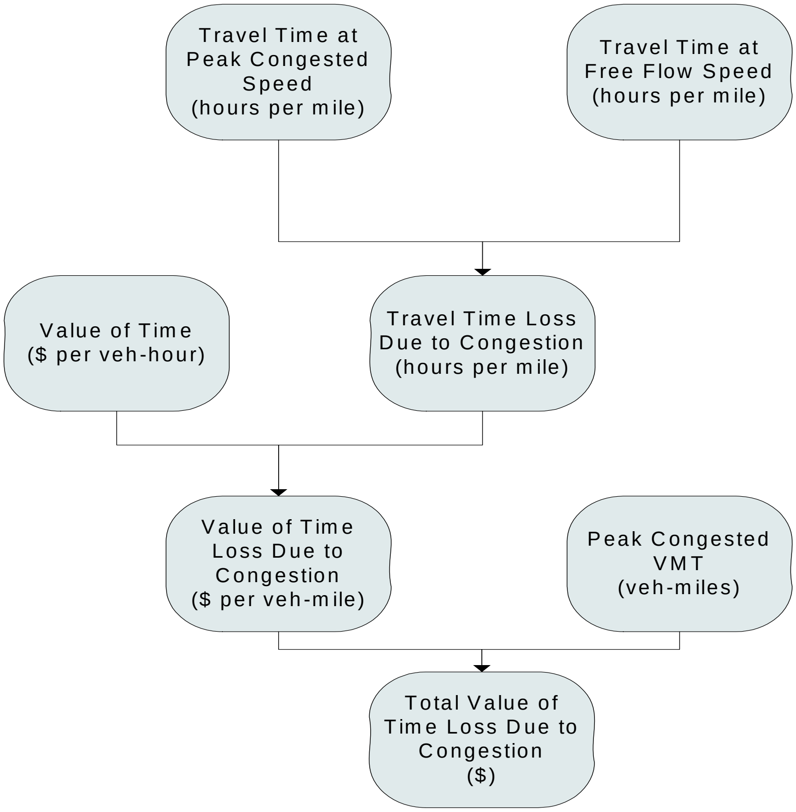


In this report, we estimate these components of congestion cost for each of the 85 urban areas analyzed in the UMR, and for additional areas aggregated in that report's "other category", for a total of 437 urban areas in the United States. The estimation methodology is described in the subsections below. The source of traffic data is the TTI Urban Mobility Report (UMR), which provides figures on peak-period volume of traffic - Vehicle Miles of Travel (VMT). Within the 8-hour peak period, the "peak congested period" is the portion during which congestion may occur. The UMR uses a Roadway Congestion Index (RCI) to estimate the percentage of VMT that occurs during this peak congested period (see Section 2.1.2.2). From these percentages and from the UMR figures on peak-period VMT, we have calculated for each area the VMT during the congested peak period for freeways and arterials.

3.1.1 Travel Time Delay

Travel time cost, the largest component of the overall cost of congestion, is the value of the total amount of time that road users can expect to lose to congestion. The amount of time lost is the difference between travel time at current congested speeds and at free-flow speed (under uncongested conditions). The identified value(s) of time is then applied to the travel time loss in order to generate the value of the time lost due to congestion. We calculate the total value of time lost due to congestion using peak congested Vehicle Miles Traveled (VMT) for each trip type, i.e. personal, business, and truck travel. According to the UMR, 50 percent of total VMT occurs during peak period, and then depending on the area under study, a percentage is applied to determine the congested portion of that peak period. The congested part is then divided into autos and trucks using the UMR estimates. Finally, using HERS estimates, autos are split into 89 percent personal and 11 percent business travel. Figure 2 illustrates the structure and logic of estimating the cost of travel time losses due to congestion.

Figure 2: Structure and Logic Diagram for Travel Time Cost



Travel time cost is estimated for each metropolitan area and is divided into three functional categories; personal travel, business travel and truck travel. For personal travel, the value of time (VOT) is estimated as 50 percent of the local wage rate, while business travel VOT is 100 percent of total compensation plus benefits (loaded wage) and truck travel VOT includes the average wage rate for truck drivers plus an inventory value for equipment and payload and is assumed to be the same in all areas. At the median level the value of time used in this study for truck travel is $45 per hour. The average wage rate was based on the median estimates published by the BLS ($15 per hour) and the inventory value for equipment and payload is estimated at about $30 per hour. This value of truck travel time is a conservative estimate compared to others used in different studies. In its cost calculator, NYSDOT allowed \$39 per hour for the cost of truck cargo, Meyer et al. (2006), in their evaluation of truck-only toll lanes proposed for Atlanta, valued truck travel time at \$35 per hour based on stated preferences studies.[5]

For the modeling of mobility cost and of congestion pricing, we calculate from the UMR data the travel time per mile in the peak congested period:

$$\text{Travel Time in peak congested period} = \frac{\text{Daily VHT in peak congested period}}{\text{Daily VMT in peak congested period}} \qquad \textbf{(EQ 2)}$$

Where, vehicle hours traveled (VHT) in peak congested period is the difference between the VHT in the entire peak period (8 hours) and the VHT in the uncongested portion of that period.

3.1.2 Unreliability

Congestion can result in travel time becoming more uncertain, forcing travelers to allocate an even greater amount of time per trip than the average trip time in order to avoid being late to their destination. Reliability problems on the roadway can be the result of variations in demand caused by vehicle crashes, breakdowns, inclement weather conditions, or construction.

Reliability can be measured using a Buffer Time Index (BTI), which describes how much more time, above the average trip time, must be budgeted to keep the odds of being late down to a certain tolerance level, usually 5 or 10 percent. The UMR derives BTI values from its analysis of data from traffic monitoring stations in nearly 30 cities. Data are limited, however, to sampled portions of the freeway networks (generally the more congested portions). For each included urban area, BTI values are reported for the sampled portion of the network, however these values are not entirely comparable across areas because of differences in data collection, coverage, and data quality.

In this study, reliability was measured as the variability or standard deviation of travel time. In other words, reliability is the unpredictable day-to-day variation of travel times during the peak congested period. Figure 3 illustrates the structure and logic for estimating the cost of reliability due to congestion. The functional form for variability is as follows: [6]

$$Var = S_0 + \frac{S_1 - S_0}{1 + \exp(b\,(v/c - a))} \qquad \textbf{(EQ 3)}$$

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[5] The wage rates and benefits are based on BLS estimates, while inventory values for equipment and payload are based on a 2008 HDR study titled “Freight Benefits/Cost Study: Highway Freight Logistics Reorganization Benefits Estimation Tool Report and Documentation” FHWA-HOP-08-017 and on New York Department of Transportation 2004 CO CA manual.

[6] The functional form for trip variability was taken from a study conducted for Transfund New Zealand (Ensor 2002). The same functional form was used to measure travel time variability by the Australian Department of Transport and Regional Services.

Where;

Var = Variability (or the standard deviation)

S_1 = Maximum level of the standard deviation of travel time

S_0 = Minimum level of standard deviation of travel time (standard deviation at free flow speed)

V/C = Volume to capacity ratio

a, b = Constants that vary for freeways and arterials. The values used are listed in APPENDIX A

Equation (3) and the values for its parameters were taken from a study conducted for Transfund New Zealand. The study applied data on daily variation in traffic volumes on various road facilities to the relationship developed by Akçelik to predict travel speed as function of a facility's traffic volume and capacity. From analysis of the results, the study developed equation (3). Validation of the equation entailed comparison of its predictions with actual estimates of variability taken from travel time surveys for 5 routes in Auckland; the comparisons showed the magnitudes to be generally similar. The study cautions, however, that the estimates of variability do not include the effects of major incidents.

In applying this equation, the report estimated an overall V/C ratio for the arterials and freeways of each urban area. The ratio in each case was derived from the Akçelik equation, shown below. This speed flow relationship introduces a delay parameter, J_a, which captures the phenomenon of queuing. The following formulation describes the speed-flow relationship used in this study:

$$T = T_f + .025P. \left[(V/C - 1) + \sqrt{(V/C - 1)^2 + \frac{8\, J_a V/C}{C\, P}} \right] \qquad \textbf{(EQ 4)}$$

Where;

T = Average travel time

T_f = Travel time at free flow speed

J_a = Delay parameter

V/C = Volume to capacity ratio

C = Capacity

P = Flow analysis period

In this study, incident delays are netted out from the UMR estimates of speeds, using incident to recurrent delay ratios published by the same source,[7] for the purpose of using the speed-flow relationship.

In addition, freeway and arterial capacities were assumed to be constant (Table 1), with freeway capacity at 2,000 vehicle/hour/lane, while arterial capacity is assumed at 1,700 vehicle/hour/lane. The flow analysis period, P, is calculated as the peak period (8 hours) multiplied by the ratio of peak congested-VHT to peak period-VHT.

Table 1: Road Capacity

Road Type	Freeway	Arterial
Capacity (Vehicle/hour/lane)	2,000	1,700

Source: Travel time functions for transport planning purposes, 1991

Variability in travel time is assigned a dollar cost through the use of value of reliability ratios (VORs). Each ratio expresses the cost to travelers of a standard deviation in travel time relative to the cost per hour of expected (average) travel time. The values assumed for the ratios are 0.9 for personal travel, 1.3 for business travel, and 2.2 for truck travel, as prescribed by Small and Verhoef (2007). The denominators of the ratios, the values per hour of expected travel time, are those described in the previous section (3.1.1). The cost of reliability can thus be written as:

$$Total\ Cost\ of\ \mathrm{Re}liability = (Var - S_0) \times VOT \times VOR \times Peak\ Congested\ VMT \qquad \textbf{(EQ 5)}$$

Where, $Var\text{-}S_0$ is the variability caused by congestion.

This method of valuing trip variability is relatively conservative due to the fact that only one unit of variation (or one standard deviation) was used to estimate the cost of reliability. In addition, this method does not take into consideration that the cost of being late is greater than the cost of being early, according to research by Brownstone and Small (2003).

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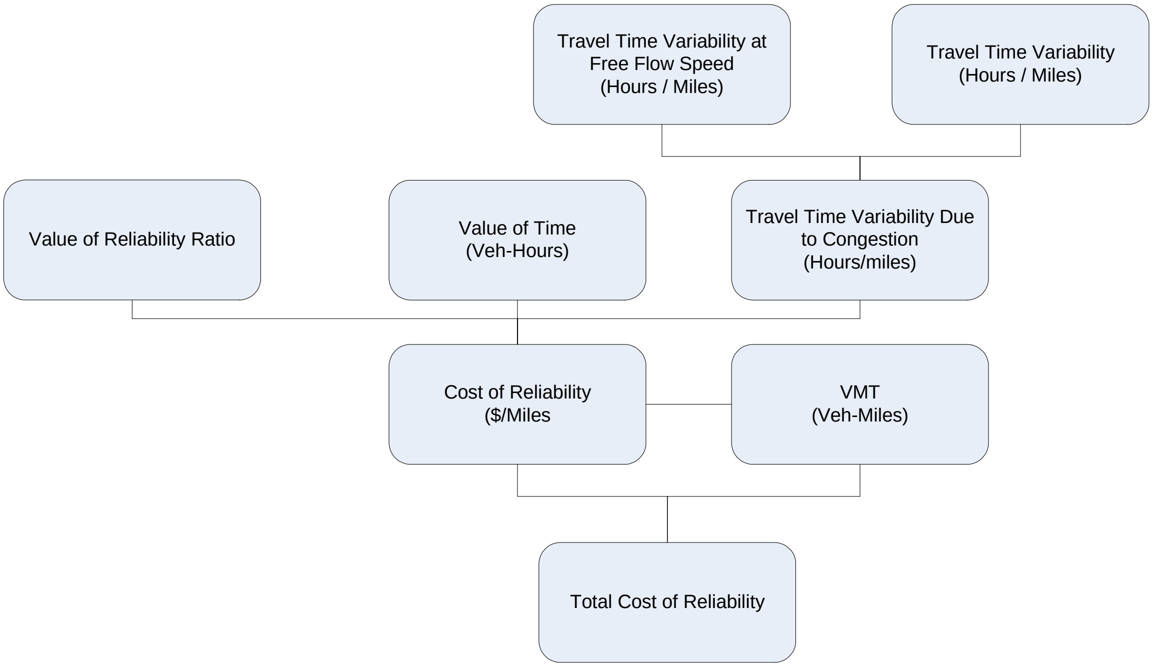
[7] The UMR published a ratio of incident to recurrent delays for the 85 areas. For arterials, the ratio was estimated as 1.1 for all areas, and for freeways, it varied between 0.7 in Los Angeles and 2.5 in New York City. A ratio of 1.1 would indicate that incident delays are estimated as 110% of recurrent delays.

Figure 3: Structure and Logic Diagram for the Cost of Reliability



3.1.3 Vehicle Operating Costs

Vehicle operating costs (VOC) are generally the most recognized congestion user costs because they typically involve the out-of-pocket expenses associated with owning, operating, and maintaining a vehicle. The cost components of VOC measured in this analysis include: fuel consumption, oil consumption, maintenance and repairs, tire wear, as well as vehicle depreciation. Figure 4 illustrates the structure and logic of the estimation of vehicle operating costs. The method used to estimate consumption rates as a function of speed, as well as unit prices of these components, is based on both the UMR for fuel consumption in addition to the Federal Highway Administration's Highway Economic Requirements System (HERS) for other components.[8]

To assess the effects of traffic congestion on vehicle operating costs, this study utilized data and information from several sources in order to develop vehicle operating cost usage rates in the current congested state and compared those rates to an un-congested highway system. In doing so, vehicle operating costs for five cost components were analyzed: fuel consumption, oil consumption, tire wear, vehicle depreciation, and maintenance and repair costs. These consumption components were calculated for both autos and trucks on arterials as well as freeways.

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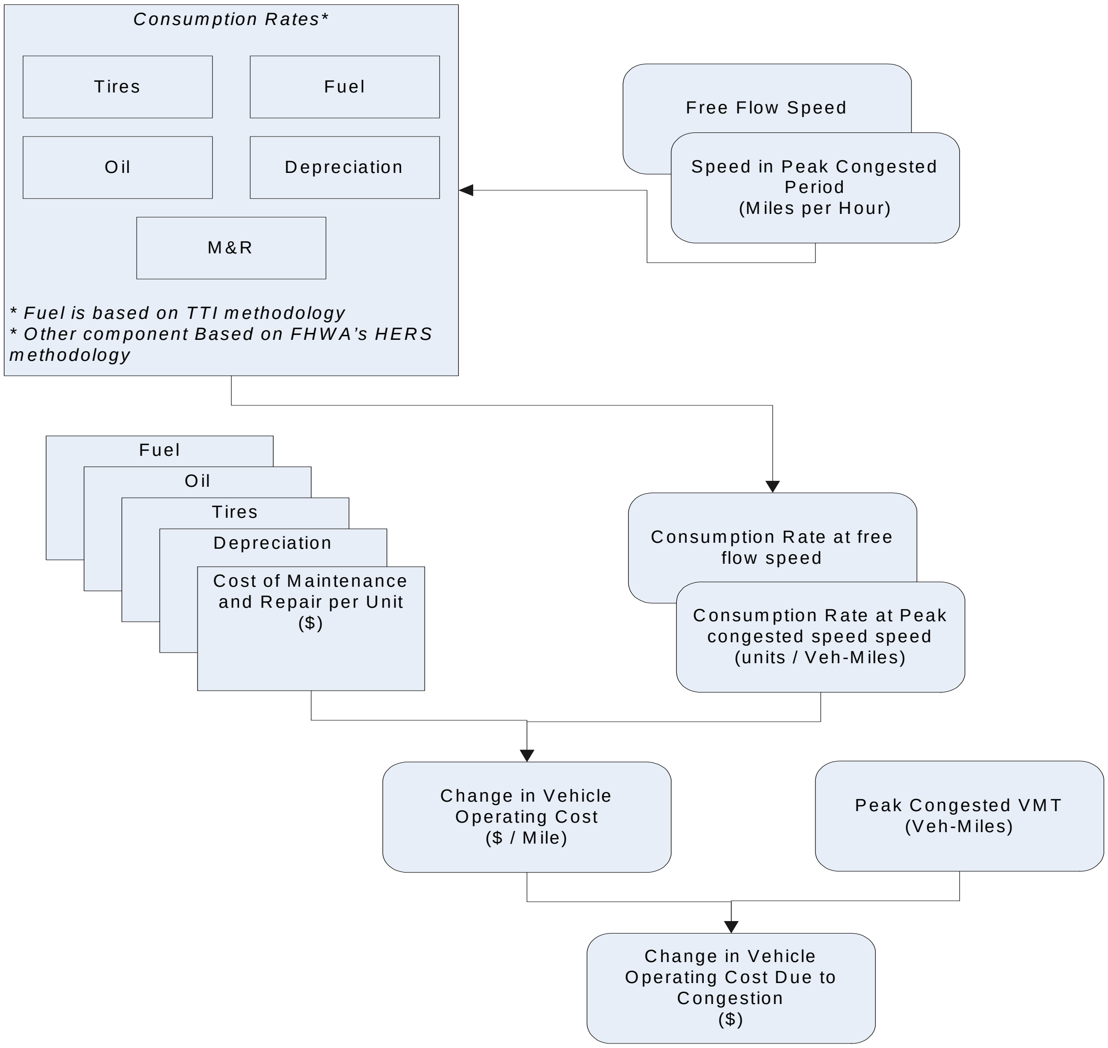
[8] Highway Economic Requirements System Technical Report, Federal Highway Administration, August 2005.

Figure 4: Structure and Logic Diagram for Vehicle Operating Cost



Average speeds during peak congested periods were derived from the average vehicle speeds reported by the UMR for the entire peak period, together with the UMR assumption that average speeds during the uncongested portion of the peak are at free flow speeds.

Using the peak congested speed estimates, this study referenced VOC component consumption rate equations as generated by the UMR for fuel and by the HERS model for other VOC components. The HERS VOC component consumption rate equations consist of two rates for each component; a constant speed component, and an excess rate component. Both rates were calculated and combined to generate an overall VOC component usage rate. The constant speed component rates (listed in APPENDIX A are strictly a function of vehicle speed and type. Meanwhile, the excess component usage rates are a function of vehicle speed cycles. Vehicle speed cycles are the slowing down and speeding up situations that arise during congested vehicle travel, sometimes referred to as “stop-and-go” travel. Furthermore, vehicle mix rates were also used to divide "autos" and "trucks" into more diverse classifications that are required for each HERS consumption rate table.[9]

By combining the constant speed and excess speed components, usage rates for congested travel was generated. Similarly by assuming the travel speeds were at free flow speeds with no congestion, overall VOC consumption rates were calculated for uncongested roadways. The difference in these rates, when weighted by each VMT affected by congested conditions, results in the aggregate consumption of VOC components due to congested roadway conditions. Finally, a risk analysis framework was used to create the monetization of aggregate wasted VOC consumption by applying unit consumption costs.

3.1.4 Reduced Mobility

Longer and less reliable travel times discourage the use of the road network for personal or business travel. The cost of this reduced mobility is modeled as the incremental consumer surplus shown in Figure 5. To estimate the demand curve for travel, we estimate for each travel purpose category the elasticity of demand for travel with respect to the generalized cost. For personal travel, the estimate varies across areas between -0.4 and -0.6. The methodology used to estimate the elasticity of demand for each area is presented in Appendix C. The estimate is largest for the New York urban area because of the availability of a relatively attractive transit alternative to car travel. For business travel in passenger vehicle, demand is likely less price-sensitive than for personal travel, which is more discretionary. Thus, we set the elasticity of demand for business travel (passenger vehicles) at 40% of the personal travel elasticity. For truck travel, the assumed elasticity is -0.97 for truck travel.[10] Generalized cost per vehicle-mile of travel, C, is defined as the sum of cost components:

$$C = \mathit{Time\ Cost} + \mathit{Vehicle\ Operating\ Cost} + \mathrm{Re}\mathit{liability\ Cost} \qquad \textbf{(EQ 6)}$$

An example of the costs of reduced mobility is the productivity losses that occur when congestion limits how far a commuter is willing to travel from home. Because of this constraint, workers will sometimes decline employment at workplaces where they would be productive. This along with other costs from reduced traveler mobility will be captured by our measure of consumer surplus.

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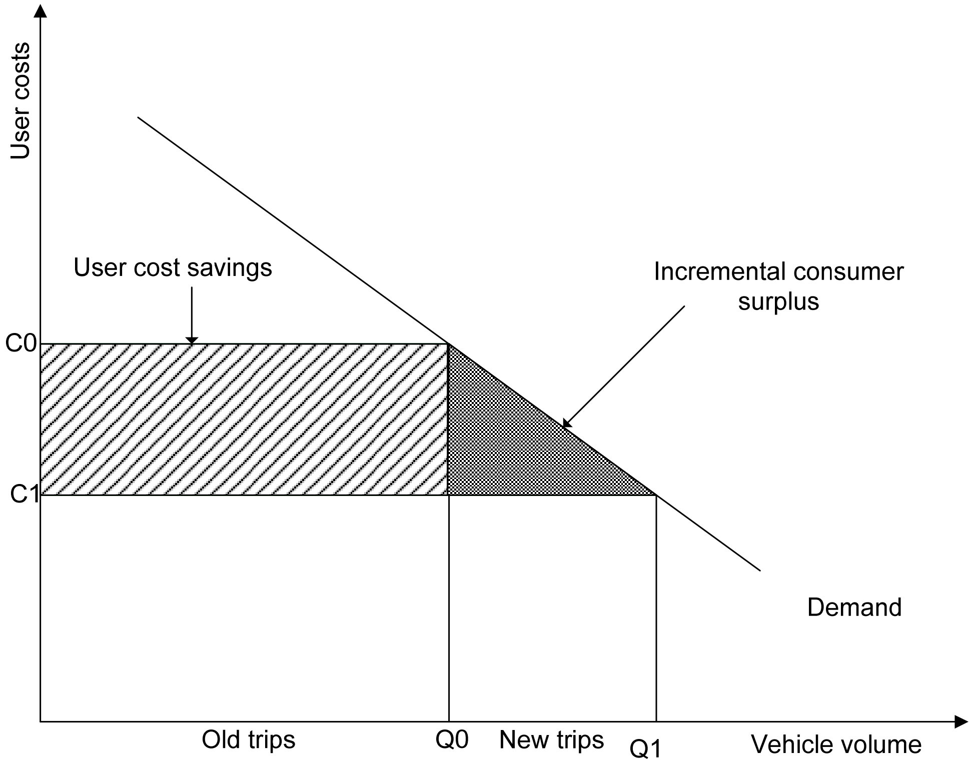
[9] Detail on vehicle mix used in this study as well as lookup tables for the excess consumption rate equations by cost component are presented in Appendix A.

[10] The elasticity estimates are based on a HDR study titled: "Freight Benefits/Cost Study: Highway Freight Logistics Reorganization Benefits Estimation Tool Report and Documentation" FHWA-HOP-08-017 and on a study by Graham and Glaister (2004). The methodology used to estimate the elasticity of demand for each metropolitan area is presented in Appendix C.

Figure 5: User Benefits and Consumer Surplus



3.1.5 Excess Emissions

Environmental costs are gaining increasing attention as an important component in the economic evaluation of congestion. The main environmental impact of vehicle use is exhaust emissions, which impose wide-ranging social costs. The negative effects of pollution depend not only on the quantity of pollution produced, but also on the types of pollutants emitted as well as the conditions into which they are released. Figure 6 describes the structure and logic of the estimation of emissions costs.

Emissions costs due to roadway congestion were assessed using emission consumption tables generated by the Environmental Protection Agency's (EPA) MOBILE 6 system,[11] except for California where the CAL-BC model consumption tables were used. Carbon dioxide emissions were calculated based on the amount of fuel expended and on relationships developed by the EPA for the number of grams of carbon dioxide burned per gallon of diesel or gasoline. Emissions for 6 types of pollutants were calculated, including volatile organic chemicals, carbon monoxide, nitrous oxides, sulfur oxide, particulate matter 10, and carbon dioxide.

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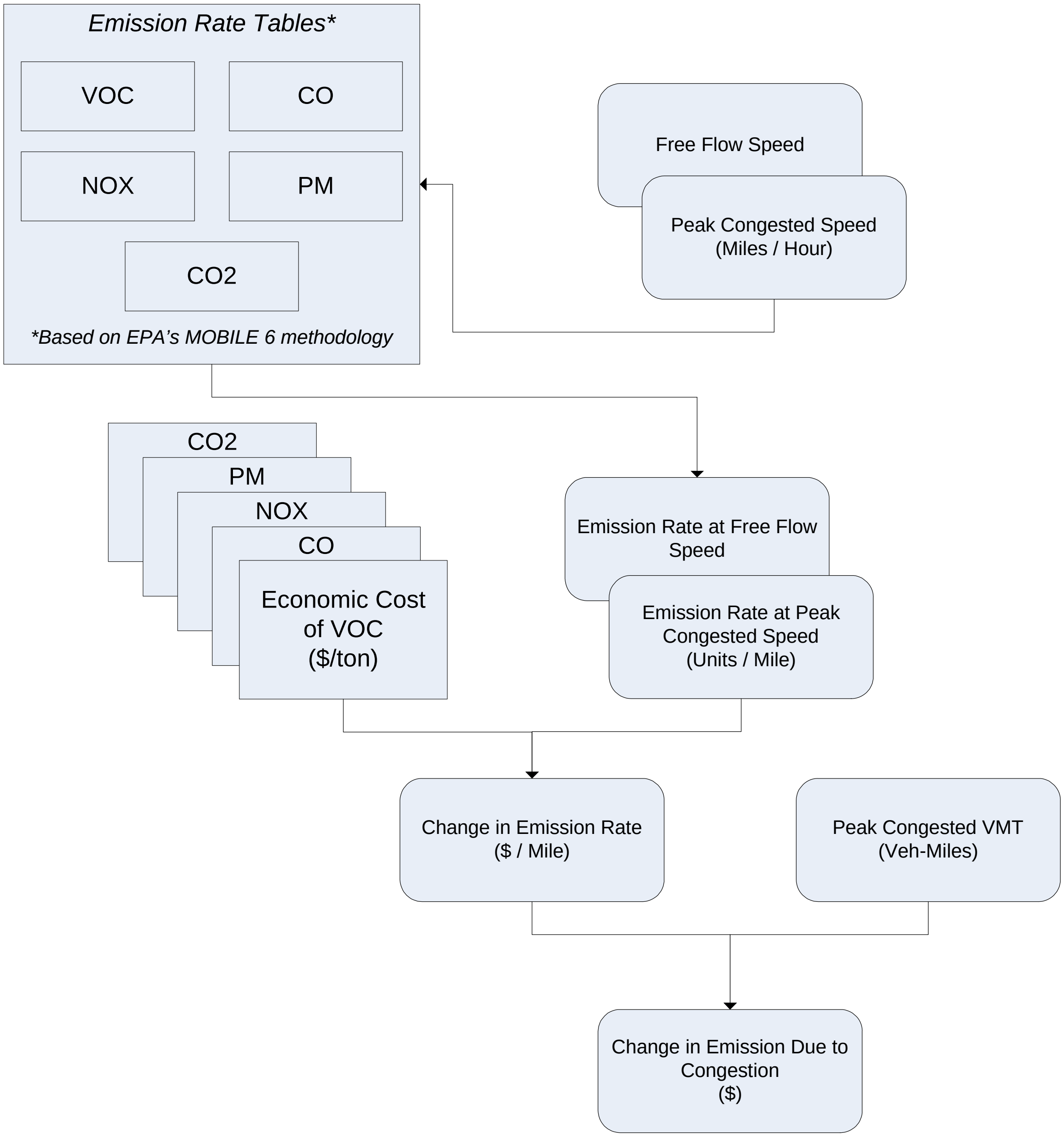
[11] Environmental Protection Agency MOBILE 6 Vehicle Emissions Modeling Software, http://www.epa.gov/OTAQ/m6.htm.

Figure 6: Structure and Logic Diagram for Emission Cost



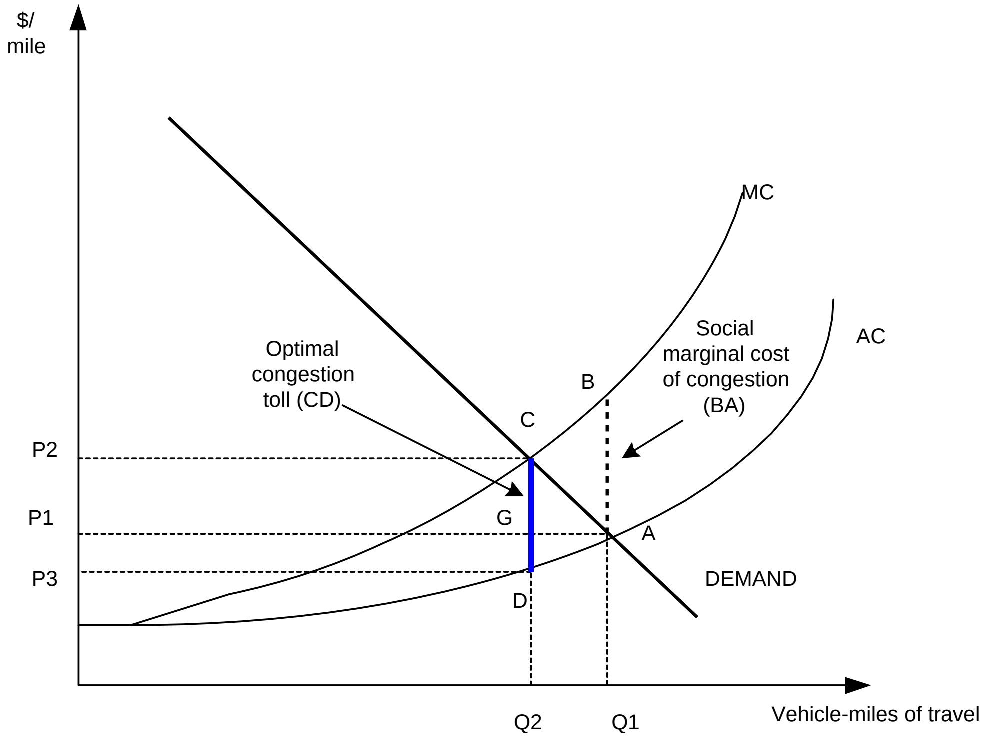
Using speeds for congested and un-congested states, emission rates per mile of vehicle travel were generated for all of the areas under analysis. Overall tons of emissions were calculated by multiplying the rate per mile by the overall vehicle miles traveled during congested conditions and by vehicle type. The differences in overall tonnage of each emission type between the congested and un-congested conditions were monetized using unit prices of each emission type.

3.2 Congestion Pricing

The cost estimates of congestion described in the previous section (3.1) are based on the excess cost incurred by actual traffic over those costs that would have occurred had that same traffic volume operated under completely free-flow conditions. These cost estimates are useful as trend indicators, when comparing traffic conditions over time, rather than a direct measure of actual savings in social costs that may possibly be made if congestion was reduced to an efficient level.

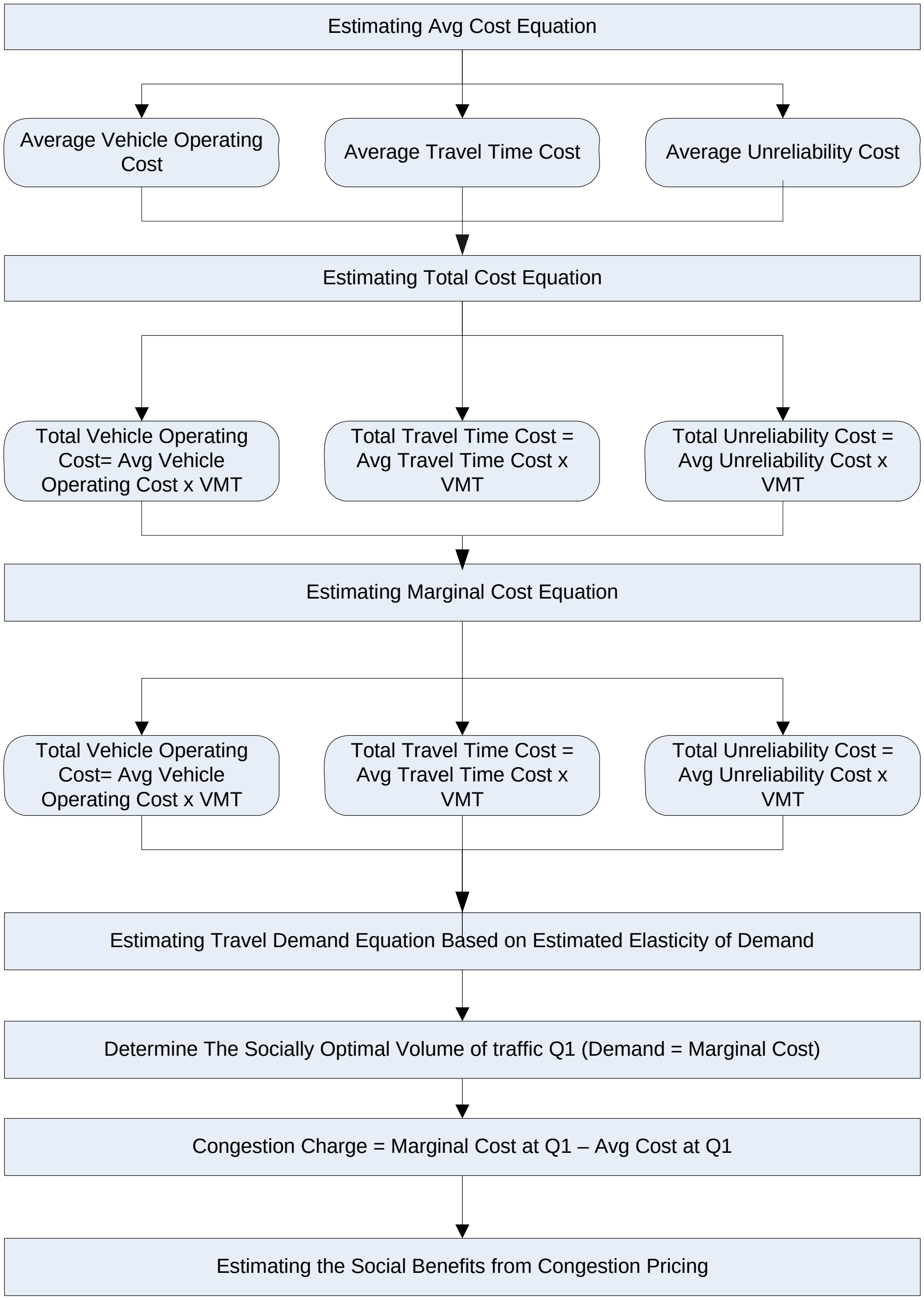
A better set of values to use are the estimated Deadweight Loss (DWL) values, or the avoidable social costs of congestion associated with a particular congestion level. The DWL values give an estimate of how much "total social costs" could be reduced if traffic volumes were reduced to an economically efficient level. Graphically DWL loss can be illustrated by a triangle area between the marginal cost curve and the demand curve at the market volume of travel (area CBA at the volume of travel equal to Q_1 in Figure 7).

Figure 7: Economic Analysis of Congestion Pricing



In assessing the impact of congestion pricing, all freeways and arterials in an urban area are treated as a single link, which could lead to under-estimation of benefits of congestion pricing. In our framework, congestion pricing produces zero benefit if the elasticity of demand is zero. In reality, even with no impact on total peak-period VMT, congestion pricing can have benefit by redistributing VMT from more to less congested portions of network. Figure 8 illustrates the methodology used for estimating the impact of congestion pricing.

Figure 8: Methodology Used for Estimating the Impact of Congestion Pricing



3.2.1 Derivation of Congestion Tolls

Tolls based on marginal costs represent the sum of marginal congestion costs imposed by a highway user on all other users. The “optimal congestion toll” is equal to the difference between the marginal cost and the average cost of highway use at the volume of traffic where the social marginal cost curve intersects the demand curve.

This approach is consistent with the traditional modeling of efficient road pricing, or congestion pricing, in economic literature. Additionally, this method reflects the observation that under congested road conditions each additional user entering the road imposes a cost on all other road users. This is mainly because each additional user slows down other drivers that are already on the road. In the absence of road pricing, this cost – a congestion cost – is not fully internalized by the road user. As a result, the volume of travel exceeds the efficient level, or the level that reflects full social costs of driving.

The imposition of tolls corrects for this inefficiency, and the congestion cost at the volume of travel where the social marginal cost curve intersects the demand curve represents the equilibrium congestion toll. This framework is illustrated in Figure 7.

Figure 7 shows the demand for car and truck trips, or the level of traffic (in terms of vehicle-miles), as a function of the cost of driving. The demand curve was derived based on the elasticity of travel demand with respect to the generalized cost. The functional form of the inverse demand curve is:

$$\text{Cost of driving} = aQ + b \qquad \textbf{(EQ 7)}$$

Where:

a is the slope,

Q is the level of traffic, and

b is the intercept.

The average cost of driving represents the unit cost faced by drivers. In this analysis, average cost of driving is comprised of fuel cost based on the UMR fuel consumption equation, travel time cost, and unreliability cost.

In the absence of tolls, the volume of travel is determined by the intersection of the private average cost curve and the demand curve. In Figure 7, this volume of travel is equal to Q_1.

Meanwhile, the Curve labeled MC in Figure 7 represents the marginal cost curve derived as the derivative of total costs of driving (which in turn is the product of average costs of driving times the volume of travel).

At the market equilibrium without congestion pricing, with traffic volume at Q_1, not all costs of driving are fully internalized by drivers. As mentioned earlier, each car entering the road imposes a cost on all other road users by contributing to the congestion and the reduction in travel speed. This cost is illustrated as the distance AB (distance between the average cost curve and marginal cost curve at Q1; see Figure 7).

The optimal volume of traffic is determined by the point where the marginal cost curve and the demand curve intersect. At this point the volume of traffic is Q_2. This traffic level is achieved by the use of a congestion toll in the amount of CD dollars per mile imposed on each vehicle. The quantitative magnitude of the optimal congestion cost as represented by the distance CD is derived using iterative procedure and assumptions with respect to the average cost curve, marginal cost curve, and the elasticity of travel demand as follows.

Average Cost of Driving:

The average cost of driving was measured inclusive of fuel and time. This cost can be expressed as:

$$AC = AC\ fuel + AC\ travel\ time + AC\ reliability \qquad \textbf{(EQ 8)}$$

Where;

AC fuel = is the average cost of fuel equation established by the UMR and is a function of travel time.

AC travel time = is the average cost of travel time and is a function of travel time (EQ 4) and the value of time.

$$AC\ Travel\ Time = T * VOT \qquad \textbf{(EQ 9)}$$

AC reliability = is the average cost of reliability and is a function of variability (EQ 3), value of time, and value of reliability ratio.

$$AC\ reliability = Var \times VOT \times VOR \qquad \textbf{(EQ 10)}$$

Marginal Cost of Driving:

The marginal cost curve is derives from the total cost curve as follows:

$$TC = AC \times \mathrm{Q} \qquad \textbf{(EQ 11)}$$

Where;

TC = total cost

Q = volume of travel or VMT

AC = average cost of driving, as defined earlier

Using the definition of marginal costs as the differential of total cost and the expression derived earlier we have:

$$\mathrm{MC} = \frac{\partial \mathrm{TC}}{\partial \mathrm{Q}} = \mathrm{AC} + \mathrm{Q} \, . \frac{\partial \mathrm{AC}}{\partial \mathrm{Q}} \qquad \textbf{or}$$

$$\begin{aligned} MC = {} & AC\,fuel + \\ & AC\ travel\ time + \\ & AC\ reliability + \\ & \left[\frac{\partial ACfuel}{\partial T}\cdot\frac{\partial T}{\partial Q}+\frac{\partial ACtravel\ time}{\partial T}\cdot\frac{\partial T}{\partial Q}+\frac{\partial ACreliability}{\partial Q}\right]\cdot Q \end{aligned} \qquad \textbf{(EQ 12)}$$

Where, MC is the marginal cost.

Finally, Deriving the Congestion Cost:

Consequently, the congestion toll and the optimal level of traffic charge were derived by finding the level of traffic Q_2 where demand curve interests the marginal cost (MC) curve.

$$MC(Q_2) = Demand(Q_2) \qquad \textbf{(EQ 13)}$$

3.2.2 Estimation of Deadweight Loss

The effects of market inefficiencies are often quantified in empirical research using the concept of deadweight loss (DWL) resulting directly from that inefficiency. The deadweight loss is a net loss in social benefits, or welfare that results because the benefit generated by an action is smaller than its cost.

Failure to charge for road congestion creates a loss in economic benefit for some marginal road users during the peak period– those who would not be willing to pay a toll if there was one – as the total costs that their road use creates, including congestion burdens on other travelers, exceed the total benefits these users derive from their highway use. In the case of transportation, this inefficiency consists primarily of travel delays and highway maintenance partially reduced by the consumer surplus to those road users who would not be on the road in the presence of road charges.

Deadweight loss is often referred to as “welfare triangle” since graphically, the deadweight loss can be illustrated by a triangular area between the marginal cost curve and the demand curve at the market volume of travel (area CBA at the volume of travel equal to Q1 in Figure 7). From that figure we can see that the DWL is the difference between the cost saved (the area below MC curve) and benefit forgone (the area below the demand curve) when reducing traffic from Q1 to the efficient level Q2. The DWL area is equal to the difference between area Q2CBQ1 and the area GCA plus area Q2GAQ1.

Q_2GAQ_1 the area underneath the MC cost curve is equal to

$$Q_2CBQ_1 = \mathrm{TC}\,(\mathrm{Q}_1) - \mathrm{TC}\,(\mathrm{Q}_2) \qquad \textbf{(EQ 14)}$$

Furthermore, area GCA is the consumer surplus to road users who are using the roads in the absence of tolls but who would not be using the roads after the introduction of tolls.

$$GCA = \frac{(\mathrm{AC}(\mathrm{Q}_1) - AC(Q_2)) \cdot (Q_1 - Q_2)}{2}$$ **(EQ 15)**

Finally, area Q_2GAQ_1 is the driving cost incurred by road users who are using the roads in the absence of tolls but who would not be using the roads after the introduction of tolls.

$$Q_2GAQ_1 = AC(Q_1) \cdot (Q_1 - Q_2)$$ **(EQ 16)**

4 ROADWAY CONGESTION FINDINGS

This chapter summarizes the findings of the analysis. Results are presented for the costs of congestion and the outcomes of the risk analysis for freeways and arterials. In addition, the results for congestion pricing are also presented together with the risk analysis for the 14 very large cities covered in this study.

4.1 Costs of Congestion

As discussed in the previous chapter, the cost categories included are: travel time, reliability, VOC, mobility, and emissions cost. Table 2 shows the annual cost of congestion for the five cost categories including both freeways and arterials. In addition, the annual costs per commuter, at the expected values, are also included. All cost values are expressed in 2008 dollars.

Table 2: Overall Annual Cost of Congestion

Category	Overall Total ($M)	Total per Commuter ($)
Travel time	$60,562	$541.35
Reliability	$10,098	$90.26
VOC	$11,251	$101
Emissions	$330	$2.95
Mobility	$3,155	$28.20
Overall Cost	$85,395	$763.33

While the over all cost of congestion in all urban areas is estimated at $85.4 billion, travel time represents the largest category at $60.6 billion, nearly 71 percent of total. Meanwhile vehicle operating costs are second contributor to the overall cost of congestion with $11.3 billion. Emissions costs on the other hand were the least contributor to the overall cost of congestion at an estimated at $330 million. At the same time, annual congestion costs were estimated at $763 per commuter, mainly due to a $541 in annual wasted travel time cost for each commuter.

Table 3 show the breakdown of the annual cost of congestion and the average annual cost per urban area divided by city size. Urban areas were divided into four main categories, representing very large, large, medium as well as small and other cities, similar to the breakdown adapted by the UMR. The annual congestion cost for very large cities amounts to $53.8 billion, which represents almost 62 percent of overall congestion cost in the United States. This mainly reflects the fact that congestion in very large cities such as Los Angeles, CA has a bigger impact on total congestion than medium or smaller cities such as Akron, OH. Meanwhile, the cost of wasted time (average time spent in traffic) is again the largest component across the four major size categories, with very large cities contributing $37.1 billion to the overall cost of congestion, or almost 44 percent.

Reliability-related costs nevertheless add appreciably the costs of wasted time—an estimated 17 percent nationally and 20 percent in the very large urban areas. These estimates are necessarily rough owing to limitations of available data on variability of travel times, and are likely conservative owing to our reliance on a methodology that excludes the effects of major traffic incidents. Nevertheless, our estimates are in the same ballpark as estimates from other studies. A study of road congestion costs in large Australian cities, using a similar methodology, found that reliability-related costs added about 25 percent to the cost of wasted time (BTRE 2007, p.95). Another point of comparison is the estimate, discussed in Chapter 2, that cordon pricing in Stockholm produced benefits in improved reliability that amounted to 15 percent of the benefits in time savings.

Table 3: Annual Cost of Congestion by City Size

Category	Total Very Large Cities ($M)	Total Large Cities ($M)	Total Medium Cities ($M)	Total Small & Other Cities ($M)
Travel time	$37,135	$12,060	$4,312	$7,055
Reliability	$7,311	$1,474	$141	$1,172
VOC	$5,658	$2,336	$1,151	$2,107
Emissions	$237	$49	$11	$32
Mobility	$2,508	$475	$84	$87
Overall Cost	$52,849	$16,394	$5,699	$10,453

Table 4 illustrates the annual average cost per urban are, with congestion costing a typical very large urban area an estimated $3.78 billion per year. On the other hand, small cities and towns face a much lower cost of congestion, averaging at $30 million annually.

Table 4: Annual Average Cost per Urban Area by Size

Category	Total Very Large Cities ($M)	Total Large Cities ($M)	Total Medium Cities ($M)	Total Small & Other Cities ($M)
Travel time	$2,653	$482	$144	$19
Reliability	$522	$59	$5	$3
VOC	$404	$93	$38	$6
Emissions	$17	$2	$1	$1
Mobility	$179	$19	$3	$1
Overall Cost	$3,775	$655	$191	$30

In comparing congestion costs estimates in this study to those of the UMR, it is important to note that the overall cost of congestion in this report was estimated to be 9.2 percent higher than that of the UMR. The differences are even greater when comparing very large cities, where the cost of congestion was estimated at $52.8 billion, or 17.7% higher than the UMR estimates. On the other hand, estimates of the cost of congestion for medium and small cities are smaller because unlike the UMR, this study utilizes differing value of time for each city.[12] As a result, medium and small cities tend to have a value of time that is smaller than the one used across the board by the UMR, ($14.60 per hour) see Table 5.

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[12] In this study as mentioned in the methodology value of time was based on the wage rate published by the BLS.

Table 5: Cost of Congestion Compared to the UMR

Category	Cost of Congestion (HDR)	UMR	Var (%)
Overall Total ($M)	$85,395	$78,200	9.20%
Very Large Cities ($M)	$52,849	$44,900	17.70%
Large Cities ($M)	$16,394	$15,700	4.42%
Medium Cities ($M)	$5,699	$6,200	-8.08%
Small & Other Cities ($M)	$10,452	$11,400	-8.31%

Table 6 shows the breakdown of the cost of congestion by categories (travel time, reliability, VOC, emissions, and mobility), along with the total cost that these categories generate, at the expected values for the 14 largest and most congested urban areas in the United States. The Los Angeles urban area has by far the largest total congestion cost, amounting to $12.8 billion annually, followed by New York at $7.5 billion. For the Los Angeles urban area (which includes Orange County), a possible point of comparison is the estimate from Small, Winston, and Yan (2005) that users of the tolled express lanes on SR 91 in Orange County derive benefits that consist one-third of improved reliability and two-thirds of time savings. From Table 6, the ratio of reliability to travel time costs in the Los Angeles area is about the same, 30 percent.

Table 6: Cost of Congestion for Very Large Cities ($M)

City/Group	Travel time	Reliability	VOC	Emissions	Mobility	Overall Cost
Los Angeles-Long Beach-Santa Ana, CA	$8,277	$2,396	$1,191	$122	$783	$12,768
New York-Newark, NY-NJ-CT	$5,566	$745	$815	$11	$362	$7,499
Chicago, IL-IN	$3,244	$880	$465	$10	$302	$4,900
San Francisco-Oakland, CA	$2,541	$691	$331	$25	$197	$3,785
Washington, DC-VA-MD	$2,604	$344	$302	$10	$140	$3,400
Atlanta, GA	$2,055	$425	$340	-$1	$126	$2,944
Dallas-Fort Worth-Arlington, TX	$1,951	$385	$353	$10	$99	$2,798
Miami, FL	$2,072	$197	$363	$19	$104	$2,755
Detroit, MI	$1,707	$151	$304	$14	$61	$2,238
Houston, TX	$1,688	$324	$304	$8	$91	$2,414
Philadelphia, PA-NJ-DE-MD	$1,546	$100	$273	$7	$51	$1,977
Boston, MA-NH-RI	$1,454	$133	$234	-$2	$49	$1,869
Phoenix, AZ	$1,250	$241	$200	$5	$70	$1,765
Seattle, WA	$1,182	$301	$182	$0	$72	$1,737

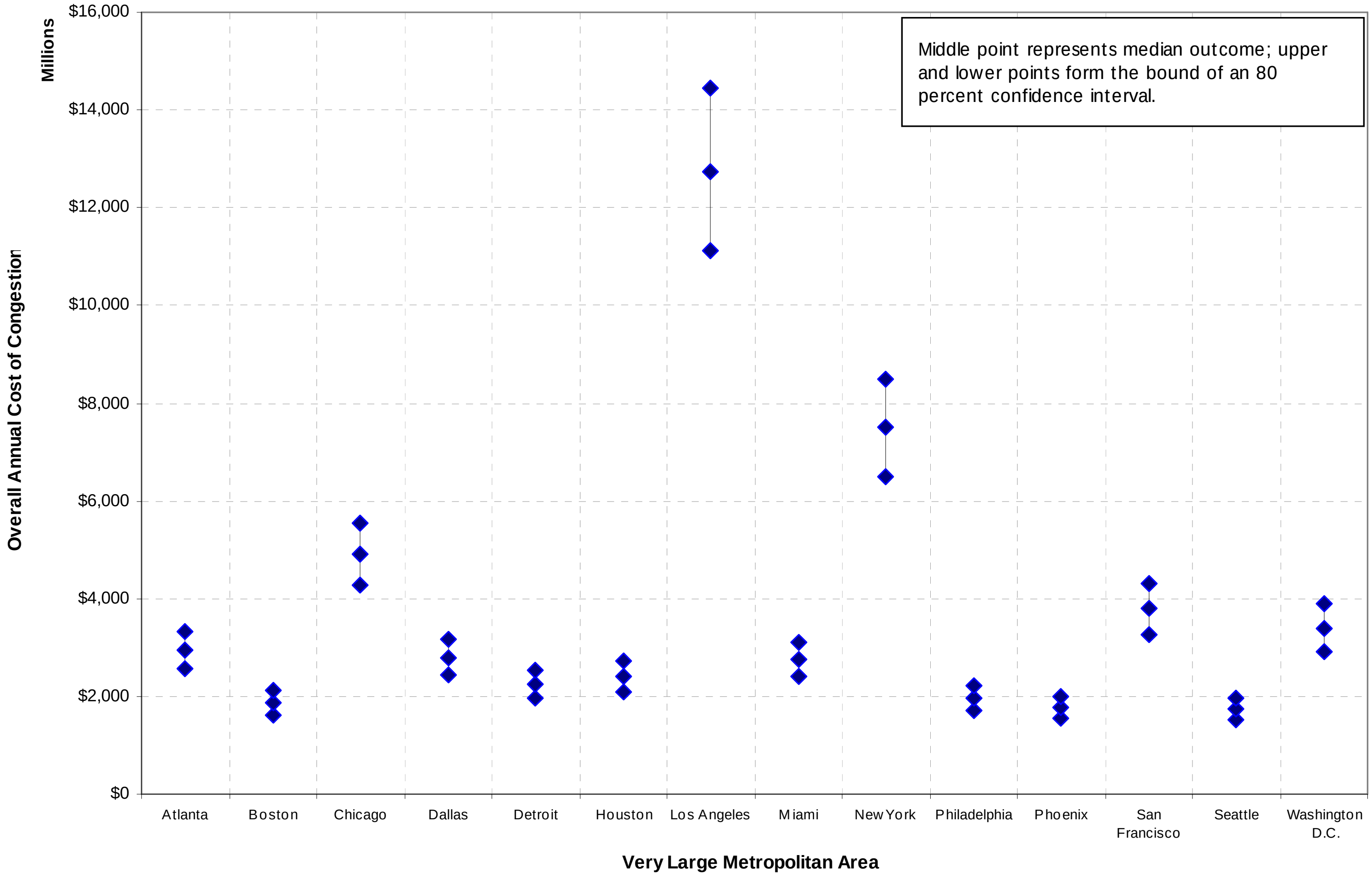
4.2 Cost of Congestion Risk Analysis Results

Economic forecasts traditionally take the form of a single “expected outcome” supplemented with alternative scenarios. The limitation of a forecast with a single expected outcome is clear - while it may provide the single best statistical estimate, it offers no information about the range of other possible outcomes and their associated probabilities. The problem becomes acute when uncertainty surrounding the forecast’s underlying assumptions is material.

Risk Analysis provides a way around the problems outlined above. It helps avoid the lack of perspective in “high” and “low” cases by measuring the probability or “odds” that an outcome will actually materialize. This is accomplished by attaching ranges (probability distributions) to the forecasts of each input variable, such as fuel prices and the value of time. The approach allows all inputs to be varied simultaneously within their distributions, thus avoiding the problems inherent in conventional sensitivity analysis. The approach also recognizes interrelationships between variables and their associated probability distributions.

Figure 9 illustrates the ranges, with 80% confidence, of what the actual cost of congestion would be for each very large city, given uncertainties in unit costs and value of times used. The chart depicts the median, or 50% probability level, bounded by an 80% confidence interval for each of the very large city. In other words, based on the analysis, there is an 80% probability that the realized cost will fall within that range. Conversely, this also means that there is only a 20% chance that the true total cost will fall outside of the ranges in the graph.

Figure 9: Risk Analysis of the Cost of Congestion for the Very Large Cities



4.3 Congestion Pricing

In this study, a congestion pricing model was built only for very large and large cities since they are the ones that are greatly affected by congestion and will significantly benefit from a reduction in congestion. In this analysis, congestion pricing was applied on freeways and arterials based on peak congested VMT. This section presents the results of the model. The incident to recurrent delay ratios, from the UMR, for each urban area is treated as constant, so that congestion pricing reduces them both in equal proportion.

Table 7 shows the average peak toll that would be charged on freeways to reduce traffic to its efficient level, in addition to the new speeds achieved and the percent reduction in traffic. Evaluated at the expected value, the average toll that should be charged to obtain an efficient level of traffic, where each trip provides benefits at least as great as its marginal cost, is estimated at $0.35 per mile for very large cities and $0.26 per mile for large cities. In addition, this congestion charge improves the roadway speeds by 47 percent in very large cities, while decreasing average VMT by only 8.9 percent.

Table 7: Freeway Congestion Pricing

Category	Avg Peak Toll weighted by VMT, $/mile	Original Speed, miles/hour	Speed After Congestion Pricing, miles/hours	Average Percent Decrease in VMT
Very Large Cities	$0.35	37.82	55.73	8.92%
Large Cities	$0.26	42.73	56.03	8.90%

Table 8 shows the summary of congestion pricing for arterials. Evaluated at the expected value, the average toll that needs to be charged to bring traffic to its efficient level, where social costs equal the benefits generated is about $0.22 per mile for both very large and large cities. Additionally, arterial speeds in very large cities are estimated to improve by 37 percent, while average VMT is expected to decrease by 8.58 percent.

Table 8: Arterials Congestion Pricing

Category	Avg Peak Toll weighted by VMT, $/mile	Original Speed, miles/hour	Speed After Congestion Pricing	Average Percent Decrease in VMT
Very Large Cities	$0.22	24	33	8.58%
Large Cities	$0.22	25	33	8.29%

Additionally, the social benefits that could be gained from congestion pricing, described as the dead weight loss of current traffic, are estimated at $13.9 billion annually in very large cities, which amount to $620 per commuter. Large cities on the other hand stand to gain an estimated $3.6 billion annually, or $255 per commuter.

Table 9: Social Gain from Congestion Pricing

Category	Annual Social Gain From Congestion Pricing, $M	Avg Annual Social Gain From Congestion Pricing per commuter, $
Very Large Cities	$13,954	$620
Large Cities	$3,598	$255

Table 10 and Table 11 present in detail the result of congestion pricing on freeways and arterials, respectively, for each of the 14 very large cities under study. The allowance for vehicle operating cost is limited to fuel, since the relationship between other components and speed proved problematic in our analysis. Consideration of the fuel costs resulting from congestion adds only a few cents to the congestion charges that are justified by the time costs.

For freeways the time-based charges vary from 17 cents per mile in Detroit to 28 cents per mile in Los Angeles; for arterials, the variation is from 16 cents in Phoenix to 29 cents in New York. The small contribution of fuel costs to the congestion charges is consistent with Mohring and Anderson (1994), which found quasi-optimal charges in the Twin Cities region to be insensitive to the inclusion of vehicle operating costs.

For freeways, the contribution of reliability-related costs to our estimates of congestion charges varies greatly among urban areas, from a penny per mile in New York and Philadelphia to 14 cents in Los Angeles. This variation stems partly from variation in the values of travel time, but more from differences in the volume-to-capacity ratio during the congested peak period in the new equilibrium (with congestion pricing in place).

Among the cities compared, the volume-to-capacity ratio is lowest in New York and Philadelphia. Given the curvature of the relationship we are using between the amount of unreliability (standard deviation of travel time) and the volume-to-capacity ratio, the differences in VCR produce sharp differences in the marginal impact of traffic on reliability cost.

The particular relationship we used, taken from a New Zealand study, was based on a particular speed-flow curve (derived by Akçelik), and represents only a rough attempt to incorporate reliability into static travel demand models. More realistic relationships that may be developed in the future could notably have different curvature properties. For arterials, the reliability component of the toll is very insignificant because the incident to recurrent delay is high in all areas.[13]

The congestion charges derived from this model are also dependant on the use of a single number for each urban area, an estimated average, to describe traveler values of time. In this model, the congestion charge has to reduce demand for peak-period travel by the amount needed to raise average peak-period speed to the new, relatively uncongested level. The model also implicitly assumes that travelers deterred by the congestion charge

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[13] The UMR published a ratio of incident to recurrent delays for the 85 areas. For arterials that ratio was estimated as 1.1 for all areas, and freeway it varied between 0.7 in Los Angeles and 2.5 in New York City. A ratio of 1.1 would indicate that incident delays are estimated as 110% of recurrent delays.

value their travel time on average by the same amount as the undeterred travelers (who remain on the roads during the peak period). In reality, travelers priced off the road during the peak period are likely to have below-average values of time. Many of these travelers will switch their peak-period mode to transit, which being typically slower than car travel, tends to attract those with relatively low values of time. Moreover, at a low value of time, willingness to pay a congestion charge for peak-period travel by car (in lieu of the slower transit alternative) will also be comparatively low. Accordingly, the congestion charge we estimate based on a uniform value of time will likely exaggerate the average charge that would result from quasi-optimal pricing.

Despite this and other limitations of the framework being used, estimates of net benefits from comprehensive congestion pricing are of the right order of magnitude. For example, the estimate of the welfare gain for the Washington, D.C. area is $755 million (the sum of the entries for freeways and arterials in Tables B1 and B2), which compares to the estimate of $558 million derived from the far more elaborate model used by Safirova, Houde, and Harrington (2007). Some of the modest difference would stem from the present study’s use of more current reference years - 2005 for traffic and 2008 for prices versus 2000 in the other study.

Table 10: Freeway Congestion Tolls for Very Large Cities

Category	Peak Toll ($/mile)	Toll by Components, ($/mile)			Original Speed	Speed After Congestion Pricing	Percent Decrease in VMT
		voc	Time	Reliability			
Los Angeles-Long Beach-Santa Ana CA	$0.45	$0.03	$0.28	$0.14	32.47	55.80	8.18%
New York-Newark, NY-NJ-CT	$0.31	$0.03	$0.27	$0.01	35.13	54.66	10.71%
Chicago, IL-IN	$0.37	$0.03	$0.26	$0.09	36.32	56.01	8.58%
San Francisco-Oakland, CA	$0.41	$0.03	$0.29	$0.09	36.46	55.87	8.58%
Washington, DC-VA-MD	$0.35	$0.02	$0.27	$0.06	40.43	56.22	8.72%
Atlanta, GA	$0.31	$0.03	$0.24	$0.05	38.92	55.86	8.78%
Dallas-Fort Worth-Arlington, TX	$0.35	$0.03	$0.26	$0.06	34.69	55.19	8.67%
Miami, FL	$0.25	$0.03	$0.19	$0.04	39.99	56.03	8.64%
Detroit, MI	$0.21	$0.02	$0.17	$0.02	43.89	56.25	8.77%
Houston, TX	$0.34	$0.03	$0.23	$0.07	35.94	55.77	8.41%
Philadelphia, PA-NJ-DE-MD	$0.24	$0.02	$0.21	$0.01	39.97	55.28	10.12%
Boston, MA-NH-RI	$0.31	$0.03	$0.25	$0.03	39.08	55.60	9.36%
Phoenix, AZ	$0.33	$0.03	$0.23	$0.07	37.61	55.91	8.47%
Seattle, WA	$0.32	$0.03	$0.25	$0.04	38.57	55.75	8.93%

Table 11: Arterials Congestion Tolls for Very Large Cities

Category	Peak Toll ($/mile)	Toll by Components, ($/mile)			Original Speed	Speed After Congestion Pricing	Percent Decrease in VMT
		voc	Time	Reliability			
Los Angeles-Long Beach-Santa Ana, CA	$0.19	$0.01	$0.17	$0.00	24.53	33.31	7.54%
New York-Newark, NY-NJ-CT	$0.31	$0.02	$0.29	$0.00	23.31	32.14	11.95%
Chicago, IL-IN	$0.22	$0.01	$0.21	$0.00	22.77	33.13	9.00%
San Francisco-Oakland, CA	$0.25	$0.01	$0.23	$0.00	23.97	33.14	8.54%
Washington, DC-VA-MD	$0.28	$0.01	$0.26	$0.00	23.43	33.09	8.71%
Atlanta, GA	$0.21	$0.01	$0.19	$0.00	24.95	33.05	7.98%
Dallas-Fort Worth-Arlington, TX	$0.19	$0.01	$0.18	$0.00	25.76	32.98	7.56%
Miami, FL	$0.20	$0.02	$0.18	$0.00	23.69	32.99	8.34%
Detroit, MI	$0.23	$0.02	$0.21	$0.00	23.99	32.87	8.50%
Houston, TX	$0.17	$0.01	$0.15	$0.00	25.36	33.22	7.20%
Philadelphia, PA-NJ-DE-MD	$0.27	$0.02	$0.25	$0.00	24.43	32.32	10.18%
Boston, MA-NH-RI	$0.25	$0.01	$0.24	$0.00	24.98	32.84	9.12%
Phoenix, AZ	$0.18	$0.01	$0.16	$0.00	25.86	33.31	7.30%
Seattle, WA	$0.21	$0.01	$0.20	$0.00	25.55	33.08	8.11%

4.4 Congestion Pricing Risk Analysis Results

The estimates of optimal peak tolls for very large areas were subjected to the same sort of risk analysis as was conducted for the total cost of existing congestion (section 4.2). The uncertain elements the analysis accounts for are the fuel price and the value of travel time. Tables 12 and 13 in addition to Charts 10 and 11 illustrate the risk analysis ranges, with 80% confidence, of what the actual congestion pricing should be for each very large city, given uncertainties. The tables and charts depict the median, or 50% probability level, bounded by an 80% confidence interval for each of the very large cities. In other words, based on the analysis, there is an 80% probability that the realized congestion price should fall within that range for efficient level of traffic.

Table 12: Risk Analysis of Freeway Peak Toll

City	Peak Toll, ($/mile)		
	10%	50%	90%
Atlanta	0.28	0.32	0.36
Boston	0.27	0.31	0.36
Chicago	0.33	0.38	0.43
Dallas	0.31	0.36	0.41
Detroit	0.19	0.22	0.24
Houston	0.30	0.35	0.39
Los Angeles	0.40	0.46	0.52
Miami	0.22	0.26	0.29
New York	0.27	0.31	0.35
Philadelphia	0.22	0.25	0.28
Phoenix	0.29	0.34	0.38
San Francisco	0.36	0.42	0.48
Seattle	0.28	0.33	0.37
Washington D.C.	0.31	0.36	0.41

Table 13: Risk Analysis of Arterial Peak Toll

City	Peak Toll ($/mile)		
	10%	50%	90%
Atlanta	0.18	0.21	0.25
Boston	0.22	0.26	0.32
Chicago	0.20	0.23	0.26
Dallas	0.17	0.20	0.24
Detroit	0.21	0.24	0.28
Houston	0.15	0.17	0.21
Los Angeles	0.17	0.19	0.23
Miami	0.17	0.20	0.23
New York	0.27	0.32	0.37
Philadelphia	0.24	0.28	0.34
Phoenix	0.16	0.18	0.22
San Francisco	0.22	0.25	0.30
Seattle	0.19	0.22	0.26
Washington D.C.	0.24	0.29	0.34

Figure 10: Risk Analysis Graph for Highway Congestion Pricing

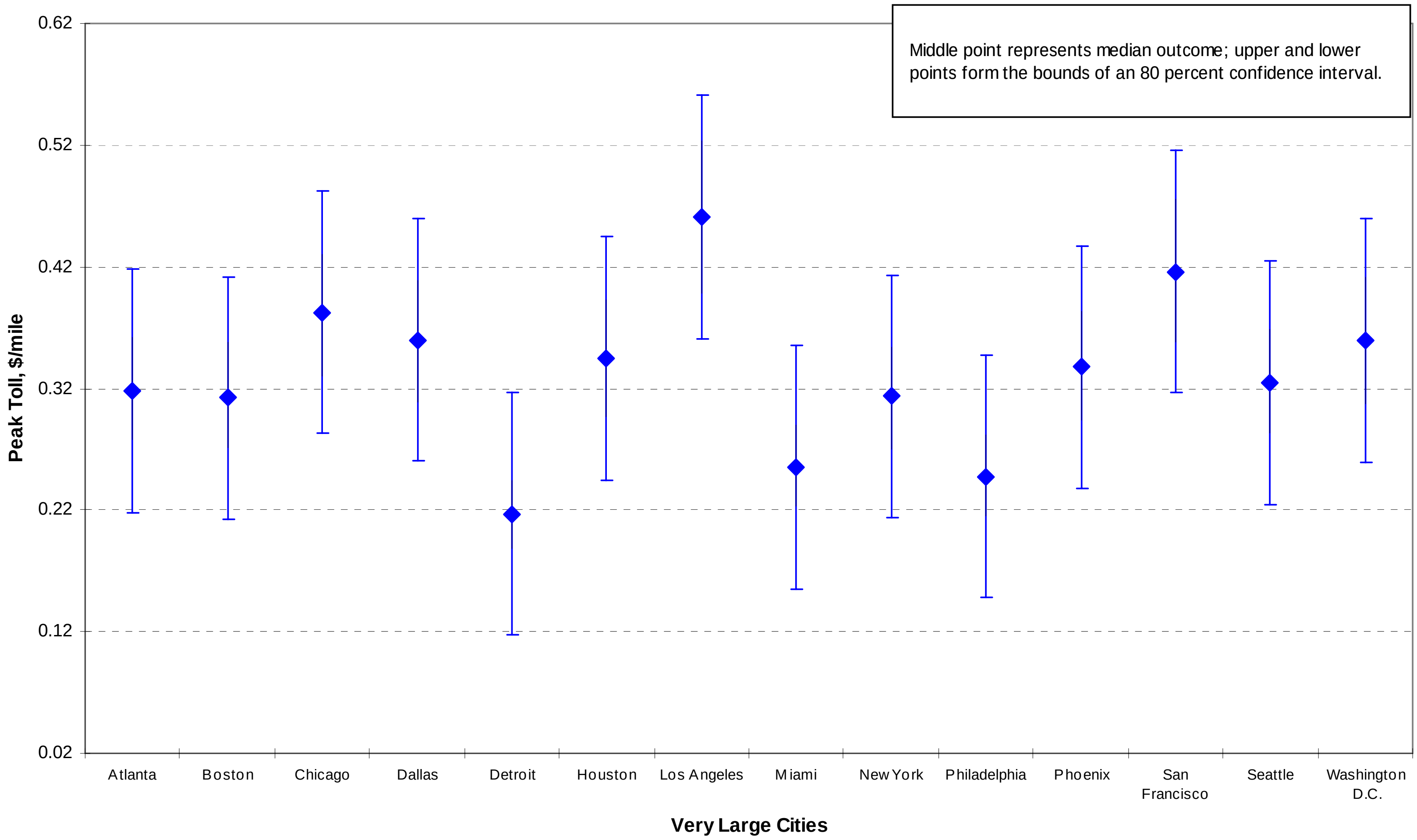
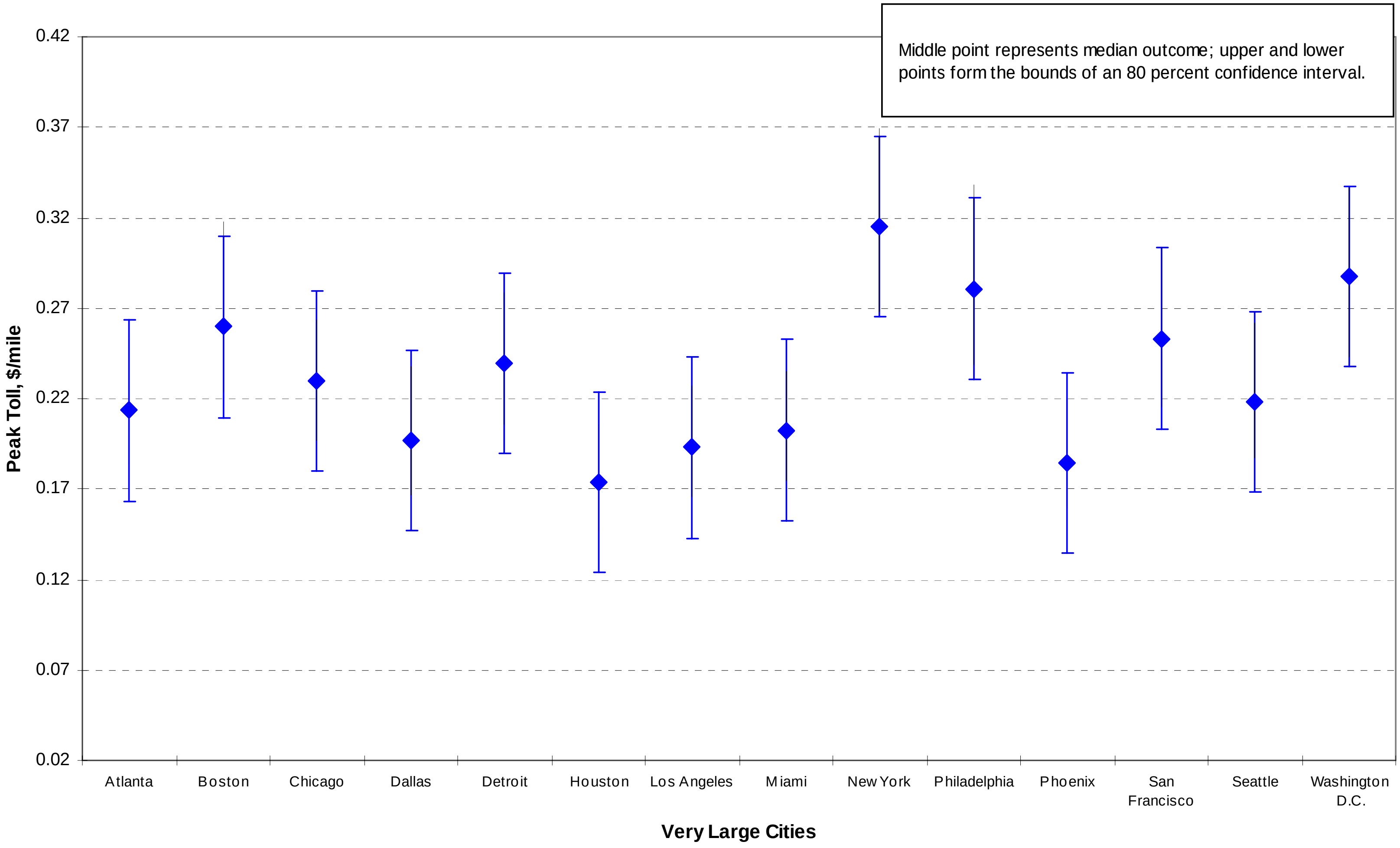


Figure 11: Risk Analysis Graph for Arterial Congestion Pricing



5 CONGESTION ON OTHER TRANSPORTATION MODES

While there is a considerable amount of literature discussing road congestion pricing, the same does not hold true for other modes of transportation such as rail freight, public transit, and inland waterways. In addition, the issues pertaining to congestion pricing for these modes are somewhat different to those of road pricing. For one thing, these are network-based modes, with stations and ports, and generally consist of hub-and spoke connectivity. Furthermore, unlike roads and highways with many individual infrastructure users and operators, these modes of transportation services are usually produced by a much smaller pool of economic agents.

The lack of publicly available data is also an important impediment to determining the cost of congestion outside the road network. This shortcoming is especially pronounced in the inland waterway networks, where detailed information on passing time is often unavailable, making traffic flow measurements difficult. In the discussion to follow, the report looks at the issues concerning congestion pricing for these other modes of transportation, with particular emphasis on the relevance of congestion pricing as a public policy, and the extent to which it is currently practiced.

5.1 Public Transit

The public transportation system in the United States is a $44 billion industry,[14] encompassing more than 6,500 providers of public and community transportation services, including buses, and commuter trains. Time-based differential pricing is sometimes used in public transit to relieve peak-time congestion and encourage a shift in the pattern of demand. This is mainly due to overcrowding on metro rail, buses, and stations during peak hours, which negatively impact service quality and safety. To increase ridership during off peak hours, lower fares are sometimes used to encourage greater utilization of the public transit network throughout the day.

Of the 20 major transit authorities in the United States, only four utilize time-based differential pricing, namely those in Washington, D.C., Seattle, Minneapolis/St. Paul, and Pittsburg.[15] Peak period pricing varies from 4% to as much as 66% greater than off-peak fares, with three transit systems incorporating distance-based pricing into the overall fare. While this type of congestion pricing in public transit could be perceived to have a negative impact on road congestion by shifting demand from public transit to roads and highways, a study by the Victoria Transport Policy Institute demonstrated that peak-period transit travel is relatively inelastic.[16] Moreover, the rail transit fare elasticity (such

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[14] Facts on Public Transportation, American Public Transportation Association, http://www.publictransportation.org/facts/

[15] Exploring the Merits of a Time-Based Fare Structure for Transit, Presentation by Matt Smith for Transport Chicago, Illinois Institute of Technology, June 1, 2007. http://cta21.utc.uic.edu/Presentations/TransportChicago07/Matt%20Smith.pdf

[16] Transit Price Elasticities and Cross-Elasticities, Todd Litman, Victoria Transport Policy Institute, 17 August 2007. http://www.vtpi.org/tranelas.pdf

as metro) is typically about half that of bus fare elasticity.[17] Additionally, rider sensitivity to fare changes appears to decrease with increasing city size, while off-peak transit ridership exhibits roughly twice the sensitivity to fare changes of peak period ridership. All of which suggests that public transit congestion pricing works best on rail systems.

Nonetheless, it is important to consider public transit congestion pricing as part of a comprehensive congestion policy that includes roads, highways, as well as transit. Furthermore, with transit authorities facing financial strains and pressure on local governments to reduce subsidies, congestion pricing strategies could provide the necessary mechanism to raise revenues. Finally, economic theory indicates that a uniform fare structure is not optimal since it doesn't account for varying operating costs throughout the day and doesn't take into account rider's willingness to pay at different times. Despite that, a number of the nation's largest transit systems (including New York, Chicago, and Los Angeles) implement market-based uniform fare pricing mechanisms, while an differential pricing scheme (like the one in Washington, D.C.) might be more appropriate.

5.2 Freight Rail

The nation's 140,000-mile network of rails devoted to carrying everything from cars to grain by freight rail is already suffering under the strain of congestion, with trains forced to stand aside for hours because of one-track rail lines. Furthermore, bottlenecks at key hubs like Chicago, which handles about 40 percent of all rail freight, equaling 180,000 trains a year,[18] is contributing to the ripple effect. This congestion negatively impacts not only producers, shippers, and receivers, but also passenger traffic and individuals living in congested areas.

While freight rail tonnage represents only around 12% of total freight shipments,[19] it is estimated that 42% of inter-city freight, measured in ton miles, moves on rail lines. In addition, freight rail is particularly important for certain industries, where 70% of automobiles manufactured domestically, 70% of coal delivered to power plants, and 32% of grain moves by freight rail.[20] Moreover, the U.S. Chamber of Commerce estimates that expanding capacity on the more than 150-year-old rail system would cost $148 billion over 30 years, with private rail companies paying for most of it.

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[17] Transit Pricing and Fares: Traveler Response to Transportation System Changes, McCollom, B. and Pratt, R., TCRP Report 95, Transportation Research Board, 2004. http://onlinepubs.trb.org/Onlinepubs/tcrp/tcrp_rpt_95c12.pdf

[18] AP Impact: US freight rail congestion a concern, Tarm, M., USA Today, May 30, 2008. http://www.usatoday.com/money/economy/2008-05-29-1091665794_x.htm

[19] Report to the Ranking Member, Committee on Environment and Public Works, U.S. Senate, Freight Transportation, National Policy and Strategies Can Help Improve Freight Mobility (GAO-08-287) January 2008. http://www.gao.gov/new.items/d08287.pdf

[20] Statement of JayEtta Z. Hecker, Director, Physical Infrastructure Issues, Freight Railroads: Preliminary Observations on Rates, Competition, and Capacity Issues, United States Government Accountability Office, (GAO-06-898T) June 21, 2006. http://www.gao.gov/new.items/d06898t.pdf

When addressing congestion pricing in freight rail, a major issue is the lack of data and information needed to quantify the extent of the problem. The freight rail network is operated, for the most part, by private entities, which consider such data on private freight movement proprietary. For example, a consortium of four local transportation agencies in Houston, Texas collects and provides information on the area's major roadway system. While the consortium has the capability to extend its tag-reading technology to track overall freight rail traffic, the railroads do not allow this practice because they consider that information proprietary.

Meanwhile, since the implementation of the Staggers Rail Act of 1980, railroads were allowed to set their own pricing mechanisms. Therefore, implementing congestion pricing, from a public policy standpoint, may not be as clear cut, given that railroad operations are privately owned and operated. As a result, when setting policy for railroad congestion pricing, there needs to be a clear distinction between infrastructure owners/operators and users. In addition, railroads already utilize demand-based differential pricing, by setting higher rates for traffic with fewer transportation alternatives than for traffic with more choices to maximize highest margin freight.

Having said that, with excess freight rail capacity diminishing, capital investment to increase it remains constrained, despite recent profitability, due to high initial investment costs. As a result, a freight rail congestion pricing mechanism, based on route rather than peak/off-peak scheme, might increase the efficient use of existing rail infrastructure by reducing chock points at major hubs like Chicago. However, such a scheme might result in shifting freight transportation to the road network, thereby augmenting externalities of road congestion.

5.3 Inland Waterways

Of the 25,000 miles of inland, intercostal, and coastal waterways, the inland waterway system of the United States includes 12,000 miles of commercially active and navigable waterways.[21] The U.S. Army Corps of Engineers (USACE) is responsible for most of these commercially important waterways, including 11,000 miles of fuel taxed waterways. Commercial operators on these designated waterways pay a fuel tax (20 cents per gallon) deposited in the Inland Waterways Trust Fund, which funds half the cost of new construction and major rehabilitation of the inland waterways infrastructure.

According to figures published by the USACE, inland waterways handled over 628 tons of freight in 2006,[22] valued at over $70 billion,[23] which translates into an average

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[21] Inland Waterway Navigation: Value to the Nation, U.S. Army Corps of Engineers, May 2000. http://www.iwr.usace.army.mil/docs/InlandNavigation.pdf

[22] The U.S. Waterway System, Transportation Facts, Navigation Data Center, U.S. Army Corps of Engineers, December 2007. http://www.iwr.usace.army.mil/ndc/factcard/fc07/factcard.pdf

[23] Navigation: Economic Impact, U.S. Army Corps of Engineers, October 2005. http://www.vtn.iwr.usace.army.mil/navigation/naveconomic.htm

transportation saving of $11 per ton of freight.[24] The principal value of the inland waterways is their ability to efficiently transport large volumes of bulk commodities, much more so that freight rail and trailer trucks. It is estimated that one barge can haul more dry cargo than 16 rail cars or 70 trailer trucks. Furthermore, cargo transported on the inland waterways system each year would require 6.3 million rail cars or 25.2 million trucks to carry the same load.

With the average age of locks and dams on the nation's inland waterways about 56.5 years, the system is in constant need of rehabilitation work. Meanwhile, aging locks and dam systems are affecting the overall system capacity and reliability. Fuel tax receipts are the main funding source of the Inland Waterway Trust Fund (the other source being interest earned). However, in 2007, the Fund earned $101.5 million, of which $91.1 million came from the fuel tax paid by the barge and towing industry and $10.4 million interest. At the same time, outlays for construction and rehabilitation amounted to $159.8 million, leaving the Fund balance at $209.4 million, its lowest level since 1993.[25] According to a 2003 report by the Transportation Research Board (TRB), of the National Academy of Sciences,[26] inland waterway users pay only 8% of the costs of infrastructure construction and operations and maintenance, while railroad users pay nearly 100 percent of these costs and highway users pay 80 percent to construct and maintain highways.

These funding requirements, in addition to congestion of the inland waterway network, due to failing and outdated locks, necessitates the search for new and more innovative sources of funding. A recent study identified lock outages and spikes in demand as sources of congestion that can lead to delays for commercial traffic on inland waterways.[27] According to industry association estimates cited in Plott and Cook (2005), the congestion on only one of the thirty-eight active locks on the Inland Waterways cost $209 million annually. Congestion delays result in direct costs for carriers, including those associated with the additional time spent waiting in the queue, as well as indirect costs including business lost due to other methods of transportation and potentially less valuable contracts. Currently, lock operators move barges on a first come first serve basis, which exacerbates the problem and adds to delays and inefficiency.

Congestion pricing on the inland waterways could be a possible solution for managing congestion and generating funds for the rehabilitation of the system. Cook and Plott, 2005, investigated tradable priority permits (Slots) for inland waterways by giving the holder the right to move ahead of all barges waiting for access to the lock. While these permits are similar to airport landing rights used in the air transportation industry to solve congestion problems, they differ in that they are priority rights rather than exclusive use

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[24] A Modal Comparison of Domestic Freight Transportation Effects on the General Public, Center for Ports and Waterways, Texas Transportation Institute, November 2007. http://www.americanwaterways.com/industry_stats/facts_about_ind/public%20study.pdf

[25] The U.S. Waterway System, Transportation Facts, Navigation Data Center, U.S. Army Corps of Engineers, December 2007. http://www.iwr.usace.army.mil/ndc/factcard/fc07/factcard.pdf

[26] Freight Capacity for the 21st Century, Special Report 271, Transportation Research Board of the National Academies, 2003. http://onlinepubs.trb.org/Onlinepubs/sr/sr271.pdf

[27] Congestion at Locks on Inland Waterways: An Experimental Testbed of a Policy of Tradable Priority Permits for Lock Access, Joseph P. Cook, & Charles R. Plott, California Institute of Technology, Social Science Working Paper 1240, November 2005. http://ideas.repec.org/p/clt/sswopa/1240.html

rights, at a specific time. Other forms of congestion pricing may involve charging lockage fees at different rates, with higher charges for peak periods, or additional fees added to slower lockage. Furthermore, in a 2005 National Research Council (NRC) independent review of a USACE feasibility study to examine increasing the size of existing locks, NRC suggested that the USACE make better use of the existing lock infrastructure on the Upper Mississippi River before constructing larger locks. The policy recommendations included congestion-related fees and tradable lockage permits among others.[28]

Implementing congestion pricing on inland waterways is not a straightforward exercise, given that "marginal" congestion costs are difficult to determine in this mode of transportation. In general, such costs are determined using speed-flow functions (for roads) or demand-delay functions (for rail), requiring detailed information on passing times, of which data is usually not available on inland waterways. Furthermore, some researchers suggest that congestion for non-road modes is internal, especially if there is only one operator, and is usually offset by realistic scheduling.[29]

5.4 Ports

For ports, congestion is mainly due to the fact that terminals are not adequately configured to handle today's high volumes, in addition to highway and rail access being badly congested. Furthermore operating hours of many major ports do not match the 24-hour, seven days a week business cycle of major shippers and receivers. Consequently, backups are created adding to congestion in and around ports. These capacity constraints at major ports are forcing importers to disperse shipments through multiple ports instead of moving all their shipments through the nearest port.[30]

However, in southern California, the *PierPass* program, a not-for-profit company was created by marine terminal operators at the ports of Los Angeles and Long Beach to address multi-terminal issues such as congestion, security, and air quality. *PierPass* implemented in 2005 a form of congestion pricing, called the Off-Peak Program, whereby a $50 per twenty foot equivalent unit fee is imposed on loaded containers that move through peak hours. This Traffic Mitigation Fee encourages cargo owners to arrange transportation during nights and weekends. This has resulted in approximately 36% of traffic moving at night, taking thousands of trucks off the highways during peak daytime hours,[31] thus alleviating daytime congestion.

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[28] Decision Tools for Reducing Congestion at Locks on the Upper Mississippi River, James F. Campbell, L. Douglas Smith et al, College of Business Administration, University of Missouri, St. Louis, 2007. http://www.hicss.hawaii.edu/hicss_40/decisionbp/02_04_01.pdf

[29] Charging and pricing in the area of 12 inland waterways, ECORYS TRANSPORT, Report for European Commission - DG TREN, Aug 2005. http://ec.europa.eu/transport/iw/studies/doc/2005_charging_and_princing_study_en.pdf

[30] The Transportation Challenge: Moving the U.S. Economy, U.S. Chamber of Commerce, April 2008. http://www.uschamber.com/publications/reports/0804transportationchallenge.htm

[31] Report to the Ranking Member, Committee on Environment and Public Works, U.S. Senate, Freight Transportation, National Policy and Strategies Can Help Improve Freight Mobility (GAO-08-287) January 2008. http://www.gao.gov/new.items/d08287.pdf

6 CONCLUDING REMARKS

6.1 Costs of Road Congestion

> "Growing congestion in the U.S. transportation network poses a substantial threat to the U.S. economy and to the quality of life of millions of Americans"
> (*United State Department of Transportation website, http://www.fightgridlocknow.gov)*

One of the lessons from our results is that assessments such as this are not alarmist. Congestion on the urban road network costs the nation about $85 billion per year in longer and less reliable journey times, reduced mobility, increased vehicle operating costs, and environmental degradation. To put this number in perspective, a saving of that amount in what Americans spent at the pump on gasoline in 2005 would have reduced their gasoline bill by over 40 percent. Elimination of even a substantial reduction in road congestion would clearly provide benefits that would noticeably improve the quality of life for many Americans.

Another conclusion is that the very large metropolitan areas (population over 1 million) bear most of these costs from road congestion – about 62 percent. This share is larger than indicated in the UMR (56 percent) because our analysis recognizes household income levels, and hence values of travel time, tend to be higher in the largest metro areas.

About the composition of the costs of urban road congestion by cost category, we draw the following lessons:

- *Travel time cost*. The increase in the average amount of time required to make a road trip accounts for the bulk of the estimated costs of urban road congestion. Factoring in the cost of cargo delay substantially increases the valuation of the congestion delays experienced by trucks, but has a much smaller effect on the estimates of total cost of congestion delay because traffic consists mostly of cars rather than trucks. That said, congestion costs incurred that fall specifically on truck travel are of interest in various contexts, including in the analysis of how congestion affects the market economy.

- *Unreliability of travel time.* Factoring in the costs of unreliability adds appreciably the costs associated with average travel time —an estimated 17 percent nationally and 20 percent in the largest urban areas. These estimates are necessarily rough owing to limitations of available data on variability of travel times, and are likely conservative owing to our reliance on a methodology that excludes the effects of major traffic incidents. Nevertheless, as discussed in Chapter 3, our estimates are reasonably consistent with evidence from other studies.

- *Mobility costs*. Much as some workers hold off their job search when prospects look too bleak, road congestion will discourage some road users from undertaking certain travel during the peak period. The loss of mobility has a net cost—for example, an increase in overall logistic cost due to less frequent deliveries necessitating higher levels of inventory. Our estimate that mobility costs contribute only a small amount to the total cost of congestion is line with other evidence. In Vary, Weissbrod, & Treyz (2001), reviewed in Chapter 2, the studied mobility costs—those associated with commuting and business travel (including freight)—were negligible as a component of the benefit from simulated reductions in road congestion.

- *Vehicle emissions.* By our estimates, vehicle emissions contribute negligibly to the costs of congestion. Likewise, simulations of increases in highway spending based on HERS-ST show emission reduction benefits to be minuscule compared to the savings in travel time. Indeed, in some simulations, the road improvements increase the costs of emissions because: (1) the relationship between the per mile emission rates and vehicle speed is U-shaped, with emission rates increasing as speeds near free-flow, and (2) the road improvements induce additional traffic.
- *Vehicle operating costs.* That time costs of congestion dwarf the vehicle operating costs should come as no surprise to those experienced in benefit-cost analysis of highway projects— that the benefits of these improvements consist predominantly of time savings is a standard result. On the other hand, a return to the peak gasoline price experienced earlier this year of about $4.00 per gallon would somewhat alter this picture. The ratio of VOC to time costs would then increase from our estimate of 19 percent based on a $2.00 per gallon price to nearly 30 percent. Our results also suggest that going beyond fuel in estimating the vehicle operating costs of congestion is worth the effort. At the $2.00 per gallon price of gasoline, the non-fuel components account for about 40 percent of our estimate of total VOC costs.

6.2 Road Congestion Pricing

The results of our modeling are consistent with the following assessment from a recent review of international evidence on road congestion pricing: "Often, only a modest reduction in [road] use during congested periods is required to significantly improve road traffic flow"[32] For the very large urban areas taken together, our estimates show that during currently congested portions of the peak period, congestion pricing would increase average freeway speed from 38 mph to 55 mph, while reducing VMT by 9 percent. For arterials, the results are likewise encouraging. Gross of costs for toll collection, congestion pricing on the freeways and arterials of the very large urban areas would produce an annual welfare gain that we estimate at $17.5 billion. Of the four-fifths of this gain that would come from congestion pricing on freeways, the costs of toll collection, via currently used ETC technology, would likely consume only a modest

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[32] Moving Urban Australia: Can Congestion Charging Unclog Our Roads?, Working Paper 74, October, 2008, pp. 55, Bureau of Infrastructure, Transport and Regional Economics, Department of Infrastructure, Transport, Regional Development and Local Government, Government of Australia.

portion. Comprehensive congestion pricing on both freeways and arterials would require an alternative technology such as GPS-based tolling.

6.3 Recommendations for Future Research

For more complete and reliable assessment of the costs of congestion and the benefits of congestion pricing in relation to surface transportation, we recommend a more bottom-up approach that synthesizes the results of studies undertaken for individual urban areas using detailed travel demand models. A sketch-planning framework that relies on highly aggregated data on the highway system performance in an urban area can provide only so much enlightenment. The sketch-planning framework used for this report relies on aggregate traffic data —total volumes and average speeds for arterials and freeways— from the TTI Urban Mobility Report, which, in turn, relied on the HPMS sample data for each area. As discussed in this report (Section 2.1.2), the HPMS sample has limitations in relation to the way the UMR makes use of it. Particularly for the modeling of congestion pricing, studies that use detailed travel demand models for individual urban areas have much more potential than this report's sketch-planning framework. In applying speed-flow relationships, our framework treats each area's freeways (arterials) as though they constituted a single link, which clearly produces aggregation errors.

Thus far, detailed bottom-up modeling of comprehensive congestion pricing has been undertaken only for a few of our nation's urban areas, such as Washington, D.C., and more are needed. The studies filling this information gap should be documented as transparently as possible to allow investigation of any differences in findings. The problems with existing urban travel demand models, such as the limitations of the traffic data, have been discussed extensively elsewhere, and here we only wish to highlight four that have particular relevance to our study objectives:

1. The existing travel demand models are generally static frameworks; even with the incorporation of quasi-dynamic speed-flow curves, such models are much less suitable for modeling congestion pricing than a truly dynamic framework.

2. The continued use of vehicle operating cost equations that have been derived from extremely old data that, in some cases, assume uniform speeds (without taking account of speed cycles) is outdated and is in need of revision. Particularly if fuel prices head back up, this gap in modeling knowledge needs urgently to be filled.

3. More research is needed to reliably value travel time and reliability. The present study relied on the USDOT guidance on the valuation of travel time, including the rule for valuing personal (unpaid) travel time at 50 percent of an income-based measure. This guidance dates back to 1997 and the literature review that on which it was based drew on a variety of studies that may not have been careful to empirically distinguish between values of time and reliability. Although we have treated the values of time based on the USDOT guidance as pure values of time, they may be better interpreted as values that also reflect the costs of unreliability. If so, our analysis may have double-counted the costs of unreliability to some extent. Future efforts should also aim at providing additional information on the

distribution of values of time and reliability within the population of travelers, and incorporate as much of this information as possible into travel demand models. As was discussed in the recent HDR (2008) report on congestion pricing, modeling this heterogeneity is important for predicting the impacts and welfare gains from congestion pricing.

4. Travel demand models need to endogenously treat land use patterns. This is an extremely challenging order, but the results of a study for the Washington, D.C. area suggests that much of the welfare gain from congestion pricing may arise through changes in land use.

The increased use of urban travel demand models to study the questions we investigated in this report will also have the side-benefit of taking more account of "rural" road congestion than is possible with the reliance on the HPMS data. The travel demand models generally cover a metropolitan region that includes some quasi-rural areas that lie outside the urbanized areas for which HPMS measures data. For some metropolitan regions, this distinction can be important.

For surface transportation modes other than road travel, we recommend further investigation of the potential of congestion pricing for water transportation (especially at congested locks on inland waterways), truck access to seaports (along the lines of the successful *PierPass* program in Southern California), and for transit usage. In relation to transit, it came as a surprise to us that of the 20 major transit authorities in the United States, only four utilize time-based differential pricing.

Lastly, though to recommend further research into the costs of toll collection would seem almost superfluous, the need is obvious. The relatively high collection costs for cordon pricing in central London created a certain amount of reluctance in the United Kingdom to implement other road congestion pricing schemes, and United States stakeholders will be seeking assurance that the costs of collection will not wipe out proposed scheme benefits. The research on collection costs will need to be an ongoing effort to update estimates for rapidly improving technology.

APPENDIX A : DATA TABLES

This appendix presents the data and assumptions used in this study.

Table A1: Value of time and ranges used for each metropolitan area:

Area	VOT (Personal Travel)			VOT (Business Travel)			VOT (TRUCK)		
	Lower 10 %	Median	Upper 10 %	Lower 10 %	Median	Upper 10 %	Lower 10 %	Median	Upper 10 %
Akron, OH	$10	$12	$14	$22	$27	$32	$33	$45	$60
Albany-Schenectady, NY	$11	$14	$17	$20	$25	$30	$33	$45	$60
Albuquerque, NM	$10	$12	$14	$18	$22	$27	$33	$45	$60
Allentown-Bethlehem, PA-NJ	$11	$14	$17	$19	$23	$28	$33	$45	$60
Anchorage, AK	$13	$17	$20	$22	$27	$32	$33	$45	$60
Atlanta, GA	$12	$15	$18	$19	$24	$29	$33	$45	$60
Austin, TX	$11	$14	$17	$19	$23	$28	$33	$45	$60
Bakersfield, CA	$9	$12	$14	$18	$23	$27	$33	$45	$60
Baltimore, MD	$13	$16	$20	$21	$26	$31	$33	$45	$60
Beaumont, TX	$9	$11	$13	$18	$22	$26	$33	$45	$60
Birmingham, AL	$10	$12	$14	$18	$23	$27	$33	$45	$60
Boston, MA-NH-RI	$14	$17	$21	$23	$29	$35	$33	$45	$60
Boulder, CO	$17	$22	$26	$22	$27	$32	$33	$45	$60
Bridgeport-Stamford, CT-NY	$16	$21	$25	$22	$28	$34	$33	$45	$60
Brownsville, TX	$6	$7	$9	$14	$18	$22	$33	$45	$60
Buffalo, NY	$12	$15	$19	$19	$23	$28	$33	$45	$60
Cape Coral, FL	$12	$15	$18	$18	$22	$27	$33	$45	$60
Charleston-North Charleston, SC	$10	$12	$15	$18	$22	$27	$33	$45	$60
Charlotte, NC-SC	$11	$13	$16	$19	$24	$28	$33	$45	$60
Chicago, IL-IN	$12	$15	$18	$20	$25	$30	$33	$45	$60
Cincinnati, OH-KY-IN	$11	$13	$16	$19	$24	$29	$33	$45	$60
Cleveland, OH	$10	$12	$15	$19	$24	$29	$33	$45	$60
Colorado Springs, CO	$11	$14	$17	$19	$24	$29	$33	$45	$60
Columbia, SC	$10	$12	$15	$18	$23	$27	$33	$45	$60
Columbus, OH	$11	$13	$16	$19	$24	$29	$33	$45	$60

Area	VOT (Personal Travel)			VOT (Business Travel)			VOT (TRUCK)		
	Lower 10 %	Median	Upper 10 %	Lower 10 %	Median	Upper 10 %	Lower 10 %	Median	Upper 10 %
Corpus Christi, TX	$8	$10	$12	$16	$21	$25	$33	$45	$60
Dallas-Fort Worth-Arlington, TX	$11	$14	$17	$19	$23	$28	$33	$45	$60
Dayton, OH	$10	$12	$14	$19	$24	$28	$33	$45	$60
Denver-Aurora, CO	$12	$15	$18	$21	$26	$31	$33	$45	$60
Detroit, MI	$11	$14	$17	$22	$27	$32	$33	$45	$60
El Paso, TX-NM	$7	$9	$10	$16	$20	$24	$33	$45	$60
Eugene, OR	$9	$11	$14	$18	$23	$27	$33	$45	$60
Fresno, CA	$9	$11	$14	$18	$22	$27	$33	$45	$60
Grand Rapids, MI	$10	$12	$15	$19	$24	$29	$33	$45	$60
Hartford, CT	$13	$17	$20	$22	$28	$33	$33	$45	$60
Honolulu, HI	$14	$17	$20	$19	$24	$29	$33	$45	$60
Houston, TX	$11	$13	$16	$19	$23	$28	$33	$45	$60
Indianapolis, IN	$11	$14	$16	$19	$24	$28	$33	$45	$60
Jacksonville, FL	$11	$13	$16	$18	$23	$27	$33	$45	$60
Kansas City, MO-KS	$11	$14	$17	$19	$24	$29	$33	$45	$60
Laredo, TX	$7	$9	$11	$15	$19	$22	$33	$45	$60
Las Vegas, NV	$11	$14	$17	$18	$23	$27	$33	$45	$60
Little Rock, AR	$10	$12	$14	$18	$22	$26	$33	$45	$60
Los Angeles-Long Beach-Santa Ana, CA	$12	$15	$18	$20	$25	$30	$33	$45	$60
Louisville, KY-IN	$10	$12	$14	$18	$23	$27	$33	$45	$60
Memphis, TN-MS-AR	$9	$11	$14	$18	$22	$27	$33	$45	$60
Miami, FL	$10	$12	$15	$18	$23	$27	$33	$45	$60
Milwaukee, WI	$11	$13	$16	$20	$24	$29	$33	$45	$60
Minneapolis-St. Paul, MN	$13	$17	$20	$21	$26	$32	$33	$45	$60
Nashville-Davidson, TN	$10	$13	$15	$18	$23	$28	$33	$45	$60
New Haven, CT	$12	$15	$18	$21	$26	$32	$33	$45	$60
New Orleans, LA	$10	$12	$15	$18	$23	$27	$33	$45	$60
New York-Newark, NY-NJ-CT	$13	$16	$19	$22	$28	$33	$33	$45	$60
Oklahoma City, OK	$9	$11	$13	$18	$22	$26	$33	$45	$60

Area	**VOT (Personal Travel)**			**VOT (Business Travel)**			**VOT (TRUCK)**		
	Lower 10 %	**Median**	**Upper 10 %**	**Lower 10 %**	**Median**	**Upper 10 %**	**Lower 10 %**	**Median**	**Upper 10 %**
Omaha, NE-IA	$11	$14	$17	$18	$23	$28	$33	$45	$60
Orlando, FL	$10	$13	$16	$18	$22	$26	$33	$45	$60
Oxnard-Ventura, CA	$15	$19	$23	$20	$25	$30	$33	$45	$60
Pensacola, FL-AL	$10	$12	$14	$17	$22	$26	$33	$45	$60
Philadelphia, PA-NJ-DE-MD	$12	$15	$18	$20	$25	$30	$33	$45	$60
Phoenix, AZ	$11	$14	$17	$18	$23	$28	$33	$45	$60
Pittsburgh, PA	$9	$12	$14	$18	$23	$28	$33	$45	$60
Portland, OR-WA	$11	$14	$17	$20	$25	$30	$33	$45	$60
Providence, RI-MA	$11	$14	$17	$19	$24	$29	$33	$45	$60
Raleigh-Durham, NC	$12	$15	$18	$19	$24	$29	$33	$45	$60
Richmond, VA	$11	$14	$17	$19	$24	$29	$33	$45	$60
Riverside-San Bernardino, CA	$11	$14	$17	$19	$23	$28	$33	$45	$60
Rochester, NY	$10	$13	$15	$19	$24	$29	$33	$45	$60
Sacramento, CA	$12	$15	$18	$21	$26	$31	$33	$45	$60
Salem, OR	$10	$12	$15	$18	$23	$27	$33	$45	$60
Salt Lake City, UT	$11	$14	$17	$19	$23	$28	$33	$45	$60
San Antonio, TX	$10	$12	$14	$17	$21	$25	$33	$45	$60
San Diego, CA	$13	$16	$19	$20	$25	$30	$33	$45	$60
San Francisco-Oakland, CA	$15	$19	$23	$24	$30	$36	$33	$45	$60
San Jose, CA	$17	$22	$26	$25	$31	$38	$33	$45	$60
Sarasota-Bradenton, FL	$10	$13	$15	$18	$22	$27	$33	$45	$60
Seattle, WA	$13	$16	$19	$22	$28	$33	$33	$45	$60
Spokane, WA	$9	$11	$14	$19	$23	$28	$33	$45	$60
Springfield, MA-CT	$10	$13	$15	$20	$25	$30	$33	$45	$60
St. Louis, MO-IL	$11	$13	$16	$19	$24	$29	$33	$45	$60
Tampa-St. Petersburg, FL	$9	$12	$14	$18	$22	$27	$33	$45	$60
Toledo, OH-MI	$10	$12	$14	$19	$23	$28	$33	$45	$60
Tucson, AZ	$9	$11	$14	$18	$23	$27	$33	$45	$60
Tulsa, OK	$9	$11	$13	$18	$22	$26	$33	$45	$60
Virginia Beach, VA	$11	$14	$17	$18	$23	$27	$33	$45	$60
Washington, DC-VA-MD	$17	$21	$25	$23	$29	$35	$33	$45	$60

Area	VOT (Personal Travel)			VOT (Business Travel)			VOT (TRUCK)		
	Lower 10 %	**Median**	**Upper 10 %**	**Lower 10 %**	**Median**	**Upper 10 %**	**Lower 10 %**	**Median**	**Upper 10 %**
Washington, DC-VA-MD	$17	$21	$25	$23	$29	$35	$33	$45	$60

Sources: The value of time for personal and business travel are based on the median wage rate published by the BLS.
The value of time for truck travel is based on a NYDOT study and previous HDR studies.

Table A2: Coefficient used in variability equation (EQ 2)

Variable	Freeway	Arterial
So	0.83	0.117
S1	0.9	0.89
B	-52	-28
A	1	1

Source: Methodology to Assess the Benefits of Improved Trip Reliability, (Ensor, 2002)

Table A3: Constant Speed Vehicle Operating Cost Fuel Consumption Table

Fuel Consumption									
Vehicle Type / Speed	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**
4-Tire Truck	15.67	17.83	19.30	19.97	19.65	18.45	16.64	15.12	13.83
6-Tire Truck	7.16	7.95	8.40	8.47	8.26	7.90	7.51	7.55	7.06
3-4 Axle Truck	5.64	6.31	6.70	6.87	6.87	6.76	6.58	6.37	6.13
4-Axle Comb.	5.05	5.50	5.54	5.25	4.79	4.28	3.78	3.33	2.93
5-Axle Comb.	3.45	3.70	3.67	3.45	3.13	2.80	2.48	2.20	1.95
Small Auto	26.40	32.50	38.44	43.10	45.49	45.24	42.78	38.93	34.48
Medium/Large Auto	23.73	26.90	28.67	28.38	26.14	23.58	22.32	20.57	18.56
Note: All at GRADE 0	***Miles per Gallon of Fuel***								

Source: FHWA HERS-ST Technical Report August 2005.

Table A4: Excess Vehicle Operating Cost Oil Consumption Table

Oil Consumption									
Vehicle Type / Speed	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**
4-Tire Truck	0.01	0.01	0.02	0.02	0.02	0.02	0.03	0.03	0.04
6-Tire Truck	0.05	0.05	0.06	0.08	0.09	0.10	0.12	0.14	0.16
3-4 Axle Truck	0.09	0.11	0.13	0.15	0.18	0.21	0.24	0.27	0.31
4-Axle Comb.	0.09	0.11	0.13	0.15	0.18	0.21	0.24	0.27	0.31
5-Axle Comb.	0.19	0.23	0.27	0.31	0.36	0.41	0.46	0.52	0.59
Small Auto	0.01	0.02	0.02	0.02	0.02	0.03	0.03	0.04	0.04
Medium/Large Auto	0.03	0.04	0.07	0.10	0.14	0.19	0.25	0.33	0.42
Note: All at GRADE 0	***Quarts of Oil per 1,000 Speed Cycles***								

Source: FHWA HERS-ST Technical Report August 2005.

Table A5: Speed Cycles per Mile

V/C Ratio	Freeways		Arterials	
	Auto	Truck	Auto	Truck
0.0	0.000	0.000	0.000	0.000
0.2	0.238	0.166	0.300	0.216
0.4	0.476	0.332	0.600	0.432
0.6	0.714	0.498	0.900	0.648
0.8	0.952	0.664	1.200	0.864
1.0	3.900	5.610	3.890	5.870
1.2	4.106	7.106	4.696	7.142
1.4	3.002	7.080	3.622	7.028
1.6	2.520	5.540	2.550	5.532
1.8	2.520	4.000	2.550	4.040
2.0	2.520	4.000	2.550	4.040

Source: *"Technical Memorandum for National Cooperative Highway Research Program (NCHRP) Project 7-12",* Texas Transportation Institute, 1990.

Table A6: Vehicle Operating Cost Components – Unit Prices

Cost Component	Lower 10%	Median	Upper 10%	Unit
Auto Fuel	$1.57	$1.66	$4.06	Per Gal.
Auto Oil	$5.60	$7.00	$8.40	Per Qt.
Auto Tire	$60.47	$75.58	$90.70	Per Tire
Auto Maintenance & Repair	$119.98	$149.98	$179.97	Per Repair Visit
Auto Depreciation	$16,009.21	$20,011.51	$24,013.82	Vehicle Depreciable Value
Truck Fuel	$3.12	$3.73	$4.85	Per Gal.
Truck Oil	$2.24	$2.80	$3.36	Per Qt.
Truck Tire	$360.30	$450.37	$540.45	Per Tire
Truck Maintenance & Repair	$367.19	$458.99	$550.78	Per Repair Visit
Truck Depreciation	$58,210.53	$72,763.16	$87,315.79	Vehicle Depreciable Value

Source: (All components except fuel) FHWA HERS-ST 2002 report, inflated to 2008 $'s using component specific CPIs from the Bureau of Labor Statistics
& (Fuel) AAA Fuel Gauge Report on Diesel and Gasoline Prices; low values reflect the minimum average price of the last 4 years; high value reflect the maximum average price of the last 4 years; median is the actual national average price on 12/19/08.

Table A7: VOC Vehicle Mix - Freeways

Vehicle Type	Fraction of Auto Traffic	Fraction of Truck Traffic	Source
Small Auto	31.40%		HERS 2005 Technical Report
Medium/Large Auto	38.10%		HERS 2005 Technical Report
4-Tire Truck	30.50%		HERS 2005 Technical Report
6-Tire Truck		21.60%	HERS 2005 Technical Report & HPMS VMT for 1999 by Road and Vehicle Type
3-4 Axle Truck		4.71%	HERS 2005 Technical Report & HPMS VMT for 1999 by Road and Vehicle Type
4-Axle Comb.		9.14%	HERS 2005 Technical Report & HPMS VMT for 1999 by Road and Vehicle Type
5-Axle Comb.		64.55%	HERS 2005 Technical Report & HPMS VMT for 1999 by Road and Vehicle Type
Total	**100%**	**100%**	

Table A8: VOC Vehicle Mix - Arterials

Vehicle Type	Fraction of Auto Traffic	Fraction of Truck Traffic	Source
Small Auto	29.50%		HERS 2005 Technical Report
Medium/Large Auto	35.70%		HERS 2005 Technical Report
4-Tire Truck	34.70%		HERS 2005 Technical Report
6-Tire Truck		36.14%	HERS 2005 Technical Report & HPMS VMT for 1999 by Road and Vehicle Type
3-4 Axle Truck		13.03%	HERS 2005 Technical Report & HPMS VMT for 1999 by Road and Vehicle Type
4-Axle Comb.		8.44%	HERS 2005 Technical Report & HPMS VMT for 1999 by Road and Vehicle Type
5-Axle Comb.		42.39%	HERS 2005 Technical Report & HPMS VMT for 1999 by Road and Vehicle Type
Total	**100%**	**100%**	

Table A9: Constant Speed Vehicle Operating Cost Fuel Consumption Table

CO2 Emission Rates	Unit	Source
8,788	Grams/Gasoline Gallon	EPA
10,084	Grams/Diesel Gallon	EPA

Table A10: Emission Cost – Unit Prices

Emission Type	Lower 10%	Median	Upper 10%	Unit
VOC	$5,167.09	$11,204.70	$17,242.31	Per Ton
CO	$125.26	$322.71	$520.16	Per Ton
NOx	$6,811.17	$12,624.92	$18,438.68	Per Ton
SO2	$8,811.51	$12,297.31	$15,783.12	Per Ton
PM10	$6,043.93	$6,218.36	$6,392.78	Per Ton
CO2	$15.40	$18.62	$21.85	Per Ton

Source: CO2 prices were developed by information from companies trading carbon offsets (http://www.tufts.edu/tie/tci/carbonoffsets/price.htm) and by Victoria Transportation Policy Institute values. All values were inflated to 2008 $'s using an all urban consumers CPI from the Bureau of Labor Statistics.

Source: Other unit price ranges were developed from Victoria Transportation Policy Institute and HERS prices. All values were inflated to 2008 $'s using an all urban consumers CPI from the Bureau of Labor Statistics.

Table A11: Emissions Vehicle Mix

Type	Description	Fraction of Auto Traffic	Fraction of Truck Traffic	Source
LDGV	Light duty gasoline vehicle	67.40%		HERS 2005 Technical Report
LDGT	Light duty gasoline truck	32.60%		HERS 2005 Technical Report
HDDV	Heavy duty diesel truck		100%	HDR Assumption
	Total	**100%**	**100%**	

Source: All truck traffic was assumed to be of the HDDT type.

APPENDIX B : CONGESTION PRICING RESULTS

This section presents the congestion pricing results on freeways and arterials for very large and large areas.

Table B1: Congestion Pricing Results on Freeways for Very Large and Large Areas

Area	Toll, $/mile	Toll by components			Original speed	New Speed	Annual Social Gain from congestion ($M)
		voc	time	reliability			
Very Large Areas							
Atlanta, GA	0.31	0.03	0.24	0.05	38.92	55.86	$638.20
Boston, MA-NH-RI	0.31	0.03	0.25	0.03	39.08	55.60	$373.04
Chicago, IL-IN	0.37	0.03	0.26	0.09	36.32	56.01	$1,138.24
Dallas-Fort Worth-Arlington, TX	0.35	0.03	0.26	0.06	34.69	55.19	$772.58
Detroit, MI	0.21	0.02	0.17	0.02	43.89	56.25	$178.06
Houston, TX	0.34	0.03	0.23	0.07	35.94	55.77	$696.01
Los Angeles-Long Beach-Santa Ana, CA	0.45	0.03	0.28	0.14	32.47	55.80	$3,804.72
Miami, FL	0.25	0.03	0.19	0.04	39.99	56.03	$429.02
New York-Newark, NY-NJ-CT	0.31	0.03	0.27	0.01	35.13	54.66	$1,361.79
Philadelphia, PA-NJ-DE-MD	0.24	0.02	0.21	0.01	39.97	55.28	$212.10
Phoenix, AZ	0.33	0.03	0.23	0.07	37.61	55.91	$395.86
San Francisco-Oakland, CA	0.41	0.03	0.29	0.09	36.46	55.87	$1,049.74
Seattle, WA	0.32	0.03	0.25	0.04	38.57	55.75	$373.80
Washington, DC-VA-MD	0.35	0.02	0.27	0.06	40.43	56.22	$605.29
Large Areas							
Baltimore, MD	0.31	0.03	0.25	0.04	39.39	55.72	$277.79
Buffalo, NY	0.19	0.02	0.16	0.00	45.59	55.99	$6.11
Cincinnati, OH-KY-IN	0.21	0.02	0.17	0.02	43.10	56.11	$75.77
Cleveland, OH	0.15	0.02	0.13	0.00	46.89	56.42	$17.18

Area	Toll, $/mile	Toll by components			Original speed	New Speed	Annual Social Gain from congestion ($M)
		voc	time	reliability			
Columbus, OH	0.19	0.02	0.16	0.01	45.08	56.34	$51.54
Denver-Aurora, CO	0.29	0.03	0.23	0.04	39.01	55.76	$200.61
Indianapolis, IN	0.16	0.02	0.13	0.01	47.93	56.84	$26.92
Kansas City, MO-KS	0.18	0.02	0.16	0.00	44.71	55.58	$16.89
Las Vegas, NV	0.28	0.03	0.22	0.04	39.52	55.92	$93.74
Memphis, TN-MS-AR	0.19	0.02	0.16	0.01	42.74	55.88	$22.29
Milwaukee, WI	0.29	0.03	0.21	0.05	38.35	55.89	$65.57
Minneapolis-St. Paul, MN	0.31	0.03	0.25	0.03	38.43	55.52	$267.45
New Orleans, LA	0.16	0.02	0.13	0.01	46.67	56.58	$10.55
Orlando, FL	0.16	0.02	0.14	0.01	46.39	56.45	$35.48
Pittsburgh, PA	0.13	0.02	0.12	0.00	47.34	56.04	$6.69
Portland, OR-WA	0.28	0.03	0.22	0.03	38.80	55.68	$129.36
Providence, RI-MA	0.19	0.02	0.16	0.00	43.03	55.61	$24.37
Riverside-San Bernardino, CA	0.34	0.03	0.24	0.07	37.21	55.89	$385.63
Sacramento, CA	0.28	0.02	0.21	0.04	40.98	56.11	$163.14
San Antonio, TX	0.19	0.02	0.15	0.02	43.60	56.29	$74.12
San Diego, CA	0.33	0.03	0.23	0.07	38.62	56.11	$636.79
San Jose, CA	0.36	0.03	0.29	0.04	40.02	55.83	$221.13
St. Louis, MO-IL	0.19	0.02	0.16	0.01	44.60	56.34	$75.33
Tampa-St. Petersburg, FL	0.16	0.02	0.13	0.01	45.89	56.26	$34.25
Virginia Beach, VA	0.19	0.02	0.16	0.00	44.28	55.71	$30.07

Table B2: Congestion Pricing Results on Arterials for Very Large and Large Areas

Area	Toll, $/mile	Toll by components			Original speed	New Speed	Annual Social Gain from congestion ($M)
		voc	time	reliability			
Very Large Areas							
Atlanta, GA	0.21	0.01	0.19	0.00	24.95	33.05	$83.84
Boston, MA-NH-RI	0.25	0.01	0.24	0.00	24.98	32.84	$76.83
Chicago, IL-IN	0.22	0.01	0.21	0.00	22.77	33.13	$169.57
Dallas-Fort Worth-Arlington, TX	0.19	0.01	0.18	0.00	25.76	32.98	$58.00
Detroit, MI	0.23	0.02	0.21	0.00	23.99	32.87	$126.14
Houston, TX	0.17	0.01	0.15	0.00	25.36	33.22	$46.91
Los Angeles-Long Beach-Santa Ana, CA	0.19	0.01	0.17	0.00	24.53	33.31	$230.91
Miami, FL	0.20	0.02	0.18	0.00	23.69	32.99	$126.69
New York-Newark, NY-NJ-CT	0.31	0.02	0.29	0.00	23.31	32.14	$529.50
Philadelphia, PA-NJ-DE-MD	0.27	0.02	0.25	0.00	24.43	32.32	$149.66
Phoenix, AZ	0.18	0.01	0.16	0.00	25.86	33.31	$41.71
San Francisco-Oakland, CA	0.25	0.01	0.23	0.00	23.97	33.14	$90.84
Seattle, WA	0.21	0.01	0.20	0.00	25.55	33.08	$44.42
Washington, DC-VA-MD	0.28	0.01	0.26	0.00	23.43	33.09	$150.04
Large Areas							
Baltimore, MD	0.24	0.02	0.22	0.00	24.89	32.90	$37.50
Buffalo, NY	0.26	0.02	0.24	0.00	25.36	32.45	$6.35
Cincinnati, OH-KY-IN	0.17	0.01	0.16	0.00	26.38	33.07	$9.57
Cleveland, OH	0.19	0.01	0.17	0.00	25.53	32.83	$7.50
Columbus, OH	0.19	0.01	0.17	0.00	25.64	32.97	$11.87
Denver-Aurora, CO	0.24	0.02	0.22	0.00	23.55	32.83	$58.89
Indianapolis, IN	0.22	0.02	0.20	0.00	24.06	33.03	$23.11
Kansas City, MO-KS	0.28	0.02	0.26	0.00	24.81	32.10	$13.00

Area	Toll, $/mile	Toll by components			Original speed	New Speed	Annual Social Gain from congestion ($M)
		voc	time	reliability			
Las Vegas, NV	0.19	0.01	0.18	0.00	24.84	33.04	$20.55
Memphis, TN-MS-AR	0.16	0.01	0.15	0.00	26.33	32.86	$8.09
Milwaukee, WI	0.11	0.01	0.11	0.00	28.28	33.54	$3.20
Minneapolis-St. Paul, MN	0.22	0.01	0.20	0.00	26.00	32.99	$33.90
New Orleans, LA	0.20	0.02	0.18	0.00	24.58	32.89	$10.02
Orlando, FL	0.25	0.02	0.23	0.00	22.38	32.61	$56.12
Pittsburgh, PA	0.24	0.02	0.22	0.00	24.52	32.08	$19.01
Portland, OR-WA	0.20	0.01	0.18	0.00	25.26	32.96	$21.77
Providence, RI-MA	0.26	0.02	0.24	0.00	24.35	32.27	$19.41
Riverside-San Bernardino, CA	0.14	0.01	0.13	0.00	27.31	33.46	$8.79
Sacramento, CA	0.21	0.01	0.20	0.00	24.56	33.06	$28.68
San Antonio, TX	0.18	0.02	0.17	0.00	24.44	32.98	$15.97
San Diego, CA	0.20	0.01	0.19	0.00	24.66	33.24	$44.12
San Jose, CA	0.32	0.02	0.30	0.00	23.71	32.84	$63.05
St. Louis, MO-IL	0.23	0.02	0.21	0.00	23.61	32.83	$25.90
Tampa-St. Petersburg, FL	0.22	0.02	0.21	0.00	23.54	32.57	$69.80
Virginia Beach, VA	0.26	0.02	0.24	0.00	24.75	32.29	$33.40

APPENDIX C : Estimating Elasticity of Travel Demand

The overall elasticity of demand for road travel is estimated as a weighted average of the separate elasticities for truck travel, business travel, and personal travel:

$$\varepsilon = sT\ \varepsilon T + sB\ \varepsilon B + sP\ \varepsilon P \qquad \text{(EQ C1)}$$

Where;

ε = the overall elasticity of VMT with respect to generalized cost

εT, εB, εP = the elasticity of truck, car business, and car personal VMT with respect to generalized cost

sT, sB, sP = the truck, car business, and car personal share of VMT

The elasticity of truck travel is assumed to be fixed across areas, while the elasticity of business travel is assumed to be 40% of personal travel. Personal travel, on the other hand, varies across areas.

The availability of transit only affects the calculation of the elasticity for personal travel by car:

$$\varepsilon P = \theta H\ \zeta P + \theta T \sigma \qquad \text{(EQ C2)}$$

where;

θH = the car mode share of the total private costs of personal travel by car and transit.

θT = the transit mode share of the total private costs of personal travel by car and transit.

ζP = the elasticity of personal travel with respect to the overall cost of personal travel.

σ = the elasticity of substitution between transit and car modes for personal travel.

To estimate the elasticities on equation C2, a corresponding equation for the own-cost elasticity of demand for personal travel by transit versus car is used:

$$\varepsilon T = \theta T\ \zeta P + \theta H \sigma \qquad \text{(EQ C3)}$$

Where εT is the elasticity of demand for personal travel by transit with respect to own generalized cost.

To solve for the income and substitution elasticities ζP and σ, representative values for the transit and car shares of personal travel cost are calculated based time cost, since this is the dominant component of travel cost. Once the income and substitution elasticities are estimated, the cost shares for each urban area are estimated using EQ C3. Inserted into equation (2), the cost shares combined with values for ζP and σ will, via equation (2), yield an estimate for each area of εP.

It is important to note, however, that this paradigm ignores that some transit travel (i.e. bus travel) generates VMT; for personal travel, it equates the demand for road travel with demand for car travel. It also simplifies by assuming a constant budget for personal travel – the total generalized cost of the amount of personal travel undertaken is fixed.

APPENDIX D : LIST OF ACRONYMS

ALS	Area License Scheme
ARC	Atlanta Regional Commission
ATA	American Trucking Association
BPM	Best Practices Model
BPR	Bureau of Public Roads
BTI	Buffer Time Index
CBD	Central Business District
CMP	Congestion Management Program
CMS	Congestion Management System
DWL	Deadweight Loss
EPA	Environmental Protection Agency
ERP	Electronic Road Pricing
FHWA	Federal Highway Administration
HCM	Highway Capacity Manual
HERS	Highway Economic Requirements System
HPMS	Highway Performance Monitoring System
HOT	High Occupancy Toll
HOV	High Occupancy Vehicle
LOS	Level of Service
MPG	Miles per Gallon
MPH	Miles per Hour
MPO	Metropolitan Planning Organization
NCHRP	National Cooperative Highway Research Program
NCTCOG	North Central Texas Council of Governments

NYMTC	New York Metropolitan Transportation Council
OST	Office of the Secretary of Transportation
PCE	Passenger Car Equivalent
RAS	Regional Arterial System
RCI	Roadway Congestion Index
RTP	Regional Transportation Plan
SANDAG	San Diego Association of Governments
SCAG	Southern California Association of Governments
SOV	Single Occupancy Vehicles
TRP	Transportation Research Board
TTI	Texas Transportation Institute
UMR	Urban Mobility Report
USDOT	United States Department of Transportation
VCR	Volume to Capacity Ratio
VHT	Vehicle Hours Traveled
VMT	Vehicle Miles Traveled
VOC	Vehicle Operating Costs
VOR	Value of Reliability
VOT	Value of Time

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