ABSTRACT

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Road users fail to realize their role in congestion. This thesis aims to calculate the appropriate charges required for users of I-495 – the Capital Beltway surrounding Washington, D.C. – in order to fulfill their portion of congestion costs. By developing a model from existing data that showcases traffic characteristics causing congestion, the user charges necessary to cause drivers to realize the congestion costs that their vehicles impose on the rest of the traffic stream are determined.

This study concludes that under typical traffic flow conditions for the Capital Beltway, charges ranging from $0.03 to $0.08 per passenger car equivalent (PCE) per mile during AM and PM peak periods cause drivers to realize their contribution to congestion costs. These results are lower than the $0.08 to $0.50 per-mile charges that previous research has estimated. As vehicles occupy various amounts of road space, charges on a PCE basis are most equitable.

CONGESTION PRICING FOR THE CAPITAL BELTWAY

By

Joshua Lee Crunkleton

Thesis submitted to the Faculty of the Graduate School of the
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Advisory Committee:
Dr. Kelly Clifton, Chair
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Dr. Stanley Young

Dedication

To my grandfather, Joseph A. Crunkleton – this is for you, Pop.

Acknowledgements

I would like to extend my sincere gratitude to the network of people who helped make this thesis possible.

To my wonderful family and friends: thank you for your perpetual support. It means more than you know. Without the insight, suggestions, and prior methodology of Mr. Gabriel Roth, this study would have never existed. Through the guidance of Dr. Kelly Clifton and my advisory committee – Dr. Cinzia Cirillo and Dr. Stanley Young – this thesis was able to reach fruition. Last, but definitely not least, Tom Schinkel, Randy Dittberner, and others with the Virginia Department of Transportation (VDOT) deserve special thanks in terms of data collection and much-appreciated feedback.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

1.1 Background

Traffic congestion is the topic of daily news broadcasts, water cooler horror stories and mounting frustration nationwide. As slower driving speeds, increased queuing and worsened travel reliability take center stage, we are left wondering what led to this condition and, more importantly, where we can turn for relief.

Traffic congestion is a familiar problem around the world, especially for those in urban areas. Congestion affects everyone and is usually defined in terms of excess vehicles on a portion of roadway at a certain time that results in speeds that are slower than free-flow conditions. At its most basic level, the consequence of failing to effectively manage the capacity of a roadway system results in congestion. Road capacity has not grown as quickly as road use – between 1990 and 2005, for example, vehicle-miles traveled increased by 44 percent, while highway lane miles only increased 4 percent (FHWA 2005, 1990). It goes without saying that if vehicle-miles traveled have increased at a rate much greater than that of the construction of new highway lanes, congestion has been a direct result.

Among professionals, metropolitan traffic congestion is often deemed the single most critical issue we face today in the transportation industry – an idea that is slowly being expressed by government figures across the country. According to the Texas Transportation Institute's 2007 Urban Mobility Report, congestion in America's urban areas is estimated to cost approximately $78 billion per year in wasted fuel and delay costs (Schrank 2007). In addition to these commuting costs, Americans see reductions in both quality of life (reduced air quality, less time with family and friends, etc.) and productivity. Industry costs relating to the movement of goods by truck are rising. Congestion in the United States is affecting more roads for more people – it is estimated that the average weekday peak period trip takes almost 40 percent longer than an identical off-peak trip; this compares to only a 13 percent increase in 1982 (Dodgson 2006). AM and PM peak periods have also expanded. In larger cities, drivers spend the equivalent of almost 8 work days each year stuck in traffic (Paniati 2006) and the situation is only escalating – the duration, extent and intensity of congestion is increasing annually.

It must be noted in this discussion that congestion is not viewed only in negative light – there are some who consider traffic congestion to be an inherent sign of success. More or less, people want to be where opportunities are located and, often, when the automobile is the dominant mode choice, congestion is a result. While it is true that a different spin can be placed on any situation, the impact of congestion on urban areas at the local, regional and national level cannot be refuted. Effective, accessible transportation networks are key instruments in enhancing quality of life and, for this reason, congestion issues need to be addressed instead of ignored.

Many analysts believe that efficient transportation depends more on managing existing demand than on adding new supply (Victoria Transport Policy Institute 2007). The fact that vehicle-miles traveled are increasing at a rate far greater than roadway construction is evidence that we cannot possibly build our way out of congestion. Studies have shown that 60-90% of new road capacity is anticipated to be filled within 5 years of construction and that induced demand (i.e. increased traffic) comes with added capacity (Replogle 2007). This is not surprising, as traffic attempts to flow along the path of least resistance – if new roads or lanes are constructed, more people will choose to utilize these paths until the level of congestion returns to its previous state, at which time users will choose alternate routes.

Travel is mainly a derived demand, meaning it is usually demanded not for its own sake but as a means of consuming some other good or service or to participate in economic activities (i.e. work). Because the activities with which transportation is associated vary over time, the demand for travel is not constant over time. For example, many towns and cities experience traffic congestion during peak morning and evening commuting times, and holiday routes experience seasonal congestion (Button 2004). Traffic demand has to be adjusted in order to make any tangible difference.

A key tool for such demand management is user charges (i.e. pricing). In concept, the ideal form of pricing is *congestion pricing*, which charges highway users based on their contribution to highway congestion, which means that the charges are specific to both a place and a time. Transportation is over-consumed as a direct result of inadequate pricing. If priced properly, fewer miles will be driven per vehicle and less transportation will be consumed. Congestion pricing is currently the source of heated political debate regarding potential congestion solutions and aims to adjust traffic demand in order to alleviate traffic congestion qualms. Further, there is consensus among economists that congestion pricing represents the single most viable and sustainable approach to reducing traffic congestion. Free road use ultimately leads to congestion, which is detrimental to all users. Congestion pricing is a way of ensuring that those using valuable and congested road space make a financial contribution, encourages the use of other transportation modes and is intended to ensure that, for those who have (or choose) to use the roadways, trip times are faster and more reliable.

Critics argue that users pay for their road usage through gas tax revenue – generated from the levy imposed on the per-gallon sale of motor fuels at both the state and federal levels. While this idea is not totally discredited, current gas tax revenue figures are not enough to justify the amount of road usage that is occurring in our society. In many states, gas taxes have not been raised since the early 1990s and when they happen to be raised, it is generally not enough to keep up with inflation. In fact, twenty-eight states have raised their gas tax rates since 1992, but only three have raised it enough to keep pace with inflation (Brookings Institute 2003). The public tends to unknowingly think that their annual contribution to the gas tax is much greater than it actually is. On average, between $500 and $600 is paid per vehicle per year towards the gas tax – less than most annual cable television bills.

1.2 Problem Statement

Most people fail to consider the adverse effect that their traveling places on others – it is the aim of this thesis to address and explore this inadequacy. Many road users have come to believe that they currently own the right to travel freely and uninterrupted and that roadways are provided exclusively in order for them to achieve this goal. Only by attaching a usage-based price to travel habits will drivers understand, and curb, their role in congestion. Roadways should be viewed as a commodity, in the same light as public utilities (telephone and electric services), movie tickets or airline pricing, where the price of the services are usage-based and increase as the demand increases over a certain threshold. Companies in these fields have used peak period pricing for years – why shouldn't transportation agencies do the same?

In this region, traffic congestion is a daily concern on I-495, surrounding Washington, D.C. Figure 1-1 shows this roadway in context of the region. Correct user pricing for all lanes of I-495 would ultimately be beneficial to society. It is important that the optimal price is determined, as incorrect pricing can have an adverse effect on the economy and inadequate pricing will fail to curb demand.

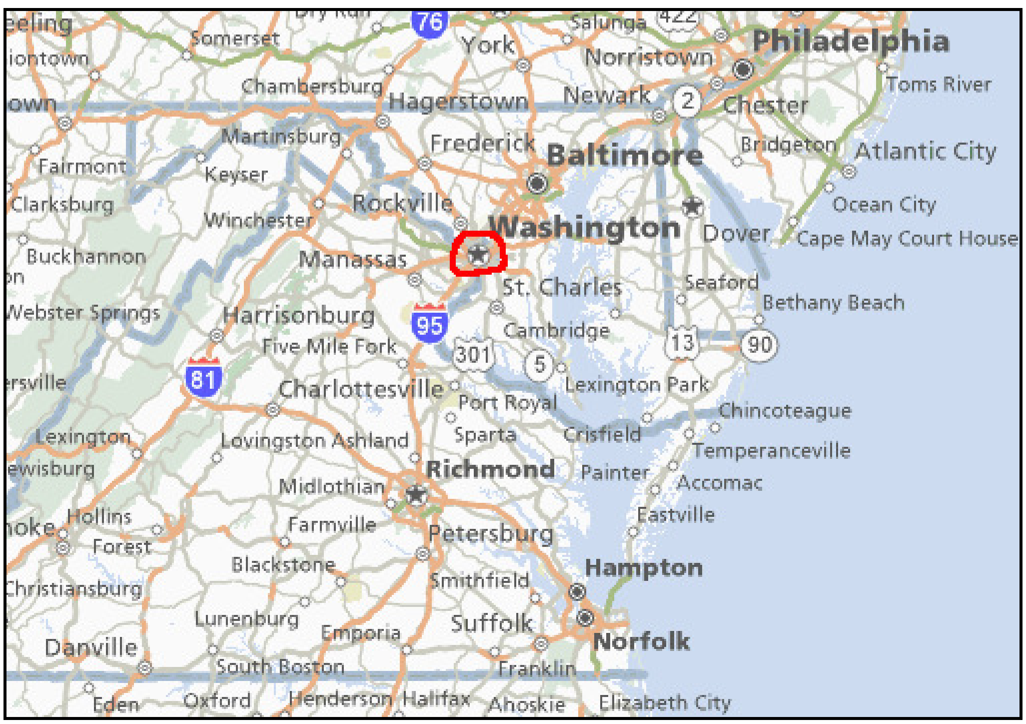


Figure 1-1: I-495 Region Map
Source: MapQuest

1.3 Research Objectives

Due to the aforementioned fact that travelers fail to realize their role in congestion, the goal of this thesis is to calculate the appropriate charges required for users of I-495 – the Capital Beltway surrounding Washington, D.C. – in order to fulfill their portion of congestion costs. The first objective is to develop a model from existing data that showcases traffic characteristics that cause congestion, in addition to the results of such interactions. Secondly, the charges necessary to cause vehicle users to realize the congestion costs that their vehicles impose on the rest of the traffic stream will be determined. This will be accomplished using prior methodology set forth by Gabriel Roth and Olegario Villoria (2001). The contribution of this thesis lies not in the method itself, but by examining the model in the context of a freeway (I-495) instead of city streets. The third objective of this thesis is to examine the potential financial implications (costs and revenue) that would be associated with the proposed congestion pricing system on I-495.

1.4 Document Organization

This thesis is organized into seven chapters and one ancillary appendix. The previous sections of Chapter 1 contained introductory information regarding traffic congestion and described the purpose and scope of this work. Chapter 2 serves as a review of existing literature applicable to this thesis, including information on congestion/road pricing theory, implementation, and studies. Chapter 3 introduces the proposed method behind this thesis and the entire model formulation is set forth in detail – the methodology, from obtaining initial data through creating a functional model, is also discussed. Drawing upon the aforementioned work by Roth and Villoria, data from detector locations on the Capital Beltway, dating back to 2002, are examined. Chapter 4 provides an evaluation of the proposed system, along with a demonstration of the model. Based on this evaluation, optimal pricing ranging from $0.03 to $0.08 per mile for each passenger car is obtained. Results of applicable sensitivity analysis are also set forth in this chapter. Chapter 5 outlines potential implementation of the proposed congestion pricing strategy and includes information on current technology, equity considerations, and policy limitations. The financial implications of such a system are provided in Chapter 6, with multiple setup scenarios being examined and corresponding costs and revenue examined. The benefits and challenges associated with the system are discussed and system payoff and break-even points are addressed. Chapter 7 summarizes the results of the thesis and addresses recommendations for areas of future research.

Chapter 2: Literature Review

In terms of summarizing existing literature applicable to this thesis, there are numerous aspects of congestion/road pricing that are deserving of discussion. The following sections touch on a varied selection of topics, including congestion pricing theory, implementation, and studies.

2.1 Congestion Pricing Background/Theory

"An Inquiry into the Nature and Causes of the Wealth of Nations," written by Adam Smith in 1776, is widely considered to be the first modern work in the field of economics. Included is the following passage which deduces that road users should pay in accordance with their usage (i.e. the magnitude of the road damage they cause):

> "When the carriages which pass over a highway or a bridge (...) pay toll in proportion to their weight or their tonnage, they pay for the maintenance of those public works exactly in proportion to the wear and tear which they occasion of them. It seems scarce possible to invent a more equitable way of maintaining such works. This tax or toll too, though it is advanced by the carrier, is finally paid by the consumer, to whom it must always be charged in the price of the goods. (...) His payment is exactly in proportion to his gain. It is in reality no more than a part of that gain which he is obliged to give up in order to get the rest. It seems impossible to imagine a more equitable method (Smith 307)."

Following Smith's idea of charging road users appropriately leads to the idea of congestion pricing. Lindsey and Verhoef (2000) contend that the insight for congestion pricing comes from the observation that people tend to make socially efficient choices when they are faced with all the social benefits and costs of their actions. Congestion pricing is widely viewed by economists as the most efficient means of alleviating traffic congestion, because it employs the price mechanism, with all its advantages of clarity, universality, and efficiency.

Based on writings such as those by Lindsey and Verhoef (2000), an early history of congestion pricing can be determined. In the 1920s, Arthur Cecil Pigou and Frank Knight were the first advocates of theoretical congestion pricing. It was William Vickrey in the 1960s, however, who wholeheartedly promoted congestion pricing and was the most influential in making the case on both theoretical and practical grounds. Vickrey identified the potential for road pricing to influence travelers' choice of route and travel mode and his work makes clear that true congestion pricing entails setting tolls that match the severity of congestion, which requires that tolls vary according to time, location, type of vehicle, and current circumstances. Additionally, Vickrey was the first to put forward an operational plan for road pricing in a specific city (Washington, D.C.) and was steadfast in promoting the idea of congestion pricing to non-economists. Since this time, several strategies for the implementation of congestion pricing have emerged.

The four main types of congestion pricing strategies are as follows (FHWA 2001):

- *Variably priced / managed lanes* – involve variable tolls on separated lanes within a highway, such as Express Toll Lanes or High Occupancy or Toll (HOT) Lanes. HOT lanes allow low-occupancy vehicles to pay a variable toll to use the lanes, while high-occupancy vehicles are allowed to use the lanes for free.

- *Variable tolls on entire roadways or smaller sections* – both on toll roads and bridges, as well as on existing toll-free facilities during rush hours. This strategy raises existing tolls in peak periods and possibly reduces them in off-peak periods.
- *Cordon charges* – either variable or fixed charges to drive within or into a congested area within a city
- *Area-wide charges* – per-mile charges on all roads within an area that may vary by level of congestion

In all of these cases, to truly merit the title of congestion pricing, an implementation strategy must contain a time-of-day element due to the fact that usage varies with peak periods. This thesis provides area-wide pricing for an entire facility.

Historically, it is possible to identify at least three periods in which policy measures to curb congestion have emerged (Salomon and Mokhtarian 1997). Through the mid-1960s, the principal tool was expansion of infrastructure (i.e. building more roads to accommodate demand). In the 1970s, there was a shift toward improved management of the available infrastructure – Transportation Systems Management (TSM). In the early 1980s, there was an increasing realization that altering human behavior was the next necessary step. This led to the development and implementation of Transportation Demand Management (TDM) strategies, involving a wide range of policies to reduce dependence on the single-occupant automobile. The first two periods can be characterized as emphasizing supply-side measures, while the third is designed to affect demand. Congestion pricing is a demand-side measure, as it specifically used to manage demand. Salomon and

Mokhtarian (1997) also note that with a growing concern for environmental costs, the focus on congestion mitigation is also growing as congestion traffic produces more air pollutants than smooth traffic flow, involves more noise production, and consumes more energy. Thus, both the individual and society coincide in their perception of the presence of a problem but not so, however, in assessing the means for solution. Additionally, trends over the last two decades have demonstrated that little is accomplished by the variety of measures devised to reduce congestion.

Figure 2-1 shows a theoretical congestion pricing model, as exhibited by McMullen (1993). The uncongested road pricing situation is shown as demand curve D_1, the distance OA represents vehicle costs such as fuel, oil, vehicle wear and tear, and the driver's value of time, and the costs incurred by the road operation agency (road maintenance, policing, etc.) are shown as the distance AB. The horizontal line BH represents both average total cost (AC) and marginal cost (MC) up to road volume C – the roadway is not congested between O and C and, therefore, each additional vehicle trip incurs the same marginal cost as the previous one.

When demand is at D_1, the optimal user charge is AB, which results in an optimal traffic level of Q_0. After encountering congestion at traffic volume C, additional vehicle trip imposes a cost (i.e. increased travel time) on other vehicles – for this reason, the average total and marginal costs diverge at greater volumes. At demand level D_2, the roadway is congested and the optimal user charge would be GD+DE, where DE is the congestion fee.

This theoretical model infers that the main reason for excessive congestion is the fact that users are not required to pay the full social costs of driving during peak hours (McMullen 1993). This model is simplistic in that it ignores the numerous different vehicle types that utilize the same road space – this would suggest higher peak hour congest fees for trucks and other large vehicles.

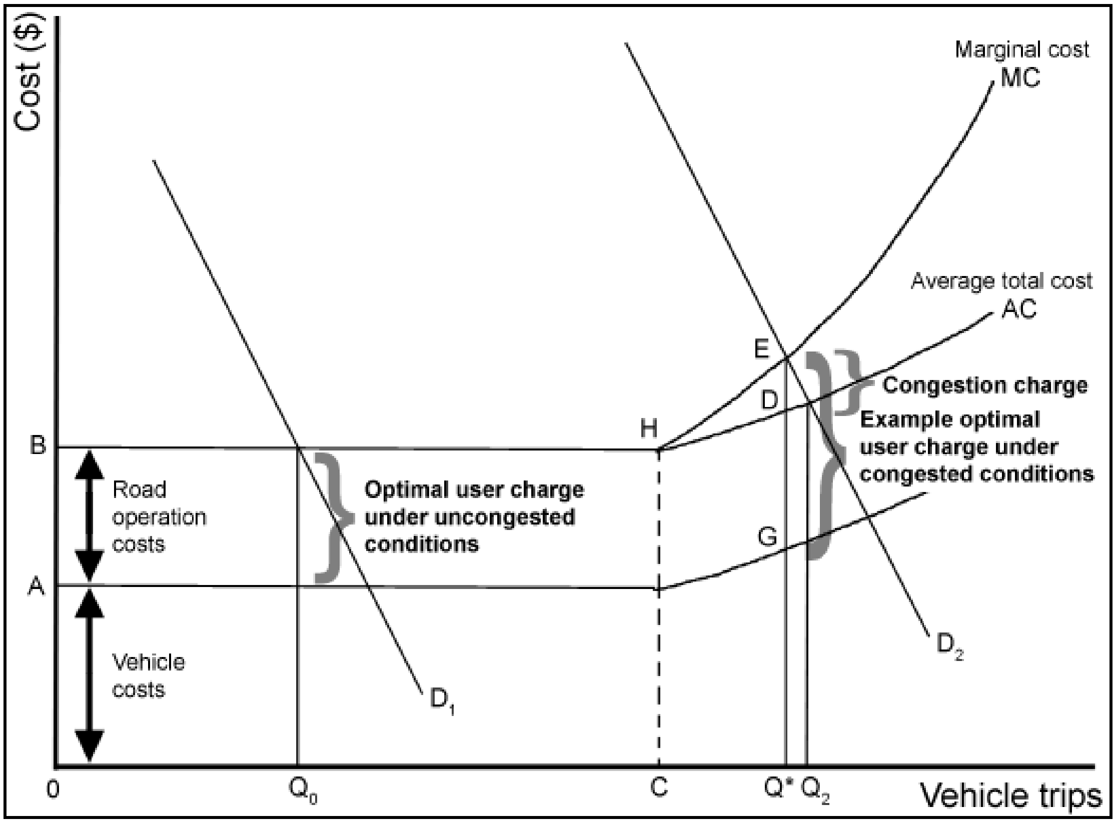


Figure 2-1: Theoretical Congestion Pricing Model

Lastly, elasticity is a term often used in the economics world, but likely to be misunderstood in the transportation realm. In simplest terms, elasticity refers to the amount of change in a dependent variable as a result of changes in an independent variable. For the purpose of this study, changes in road use as a result of increased costs (i.e. charging) are the focus.

2.1.1 Traffic Flow Theory

While discussing congestion pricing theory, it is important to mention some aspects of traffic flow theory that relate to this thesis. In regards to traffic flow theory, the topic most closely related to this specific study is the relationship between traffic flow and traffic speed. Greenshield (1935) developed a linear model of speed and density, which can be interpreted into the speed-flow relationship shown in Figure 2-2.

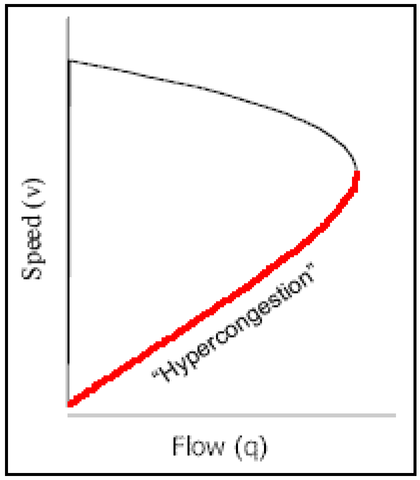


Figure 2-2: Greenshield's Model – Speed-Flow Relationship

The Highway Capacity Manual (Transportation Research Board 2000) does not portray the region of unstable/uncertain flow where the above curve wraps back around itself. This unpredictable area is referred to as hypercongestion (shown in Figure 2-2) and results in a loss of capacity due to the breakdown of traffic flow. The HCM speed-flow curves for basic freeway segments are exhibited as Figure 2-3. When comparing Greenshield's model to the HCM representation, a few differences are evident. The area of unstable flow (hypercongestion) is removed and due to the fact that speeds remain relatively constant at low volumes, the HCM shows the top of the curve as perfectly horizontal before the effects of higher flow levels begin to reduce speeds. In sum, the current HCM speed-flow relationship can be broken down into two sections: an unchanging constant portion at low flows (represented by the horizontal line) and a slowly downward-curving portion at higher flows.

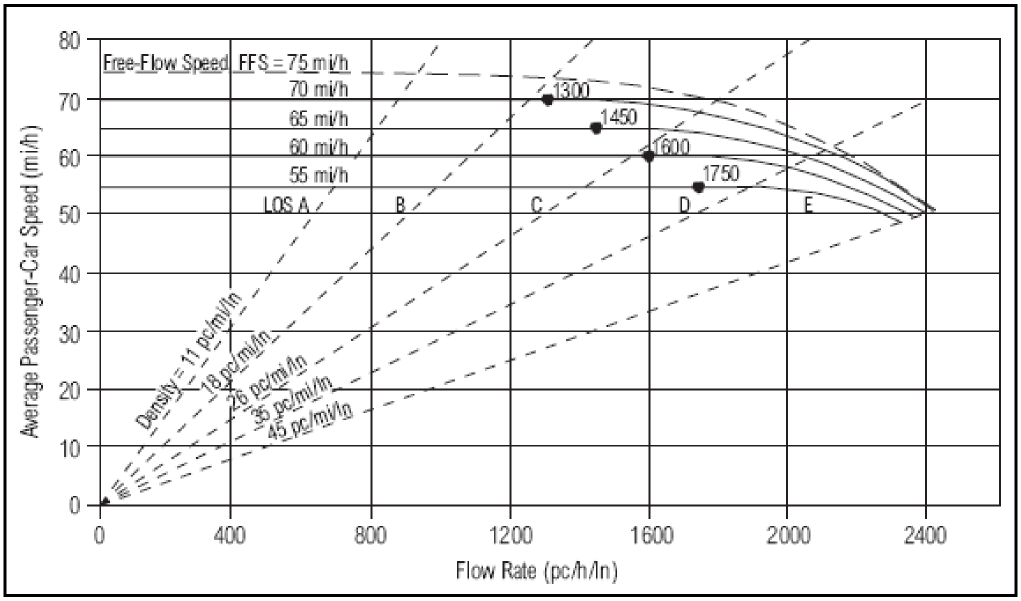


Figure 2-3: Speed-Flow Curves for Basic Freeway Segments
Source: HCM 2000 – Exhibit 23-3

2.2 Implementation

Congestion pricing is more prominent abroad than in the United States. Systems of varying technological levels have been operating since 1975 in Singapore and automated systems have been operating full-time in London and Stockholm since 2003 and 2007, respectively, in addition to various other examples in other areas.

In London, a charge is collected when a vehicle enters the central city area on weekdays between 7:00AM and 6:00PM – no per-mile charges are assessed. The standard daily charge is £8 ($16 US) if paid by midnight on the day of travel. The charge is increased to £10 ($20 US) if paid by midnight the following day. The initial charge for the strategy was £5 ($10 US), but increased to £8 ($16 US) in July 2005 (Transport for London). Based on results provided by Mayor Ken Livingstone (2007), after London put its initial congestion charging zone into place, it led to an immediate drop of 70,000 cars per day in the affected zone. Traffic congestion fell by almost 20 percent and emissions of the greenhouse gas carbon dioxide were cut by more than 15 percent. The retail sector in the zone has seen increases in sales that have significantly exceeded the national average. People are still traveling in London – they are simply doing so in more efficient and less polluting ways. There has been a marked shift away from cars and into public transport and environmentally friendly modes of travel. There has been a 4 percent modal shift into use of public transport from private cars since 2000. Simultaneously, the number of bicycle journeys on London's major roads has risen by 83 percent, to almost half a million per day. London's pricing scheme has been estimated to produce savings of about 0.7 minutes per kilometer, or 1.13 minutes per mile (Transport for London 2007).

In Stockholm, a congestion charge is imposed on Swedish registered vehicles driving into and out of the Stockholm inner city zone on weekdays between 6:30AM and 6:29PM and each passage into or out of the inner city zone costs SEK 10, 15 or 20 ($1.58 – $3.15 US), depending on the time of day. The accumulated passages made by any vehicle during a particular day are aggregated and the maximum amount charged per day and vehicle is SEK 60 ($9.45 US). As the Stockholm scheme was only implemented in mid-2007, not much actual data has become available. Therefore, the effectiveness of the scheme has been based on the Stockholm trial period that occurred before actual implementation commenced. As a result of congestion charging in Stockholm (Stockholmsförsöket 2006):

- Motor traffic decreased 22% over 24 hours
- Access improved and travel times fell as a result of the reduction in motor traffic

- Traffic reductions lead to less environmental impact and better health, as emissions from motor vehicles account for a large proportion of the total pollution in the city
- Public transport usage increased
- Road safety improved as a result of reduced traffic

Focus will shift now to implementations in the United States, as the political climate for congestion pricing differs greatly from the aforementioned regions.

The USDOT has entered into Urban Partnership Agreements with five cities, in accordance with their commitment to, among other things, implement broad congestion pricing. The five cities are: Miami, Minneapolis/St. Paul, New York City, San Francisco, and Seattle (Lake Washington). These agreements represent the future of congestion pricing in the United States, as future strategies will be based on the actual implementation and success of these proposed systems. At the time of this study, much debate is currently centered on the proposed congestion pricing strategy in New York City that has recently been voted down.

While the Washington, D.C. area is not one of the USDOT pilot areas, the first of a network of HOT lanes in Virginia could potentially open in just two years, and the variably-tolled intercounty connector in Maryland is scheduled for completion by 2012. Additionally, the state of Oregon is in the process of developing GPS-based distance measurements to replace the fuel taxes it now uses to pay for road usage. At the onset, Oregon would not require all vehicles to have the GPS system – road users would initially have the choice of paying either fuel taxes or mileage-based charges.

Sullivan (2003) notes that in the mid-1970s, the federal government offered funds to U.S. cities willing to try a pricing scheme to reduce congestion. Although some implementation studies that produced findings favorable to the concept were conducted, all of these early initiatives failed, largely due to local community opposition. In 1991, the U.S. Congress passed a surface transportation act called the "Intermodal Surface Transportation Efficiency Act (ISTEA)." This act created the U.S. Congestion Pricing Pilot program, which directed the USDOT to help develop and fund congestion pricing pilot projects. In 1998, this program was renamed the "Value Pricing Pilot Program."

A common feature of value pricing projects is that pricing (i.e. the toll) varies with the time of day, in an effort to encourage traffic to shift away from peak periods. Tolls on value pricing facilities are generally determined by the responsible operating authorities, which include private companies, state DOTs, and regional government agencies – toll-setting by government agencies involves due process, including public comment. At the national level, it was recognized that using the rather academic title "Congestion Pricing" elicited negative emotions. Switching to "Value Pricing" provided a more positive way to identify the same notion – additionally, toll collection technologies are usually identified using positive labels, such as "Fastrak," "QuickRide," or "E-ZPass (Sullivan)."

2.3 Studies

Many studies have taken place involving the numerous facets of congestion and congestion pricing. Salomon and Mokhtarian (1997) identified and classified user responses relating to congestion, which showcase the various options that travelers have in regards to potential congestion pricing:

1) Accommodate congestion costs/do nothing
2) Reduce congestion costs
3) Change departure time
4) Change route
5) Buy time
6) Invest in productivity-enhancing technology at home
7) Adopt flextime
8) Adopt compressed work week
9) Change mode of travel
10) Telecommute from home
11) Telecommute from a telecenter
12) Change workplace
13) Relocate home
14) Change from full-time to part-time work
15) Start a home-based business
16) Quit work

A system of “first-best” pricing sets tolls to completely match the external costs generated by each traveler. This is accomplished by having variable charges that change in real-time with existing conditions. Although useful in a theoretical sense, “first-best” pricing has limited practicality. “Second-best” congestion pricing is more realistic and denotes a more static strategy where drivers are aware of applicable charges in advance. This includes the use of step-tolls instead of smoothly time-varying tolls or tolling according to a fixed daily schedule rather than day-specific traffic conditions (Lindsey and Verhoef 2000). Table 2-1 ranks common vehicle charging options in terms of how well they represent the costs imposed by a particular vehicle trip (Victoria Transport Policy Institute 2007).

Table 2-1: Common Vehicle Charging Options

Rank	General Category	Examples
Best	Time- and location-specific road and parking pricing	Variable road pricing, location-specific parking management, location-specific emission charges
Second Best	Mileage-pricing	Weight-distance charges, mileage-based vehicle insurance, prorated motor vehicle excise tax, mileage based emission charges
Third Best	Fuel charges	Increase fuel tax, apply general sales tax to fuel, pay-at-the-pump insurance, carbon tax, increase hazardous substance tax
Bad	Fixed vehicle charges	Current motor vehicle excise tax, vehicle purchase and ownership fees
Worst	External costs (not charged to motorists)	General taxes paying for roads and traffic services, parking subsidies, uncompensated external costs

As congestion pricing is quite controversial, Jones (1998) outlined potential reasons for opposing congestion pricing:

- Drivers find it difficult to accept the idea of being charged for something they wish to avoid (congestion) and also feel that congestion is not their fault, but rather something that is imposed on them by others
- Road pricing is not needed, either because congestion is not bad enough or because other measures are superior
- Pricing will not get people out of their cars
- The technology will not work
- Privacy concerns
- Diversion of traffic outside the charged area

- Road pricing is just another form of taxation
- Perceived unfairness

Two critical questions generated by the idea of congestion pricing focus on the optimal user charge amount and the effectiveness of the system. In terms of actual per-mile charge estimates, McMullen (1993) shares that previous research has estimated that, in 2007 amounts, efficient peak-period tolls in the range of $0.08 to $0.50 per mile are appropriate. The effectiveness question is answered by the aforementioned idea of elasticity. Based on studies by Oum et al. (1992), changes in road use as a result of increased costs are consistent with elasticities of -0.5 or less. Additionally, results from strategies in locations such as Stockholm are more consistent with an approximate elasticity of -0.2 (Victoria Transport Policy Institute 2007). A negative elasticity indicates that an increase in road pricing is associated with a decrease in demand/usage. Unfortunately, this value cannot be determined in advance of actual congestion pricing imposition. For this thesis specifically, the elasticity estimate shows how well a pricing strategy actually works. As an example, a price elasticity of -0.2 means that for every 10% increase in road user charges, a 2% reduction in road usage occurs.

Sullivan (2003) concludes that forward momentum has been established for innovative road pricing, but future progress toward more widespread use of congestion-based pricing is likely to take advantage of local opportunities which present themselves, and will proceed cautiously. Considerable emphasis will be placed on marketing strategies in order to win consumer acceptance. By preventing the loss of vehicle throughput that results from a breakdown of traffic flow, congestion pricing maximizes the return on the public's investment in highway facilities. Society as a whole also benefits by reducing fuel consumption and vehicle emissions and allowing more efficient land use decisions (FWHA 2001).

2.4 Closing Remarks

The provided information in this chapter helps to set the framework for this Capital Beltway study. Area-wide congestion pricing has been shown as a successful strategy in various parts of the world, but few implementations are operating or being discussed in the United States. This thesis fills a practical gap in the Washington, D.C. area – especially as congestion pricing is being considered on the horizon. As there is limited experience to draw upon, this study attempts to provide meaningful information.

Chapter 3: Methods and Data

3.1 Introduction

This study proposes a method to calculate the appropriate charges required for users of the Capital Beltway in order to fulfill their portion of congestion costs and is based upon previous methodology developed by Roth and Villoria (2001). These charges are calculated through the use of an optimization model. The method is based primarily on the relationship between traffic speed and traffic flow, from which delay calculations are determined.

3.2 Proposed Method

This study aims to determine the charge necessary to cause drivers to realize their congestion costs. The proposed method is illustrated, in the form of a flowchart, in Figure 3-1 and each step is discussed in-depth.

The first step in this method is to define the study area. I-495, the Capital Beltway that surrounds Washington, D.C., is an ideal candidate due to the fact that it exhibits recurring AM and PM peak period congestion problems. This area was shown in context of the region in Figure 1-1. As the only circumferential roadway in the area, many key routes connect to the Capital Beltway along its 64 mile length, providing a critical highway link to other transportation services, including three regional airports, transit and rail facilities, and port terminals. Due to this connectivity with other transportation facilities in the area, traffic congestion on I-495 has severe effects on regional mobility, even though it generally consists of 4-lane travel in both directions. In accordance with other locations that have implemented congestion pricing, the Washington, D.C. area exhibits severe traffic congestion. Key interchanges are consistently acknowledged as areas of overwhelming congestion and even though some travel alternatives exist, the automobile is the dominant mode.

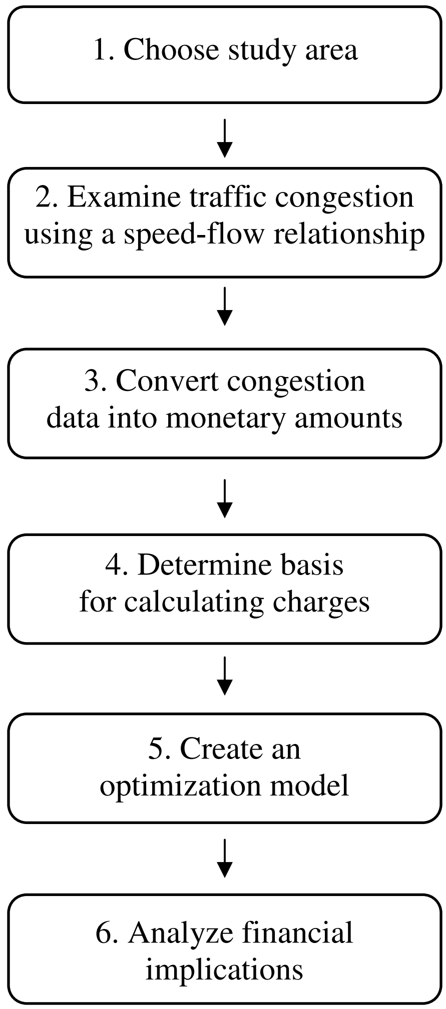


Figure 3-1: Proposed Method

Secondly, traffic congestion is examined using the relationship between traffic flow and traffic speed – this approach is utilized within the Highway Capacity Manual (Transportation Research Board 2000). In a strictly hypothetical sense, as flow increases towards roadway capacity, speed should decrease accordingly. The relationship between traffic flow and traffic speed enables the calculation of delay imposed by users on other vehicles on the roadway. Specific details on developing and expanding on this speed-flow relationship will be discussed as part of the model formation later in this chapter.

Next, any applicable congestion data, such as delay imposed, should be converted into dollar values. This is done by estimating user value of time and operating costs for the vehicles on the Capital Beltway.

The fourth step in this method is to determine the basis for calculating user charges. As different vehicles consume varying amounts of road space, it would be unjust to impose equal charges to every user. Using the Federal Highway Administration's (FHWA) vehicle classification system (shown below as Figure 3-2) and average vehicle lengths, estimates of passenger car equivalents (PCE) for each vehicle classification can be determined. This table of information is included as Table 3-1 and allows for extrapolation after calculating optimal charges per PCE.

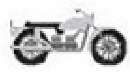
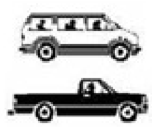
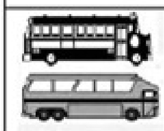
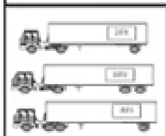
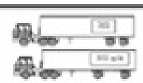
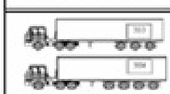
	**CLASS 1:** ***Motorcycles*** -- All two or three-wheeled motorized vehicles. Typical vehicles in this category have saddle type seats and are steered by handlebars rather than steering wheels. This category includes motorcycles, motor scooters, mopeds, motor-powered bicycles, and three-wheel motorcycles.
	**CLASS 2:** ***Passenger Cars*** -- All sedans, coupes, and station wagons manufactured primarily for the purpose of carrying passengers and including those passenger cars pulling recreational or other light trailers.
	**CLASS 3:** ***Other Two-Axle, Four-Tire Single Unit Vehicles*** -- All two-axle, four-tire vehicles, other than passenger cars. Included in this classification are pickups, panels, vans, and other vehicles such as campers, motor homes, ambulances, hearses, carryalls, and minibuses. Other two-axle, four-tire single-unit vehicles pulling recreational or other light trailers are included in this classification.
	**CLASS 4:** ***Buses*** -- All vehicles manufactured as traditional passenger-carrying buses with two axles and six tires or three or more axles. This category includes only traditional buses (including school buses) functioning as passenger-carrying vehicles. Modified buses should be considered to be a truck and should be appropriately classified.
	**CLASS 5:** ***Two-Axle, Six-Tire, Single-Unit Trucks*** -- All vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., with two axles and dual rear wheels.
	**CLASS 6:** ***Three-Axle Single-Unit Trucks*** -- All vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., with three axles.
	**CLASS 7:** ***Four or More Axle Single-Unit Trucks*** -- All trucks on a single frame with four or more axles.
	**CLASS 8:** ***Four or Fewer Axle Single-Trailer Trucks*** -- All vehicles with four or fewer axles consisting of two units, one of which is a tractor or straight truck power unit.
	**CLASS 9:** ***Five-Axle Single-Trailer Trucks*** -- All five-axle vehicles consisting of two units, one of which is a tractor or straight truck power unit.
	**CLASS 10:** ***Six or More Axle Single-Trailer Trucks*** -- All vehicles with six or more axles consisting of two units, one of which is a tractor or straight truck power unit.
	**CLASS 11:** ***Five or fewer Axle Multi-Trailer Trucks*** -- All vehicles with five or fewer axles consisting of three or more units, one of which is a tractor or straight truck power unit.
	**CLASS 12:** ***Six-Axle Multi-Trailer Trucks*** -- All six-axle vehicles consisting of three or more units, one of which is a tractor or straight truck power unit.
	**CLASS 13:** ***Seven or More Axle Multi-Trailer Trucks*** -- All vehicles with seven or more axles consisting of three or more units, one of which is a tractor or straight truck power unit.

Figure 3-2: FHWA Vehicle Classifications (FHWA 2001)

Table 3-1: Vehicle Classification PCE Factors

Vehicle Class	Vehicle Description	Average Length (feet)	PCE Factor
1	Motorcycle	6	0.38
2	Passenger Cars	16	1.00
3	Other Two-Axle, Four-Tire single Unit Vehicles	18	1.13
4	Buses	38	2.38
5	Two-Axle, Six-Tire, Single-Unit Trucks	26	1.63
6	Three-Axle Single-Unit Trucks	25	1.56
7	Four or More Axle Single-Unit Trucks	32	2.00
8	Four or Fewer Axle Single-Trailer Trucks	44	2.75
9	Five-Axle Single-Trailer Trucks	64	4.00
10	Six or More Axle Single-Trailer Trucks	63	3.94
11	Five or Fewer Axle Multi-Trailer Trucks	68	4.25
12	Six-Axle Multi-Trailer Trucks	73	4.56
13	Seven or More Axle Multi-Trailer Trucks	69	4.31

The fifth step in this method is to create an optimization model. For the purposes of this study, the model will be created using the Solver tool in Microsoft Excel. In a nutshell, Excel Solver generates specific values (i.e. charges) to optimize a certain objective. In the case of this study, the optimized variable is the dollar amount that users of I-495 should be charged per-mile.

Lastly, the financial implications of user-based charging on the Capital Beltway will be analyzed. Estimates of potential costs and revenue will be examined in order to provide information on this feasibility aspect.

3.3 Methodology

This section focuses on formulating the model used in this thesis. The following main points will be addressed:

- The process of obtaining usable data for this study
- Preparing the data for speed and flow analysis

- Using the relationship between traffic speed and traffic flow to perform delay calculations
- Applying relevant user value of time and vehicle operating cost estimations to setup the model to optimize congestion charges for the Capital Beltway

3.3.1 Data

The first stage of this thesis involved obtaining I-495 detector data for use in the study. When contacting the Maryland State Highway Administration (MD SHA) and the Virginia Department of Transportation (VDOT), the following main components of desired data were expressed:

- Detector locations on I-495 in Maryland or Virginia
- Permanent detection stations reporting data in intervals less than or equal to one hour for all hours of the day
- Volume count information (both total counts and counts broken down by FHWA vehicle classification)
- Vehicle speed information
- Data archived for multiple years

In-road detectors (i.e. loop detectors) are the most commonly used technology for collecting traffic data and agencies often have permanent detection locations reporting data. Temporary tubes are sometimes used for specific purposes, but in general, agencies rely on loop detection for their traffic data. To this extent, Tom Schinkel of the VDOT Mobility Management Division was able to provide study data from six permanent detection locations within the Virginia section of I-495. As these detection locations are split directionally, they encompass three general locations. The following table provides general detector location details and these locations are also shown graphically in Figure 3-3.

Table 3-2: I-495 Detector Location Information

Detector ID	Direction	Start Location	End Location
90202	North	Eisenhower Ave Connector	SR 241/Telegraph Rd
190004	South	Eisenhower Ave Connector	SR 241/Telegraph Rd
90138	North	I-95/I-395	29-620/Braddock Rd
190057	South	I-95/I-395	29-620/Braddock Rd
90275	North	Dulles Access Rd; SR 267/Dulles Toll Rd	SR 193/Georgetown Pike
190064	South	Dulles Access Rd; SR 267/Dulles Toll Rd	SR 193/Georgetown Pike

It should be noted that the detectors are physically located between the given landmarks, which are easier to decipher while looking at a map than the actual latitude and longitude coordinates.

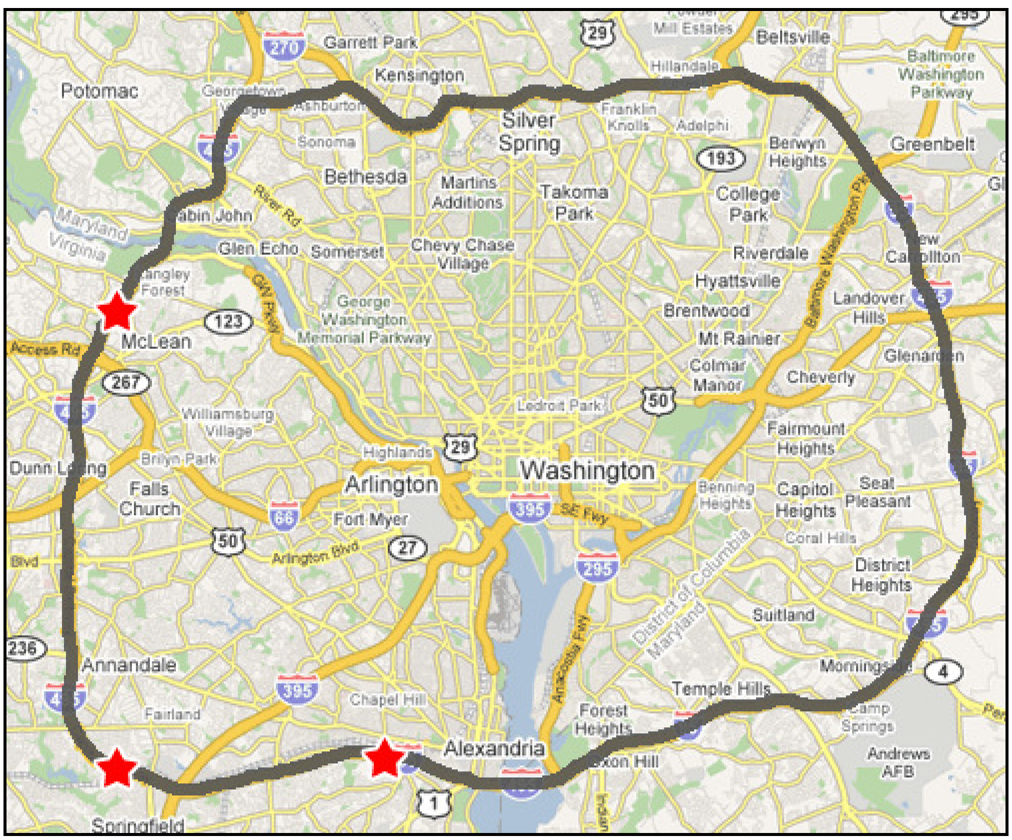


Figure 3-3: I-495 Data Locations
Source: Google Maps

For this study, it is assumed that the available VDOT detector data is representative of the entire Virginia portion of I-495. The data was collected on a per-lane basis and in 15 minute intervals, and was provided in aggregate form with all lanes combined by direction and data based hourly.

Unfortunately, MD SHA was unable to provide data for this study, as no functioning permanent detection stations that collected all of the required information were available. This was based on the fact that this data was not available from any of the five automatic traffic recorder (ATR) stations located on the Maryland section of I-495. As such, the data provided by VDOT was used as representative for all of the Capital Beltway.

The hourly speed and volume data, ranging from as far back as 2002, were cleansed and laid out in spreadsheet form by detector ID and year in order to provide consistency for analysis purposes. Due to the fact that detection equipment sometimes reports false data (i.e. zero volumes, exorbitant speeds, etc.), "cleansing" of such data is required. This process, in its most basic form, consisted of the following:

- Separate and organize data from all detectors into individual years
- Determine the day of week that each data point was collected and delete all weekend data
- Delete any speed and volume outlier data (significant errors in data collection)
- Assign an hour code (0-23) to each data point

- Spreadsheets were setup to contain Detector ID, Hour Code, Volume By Vehicle Classifications (split from 1-13), and Average Speed For All Vehicles on each row

As expected with any research, data limitations exist in this study. Since there was no Maryland data available for use, Virginia data is assumed representative across the entire Capital Beltway. Although this may not be an entirely valid assumption, it can be used for information purposes and to calculate pricing for the Virginia portion of I-495. Also of note, some of the detectors, whether it is based on their location or specific direction, don't provide particularly exciting data at all times. Whether that means certain detectors show consistent speeds throughout the day or only one pronounced peak period, all data is considered meaningful. Not all locations on I-495 experience severe AM and PM peak period congestion and this data tends to make the model more representative instead of over-inflating it to the side of congestion. If only data from congested locations were used, it would be inferred that traffic is uniform along the entire Capital Beltway, which is not the case.

3.3.2 Speed Analysis

The provided speed data were broken down by each vehicle classification. Using weighted averages based on the number of vehicles in each associated category, average hourly speeds for the entire traffic stream were calculated. For each of the 24 hours in a day, average speed tables were created for each detector. With data existing from previous years, the hourly speeds were overlaid to view yearly changes. An example of these hourly speed plots is shown as Figure 3-4 and the additional plots from the remaining detectors can be viewed in the Appendix.

Based on this plot, two peak periods are evident – one in the morning and one in the evening. The apparent extent of the evening peak spreads across more hours than the morning peak. For this thesis, peak periods are visually defined based on the hourly speed plots from the detectors. From Figure 3-4, these peaks are estimated to occur from 6AM-10AM and 2PM-7PM.

Speed data can also provide insight from another perspective. By plotting average hourly speed by year, periods of decreased speed become easily visible. An example of these hourly speed plots is shown as Figure 3-5 and the additional plots from the remaining detectors can be viewed in the Appendix. Based on this plot, decreases in speed are evident from 8AM-10AM and from 3PM-7PM. Coupled with the previous plot, this information paints a clear picture of peak periods at each detector location.

For the purpose of this thesis, free-flow speed is said to equal the uncongested traffic speed – as determined by the average of the 85th percentile speeds for each detector between 1AM and 4AM for all of 2007. Free-flow speed is therefore found to equal 63.8 miles per hour (mph) on the Capital Beltway, even though the posted speed limit is 55 mph.

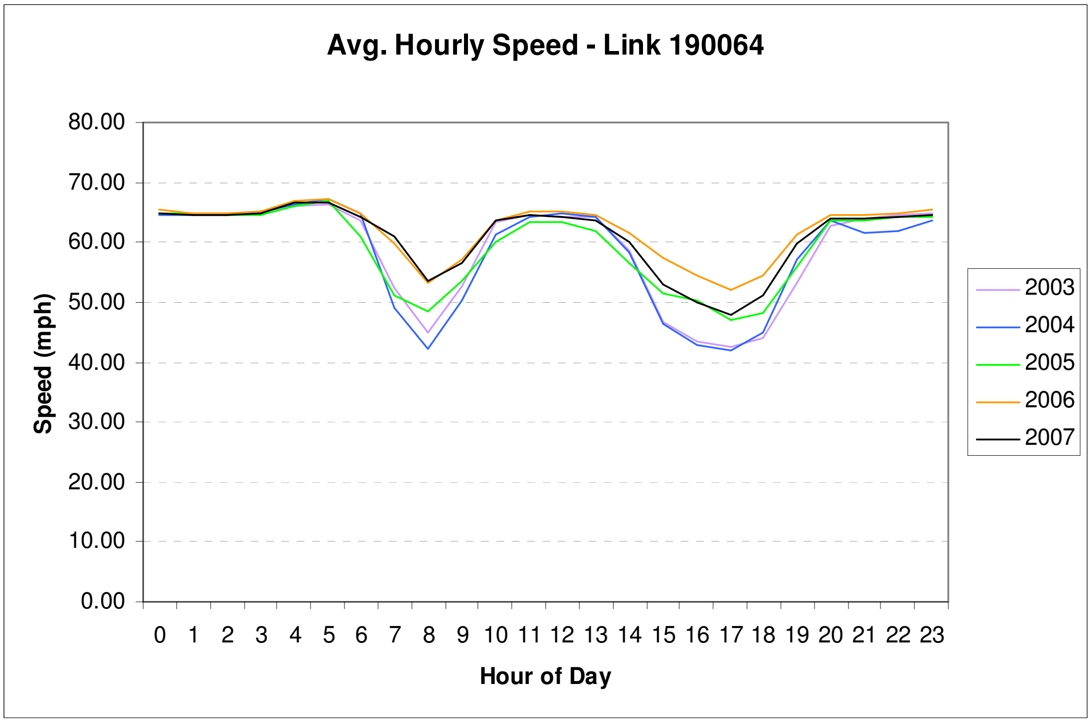


Figure 3-4: Average Hourly Speed – Detector 190064

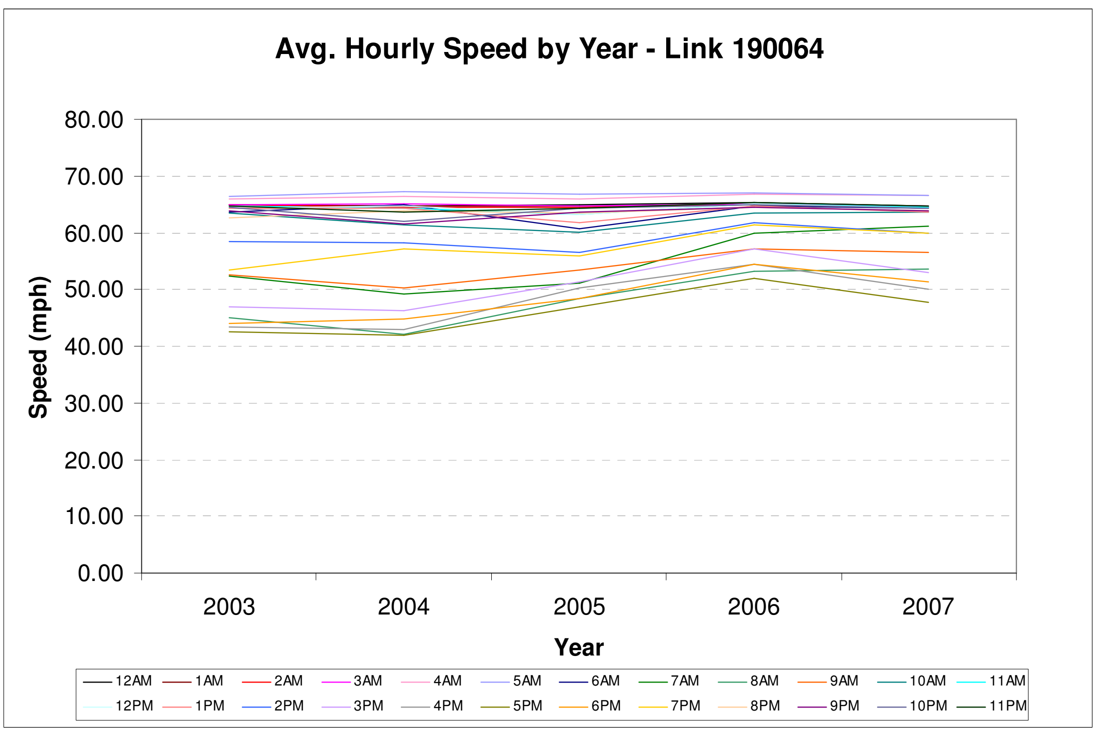


Figure 3-5: Average Hourly Speed by Year – Detector 190064

3.3.3 Flow Analysis

In a similar fashion to the speed analysis, flow analysis was conducted on the data. The provided volume data were broken down by each vehicle classification and multiplied by corresponding PCE factors to represent hourly PCE flow. For each of the 24 hours in a day, average flow tables were created for each detector. With data existing from previous years, the hourly flows were overlaid to view yearly changes. An example of these hourly speed plots is shown as Figure 3-6 and the additional plots from the remaining detectors can be viewed in the Appendix. As with the hourly speed plot presented in the previous section, two peak periods are seen – one in the morning and one in the evening. The apparent extent of the evening peak once again spreads across more hours than the morning peak – in this case, about two extra hours.

Across multiple years, changes in flow are evident. This is expected, as traffic volumes generally increase every year. In addition to higher flow rates, expanded peak periods start to occur, as traffic shifts to the hours before and after the peak periods of previous years. The flow data can also be visualized by plotting average hourly flow by year, making periods of increased flow more visible. An example of these hourly flow plots is shown as Figure 3-7 and the additional plots from the remaining detectors can be viewed in the Appendix. Based on this plot, the greatest flow occurs between the hours of 6AM-11AM and from 12PM-8PM – these are not necessarily the true peak periods at this location. These are just the times of day when there is an increase of flow at off-peak hours. Coupled with the previous plot and the speed plots from the previous section, this information provides insight to peak periods at each detector location.

From the speed analysis, it was determined that the average uncongested (free-flow) speed on I-495 was 63.8 mph. Using the 2000 edition of the Highway Capacity Manual and this given free-flow speed, the per-lane capacity of I-495 is determined to be 2,350 passenger cars per lane per hour (pc/ln/hr). For the purposes of this thesis, data will be examined on a per-lane basis instead of in terms of the total facility (i.e. four lanes). By limiting the study to a per-lane basis, uniform traffic activity across each lane is assumed, even though this is probably not the case on I-495.

Volume-to-capacity (v/c) ratio is a common statistic used by traffic engineers to gauge the health or level of service of a certain roadway. Using the flow data and the capacity figure from the Highway Capacity Manual, the hourly v/c ratio can be plotted for each detector, with data from previous years included, as well. Volume-to-capacity ratio plots are another tool used to view peak period conditions on the roadway. An example of a v/c ratio plot is shown below, with the additional plots from the remaining detectors available in the Appendix. Based on this plot, the AM and PM peaks are once again evident – the plot mimics the previous average hourly flow plot, as the observed flow is an input, along with the capacity, which stays constant.

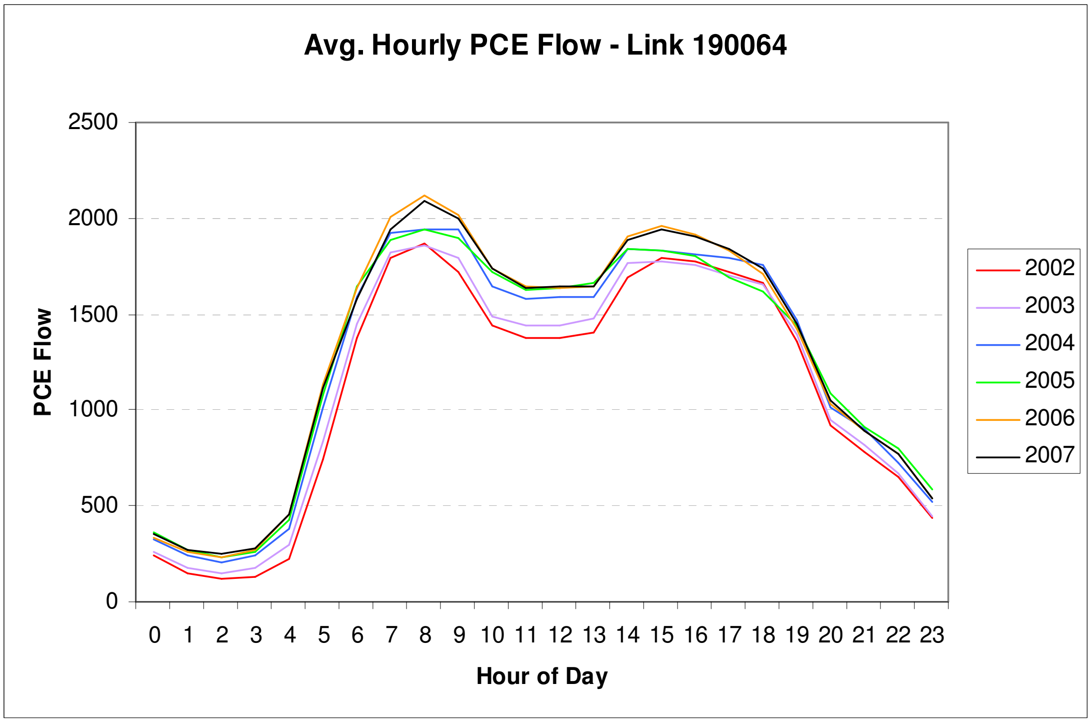


Figure 3-6: Average Hourly Flow – Detector 190064

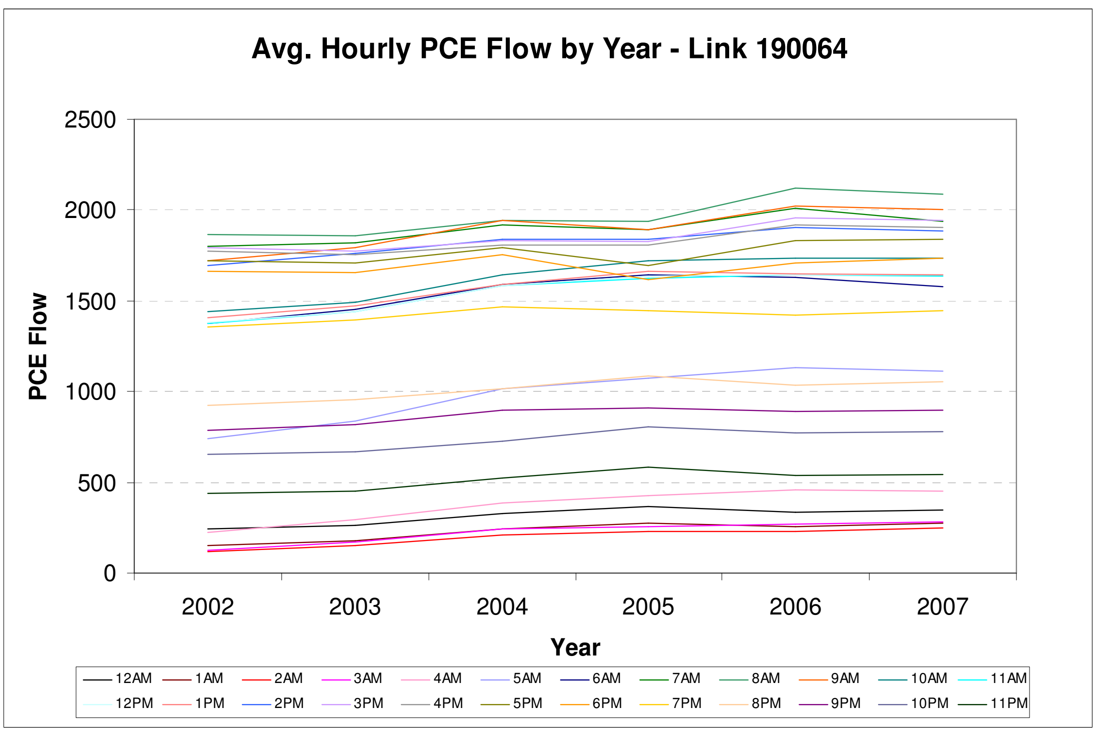


Figure 3-7: Average Hourly Flow by Year – Detector 190064

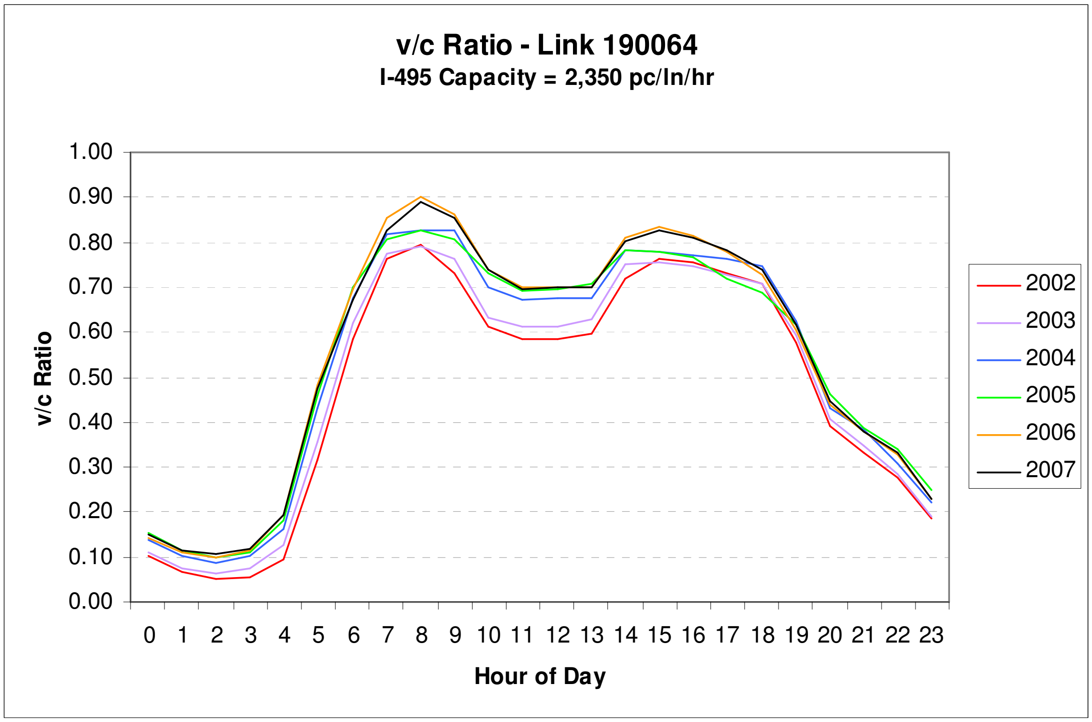


Figure 3-8: Hourly Volume-to-Capacity Ratio – Detector 190064

3.3.4 Speed-Flow Relationship

As the speed and flow data have been looked at separately up to this point, they are now combined in order to develop the relationship that is the backbone of this study. Traffic speed and traffic flow data is plotted to see the effect that flow has on speed – hypothetically, speed decreases as flow increases. While attempting to approximate the data with a straightforward linear relationship would be easy, it is far too simplistic and not realistic for this complex phenomenon.

The Highway Capacity Manual provides equations that determine speeds based on a given free-flow speed (FFS) and available flow data (flow rate v_p). As the free-flow speed was calculated to be 63.8 mph for I-495, the following equations, as set forth in Exhibit 23-3 of the Highway Capacity Manual, will be utilized:

For $55 \leq FFS \leq 70$ and for flow rate (v_p)

$(3400 - 30FFS) < v_p \leq (1700 + 10FFS)$,

$$S = FFS - \left[\frac{1}{9}(7FFS - 340)\left(\frac{v_p + 30FFS - 3400}{40FFS - 1700} \right)^{2.6} \right] \qquad \text{Eq. 1}$$

For $55 \leq FFS \leq 75$ and $v_p \leq (3400 - 30FFS)$,

$$S = FFS \qquad \text{Eq. 2}$$

The HCM equations are broken down into two sections, due to the fact that at low volumes, speed remains fairly constant and then starts to decrease at higher flow rates. As such, the current HCM speed-flow relationship is shown as an unchanging constant portion at low flows and a slowly downward-curving portion at higher flows. Based on the above equations, the ranges are 1,486 pc/ln/hr to 2,338 pc/ln/hr for the first equation and less than 1,486 pc/ln/hr for the second. By entering flow values from I-495 data and obtaining the corresponding speed values, a speed-flow plot can be created to show the effect that flow has on speed.

By plotting the HCM equations over the I-495 data points, along with the fourth-order polynomial regression equation calculated from the data, the speed-flow relationship is visualized. Within the regression equation, the constant is equal to the free-flow (uncongested) speed that was determined earlier. The lane capacity of I-495 (2,350 pc/ln/hr) is shown as the vertical dashed line in the plot.

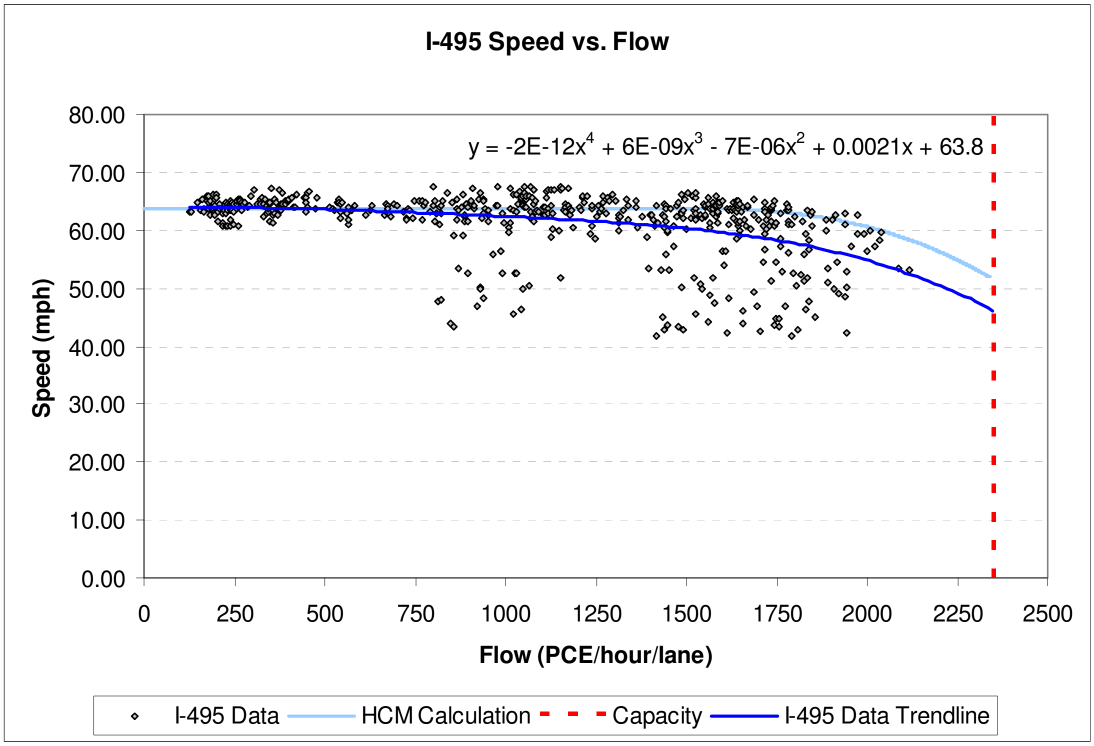


Figure 3-9: I-495 Speed vs. Flow

While the HCM calculations may look approximately appropriate to the data, the regression equation from the I-495 data decreases at a greater rate. The HCM calculations are based on national averages and I-495 data could vary for a number of reasons (year built, geometry, etc.). It goes without saying that the general HCM calculations do not represent I-495 in this case, but would be quite helpful for situations where actual data for calculations is not available. As discussed in chapter 2, the HCM does not address hypercongestion – the area of unstable flow that occurs as flow reaches capacity and the curve turns inward on itself. This area is the not within the scope of this thesis and will not be discussed. While this may seem to be a limitation, congestion pricing can improve traffic flow to the point where this scenario does not occur.

3.3.5 Delay Calculations

Based on the speed-flow relationship equation derived from the data, the amount of delay imposed on the traffic stream by an additional PCE/lane/hour (in minutes per mile) can be calculated. These calculations can be compared to those generated using the equations from the HCM in order to showcase differences and re-validate the knowledge that the HCM equations are not appropriate as a generalization in the case where actual data is present to examine. The delay calculation process is as follows:

- For possible traffic flows, calculate the corresponding travel speed
- Calculate time to travel one mile at given flow (based on speed)
- Calculate time to travel one mile at one less PCE/lane/hour (based on speed)
- Multiply the total flow by the difference in the previous two calculations to obtain the total delay imposed on traffic by an additional PCE/lane/hour

Table 3-3: Delay Calculations Using HCM Equations

Traffic Flow (PCE/lane/hour)	Travel Speed (mph)	Time to travel one mile at given volume (min./mile)	Time to travel one mile at one less PCE/lane/hour (min./mile)	Delay imposed on traffic stream by an additional PCE/lane/hour (min./mile)
50	63.80	0.94044	0.94044	0.00000
100	63.80	0.94044	0.94044	0.00000
150	63.80	0.94044	0.94044	0.00000
200	63.80	0.94044	0.94044	0.00000
250	63.80	0.94044	0.94044	0.00000
300	63.80	0.94044	0.94044	0.00000
350	63.80	0.94044	0.94044	0.00000
400	63.80	0.94044	0.94044	0.00000
450	63.80	0.94044	0.94044	0.00000
500	63.80	0.94044	0.94044	0.00000
550	63.80	0.94044	0.94044	0.00000
600	63.80	0.94044	0.94044	0.00000
650	63.80	0.94044	0.94044	0.00000
700	63.80	0.94044	0.94044	0.00000
750	63.80	0.94044	0.94044	0.00000
800	63.80	0.94044	0.94044	0.00000
850	63.80	0.94044	0.94044	0.00000
900	63.80	0.94044	0.94044	0.00000
950	63.80	0.94044	0.94044	0.00000
1000	63.80	0.94044	0.94044	0.00000
1050	63.80	0.94044	0.94044	0.00000
1100	63.80	0.94044	0.94044	0.00000
1150	63.80	0.94044	0.94044	0.00000
1200	63.80	0.94044	0.94044	0.00000
1250	63.80	0.94044	0.94044	0.00000
1300	63.80	0.94044	0.94044	0.00000
1350	63.80	0.94044	0.94044	0.00000
1400	63.80	0.94044	0.94044	0.00000
1450	63.80	0.94044	0.94044	0.00000
1500	63.80	0.94044	0.94044	0.00105
1550	63.79	0.94065	0.94064	0.01297
1600	63.74	0.94137	0.94135	0.03395
1650	63.64	0.94285	0.94281	0.06298
1700	63.47	0.94527	0.94521	0.09995
1750	63.24	0.94881	0.94873	0.14515
1800	62.92	0.95365	0.95354	0.19915
1850	62.50	0.95997	0.95983	0.26280
1900	61.99	0.96796	0.96778	0.33724
1950	61.36	0.97783	0.97761	0.42397
2000	60.62	0.98983	0.98956	0.52492
2050	59.75	1.00422	1.00391	0.64254
2100	58.75	1.02134	1.02097	0.78001
2150	57.61	1.04157	1.04113	0.94139
2200	56.32	1.06537	1.06485	1.13198
2250	54.88	1.09331	1.09271	1.35869
2300	53.28	1.12612	1.12541	1.63075
2338	51.96	1.15483	1.15403	1.87530
2500	not included in HCM equations			

Table 3-4: Delay Calculations Using I-495 Regression Equation

Traffic Flow (PCE/lane/hour)	Travel Speed (mph)	Time to travel one mile at given volume (min./mile)	Time to travel one mile at one less PCE/lane/hour (min./mile)	Delay imposed on traffic stream by an additional PCE/lane/hour (min./mile)
50	63.89	0.93914	0.93914	0.00000
100	63.95	0.93829	0.93829	0.00000
150	63.98	0.93784	0.93784	0.00000
200	63.98	0.93772	0.93772	0.00012
250	63.97	0.93789	0.93788	0.00145
300	63.95	0.93829	0.93828	0.00305
350	63.90	0.93890	0.93888	0.00481
400	63.85	0.93966	0.93964	0.00665
450	63.79	0.94055	0.94053	0.00851
500	63.73	0.94155	0.94153	0.01033
550	63.65	0.94261	0.94259	0.01210
600	63.58	0.94374	0.94372	0.01378
650	63.50	0.94491	0.94488	0.01539
700	63.42	0.94611	0.94608	0.01696
750	63.34	0.94733	0.94730	0.01851
800	63.25	0.94857	0.94855	0.02010
850	63.17	0.94984	0.94982	0.02183
900	63.08	0.95115	0.95112	0.02377
950	62.99	0.95249	0.95246	0.02605
1000	62.90	0.95390	0.95387	0.02880
1050	62.80	0.95538	0.95535	0.03218
1100	62.70	0.95697	0.95694	0.03637
1150	62.58	0.95870	0.95866	0.04157
1200	62.46	0.96060	0.96056	0.04801
1250	62.32	0.96272	0.96267	0.05593
1300	62.17	0.96510	0.96505	0.06563
1350	62.00	0.96779	0.96774	0.07741
1400	61.80	0.97086	0.97080	0.09163
1450	61.58	0.97437	0.97430	0.10870
1500	61.33	0.97839	0.97831	0.12905
1550	61.04	0.98301	0.98292	0.15321
1600	60.71	0.98832	0.98821	0.18177
1650	60.34	0.99443	0.99430	0.21541
1700	59.91	1.00144	1.00129	0.25493
1750	59.44	1.00949	1.00932	0.30127
1800	58.90	1.01873	1.01853	0.35556
1850	58.29	1.02933	1.02911	0.41915
1900	57.61	1.04149	1.04123	0.49367
1950	56.85	1.05543	1.05513	0.58113
2000	56.00	1.07143	1.07109	0.68400
2050	55.06	1.08979	1.08940	0.80541
2100	54.01	1.11091	1.11046	0.94928
2150	52.85	1.13523	1.13471	1.12066
2200	51.58	1.16331	1.16271	1.32610
2250	50.17	1.19585	1.19515	1.57426
2300	48.63	1.23371	1.23289	1.87670
2338	47.37	1.26671	1.26579	2.15236
2350	46.95	1.27799	1.27703	2.24920

3.3.6 Speed Frequency and Probability by Flow Range

The frequency of data points that fall in a certain flow range, along with the speed probabilities within a certain flow range, are interesting aspects to explore. Data existing under flow conditions less than 1,200 pc/ln/hr can be grouped together, as these low-flow areas are less interesting than periods of higher flow.

Using all of the data points, along with three speed ranges (41-50 mph, 51-60 mph, and 61-70 mph), the probability of a data point falling in each speed range can be calculated for increasing flow rates. This will show the probability of being in each speed range as a function of flow. This information is displayed in Figure 4-8 and provides a sample probability density function (PDF) for each flow range. The speed probability graph is not terribly surprising, as the probability of higher speeds decreases as flow increases. A few strange overlap areas exist, and the 1,901-2,000 pc/ln/hr flow range is particularly interesting since it is a merge point where all three speed ranges have an equal probability of occurring. Curiosity arises when that sort of uncertainty exists.

Moving forward, the frequency of data in each flow range is plotted as Figure 4-9 – the relative frequency of the various flow ranges assists with critiquing the data. When looking at the frequency of data points across different flow ranges, the vast majority of data is from periods of lower demand that exhibit low-flow conditions (i.e. off-peak hours). Although regular users of the Capital Beltway may choose to disagree, this observation makes sense, as there are more uncongested hours than congested hours in the day. Flows greater than 1,200 pc/ln/hr, are characterized by a small bell-shaped curve, with a small likelihood of encountering lower volumes at either end of the range. Whenever these situations occur, the onset of some congestion in these locations may be the result. The frequency of data greater than 2,000 pc/ln/hr is low – possibly due to the fact that traffic is unable to exhibit the steady flow conditions that enable flows at this rate or higher.

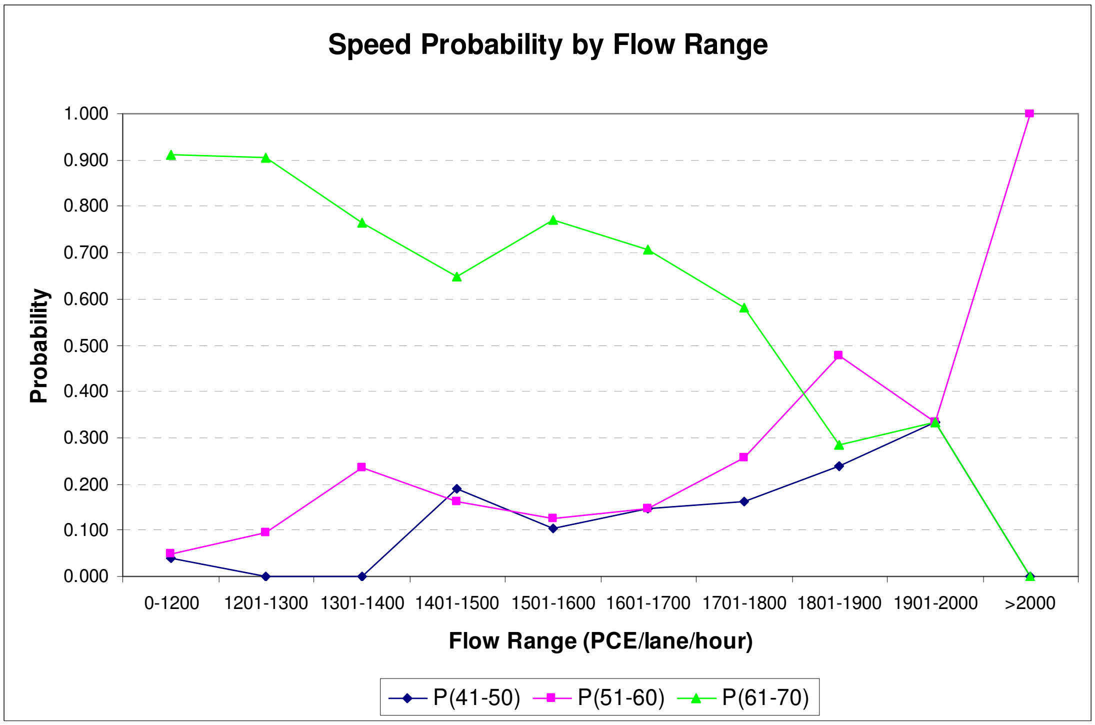


Figure 3-10: Speed Probability by Flow Range

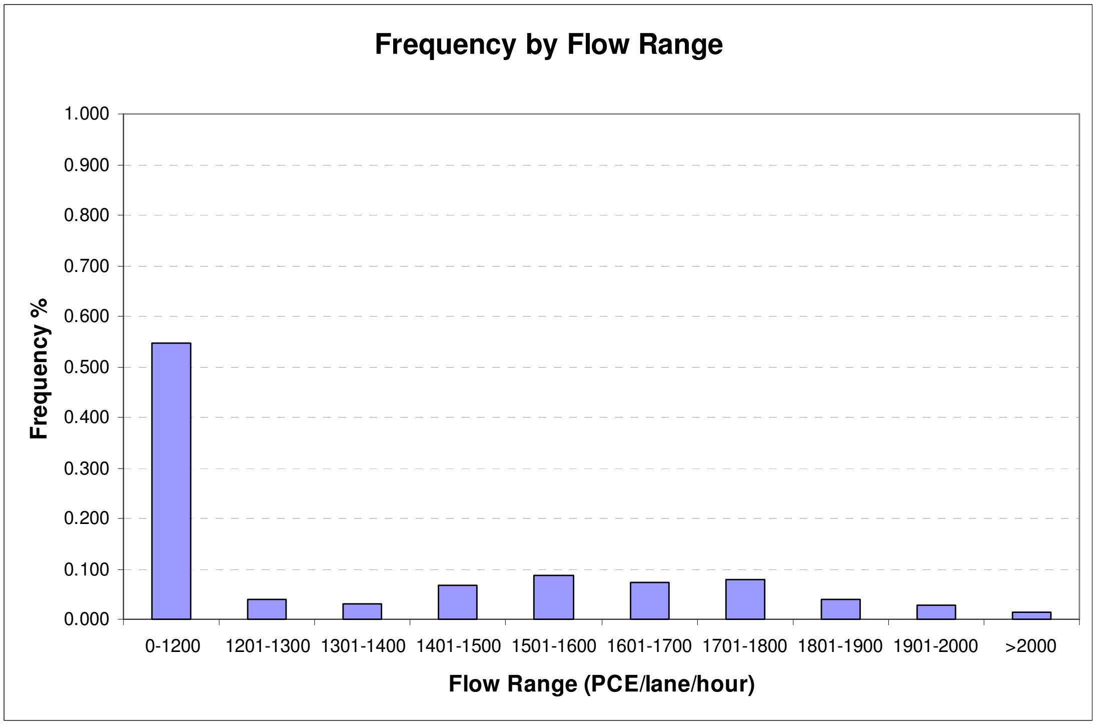


Figure 3-11: Frequency by Flow Range

3.3.7 Traffic Proportions

Traffic proportions for each of the 13 FHWA vehicle classifications are components of the optimization model and will be applied across varying flow levels. As traffic stream characteristics differ between AM and PM peak periods, analysis is completed using both periods in order to determine appropriate traffic proportion percentages. As part of the Federal Highway Administration's Highway Performance Monitoring System (HPMS), Maryland collects vehicle classification information on I-495. For this reason, data from Maryland is able to be included at this stage of the study. Although this data does not contain speed information and, therefore, cannot be used throughout the remainder of this study, traffic proportion percentages can be obtained and compared with the Virginia data that have been utilized up to this point.

Based on general knowledge and the aforementioned flow and speed graphs that showcased evident peak period times, the AM peak period is defined as 6AM-10AM and the PM peak period is defined as 3PM-7PM. After combining all relevant data for these time periods and averaging Virginia and Maryland data together, the following percentages were obtained for each of the 13 FHWA vehicle classifications:

Table 3-5: Peak Period Traffic Proportions

	AM Peak (%)	PM Peak (%)
Class 1	0.16	0.16
Class 2	83.18	86.78
Class 3	12.39	10.35
Class 4	0.68	0.42
Class 5	0.90	0.60
Class 6	0.58	0.24
Class 7	0.24	0.07
Class 8	0.22	0.16
Class 9	1.55	1.17
Class 10	0.06	0.02
Class 11	0.03	0.02
Class 12	0.01	0.01
Class 13	0.00	0.00

Although the AM and PM peak period traffic proportion percentages seem rather similar, they will be used separately when calculating the associated peak period charges.

3.4 Value of Time Estimation

In order to devise a pricing strategy, dollar amounts must be attributed to the time spent in congestion (i.e. the delay calculations set forth previously). In order to do this, user value of time estimates must first be obtained. As no studies have been undertaken in the Washington, D.C. area to associate value of time estimates to each of the 13 FHWA vehicle classifications, estimates are extrapolated from the Highway Economic Requirements System (HERS), a FHWA model designed to simulate improvement selection decisions based on the relative benefit-cost merits of alternative improvement options (FHWA 2002). The HERS model provides combined user value of time and vehicle operating costs for seven vehicle classes which differ from the 13 vehicle classifications used in this study. As the amounts provided in the model's documentation are not current, they are converted to equivalent 2007 dollars. Prevailing wage data is the general basis for user value of time and costs are compensated by the fact that operating costs differ from vehicle-to-vehicle. These values include both aspects.

Table 3-6: FHWA HERS Model – Value of Time

Vehicle Class	Value (in 2007 $/hour)
Small Auto	21.37
Med. Auto	21.43
4-Tire Truck	24.27
6-Tire Truck	27.18
3-4 Axle Truck	32.19
4-Axle Combo.	34.68
5-Axle Combo.	34.34

Based on the HERS model estimates and general assumptions about vehicle classifications, value of time and operating costs estimates are calculated for each of the 13 FHWA vehicle classifications. Table 4-6 showcases these estimates. It should be noted that operating costs for motorcycles are estimated to be half of those associated with passenger cars and user value of time is chosen to be represented by the $11.56 per hour value provided for personal, not business, travel. Additionally, since no actual occupancy data were available, standard bus occupancy is assumed to be 30 passengers, all traveling under personal user value of time estimates. While this estimate may not be precise, it will provide a rough approximation, at the very least.

Table 3-7: FHWA Vehicle Classifications – Value of Time

Vehicle Class	Value (in 2007 $/hour)
1	12.31
2	21.40
3	24.27
4	346.93
5	27.18
6	32.19
7	32.19
8	34.68
9	34.34
10	34.34
11	34.34
12	34.34
13	34.34

In this study, the distribution of trip purposes is not taken into account. Value of time is inherently laden with a trip purpose (i.e. personal use, business use, etc.) and, for this thesis, the assumption is made that value of time estimates are not reflecting varying trip purposes.

3.5 Model Formulation

As previously stated, one of the research objectives of this thesis is to develop a model that optimizes the pricing necessary to cause vehicle users on the Capital Beltway to realize the congestion costs that their vehicles impose on the rest of the traffic stream. To this extent, congestion pricing will serve as a demand management tool. While the model process will be outlined in this section, a visual demonstration will be provided in the next chapter.

Based on a model developed by Roth and Villoria (2001), the algorithm is as follows:

1. Using a provided initial flow condition and traffic proportions calculated previously, calculate the initial number of vehicles in each classification category
2. Using the aforementioned equation that relates speed and flow and the given flow condition, calculate the initial speed of the traffic system
3. Initial cost (per vehicle) to travel one mile can be calculated by dividing the total costs for each vehicle classification by the initial speed
4. A variable congestion charge is introduced at this point and the cost for each vehicle to travel one mile, including the congestion charge, is calculated - this charge will be varied by the model
5. The percent change in cost after adding the congestion charge is calculated
6. Based on the assumed negative elasticity, the initial number of vehicles, and the percent change in cost, the change in flow after imposing the congestion charge is calculated
7. The new flow for each vehicle classification is calculated by subtracting the change in flow from the initial flow
8. Using the updated total flow in the traffic system, new traffic composition proportions and speed values can be calculated
9. Calculate the average vehicle speed at one less PCE/lane/hour than the updated flow condition
10. Calculate costs per vehicle at both the current speed and the speed at one less PCE/lane/hour in order to determine the cost imposed on the entire traffic

stream by one extra PCE (this concept is similar to the delay calculation that was explained previously)

11. The total cost due to one extra PCE is the cost imposed on the entire traffic stream by the additional PCE added to the average cost per vehicle under current conditions
12. A variable percent change is introduced at this point - this is used to calculate theoretical flow and cost information which is used by the optimization model
13. Using the initial cost per vehicle to travel one mile under initial flow conditions, calculate a weighted cost average based on the new traffic proportions
14. The resulting theoretical flow is found by multiplying the initial flow by one minus the percent change times the elasticity
15. The resulting theoretical cost (i.e. the equilibrium demand price) is found by adding the weighted cost average based on the new traffic proportions to one plus the percent change
16. At this point, the model is instructed to force the resulting theoretical cost minus the total cost due to one extra PCE to equal zero and to minimize the resulting theoretical flow minus the flow after the imposing the congestion charge
17. The model runs until an optimal congestion charge solution is reached – this charge is the amount that equals the congestion cost under the conditions existing after it is inflicted

3.6 Assumptions

Throughout the model formulation process of this study, various assumptions needed to be made:

- Due to the fact that no comprehensive Maryland data was available for I-495, the obtained data from Virginia was assumed to be representative of the entire Capital Beltway. As there are varying levels of traffic collected at each of the Virginia detector locations, this assumption seems valid. While the results of this Washington, D.C.-area study may not be entirely transferable to other regions, the methodology will remain valid.
- When calculating AM and PM peak traffic proportions, it was assumed that the distribution of vehicle types across all travel lanes remained at the average values throughout the peaks (instead of changing hourly, etc.). While some changes might have occurred if the traffic proportions were analyzed on a per-hour basis, the changes would seemingly be small enough to merit using overall average values instead.
- As no user value of time or vehicle operating cost data existed that was broken down into the 13 FHWA vehicle classifications, the estimated values used in the FHWA HERS model were assumed in this study. These values were not entirely specific for each vehicle classification, but are assumed valid due to the lack of more exhaustive data. As stated previously, the distribution of trip purposes was not taken into account for the value of time estimation. The assumption is made that value of time estimates are not reflecting varying trip purposes.

- In calculating total vehicle costs, no clear estimates were found on average bus occupancy on the Capital Beltway. An average occupancy of 30 passengers was assumed, due to the lack of sufficient ridership data. As this value may seem high, it provides an approximation, although the total value of bus traffic may potentially be inflated.
- Speed and flow distributions are assumed uniformly equal across all lanes of I-495 in this study. In actuality, this is not the case. Since the user charges are calculated at the PCE level, however, this does not seem to affect the results. Regardless of the per-lane statistics, user charges are assigned to each PCE.
- User value of time estimates may actually be different than calculated. User responses to congestion charges vary and people will express varying elasticity levels. This being said, the value of time estimates set forth in this study should be taken as approximations.

Due to the various assumptions set forth in this study, it is likely that the results of this study may be artificially low. In this light, the results can be considered to be conservative estimations.

The following chapter discusses the system evaluation, along with a demonstration of the model utilized in this study. Applicable user charges and sensitivity analysis will also be presented.

Chapter 4: System Evaluation

4.1 Inputs

The input parameters for this model have been previously touched on, at least briefly, as they were obtained or calculated from available I-495 data. To summarize:

- *Flow* – measured in passenger cars per lane per hour (pc/ln/hr); obtained from I-495 data
- *Speed-flow relationship* – regression equation calculated from I-495 data obtained for this study in order to show the impact of traffic flow on traffic speed; this equation can be used to estimate speeds under various flow conditions
- *Total vehicle costs* – measured in dollars per hour ($/hr); calculated by summing user value of time and vehicle operating costs for each of the 13 FHWA vehicle classifications
- *Traffic proportions* – measured as a percentage (%); traffic proportions for each of the 13 FHWA vehicle classifications were calculated in the AM and PM peak periods based on the total traffic volume data obtained from I-495
- *Elasticity* – unitless number; a negative elasticity indicates the changes that occur in road use as a result of increased costs; the assumed elasticity of -0.2 for this model is based on a general literature search, estimates from the existing charging system in Stockholm, Sweden, and the knowledge that sufficient transit options do not exist on I-495; elasticity

must be estimated, as the true value cannot be determined unless pricing is actually implemented and travel behavior is observed

While all of these parameters are vital for a functional model, they are not all direct inputs from the user. The speed-flow regression equation and all applicable constants are programmed into the model. All other inputs are controlled by the user.

4.2 Outputs

The outputs produced by this model can be placed into two categories: process outputs and final outputs. Process outputs consist of calculations that occur throughout the iterative process of the model that lead to the final outputs – the optimized variables.

Process outputs:

- *Initial number of vehicles* – measured in passenger car equivalents (PCEs); calculated based on initial flow and traffic proportion conditions
- *Initial speed* – measured in miles per hour (mph); calculated from the speed-flow regression equation using initial flow conditions
- *Initial cost (per vehicle) to travel one mile* – measured in $/mile; calculated based on total vehicle costs and initial speed
- *Cost to travel one mile (with congestion charge)* – measured in $/mile; calculated using the initial cost (per vehicle) to travel one mile and the varying congestion charge
- *Percent change in cost (after congestion charge)* – measured as a percentage; calculated based on the initial cost (per vehicle) to travel one mile and the cost to travel one mile (with congestion charge)

- *Change in flow (after congestion charge)* – measured in pc/ln/hr; calculated using the initial number of vehicles, the assumed elasticity and the percent change in cost (after congestion charge)
- *Percent change in flow (after congestion charge)* – measured as a percentage; calculated using the initial number of vehicles and the change in flow (after congestion charge)
- *New flow (after congestion charge)* – measured in pc/ln/hr; calculated from the initial flow and the change in flow (after congestion charge)
- *New proportion of traffic (after congestion charge)* – measured as a percentage; calculated using the new flow (after congestion charge) for each vehicle classification and the total new flow (after congestion charge)
- *New speed (after congestion charge)* – measured in mph; calculated from the speed-flow regression equation using new flow conditions (after congestion charge)
- *Vehicle speed at one PCE/lane/hour less (after congestion charge)* – measured in mph; calculated from the speed-flow regression equation using one PCE less than new flow conditions (after congestion charge)
- *Average cost per vehicle (after congestion charge)* – measured in $/mile; calculated based on the new speed (after congestion charge) and the total vehicle costs
- *Average cost per vehicle at one PCE/lane/hour less (after congestion charge)* – measured in $/mile; calculated based on the vehicle speed at one PCE/lane/hour less (after congestion charge) and the total vehicle costs

- *Cost imposed on the entire traffic stream by one extra PCE* – measured in $/mile; calculated using the average cost per vehicle (after congestion charge), average cost per vehicle at one PCE/lane/hour less (after congestion charge), and new flow (after congestion charge); this calculation is similar to the delay calculation process explained previously
- *Total cost due to one extra PCE* – measured in $/mile; calculated using the weighted average cost per vehicle at one PCE/lane/hour less (after congestion charge) and the cost imposed on the entire traffic stream by one extra PCE
- *Resulting theoretical flow (i.e. equilibrium demand flow)* – measured in PCE/ln/hr; calculated using the initial flow conditions, assumed elasticity, and varying percent change
- *Resulting theoretical cost (i.e. equilibrium demand price)* – measured in $/PCE/mile; calculated using the weighted cost (per vehicle) to travel one mile under initial flow conditions and varying percent change

Final outputs:

- *Optimized congestion pricing* – measured in $/PCE/mile; obtained from the optimization model; the objective function is setup as follows:

  Minimize: equilibrium demand flow - calculated flow with the congestion charge

  Subject to the constraint: equilibrium demand price = calculated total cost due to one extra PCE

  Variables: percent change; congestion charge

- *Percent change* – measured as a percentage; obtained from the optimization model, where it is used to equate the equilibrium demand price and equilibrium demand flow; this percentage corresponds to the marginal cost of the system – the difference between the weighted cost (per vehicle) to travel one mile under initial flow conditions and the equilibrium demand price

4.3 Model Demonstration

In order to summarize accomplishments, this model utilizes the Solver tool in Excel to find the congestion charge which equates the total cost due to one extra PCE and the equilibrium demand price. The total cost due to one extra PCE varies with the congestion charge and the consequent changes in traffic volumes and speeds, taking into account changes in traffic composition by vehicle classification. The equilibrium demand price varies in accordance with the assumed elasticity, with the change in traffic conditions from the initial to the final condition determined by the Excel model (Roth 2001). The objective function of this model forces the calculated total cost due to one extra PCE to equal the equilibrium demand price; as a result, users will pay the marginal cost of the system. This results in a system-optimized network, where costs imposed by drivers are realized.

Figure 4-1 shows the model spreadsheet layout for an assumed elasticity of -0.2 and an initial flow condition of 2,000 PCE/lane/hour. From the model's standpoint, a positive elasticity input of 0.2 actually corresponds to -0.2. From Chapter 3, the initial proportion of traffic (based on the AM peak calculations) and the total vehicle costs are obtained. All calculations are displayed, including optimal congestion price ($0.14 per PCE per mile) and new anticipated flow (1,856 PCE/lane/hour). The yellow highlights denote variable inputs from the user and the green highlights indicate variables utilized by the Solver tool in Excel.

Description	Units	FHWA Vehicle Classes													Total
		Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13	
speed = (a * flow^4) + (b * flow^3) – (c * flow^2) + (d * flow) + 63.8															
a =	-0.000000000002														
b =	0.000000006														
c =	0.000007														
d =	0.0021														
average uncongested speed =	63.8 mph														
user value of time + vehicle operating costs	$/hour	12.31	21.4	24.27	346.93	27.18	32.19	32.19	34.68	34.34	34.34	34.34	34.34	34.34	
Initial flow	PCE/lane/hour														2000
Initial proportion of traffic	percentage	0.159%	83.177%	12.385%	0.683%	0.898%	0.582%	0.245%	0.224%	1.551%	0.058%	0.030%	0.006%	0.002%	100%
Initial number of vehicles	PCEs	3	1664	248	14	18	12	5	4	31	1	1	0	0	2000
Initial speed	mph	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	
Initial cost (per vehicle) to travel 1 mile	$/mile	0.21982	0.38214	0.43339	6.19518	0.48536	0.57482	0.57482	0.61929	0.61321	0.61321	0.61321	0.61321	0.61321	
Congestion charge	$/PCE/mile														0.14
Cost to travel 1 mile (with congestion charge)	$/mile	0.36212	0.52445	0.57570	6.33748	0.62766	0.71712	0.71712	0.76159	0.75552	0.75552	0.75552	0.75552	0.75552	
Elasticity		0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	
Percent change in cost (after congestion charge)	percentage	64.74%	37.24%	32.83%	2.30%	29.32%	24.76%	24.76%	22.98%	23.21%	23.21%	23.21%	23.21%	23.21%	
Percent change in flow (after congestion charge)	percentage	12.95%	7.45%	6.57%	0.46%	5.86%	4.95%	4.95%	4.60%	4.64%	4.64%	4.64%	4.64%	4.64%	
Change in flow (after congestion charge)	PCE/lane/hour	0	124	16	0	1	1	0	0	1	0	0	0	0	
New flow (after congestion charge)	PCE/lane/hour	3	1540	231	14	17	11	5	4	30	1	1	0	0	1856
New proportion of traffic (after congestion charge)	percentage	0.149%	82.966%	12.471%	0.733%	0.911%	0.596%	0.251%	0.230%	1.594%	0.060%	0.031%	0.006%	0.002%	
New speed (after congestion charge)	mph	58.22	58.22	58.22	58.22	58.22	58.22	58.22	58.22	58.22	58.22	58.22	58.22	58.22	
Flow (with congestion charge)	PCE/lane/hour														1856
Vehicle speed (with congestion charge)	mph	58.22	58.22	58.22	58.22	58.22	58.22	58.22	58.22	58.22	58.22	58.22	58.22	58.22	
Vehicle speed at one PCE/lane/hour less	mph	58.23	58.23	58.23	58.23	58.23	58.23	58.23	58.23	58.23	58.23	58.23	58.23	58.23	
Average cost per vehicle (at new vehicle speed)	$/mile	0.21145	0.36760	0.41690	5.95938	0.46688	0.55294	0.55294	0.59571	0.58987	0.58987	0.58987	0.58987	0.58987	0.42125
Average cost per vehicle at one PCE/lane/hour less	$/mile	0.21141	0.36752	0.41680	5.95805	0.46678	0.55282	0.55282	0.59558	0.58974	0.58974	0.58974	0.58974	0.58974	0.42115
Cost imposed on the entire traffic stream by one extra PCE	$/mile														0.17458
Total cost due to one extra PCE	$/mile														0.59583
Percent change	percentage														36.1
Elasticity															0.2
Initial flow	PCE/lane/hour														2000
Speed under initial flow conditions	mph	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	
Cost (per vehicle) to travel 1 mile under initial flow conditions	$/PCE/mile	0.21982	0.38214	0.43339	6.19518	0.48536	0.57482	0.57482	0.61929	0.61321	0.61321	0.61321	0.61321	0.61321	0.43791
Resulting theoretical flow (based on elasticity and % change)	PCE/lane/hour														1856
Resulting theoretical cost (based on elasticity and % change)	$/PCE/mile														0.59583
(Resulting theoretical cost - Total cost due to one extra PCE)	$/PCE/mile														0.0
(Resulting theoretical flow - Flow with congestion charge)	PCE/lane/hour														0.0

Figure 4-1: Model Demonstration

4.4 Evaluations

As the observed traffic composition differs between AM and PM peaks on the Capital Beltway, the two periods are examined as separate entities. Initial hourly volumes are calculated based on averages obtained from all detector data across that specific hour in 2007. For both the AM and PM peak periods, the average hourly volumes are provided and optimal congestion charges for an assumed -0.2 elasticity are displayed for each of the 13 FHWA vehicle classifications on a per-hour basis. Additionally, the anticipated traffic composition as a result of congestion charging is offered.

4.4.1 AM Peak

Table 4-1 and Table 4-2 show the average hourly flow and applicable congestion charges, respectively, for the AM peak period on the Capital Beltway. Table 4-3 presents the anticipated hourly traffic composition as a result of congestion charging. Most notably, it is seen that for the AM peak, the optimal congestion charge ranges from \$0.05 to \$0.08 per PCE per mile, based on average hourly flow conditions on I-495. While these figures are applicable to passenger cars, the lowest possible charges (for class 1 vehicles) range from \$0.02 to \$0.03 per mile and the highest possible charges (for class 13 vehicles) range from \$0.22 to \$0.35 per mile. The range in charges is directly obtained from the corresponding PCE factors – vehicles are charged appropriately for the amount of road space that they utilize. Information on potential charging for roadway sections with greater flow will be discussed later.

Table 4-1: Average AM Peak Hourly Flow for I-495

HOUR OF DAY	AVERAGE PCE/LANE/HOUR (2007)
6 (6AM)	1598
7 (7AM)	1743
8 (8AM)	1709
9 (9AM)	1653

Table 4-2: AM Peak Hourly Congestion Charges for I-495

Vehicle Classification	Description	PCE Factor	Congestion Charge ($/mile)			
			6AM	7AM	8AM	9AM
1	Motorcycle	0.38	0.02	0.03	0.03	0.02
2	Passenger Cars	1.00	0.05	0.08	0.07	0.06
3	Other Two-Axle, Four-Tire single Unit Vehicles	1.13	0.06	0.09	0.08	0.07
4	Buses	2.38	0.12	0.19	0.17	0.14
5	Two-Axle, Six-Tire, Single-Unit Trucks	1.63	0.08	0.13	0.11	0.10
6	Three-Axle Single-Unit Trucks	1.56	0.08	0.13	0.11	0.09
7	Four or More Axle Single-Unit Trucks	2.00	0.10	0.16	0.14	0.12
8	Four or Fewer Axle Single-Trailer Trucks	2.75	0.14	0.22	0.19	0.17
9	Five-Axle Single-Trailer Trucks	4.00	0.20	0.32	0.28	0.24
10	Six or More Axle Single-Trailer Trucks	3.94	0.20	0.32	0.28	0.24
11	Five or Fewer Axle Multi-Trailer Trucks	4.25	0.21	0.34	0.30	0.26
12	Six-Axle Multi-Trailer Trucks	4.56	0.23	0.37	0.32	0.27
13	Seven or More Axle Multi-Trailer Trucks	4.31	0.22	0.35	0.30	0.26

Table 4-3: AM Peak Traffic Composition Resulting from Congestion Pricing

Vehicle Classification	Traffic Composition (PCE/lane/hour)							
	6AM		7AM		8AM		9AM	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Total	1598	1550	1743	1668	1709	1641	1653	1596
1	3	2	3	3	3	3	3	2
2	1329	1288	1450	1385	1421	1363	1375	1326
3	198	193	216	207	212	204	205	198
4	11	11	12	12	12	12	11	11
5	14	14	16	15	15	15	15	14
6	9	9	10	10	10	10	10	9
7	4	4	4	4	4	4	4	4
8	4	4	4	4	4	4	4	4
9	25	24	27	26	27	26	26	25
10	1	1	1	1	1	1	1	1
11	0	0	1	1	1	0	0	0
12	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0

4.4.2 PM Peak

Table 4-4 and Table 4-5 show the average hourly flow and applicable congestion charges, respectively, for the PM peak period on the Capital Beltway.

Table 4-6 presents the anticipated hourly traffic composition as a result of congestion charging. Most notably, it is seen that for the PM peak, the optimal congestion charge ranges from $0.03 to $0.08 per PCE per mile, based on average hourly flow conditions on I-495. While these figures are applicable to passenger cars, the lowest possible charges (for class 1 vehicles) range from $0.01 to $0.03 per mile and the highest possible charges (for class 13 vehicles) range from $0.13 to $0.35 per mile. The range in charges is directly obtained from the corresponding PCE factors – vehicles are charged appropriately for the amount of road space that they utilize. Information on potential charging for roadway sections with greater flow will be discussed later.

Table 4-4: Average PM Peak Hourly Flow for I-495

HOUR OF DAY	AVERAGE PCE/LANE/HOUR (2007)
14 (2PM)	1733
15 (3PM)	1674
16 (4PM)	1583
17 (5PM)	1514
18 (6PM)	1439

Table 4-5: PM Peak Hourly Congestion Charges for I-495

Vehicle Classification	Description	PCE Factor	Congestion Charge ($/mile)				
			2PM	3PM	4PM	5PM	6PM
1	Motorcycle	0.38	0.03	0.03	0.02	0.02	0.01
2	Passenger Cars	1.00	0.08	0.07	0.05	0.04	0.03
3	Other Two-Axle, Four-Tire single Unit Vehicles	1.13	0.09	0.08	0.06	0.05	0.03
4	Buses	2.38	0.19	0.17	0.12	0.10	0.07
5	Two-Axle, Six-Tire, Single-Unit Trucks	1.63	0.13	0.11	0.08	0.07	0.05
6	Three-Axle Single-Unit Trucks	1.56	0.13	0.11	0.08	0.06	0.05
7	Four or More Axle Single-Unit Trucks	2.00	0.16	0.14	0.10	0.08	0.06
8	Four or Fewer Axle Single-Trailer Trucks	2.75	0.22	0.19	0.14	0.11	0.08
9	Five-Axle Single-Trailer Trucks	4.00	0.32	0.28	0.20	0.16	0.12
10	Six or More Axle Single-Trailer Trucks	3.94	0.32	0.28	0.20	0.16	0.12
11	Five or Fewer Axle Multi-Trailer Trucks	4.25	0.34	0.30	0.21	0.17	0.13
12	Six-Axle Multi-Trailer Trucks	4.56	0.37	0.32	0.23	0.18	0.14
13	Seven or More Axle Multi-Trailer Trucks	4.31	0.35	0.30	0.22	0.17	0.13

Table 4-6: PM Peak Traffic Composition Resulting from Congestion Pricing

Vehicle Classification	Traffic Composition (PCE/lane/hour)									
	2PM		3PM		4PM		5PM		6PM	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Total	1733	1660	1674	1613	1583	1537	1514	1478	1439	1411
1	3	3	3	3	3	2	2	2	2	2
2	1504	1439	1453	1398	1374	1333	1314	1282	1249	1224
3	179	173	173	168	164	160	157	153	149	146
4	7	7	7	7	7	7	6	6	6	6
5	10	10	10	10	9	9	9	9	9	8
6	4	4	4	4	4	4	4	4	4	3
7	1	1	1	1	1	1	1	1	1	1
8	3	3	3	3	3	3	2	2	2	2
9	20	20	20	19	19	18	18	17	17	17
10	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0

4.4.3 Discussion of Results

As seen in the two previous sections, the optimal AM and PM peak period charges range from \$0.03 to \$0.08 per passenger car equivalent per mile. These estimates are lower than the \$0.08 to \$0.50 per mile estimates, in 2007 dollars, taken from existing literature. In terms of the city street methodology on which this study is based, Roth and Villoria (2001) found optimal pricing in the range of \$0.29 to \$0.64 per passenger car equivalent per mile, in 2007 dollars. Based on these other figures, it seems as if there could be other factors that this study did not take into account. Other estimations may very well have other factors included. For this reason, these results should be taken as rough approximations.

4.5 Sensitivity Analysis

With any model, it is important to analyze changes in input parameters to determine the corresponding responses. This section focuses on the effects of direct inputs into the model – assumed elasticity, traffic proportions, and value of time – on the congestion charges computed. In a way, it is difficult to perform substantial sensitivity analysis with an optimization model that outputs a single "best" answer. There are relatively few parameters open for sensitivity analysis since the Solver tool optimizes the data and the key speed-flow relationship is, more or less, obvious. Initial flow is another direct input into the model, but is not available for sensitivity analysis. It goes without saying that speed is a function of flow and that as flow increases, the optimal congestion charges will increase, as congestion costs are greater.

4.5.1 Effect of Elasticity

In the previous section, congestion charges were presented based on average flow conditions in the AM and PM peak periods. This section will take a different route and present AM and PM peak congestion charge estimates for varying elasticity levels – flows ranging from 0 to 2,350 PCE/lane/hour (lane capacity) will be addressed. Figures 4-2 and 4-3 show the sensitivity of AM and PM peak congestion charges with respect to elasticity, respectively.

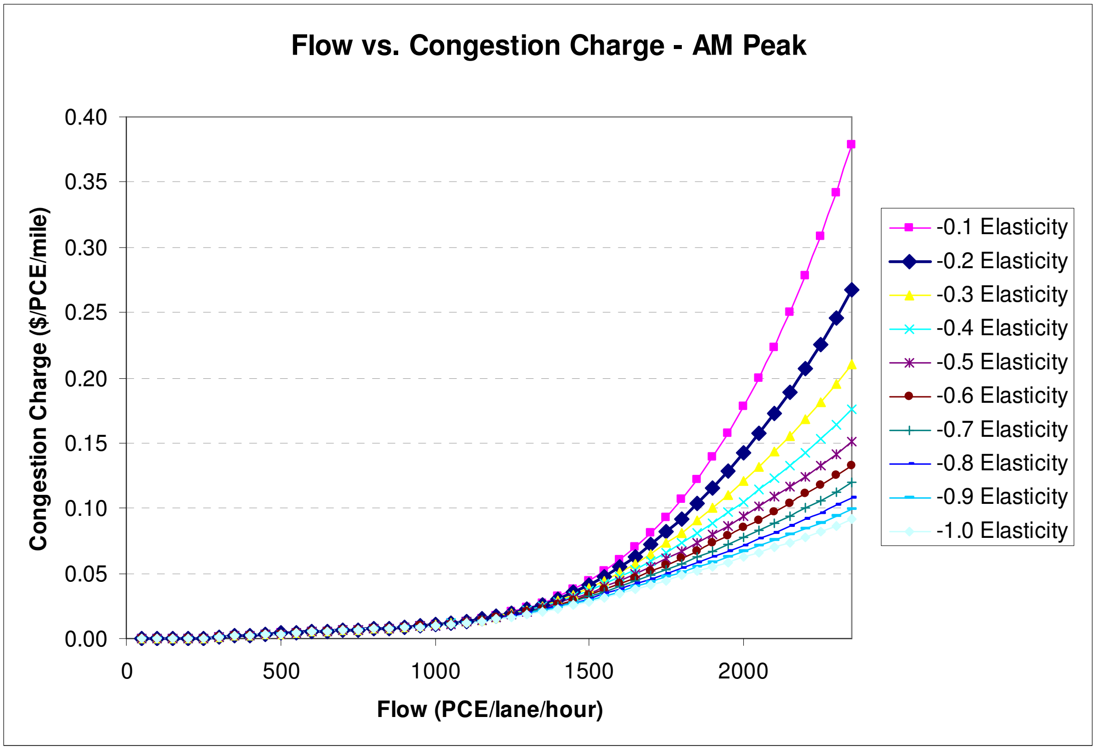


Figure 4-2: Sensitivity of Elasticity Values for Congestion Charges (AM Peak)

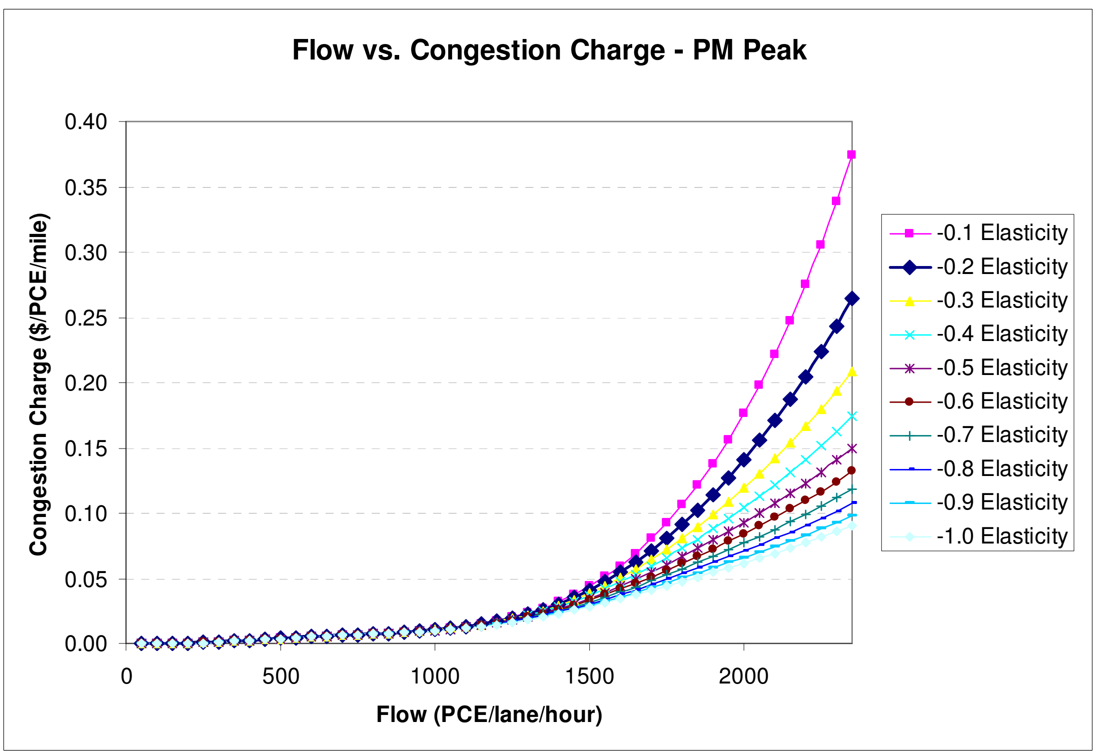


Figure 4-3: Sensitivity of Elasticity Values for Congestion Charges (PM Peak)

Especially interesting about this sensitivity analysis is that a large change in assumed elasticity does not cause similarly large changes in the congestion charge. In fact, the optimal charges at lower flow levels (less than about 1,500 PCE/lane/hour) are very similar across all elasticity levels. It is only at higher flow levels that the plots fan out from one another. At capacity, the charge varies from $0.09 to $0.38 per PCE per mile for the AM peak and from $0.09 to $0.37 per PCE per mile for the PM peak. Even though this is a spread increase of over four times, the total cost is still not significant enough to claim that assumed elasticity has a large impact on optimal congestion charges.

From these plots, the effects of elasticity can be easily seen. For an assumed elasticity value of -1.0, it can be assumed that other transportation (i.e. public transit) options are readily available. For this reason, there is a larger decrease in road usage at a lower price. As elasticity go towards -0.1, there is not as much of a decrease in road usage in the presence of pricing, so charges must be increased in order to cause a decrease in road usage.

4.5.2 Effect of Traffic Proportions

Traffic proportions have an effect on congestion charges due to the different total costs incurred per mile for each vehicle classification. For example, in the case of the I-495 data used in this study, the vast majority of vehicles are passenger cars. The total cost, per mile, to operate a passenger car is much less than the total cost, per mile, to operate a seven or more axle multi-trailer truck. For this reason, the weighted cost of the vehicles in the traffic stream will be lower when there is a greater percentage of passenger cars rather than large trucks.

To illustrate this, assume that the total flow is currently 2,000 PCE/lane/hour. For simplicity's sake, there are only two types of vehicles on the roadway: passenger cars and seven or more axle multi-trailer trucks. Using the same values of time and elasticity, the optimal congestion charge when the traffic consists of 75% passenger cars and 25% seven or more axle multi-trailer trucks is $0.15 per PCE per mile. When the traffic stream consists of 25% passenger cars and 75% seven or more axle multi-trailer trucks, the optimal congestion charge is $0.19 per PCE per mile. For a large change in traffic proportion conditions, there is a relatively small change in the optimal congestion charge.

4.5.3 Effect of Value of Time and Vehicle Operating Costs

It is difficult to address the effect of value of time and vehicle operating costs due to the fact that traffic proportions interact significantly with these values to determine the optimal congestion charge. When previously analyzing the effect of traffic proportions, it was assumed that total costs remained the same as they did throughout the study. If the total costs for a certain vehicle are incredibly high and there are none using the roadway, the weighted average of congestion costs across the traffic stream will be much lower than if there are many of these vehicles on the roadway. For this reason, the effect of total vehicle costs on optimal congestion charge is deemed to be worthy of mention, along with the fact that there is a strong correlation with traffic proportions.

4.6 Summary

This chapter has shown that optimal AM and PM peak period charges range from $0.03 to $0.08 per passenger car equivalent per mile in this study. These estimates are lower than the $0.08 to $0.50 per mile estimates taken from existing literature. Based on these figures, it seems as if there could be other factors that this study did not take into account. Other estimations may very well have other factors included. For this reason, these results should be taken as rough approximations. Additionally, lower values infer less congestion – in this case, the congestion pricing strategy should be examined to see that it is encompassing the hours of the day that truly merit such pricing, based on the context of this study.

This thesis is limited by the fact that elasticity estimates are assumed equivalent across the entire traffic population and value of time estimates are assumed equal across similar vehicle types. In actuality, this would not be the case, as not everyone is affected in the same way. It is difficult, however, to take these factors into account and, thus, this study should be viewed under hypothetical pretenses.

Based on the results set forth in this chapter, it is determined that vehicle users with a lower combined value of time and vehicle operating cost experience the most change with congestion pricing. Fewer of these users utilize the roadway after congestion pricing is implemented – this shows that, among other things, these users either change their driving habits to occur in off-peak hours or they switch to other forms of transportation. Commercial truck operations and commuters lacking flexible work schedules are significantly affected by congestion pricing. These users have a fixed schedule and lack options other than paying the congestion charge.

Chapter 5: Implementation

5.1 Overview

While previous chapters have centered on such topics as calculations and data management, this chapter will focus on the logistics behind implementing a congestion pricing system for the Capital Beltway. The optimization model developed in this study can be seen as a "first-best" congestion pricing strategy, as users realize their full congestion costs and roads are used most efficiently. Unfortunately, congestion charges that vary in real-time based on actual conditions are not practical at this point in time. For the sake of feasibility in the Washington, D.C. area, a "second-best" congestion pricing solution must be examined, where charges varying on an hourly scale instead of smoothly time-varying charges. When demonstrating the model in Chapter 4, this was the methodology considered. Without a system like this, where the general public can be aware of the charges in advance in order to make an informed decision about their driving habits, acceptance will be lacking. After a "second-best" system is implemented, more advances can be made towards a gradual "first-best" solution.

It is important to note that under a congestion pricing scheme, charges should bear some relationship to congestion costs imposed and vary by time of day and by location. Ideally, the congestion price they should equal the imposed costs (as calculated with the optimization model in this study). Instead of paying a flat fee when passing a cordon, charges should be assessed as vehicles pass pricing points setup along the roadway and calculated based on miles driven. As described previously, this strategy falls somewhere in the middle of these requirements – hourly charges enacted on a per-mile basis.

5.2 Congestion Pricing Strategy

This congestion pricing strategy is largely based on a review of other implemented systems. Obtained data from select locations of I-495 have been assumed representative across the entire Capital Beltway due to lack of other data. It should be noted that a more effective approach would be to analyze smaller sections independently (i.e. split I-495 into a number of predefined zones) based on observed data in those sections. The congestion charges, therefore, would vary by zone instead of being assumed representative of the entire roadway. For example, areas exhibiting traffic flow conditions much greater than calculated averages would be assigned charges that are higher than those assigned to sections exhibiting lower traffic flow conditions.

5.2.1 Hours of Operation

The proposed hours of operation for this congestion charging system are 6:00AM – 10:00AM and 2:00PM – 7:00PM. These timeframes encompass the morning and evening peak periods on the Capital Beltway, as exhibited in Chapter 4. The hourly extent of the PM peak period is greater than the AM peak, as represented by the proposed hours of operation. Future iterations of a congestion charging strategy could add an additional morning hour from 5:00AM – 6:00AM or implement 24-hour charging on I-495. This system will operate only on weekdays, excluding federal holidays – equating a total of 251 days per year.

5.2.2 Charges

Table 5-1 shows the hourly congestion charges for this system, in dollars per PCE per mile. Corresponding charges for each of the 13 FHWA vehicle classifications can be obtained by multiplying the charge by the PCE factors that were presented in Chapter 3.

Table 5-1: Hourly Congestion Charges for I-495

Hour	Charge ($/PCE/mile)
12:00AM - 12:59AM	NO CHARGE
1:00AM - 1:59AM	
2:00AM - 2:59AM	
3:00AM - 3:59AM	
4:00AM - 4:59AM	
5:00AM - 5:59AM	
6:00AM - 6:59AM	0.05
7:00AM - 7:59AM	0.08
8:00AM - 8:59AM	0.07
9:00AM - 9:59AM	0.06
10:00AM - 10:59AM	NO CHARGE
11:00AM - 11:59AM	
12:00PM - 12:59PM	
1:00PM - 1:59PM	
2:00PM - 2:59PM	0.08
3:00PM - 3:59PM	0.07
4:00PM - 4:59PM	0.05
5:00PM - 5:59PM	0.04
6:00PM - 6:59PM	0.03
7:00PM - 7:59PM	NO CHARGE
8:00PM - 8:59PM	
9:00PM - 9:59PM	
10:00PM - 10:59PM	
11:00PM - 11:59PM	

These charges were calculated based on an assumed elasticity estimate of -0.2, which was discussed previously in Chapter 2 and is based on theoretical studies and implementation in Stockholm. After implementation, the actual elasticity in regards to pricing could be obtained and the charges recalculated, accordingly.

5.2.3 Goals

The main goal of this congestion pricing strategy is drawn from the research objectives of this study. As travelers fail to realize their role in congestion, these charges attempt to equal their contributed congestion costs to the traffic stream. Secondary goals are operating a system that pays for itself and does not require subsidies and improved traffic conditions, among others. These are not focal points of the congestion pricing system, but are worth mentioning as potential positive outcomes.

5.2.4 Conditions

As evident with other pricing systems that are in-place, special conditions under the system must be addressed. Pricing systems are typically bogged down with numerous exemptions and this proposed system attempts to stray away from that scenario.

For this system, transit and emergency vehicles will be granted free access. While this is not specifically addressed in this study, the costs of these vehicles would be subsidized in some way. Additionally, low-income motorists may be eligible for toll credits that could be used as assistance. Prerequisites for these credits would need to be determined before implementation. Hybrid vehicle owners will not receive any discounts, although more stringent charges for vehicles exerting higher levels of pollution could be considered.

System shut-off conditions must also be in-place to accommodate unforeseen scenarios. Examples of this have not been found in existing literature and could be brought on by severe weather or traffic incidents, as examples. Under these special circumstances, the system would be shifted into “no-charge” mode and operated accordingly until the roadway network regains normal operating conditions. A full outline of potential system shut-off scenarios would be created before implementation.

5.2.5 Payment Options

Multiple payment options will exist for users of the Capital Beltway. The most efficient method, by far, will be a direct withdrawal from a user account, which travelers stock with funds in advance via the Internet, mail, or telephone. This method would be comparable to the E-ZPass toll system that exists in the northeast United States. Other post-travel options will also include Internet, mail, and telephone-based payments.

Charges accrued that are not tied to a user account will be required monthly, with users receiving a bill. In this light, congestion charges could be likened to a monthly cable or telephone bill. Although a monthly billing system would be in-place, payments would be accepted at any point in time. For example, a user could pay their total charge on a daily basis instead of waiting until the end of the month to pay all of the charges that have accumulated. If timely payments are not made, the user could be assessed a penalty amounting to 20% of the total owed.

5.2.6 Revenue Spending

Revenue spending is a key concern for any congestion pricing system. For the purposes of this system, revenue will be first utilized to cover start-up and ongoing costs – these costs are evaluated in the next chapter. After system costs are met, excess revenue can be applied to supporting public transit and road improvements, with public transit being a priority. By utilizing the revenue in this manner, the public will know that they are benefiting from the congestion charging in a tangible way.

5.2.7 Technology

Until recently, technology was not readily available to operate the proposed congestion pricing system. As the cost of equipment has decreased, complex and efficient systems are now quite possible. With the technological advances that have been made since the idea of congestion pricing originated, implementation of a pricing system is now easier than ever before. The following two sections address the technology proposed for the I-495 congestion pricing system.

5.2.7.1 Open Road Tolling

Open road tolling refers to the process of collecting tolls on a roadway without the use of toll plazas, where drivers are charged appropriately without having to stop or slow down. The major advantage to open road tolling is just that - users are not required to slow down and are able to maintain their highway travel speed. Tolls are typically collected using radio frequency identification (RFID) systems – the E-ZPass system utilized in the northeastern United States is an example of this. Figure 5-1 shows a typical open road tolling gantry setup.

Figure 5-1: Open Road Tolling Gantry

The slight disadvantage to open road tolling is the small possibility of equipment not correctly identifying vehicles. More research is required in this area, but it is not expected to severely impact systems utilizing this technology.

5.2.7.2 Enforcement/Collection

The enforcement and collection of applicable congestion charges will be overseen by a system of electronic toll collectors and cameras running to video recognition software. Open road tolling technology goes hand-in-hand with electronic toll collection (ETC). ETC systems generally use transponders to automatically debit pre-paid accounts of registered cars without having them stop or slow down – this method is, by far, most efficient. Electronic toll collection systems are based on four key components, all of which are automated. These are:

- Vehicle identification
- Vehicle classification
- Transaction processing
- Violation enforcement

As an added incentive for drivers to obtain transponders, 10,000 of them will be given away before implementation.

In the circumstances where drivers do not have a registered transponder, enforcement cameras will photograph the vehicle's license plate. Optical recognition software will be utilized to translate the images into text, which can then be searched for in the database maintained by the Department of Motor Vehicles. An example of such software, as used in London, is shown in Figure 5-2. Figure 5-3 shows a typical camera setup for the charging system implemented in Stockholm.

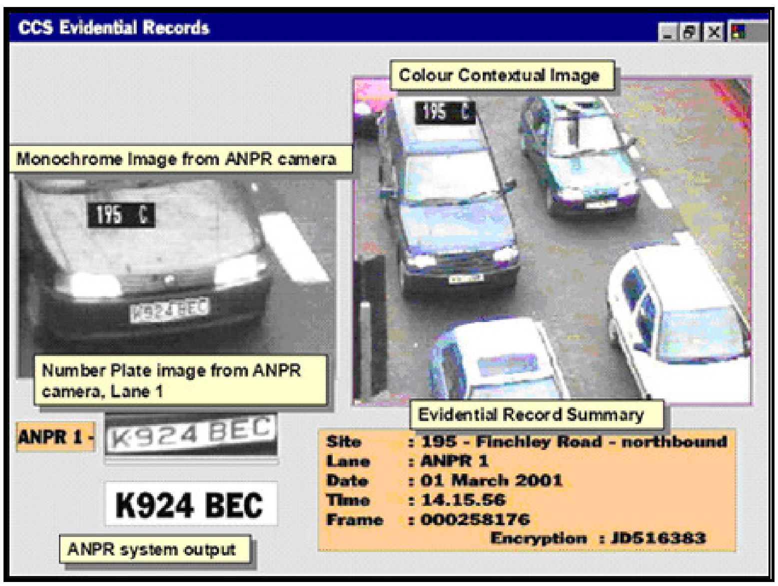


Figure 5-2: License Plate Recognition Software (London)
Source: Murray-Clark

Figure 5-3: Typical Gantry Camera Setup (Stockholm)
(Source: Vägverket)

5.2.8 Comparisons to Existing Systems

Two of the most notable pricing schemes in existence are located in London and Stockholm. This section aims to briefly compare key components of these systems to the proposed implementation.

The main difference is that this study's charging strategy is based per-mile. In both Stockholm and London, charges are collected at cordons around the city and no charging is based on actual miles driven. The essence of congestion pricing is based on location, time, and amount driven. Out of the three, only the proposed Capital Beltway strategy takes all of these components into account.

In terms of operating hours, both London and Stockholm operate from the beginning of the morning peak until the end of the evening peak, including the time between. For I-495, only the peak period hours are part of the charging strategy, as traffic flows throughout the day are not yet great enough to merit charging as a means to relieve congestion. As the system progresses, however, this is a natural expansion.

Both London and Stockholm utilize cameras with license plate recognition systems in order to charge drivers. The I-495 system will primarily use electronic toll collection through transponders, with cameras as a backup option for vehicles that are not equipped with the necessary transponder.

Revenue spending is a key concern for any pricing strategy. London spends most of the revenue gained from the system (after ongoing and operating costs are deducted) on improved bus services within the city. Stockholm, on the other hand, uses all revenue solely for road construction. It is generally regarded that public transportation and roadway improvements should be obtained from excess revenue, as the public can then see, first-hand, how the collected money is being spent. For this reason, all revenue collected on I-495 after start-up and operating costs are obtained will be dedicated to these sources.

As a final point, both the London and Stockholm systems are full of exemptions and discount options for various types of vehicles and residents. The strategy proposed in this study aimed to avoid this scenario and have as few exemptions as possible.

5.3 Equity Considerations

A major concern of congestion pricing is that it is unfair to certain groups of people. This argument stems from the belief that congestion pricing favors the rich, as the poor are unable to afford the charges. This is actually not the case, as low-income users of public transportation may benefit greatly from transit improvements brought about by collected revenue and the fact that public transit vehicles are sanctioned for use within congestion pricing areas, so greater reliability and decreased travel times could be expected. A well-designed pricing plan can be less burdensome to low-income citizens than current systems that are based on regressive taxes, such as car registration fees, sales taxes and the gas tax (FHWA 2001). Hypothetically, congestion pricing can easily be shown to increase social welfare by making travelers pay an amount closer to the full social costs resulting from their driving decisions (Harrington 1998).

Most equity arguments are assuaged though proper revenue recycling, that is, by creating a focused public benefit instead of what appears to just be a tax. The true equity impact of any roadway pricing scheme depends heavily on how the revenues are reused in the transportation system. Equity concerns can be offset by filtering revenue into programs that benefit lower-income people, such as public transit or potential pricing credits.

Paying directly for road usage is actually more equitable and efficient, since users pay in proportion to the costs they impose. Uncharged facilities force everyone to pay (through congestion), including motorists who reduce their vehicle use. Paying directly gives individual consumers the savings that result when they drive less, providing a new opportunity to save money. From a public welfare standpoint, under congestion conditions, everyone is worse off, whereas under an efficient system, society as a whole is better off. Congestion is a public "bad" that the government has the ability to increase the cost of in order to discourage (Department of Legislative

Services 2005). Moreover, everyone wins with better air quality and increased mobility.

As with any situation, there will be perceived winners and losers in regards to congestion pricing on the Capital Beltway. Before implementation, these potential conditions must be considered and evaluated in order to possibly mitigate less-than-positive scenarios. Furthermore, significant public transit options must be improved before any such system can be implemented. Without acceptable public transportation options for drivers, a congestion pricing system lacks true equity.

5.4 Policy Limitations and Recommendations

Politics can be the downfall of any congestion pricing initiative. Without political support, no system can see the light of day. As for the Capital Beltway, an entire-roadway congestion pricing system is far more feasible than, say, a cordon area surrounding Washington, D.C. Due to the amount of travelers that enter the city for employment, a move like this would be seen as a commuter tax and fought hard by all suburban centers. Unlike London or Stockholm, the Capital Beltway region is encompassed by three jurisdictions (Maryland, Virginia, and the District of Columbia), in addition to the federal government. While politics may be a hurdle, it is one worth handling for the long-term societal good.

In terms of policy suggestions specifically for this study, opinions were gathered from Patrick DeCorla-Souza, the Team Leader for Highway Pricing and System Analysis in the Office of Transportation Policy Studies and the Program Manager for the Urban Partnership Program at the Federal Highway Administration (FHWA) in Washington, D.C. Although it is out of the scope of this study, it was suggested that it would probably make more sense to start pricing the entire freeway system in the area – not just the Capital Beltway; a key to success with congestion pricing systems is the comprehensiveness of the pricing network. To make the system truly work, other taxation should be eliminated, as the system revenue would hopefully be enough to cover these costs – this way, the public would be far more accepting of road pricing. Additionally, finding funding sources for expanded transit options, telecommuting programs, and things of that nature are critical steps towards congestion pricing. Finally, there are a few political selling points that should be addressed. These are as follows:

- The congestion pricing system is a replacement of the current taxation system
- The system is fair – drivers who use more pay more
- The system is efficient – travel delay is decreased or eliminated, the economy is boosted, and freeway productivity loss is avoided
- The system is good for the environment – lowered emissions through less idling, positive global warming effect, etc.

Martin Richards, an expert on the London pricing scheme, addressed some key issues at the Transportation Research Board (TRB) 2008 Annual Meeting. For a successful system, the media and general public must be well-informed in advance of any implementation. If this aspect is lacking, the public and media will come to incorrect conclusions about the system and it then becomes easier for those opposed to propagate misleading information – thus, rational discussion about the topic is difficult. The success of system implementation is based on creating a clear vision, providing a clear execution pathway, strong leadership that won't back down or retract, and total and consistent commitment to the cause.

Lastly, there are multiple perspectives that should be reflected in any congestion pricing system to ensure effectiveness and fairness – those of the users, traffic authority, and society. The proposed system in this study addresses these perspectives, but further examination should be done for each. An outline of recommended principles for each perspective is as follows (Victoria Transport Policy Institute 2007):

From the perspective of the user, a congestion pricing system should be easy to understand, convenient (i.e. does not require vehicles to stop at toll booths), viable transportation options should exist (i.e. alternative modes, travel times, routes, and destinations), multiple easy-to-use payment options should exist (i.e. cash, prepaid card, credit card, etc.), charges should be evident before a trip is undertaken, and the privacy of users should be assured.

From the perspective of the traffic authority, a congestion pricing system should consider traffic impacts (vehicles should not be required to stop at toll booths or delay traffic in other ways), efficient and equitable charges should reflect true user costs, the system should be effective in reducing traffic congestion and other transportation problems by changing travel behavior, occasional users and different vehicle types should be easily accommodated, minimal incorrect charges should occur, minimal fraud or non-compliance should occur, there should be a positive return on the system investment (i.e. cost effectiveness), there should be minimal disruption during any development phase, and the implementation should be available for expansion, as needed.

From the perspective of society, a congestion pricing system should have positive net benefits when all impacts are considered, political acceptability (i.e. public perception of fairness and value), positive environmental impacts, and the same integrated charging system should be able to be used to pay other public service fees (i.e. parking, public transit, etc.).

5.5 Summary

In this chapter, the logistics behind implementing a congestion pricing system for the Capital Beltway were presented. Effective between weekday hours of 6AM and 10AM and 2PM and 7PM, the morning and evening peak periods on I-495 are included. As noted, potential future iterations of a pricing system could expand the hours of operation or switch to 24-hour pricing. In this study, the charges attempt to cause roadway users to equal their contributed congestion costs to the traffic stream.

While other implementations are bogged down with exemptions and discounts, the conditions of this study were relatively straightforward. Transit and emergency vehicles will be granted free access and low-income users may be eligible for travel credits. Multiple payment options via the Internet, mail, and telephone will be available to travelers. System revenue will be first utilized to cover start-up and ongoing costs. Afterward, excess revenue will be applied to supporting public transit and road improvements, with public transit being a priority.

Equity considerations must be taken extremely seriously (through revenue spending, etc.) and it must be realized that policy limitations exist. In order for a congestion pricing system to be taken seriously, citizens must believe that the system is a replacement of the current taxation system, the system is fair (i.e. drivers who use more pay more), the system is efficient (i.e. travel delay is decreased or eliminated, the economy is boosted, and freeway productivity loss is avoided), and that the system is good for the environment. Additionally, pricing on only I-495 is not a likely option. If pricing were to exist on roadways in the Washington, D.C. area, it should be implemented on all major roadways (I-495, I-270, I-70, I-95, etc.).

The financial implications for the proposed I-459 congestion pricing system are presented in the next chapter.

Chapter 6: Financial Implications

6.1 Costs

In the following sections, estimated cost information for the proposed Capital Beltway congestion pricing system is provided.

6.1.2 Scenarios Examined

Two potential open road tolling/electronic toll collection setups were considered in this study. Both involved overhead gantry systems, but differed in cost due to the layout of the gantries. The premise of this system is that vehicles are "tracked" at each gantry and if they don't reach the next gantry within a certain time (i.e. they exit I-495), their charge is calculated – this amount of time will have to reflect possible congestion or other occurrences and is not the focus of this thesis. The two strategies were as follows:

- Gantry setup directly on I-495 – across all four lanes in each direction
- Gantry setup on entrance and exit ramps to/from I-495 – gantries ranging from 1- to 3-lanes for each entrance and exit ramp

Figures 6-1 and 6-2 show each of these layouts overlaid on the same I-495 interchange.

Figure 6-1: I-495 Gantry Setup (Direct)

Figure 6-2: I-495 Gantry Setup (Entrance and Exit Ramps)

Using these two layout scenarios, cost information was estimated. The Research and Innovative Technology Administration of USDOT operates a cost-estimate database. The fairly recent study of I-75 and I-575 in Atlanta provided some cost estimates of not only gantries, but also all facets of project implementation for HOT lanes – the cost estimate aspects of design, construction, maintenance, and operation were extrapolated from their estimates for the components necessary for the proposed congestion pricing system on I-495. Table 6-1 presents the system cost breakdown for I-495 extrapolated from the USDOT database. Also factored into this table are the yearly operating costs, which will be discussed later. These categories are used for both potential scenarios.

6.1.2.1 Gantry Setup on I-495

Using a gantry setup directly on I-495 entails, on average, four 4-lane gantries at each interchange. The reasoning behind this is that gantries cannot be placed only before or after entrances and exits – they must be placed both before and after these points in order to account for all vehicles. Using roadmaps, satellite imagery, and general knowledge of the region, it is estimated that a total of 166 4-lane gantries would be required for this scenario – 106 in Maryland and 60 in Virginia. As some calculations deal with a per-lane basis, this equates to 664 total lanes – 424 in Maryland and 240 in Virginia.

Using these costs, the proposed system setup on I-495 with gantries directly on I-495 would be estimated at $58,066,275 – $35,730,075 in Maryland and $22,336,200 in Virginia.

Table 6-1: I-495 System Costs

Category	Description	Notes	Cost ($)
Construction	Gantry structure - 4 lanes	-	75000
	Gantry structure - 3 lanes	-	65000
	Gantry structure - 2 lanes	-	60000
	Gantry structure - 1 lane	-	30000
	Toll & communication equipment building	1 per exit	30000
	Electronic toll collection (ETC) reader	1 per gantry	4000
	Transceiver	1 per gantry	3500
	ETC reader controller	1 per gantry	4000
	ETC power supply	1 per gantry	250
	Camera	1 per gantry	3500
	Camera power supply	1 per gantry	250
	Image processor	per state	6500
	Optical character recognition (OCR) server	per state	7000
	OCR software/interface	per state	60000
	Vehicle detection sensor	1 per lane/per gantry	4500
	Software, interface support, engineering support, and documentation	per state	12000
	Lane controller	1 per gantry	12500
	Lane cabinet and electronics	1 per gantry	6500
	Lane software	per state	200000
	Variable message sign (approximately one per exit)	1 per exit	60000
	Fixed overhead signs on gantry	1 per gantry	10000
	Network equipment/connections	per state	200000
	Power - breaker panel	1 per exit	2000
	Power - UPS & battery cabinet	1 per exit	5000
	Power - conduit/wiring	1 per exit	20000
	Power - disconnect & bypass switch	1 per gantry	3500
	Power - generator unit	1 per exit	6500
	Power - generator wiring	1 per exit	2000
	Contingencies	25% of above total	
	Mobilization	10% of subtotal	
	Construction total	All of the above	
Design Engineering and Administration	Design engineering and admin	20% of construction total	
Capital Cost for Operations	Host server and data storage	per state	150000
	Database software and licenses	per state	50000
	Host software	per state	200000
	System applications software	per state	400000
	Maintenance management	per state	200000
	Various other computer equipment	per state	200000
	Installation and configuration support	per state	20000
	Transponders (100,000 free units to commuters)	split 50%	2500000
	Customer service center	per state	2000000
	Capital cost for operations total	All of the above	
Yearly Costs	Maintenance costs (per year)	10% of capital costs	
	Transaction processing charge ($0.12 per transaction) - 85,000,000 transactions per year	split 50%	10200000
	Yearly total	All of the above	

6.1.2.2 Gantry Setup on Entrance and Exit Ramps

Using a gantry setup on I-495 entrance and exit ramps entails gantries ranging from 1- to 3-lanes on each entrance and exit ramp to account for all vehicles entering or exiting the roadway. Using roadmaps, satellite imagery, and general knowledge of the region, it is estimated that the following gantries would be required for this scenario:

Table 6-2: Gantry Totals on Entrance and Exit Ramps

Total	1-lane	226
	2-lane	15
	3-lane	3
Maryland	1-lane	139
	2-lane	7
	3-lane	3
Virginia	1-lane	87
	2-lane	8
	3-lane	0

As some calculations deal with a per-lane basis, this equates to 265 total lanes – 162 in Maryland and 103 in Virginia.

Using these costs, the proposed system setup on I-495 with gantries on I-495 entrance and exit ramps would be estimated at $53,732,550 – $ 31,968,075 in Maryland and $21,764,475 in Virginia.

6.1.3 Chosen Scenario

Based on the cost estimates provided in the previous sections, a gantry setup on I-495 entrance and exit ramps is the most cost-effective option. This presents a significant cost savings of $4,333,725 compared to using a gantry setup directly on I-495.

6.2 Revenue

In order to calculate revenue, the assumed flow during each hour of the congestion pricing strategy is based on average flow across all detectors providing data for that hour in 2007. The optimization model was run using these average flows in order to determine the new flows that can be expected during each hour to provide revenue estimates. Since no I-495 data is collected on average miles driven per vehicle on I-495 during each peak period, National Household Travel Survey (NHTS) data were analyzed to obtain estimates. Based on the NHTS 2001 trip information for the United States, the data were split into 1-mile increments ranging from one mile to thirty-two miles. This is based on the assumptions of a distance of one mile between any two exits on the Capital Beltway and the fact that people will hypothetically travel along one-half of the 64-mile long roadway, at a maximum. Even though this method is not entirely precise, it is far more realistic in terms of potential revenue estimation than splitting up mileage level groups evenly based on traffic flow. Figure 6-3 plots the frequency distribution of trip distances that will be applied to I-495.

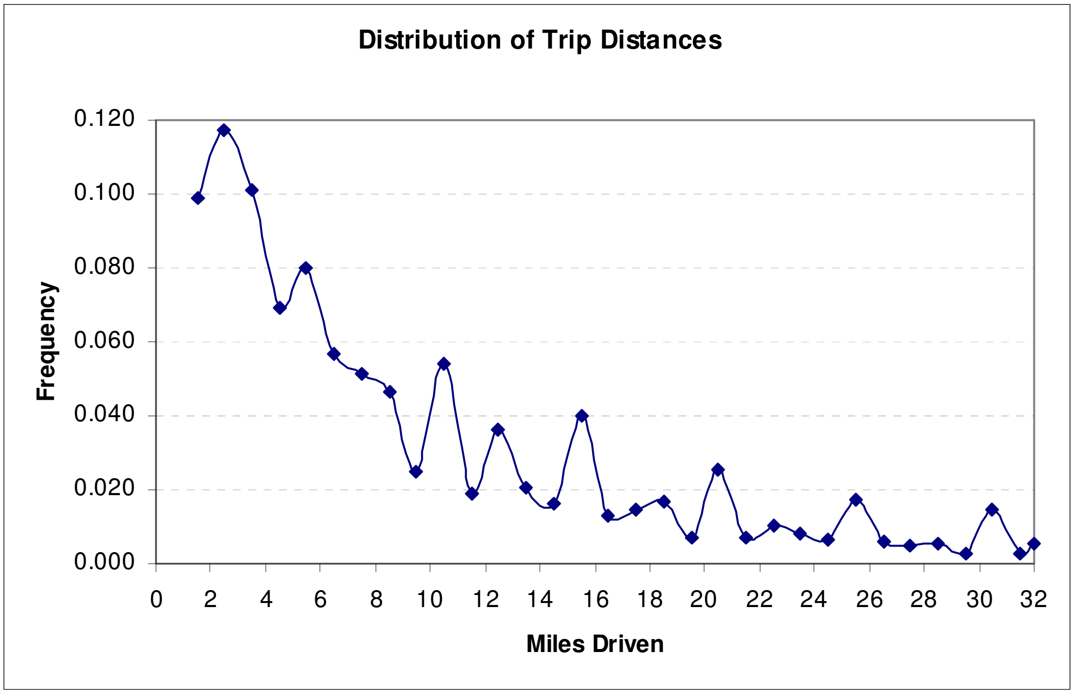


Figure 6-3: Distribution of Trip Distances
Source: NHTS 2001

In applying these trip distribution frequencies to the Capital Beltway, many assumptions were made. First, traffic in the Washington, D.C. area was assumed similar to the nationwide traffic represented in the NHTS data. Additionally, it was assumed that one-way trips on I-495 have the same trip distribution frequencies as full trips (from beginning to end) at the national level. This is a large assumption, due to the fact that travel on the Capital Beltway is only a portion of the commute experienced by travelers. Regardless of the number of assumptions, national trip distribution frequencies provide a much better estimation than uniform frequency estimates for each distance.

By using the applicable hourly charges presented in this study and the corresponding hourly flows and frequency estimates, daily revenue can be calculated. As an example of how this calculation was accomplished, for the 6:00AM - 6:59AM hour, the hourly flow on I-495 averages 1,598 PCE/lane/hour. Once congestion pricing is implemented, the hourly flow is expected to drop to 1,550 PCE/lane/hour and the associated charge is $0.05 per PCE per mile. The frequency of vehicles traveling 1.5 miles on I-495 is 0.099. This results in 153 vehicles paying $0.05 per mile for 1.5 miles – a total of roughly $11.48 for that portion of traffic (traveling in one direction) during that hour. Similar calculations are then made for each of the 32 mileage ranges for the same hour and then for every operating hour afterwards. Daily and yearly revenue estimates can then be obtained.

The total revenue per day for I-495 (in both directions) is estimated to be $60,282.63. A total of 251 charging days per year equates to a yearly revenue estimate of $15,130,939.61.

6.3 Break-Even Points/Payoff Calculations

In order to determine system break-even points and payoff calculations, the system costs were examined over a 50-year period. Taking into account the yearly costs of operation and maintenance, along with a 10-year equipment lifespan, these yearly amounts were determined. After 10 years, it is assumed that 50% of the initial system costs will be required to update the system, as some existing structure remains usable. After 20 years, however, a complete system overhaul is required. Table 6-3 shows the yearly cumulative costs for the I-495 congestion pricing system. Similarly, cumulative revenue estimates were made over a 50-year period (Table 6-4), assuming constant yearly revenue. Payoff is equal to cumulative revenue divided by cumulative cost for a given year and all estimates are kept in 2007 dollars to provide easy comparison into the future.

Table 6-3: I-495 System 50-Year Cumulative Costs

Description	Year	Cumulative Cost (2007 $)
Setup costs	-	53732550
After 1 year of operation	1	64826550
After 2 years of operation	2	75920550
After 3 years of operation	3	87014550
After 4 years of operation	4	98108550
After 5 years of operation	5	109202550
After 6 years of operation	6	120296550
After 7 years of operation	7	131390550
After 8 years of operation	8	142484550
After 9 years of operation	9	153578550
After 10 years of operation (equipment lifespan)	10	164672550
After 11 years of operation	11	202632825
After 12 years of operation	12	213726825
After 13 years of operation	13	224820825
After 14 years of operation	14	235914825
After 15 years of operation	15	247008825
After 16 years of operation	16	258102825
After 17 years of operation	17	269196825
After 18 years of operation	18	280290825
After 19 years of operation	19	291384825
After 20 years of operation (2 equipment lifespans)	20	302478825
After 21 years of operation	21	367305375
After 22 years of operation	22	378399375
After 23 years of operation	23	389493375
After 24 years of operation	24	400587375
After 25 years of operation	25	411681375
After 26 years of operation	26	422775375
After 27 years of operation	27	433869375
After 28 years of operation	28	444963375
After 29 years of operation	29	456057375
After 30 years of operation (3 equipment lifespans)	30	467151375
After 31 years of operation	31	505111650
After 32 years of operation	32	516205650
After 33 years of operation	33	527299650
After 34 years of operation	34	538393650
After 35 years of operation	35	549487650
After 36 years of operation	36	560581650
After 37 years of operation	37	571675650
After 38 years of operation	38	582769650
After 39 years of operation	39	593863650
After 40 years of operation (4 equipment lifespans)	40	604957650
After 41 years of operation	41	669784200
After 42 years of operation	42	680878200
After 43 years of operation	43	691972200
After 44 years of operation	44	703066200
After 45 years of operation	45	714160200
After 46 years of operation	46	725254200
After 47 years of operation	47	736348200
After 48 years of operation	48	747442200
After 49 years of operation	49	758536200
After 50 years of operation (5 equipment lifespans)	50	769630200

Table 6-4: I-495 System 50-Year Cumulative Revenue

Year	Annual Revenue (2007 $)	Cumulative Revenue (2007 $)	Payoff %
1	15130939.61	15130939.61	0.233
2	15130939.61	30261879.23	0.399
3	15130939.61	45392818.84	0.522
4	15130939.61	60523758.46	0.617
5	15130939.61	75654698.07	0.693
6	15130939.61	90785637.68	0.755
7	15130939.61	105916577.30	0.806
8	15130939.61	121047516.91	0.850
9	15130939.61	136178456.53	0.887
10	15130939.61	151309396.14	0.919
11	15130939.61	166440335.76	0.821
12	15130939.61	181571275.37	0.850
13	15130939.61	196702214.98	0.875
14	15130939.61	211833154.60	0.898
15	15130939.61	226964094.21	0.919
16	15130939.61	242095033.83	0.938
17	15130939.61	257225973.44	0.956
18	15130939.61	272356913.05	0.972
19	15130939.61	287487852.67	0.987
20	15130939.61	302618792.28	1.000
21	15130939.61	317749731.90	0.865
22	15130939.61	332880671.51	0.880
23	15130939.61	348011611.13	0.893
24	15130939.61	363142550.74	0.907
25	15130939.61	378273490.35	0.919
26	15130939.61	393404429.97	0.931
27	15130939.61	408535369.58	0.942
28	15130939.61	423666309.20	0.952
29	15130939.61	438797248.81	0.962
30	15130939.61	453928188.42	0.972
31	15130939.61	469059128.04	0.929
32	15130939.61	484190067.65	0.938
33	15130939.61	499321007.27	0.947
34	15130939.61	514451946.88	0.956
35	15130939.61	529582886.50	0.964
36	15130939.61	544713826.11	0.972
37	15130939.61	559844765.72	0.979
38	15130939.61	574975705.34	0.987
39	15130939.61	590106644.95	0.994
40	15130939.61	605237584.57	1.000
41	15130939.61	620368524.18	0.926
42	15130939.61	635499463.79	0.933
43	15130939.61	650630403.41	0.940
44	15130939.61	665761343.02	0.947
45	15130939.61	680892282.64	0.953
46	15130939.61	696023222.25	0.960
47	15130939.61	711154161.87	0.966
48	15130939.61	726285101.48	0.972
49	15130939.61	741416041.09	0.977
50	15130939.61	756546980.71	0.983

This revenue estimation is used, along with other potential scenarios involving yearly revenue growth, to plot system payoff potential over time. Figure 6-4 showcases the results.

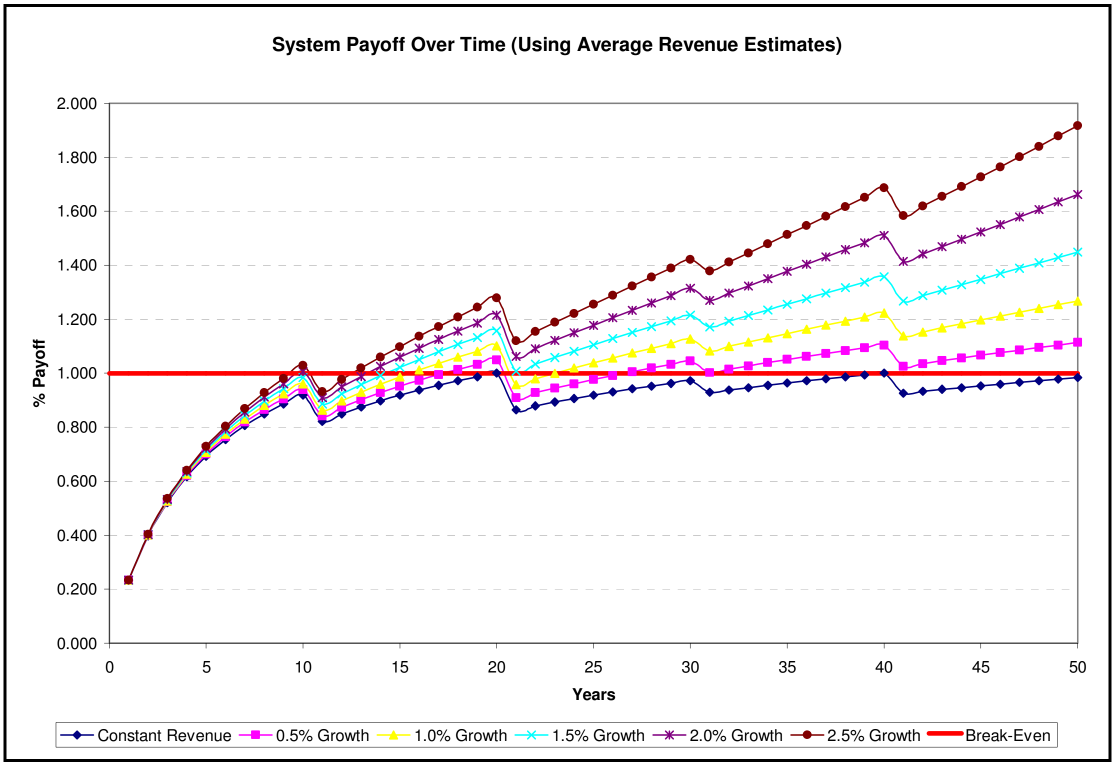


Figure 6-4: Yearly I-495 System Payoff

Looking at system payoff time based on different estimates of yearly revenue growth produces interesting results. The following can be seen:

- Assuming constant revenue, the system pays for itself every 20 years, but doesn't ever become profitable
- Assuming a 0.5% growth in revenue every year, the system becomes profitable after 27 years
- Assuming a 1.0% growth in revenue every year, the system becomes profitable after 24 years

- Assuming a 1.5% growth in revenue every year, the system becomes profitable after 15 years
- Assuming a 2.0% growth in revenue every year, the system becomes profitable after 14 years
- Assuming a 2.5% growth in revenue every year, the system becomes profitable after 12 years

As the proposed system at least breaks even with no ongoing debt, it is in the common good.

6.4 Assumptions and Conclusions

As with other sections of this study, certain assumptions were required to obtain cost and revenue estimates. First, HOT project estimates from the USDOT Research and Innovative Technology Administration were assumed representative of cost estimates for this congestion pricing system. Implementing a HOT lane is different than an entire-facility system, so this fact was taken into account with the cost estimates. Secondly, for cumulative cost estimates, 50% rebuild costs were assumed at 10 years and complete system rebuild costs were assumed at 20 years – this was based on the fact that the system equipment has a projected lifespan of 10 years. Lastly, NHTS trip data was assumed representative of one-way trips on I-495. This data was utilized assuming a distance of one mile between any two exits on I-495 and the fact that people will hypothetically travel one-half of the 64-mile long Beltway, as a maximum. As stated previously, even though this method is not entirely precise, it is far more realistic in terms of potential revenue estimation than splitting up mileage level groups evenly based on traffic flow.

Due to the fact that charges have been estimated to be lower than previous research indicates, revenue figures have also been underestimated. In light of this situation, a congestion pricing system in the Washington, D.C. area could potentially exhibit faster turnaround and pay for itself in fewer years. Excess revenue could then be spent on public transportation improvements in the area.

Chapter 7: Conclusions and Recommendations

7.1 Summary of Results

Road users must be held accountable for the true cost of highways. As travel is free on the Capital Beltway surrounding Washington, D.C., there is no current financial incentive to utilize public transportation, alter the timing of necessary trips, reduce unnecessary trips, or increase carpooling. This thesis aimed to hold users of I-495 accountable for their role in congestion by calculating appropriate congestion charges on a per-mile basis. The goal of this thesis was to calculate the appropriate charges required for users of I-495 in order to fulfill their portion of congestion costs.

This goal was reached within the study, as a model was developed from existing data on the Capital Beltway that showcases traffic characteristics that cause congestion, necessary charges for vehicle users to realize the congestion costs that their vehicles impose on the rest of the traffic stream were calculated, and potential financial implications (costs and revenue) that would be associated with congestion pricing were examined.

AM peak period charges ranging from $0.05 to $0.08 per PCE per mile cause drivers to realize their contribution to congestion and charges ranging from $0.03 to $0.08 per PCE per mile in the PM peak period accomplish the same. Tables breaking these charges down across FHWA vehicle classifications were shown in Chapter 4, along with summaries of anticipated traffic composition after implementing a congestion pricing system on I-495. These estimates are lower than those based on prior research, where efficient peak-hour congestion charges have been calculated to be between $0.08 and $0.50 per mile. This discrepancy in charging amounts can most likely be associated with additional factors that were not taken into account in this study. Chapter 6 showed that the proposed system with constant revenue will be able to pay for itself with no yearly subsidy required. If revenue increases are obtained, however, the system will both pay for itself and provide excess funds for use in transit improvements or minor roadway improvements. Additionally, since the charging estimates set forth in this thesis may be considered conservative approximations, a congestion pricing system on the Capital Beltway may be more cost effective than this study shows, with the system paying for itself in less time.

7.2 Conclusions

As mentioned previously, the proposed congestion system for the Capital Beltway is a "second-best" solution – containing charges varying on an hourly scale instead of smoothly time-varying charges. We are a long way from a potential "first-best" solution, with congestion charges varying in real-time based on actual conditions, as such a system is not practical at this point in time. Based on this fact, any solution is better than no solution – a Washington, D.C. area congestion pricing system needs to start somewhere. This study provides a good building block to the positives of congestion pricing, but there is still much ground to be covered.

Although this study is a, more-or-less, hypothetical scenario, hopefully it can pave the way for future discussion and research into facility-wide per-mile pricing systems in the United States. Based on the results of this study, the charges necessary for people to realize their congestion costs are not exorbitant. Education is key to enlightenment, however, as most people truly fail to realize how paying for something like road usage can be more beneficial for society. Proponents of congestion pricing must increase their public education efforts in hopes to gain further support. Through all of this, we must all also realize that there is not one perfect solution for congestion management – all available options must be considered, including transit advancements and pricing.

7.3 Recommendations for Future Research

In closing, as there remains much ground for future research, the following suggestions are made:

1. The entire regional freeway system should be examined in light of this study, not just the Capital Beltway – network comprehensiveness is a critical component of a successful congestion pricing strategy
2. Based on the lack of data for this study, more functioning traffic detectors are needed to collect valid speed, volume, and vehicle classification data – new sensor installations along with updates to the existing sensor network are necessary to gather more precise data. Additionally, data collection standards should exist for comprehensiveness between jurisdictions. In terms of costs, discussion with various transportation professionals has provided that installation costs for a fixed sensor network are estimated between $7,500 and $20,000 per site. The range in cost is due primarily to the extent to which existing infrastructure can be reused. Reuse of existing poles, sign trusses, and existing power and communications feeds reduce cost. Methods and technology that allow for reuse of existing

infrastructure, though more expensive, may prove to be the more cost effective option overall.

3. Congestion charging based on smaller time increments (or even real-time) would require data in much smaller increments instead of the hourly aggregations utilized in this study – various charging options should be evaluated.
4. Instead of utilizing NHTS data to estimate one-way trips during AM and PM peaks on I-495, surveys could be conducted in order to have a more precise estimate of revenue possibilities.
5. This study focused on gantries, cameras, and license plate reader technology, as costs were able to be obtained. Different technology may be cheaper and easier to install – for example, charges related to mileage driven in a priced region may be assessed by utilizing in-vehicle units (IVUs), such as those in-place in Singapore, with no need for gantries or cameras.
6. User value of time and vehicle operating cost estimates could be evaluated more precisely instead relying on FHWA estimates – future surveys and experiments could be conducted to gather this data.
7. While this study focuses on charging across all lanes on the Capital Beltway, a similar analysis could be accomplished using a HOT lane setup, like those being constructed in the region.

8. Environmental costs such as air pollution caused by idling vehicles were not considered in this thesis – special attention should be focused on various environmental costs for future work.
9. A variation of this study could be focused on finding the number of vehicles that need to be removed from a traffic stream at a given time in order to reach a certain level of service (LOS), average speed, or some other performance metric. Using a revised version of this model, corresponding pricing can be set in order to reach these traffic volume goals.

Appendix

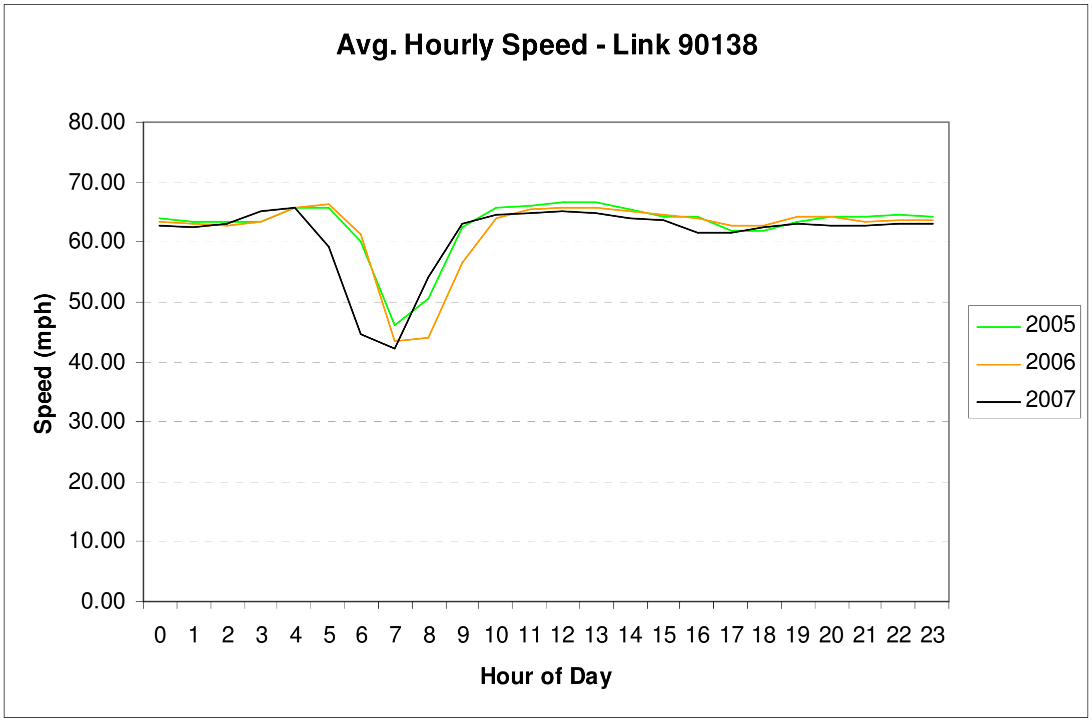


Figure A-1: Average Hourly Speed – Detector 90138

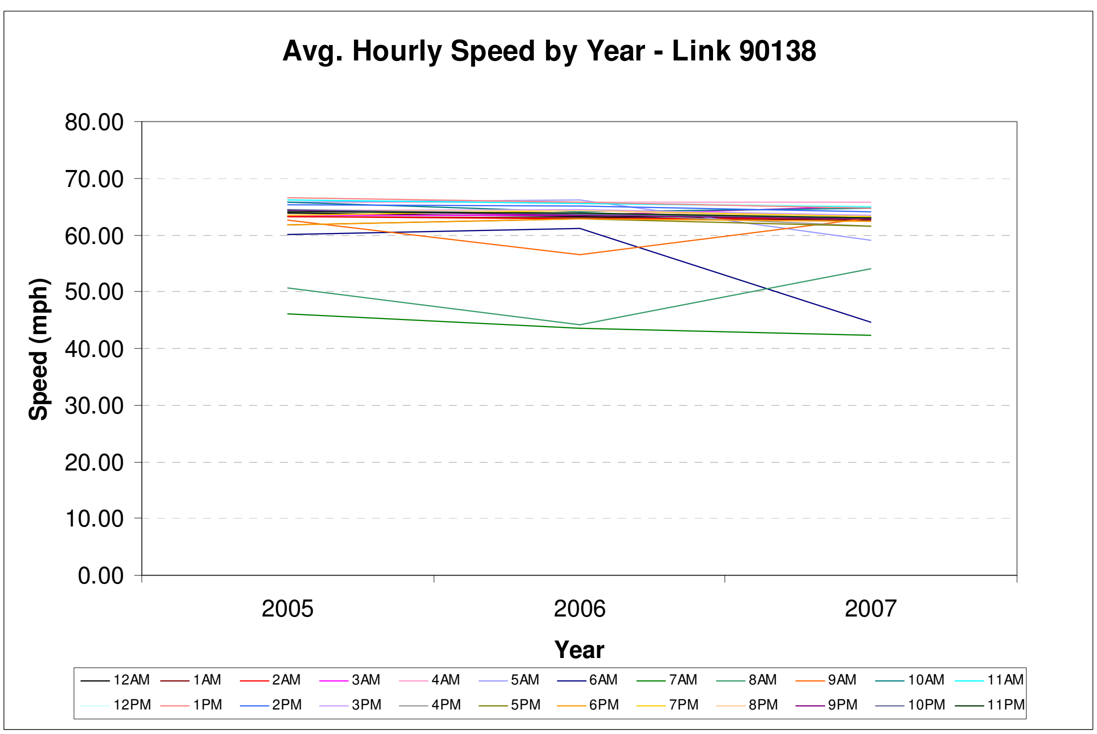


Figure A-2: Average Hourly Speed by Year – Detector 90138

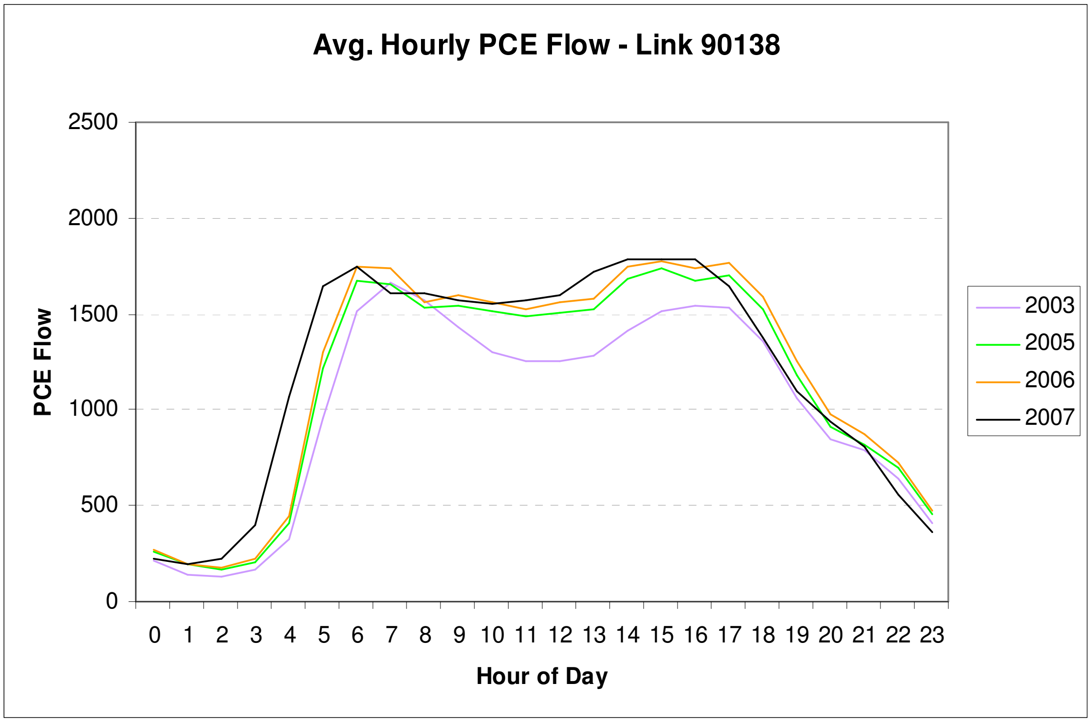


Figure A-3: Average Hourly Flow – Detector 90138

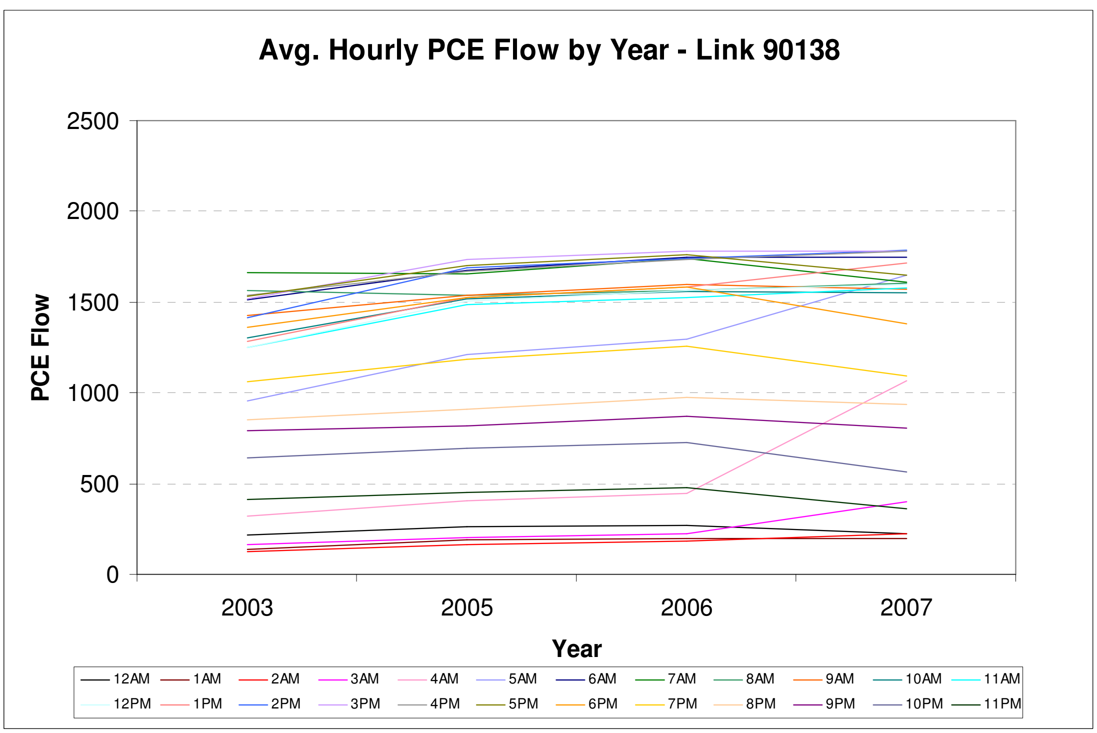


Figure A-4: Average Hourly Flow by Year – Detector 90138

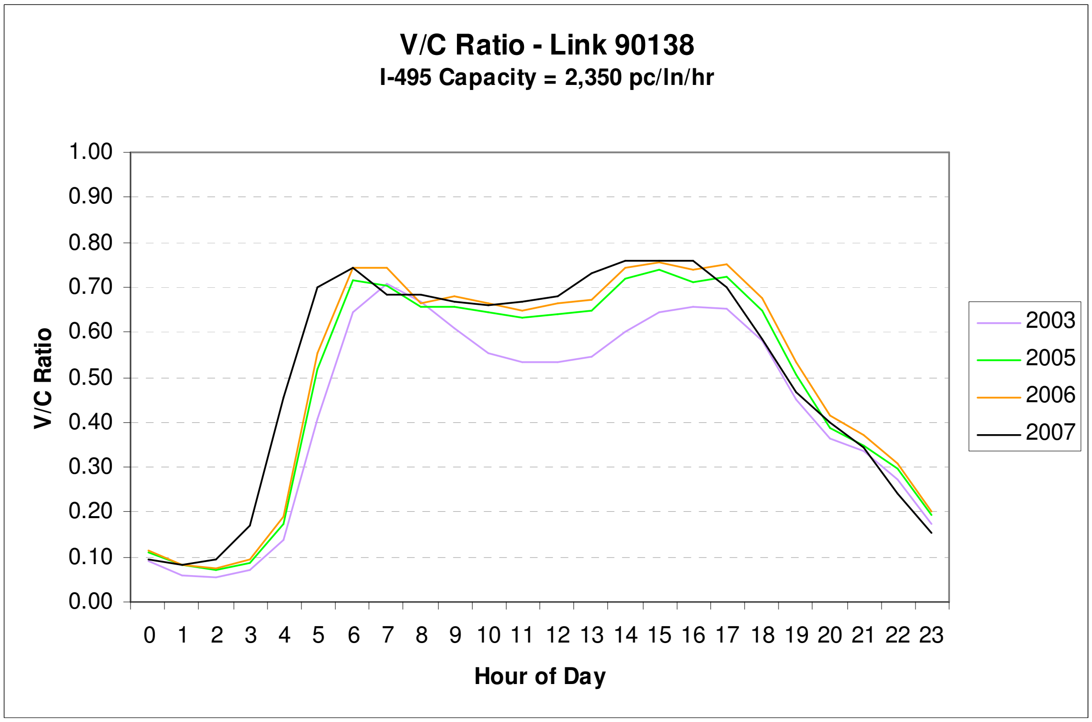


Figure A-5: Hourly Volume-to-Capacity Ratio – Detector 90138

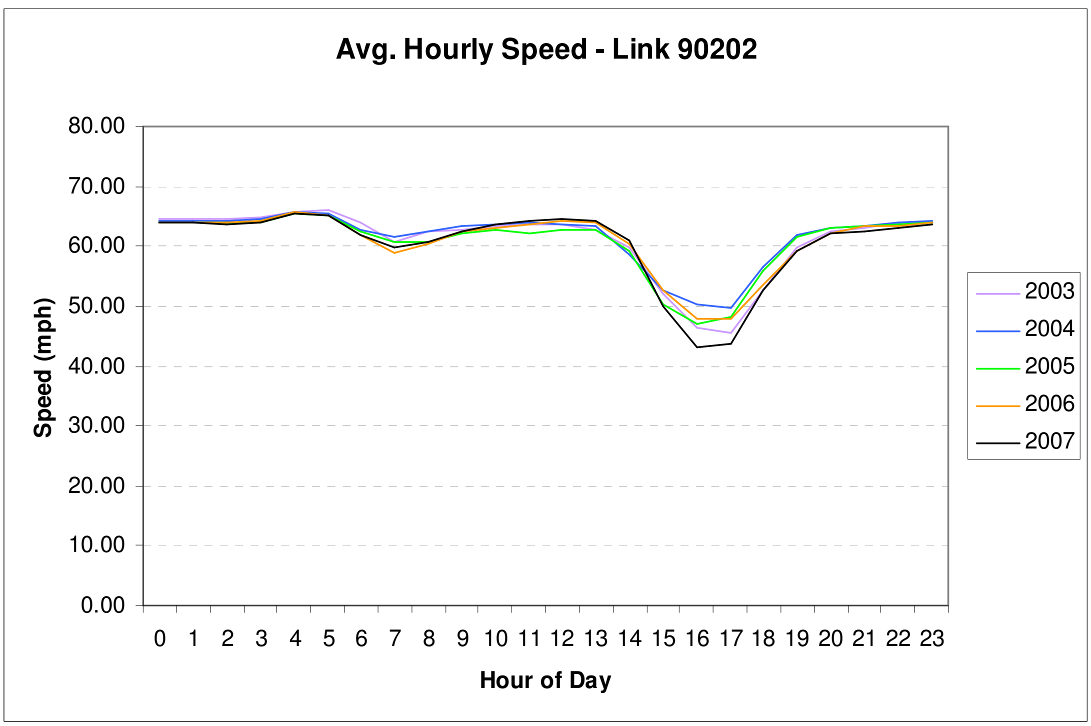


Figure A-6: Average Hourly Speed – Detector 90202

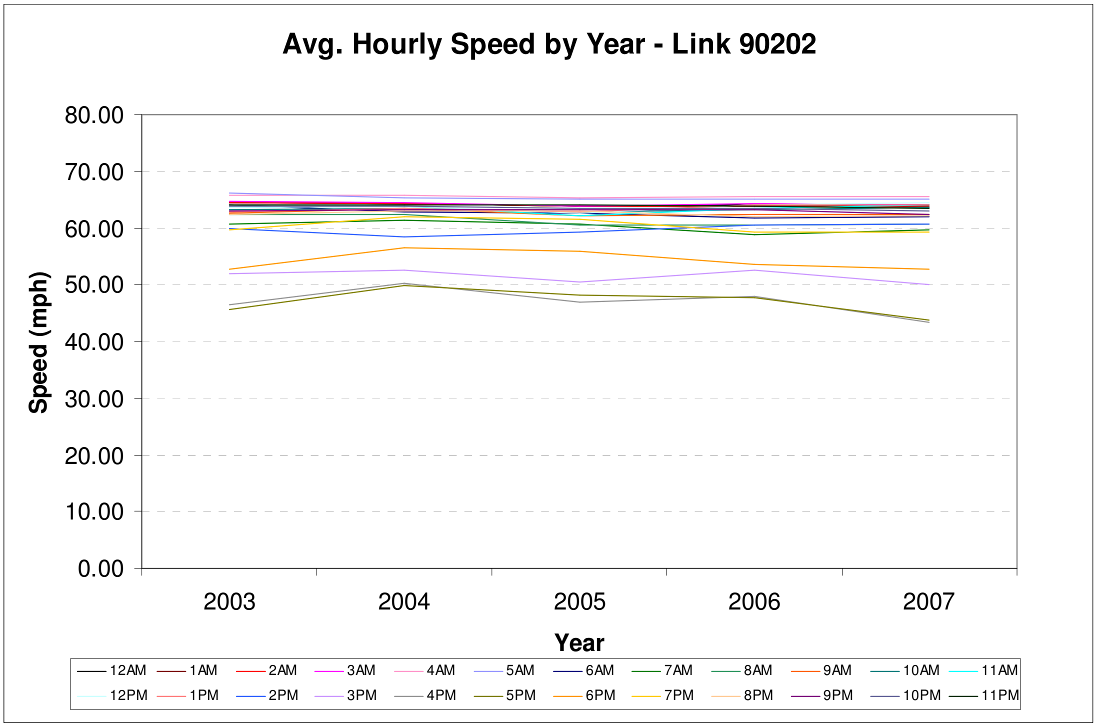


Figure A-7: Average Hourly Speed by Year – Detector 90202

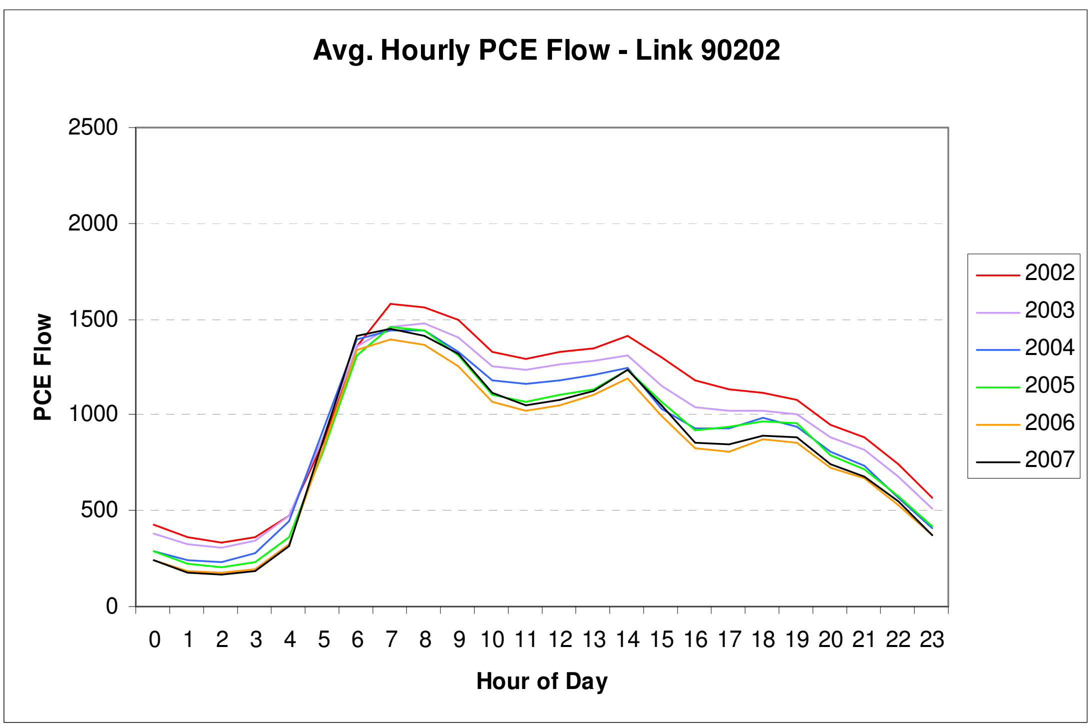


Figure A-8: Average Hourly Flow – Detector 90202

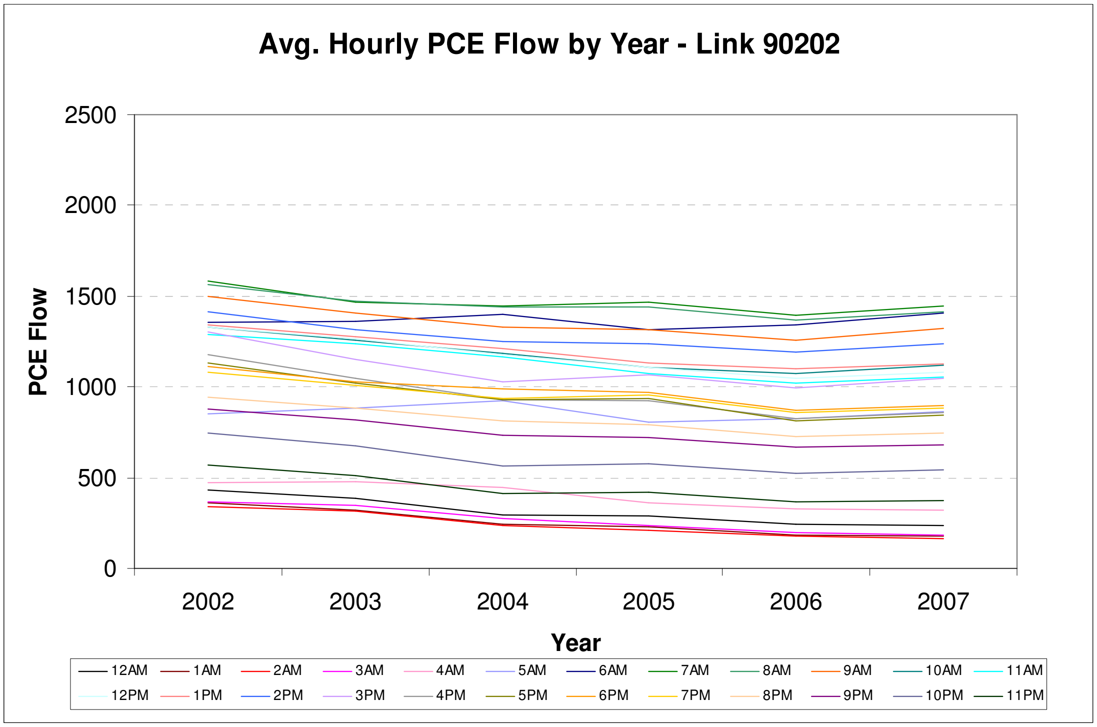


Figure A-9: Average Hourly Flow by Year – Detector 90202

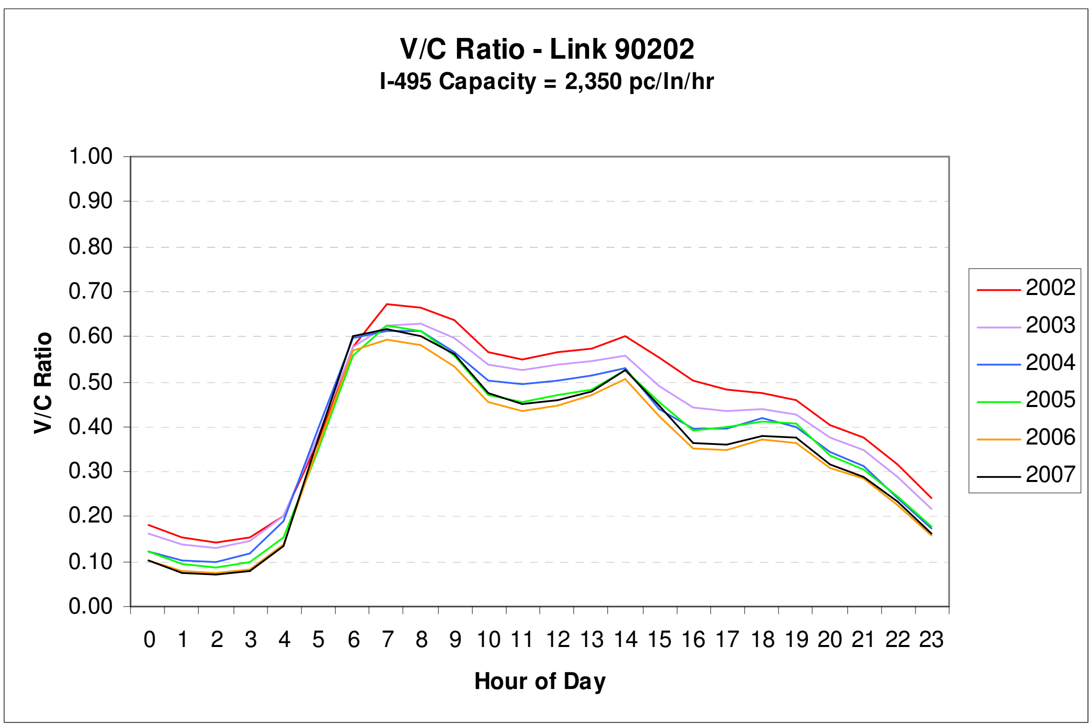


Figure A-10: Hourly Volume-to-Capacity Ratio – Detector 90202

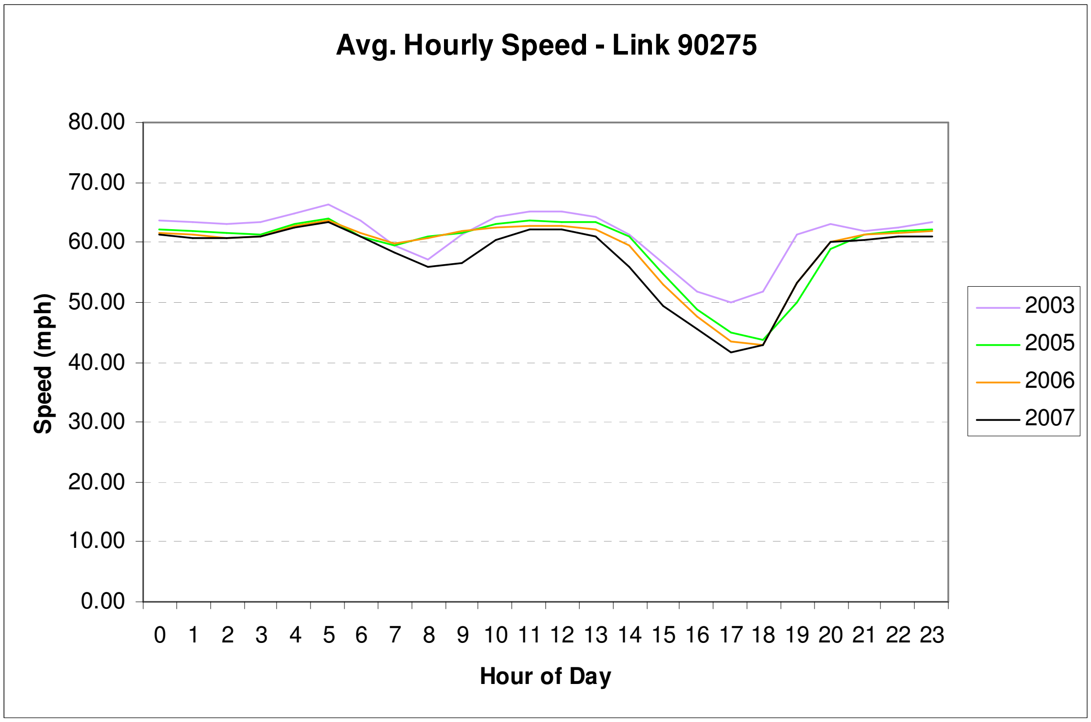


Figure A-11: Average Hourly Speed – Detector 90275

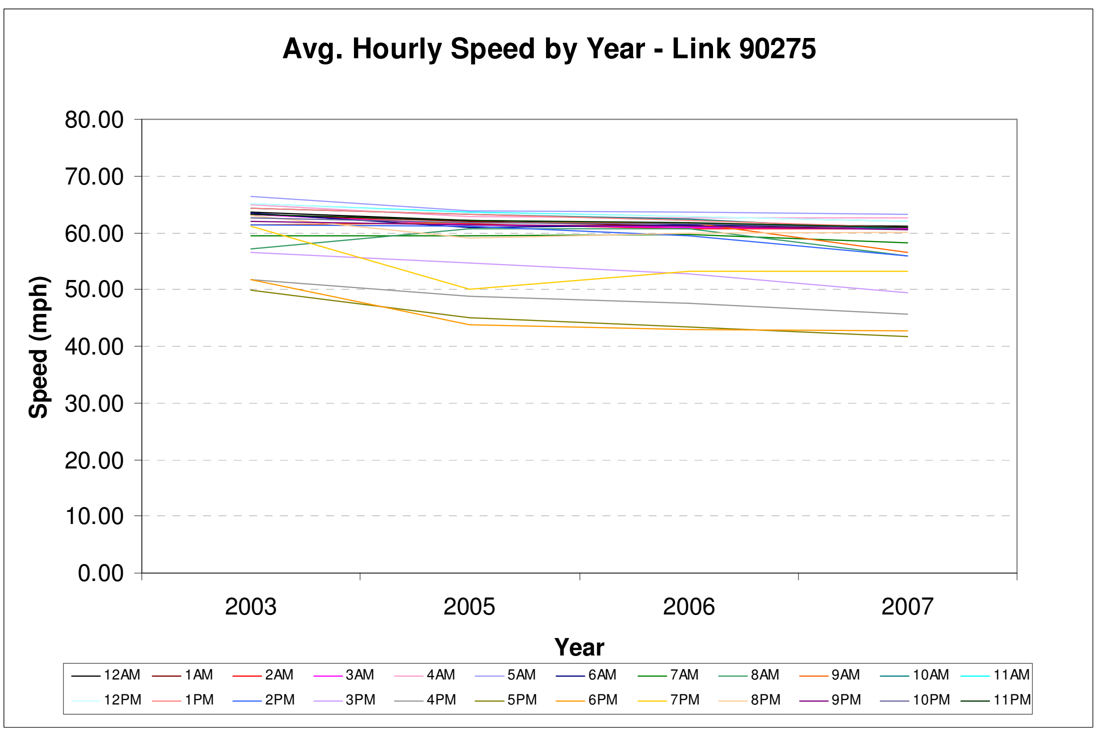


Figure A-12: Average Hourly Speed by Year – Detector 90275

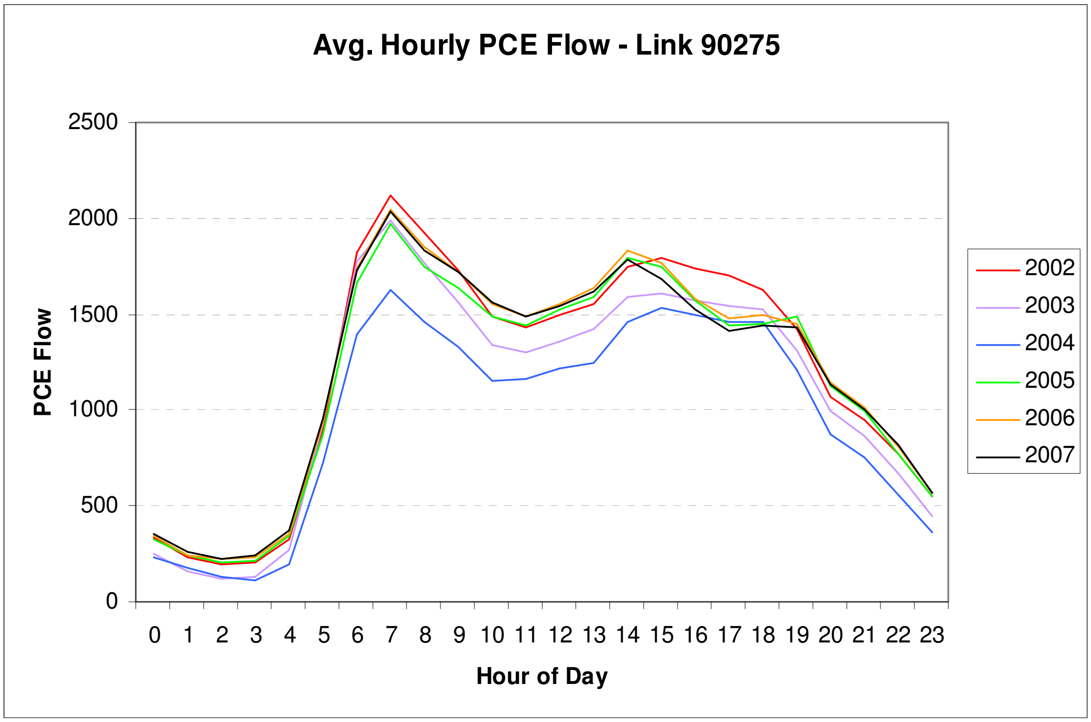


Figure A-13: Average Hourly Flow – Detector 90275

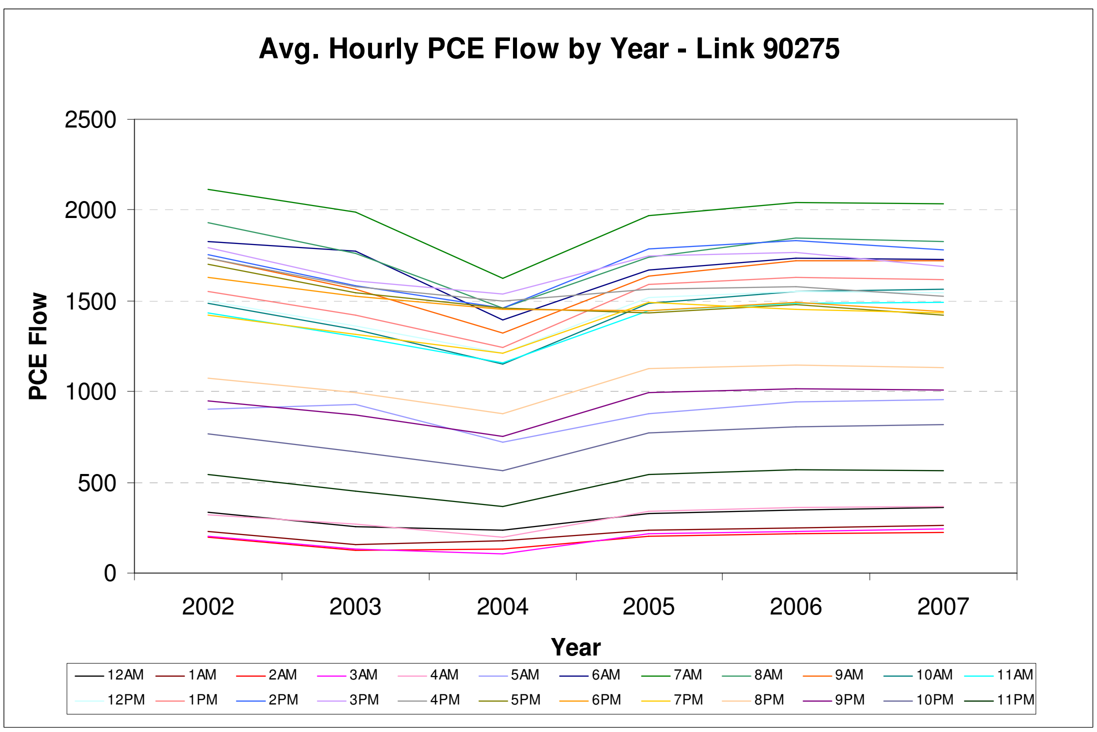


Figure A-14: Average Hourly Flow by Year – Detector 90275

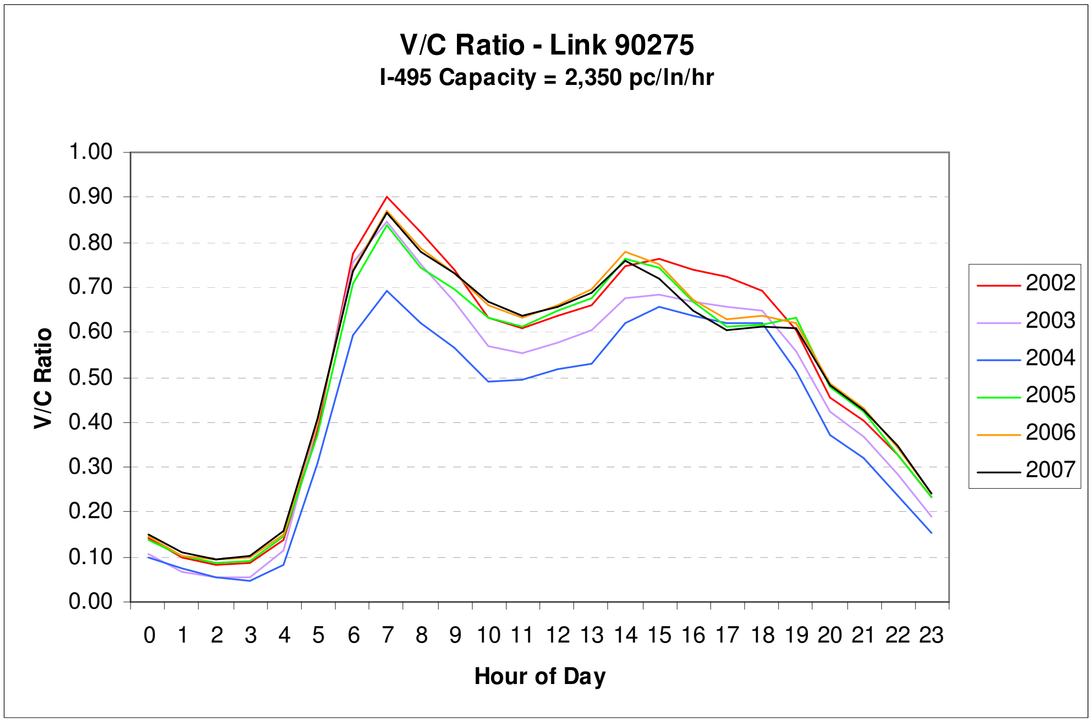


Figure A-15: Hourly Volume-to-Capacity Ratio – Detector 90275

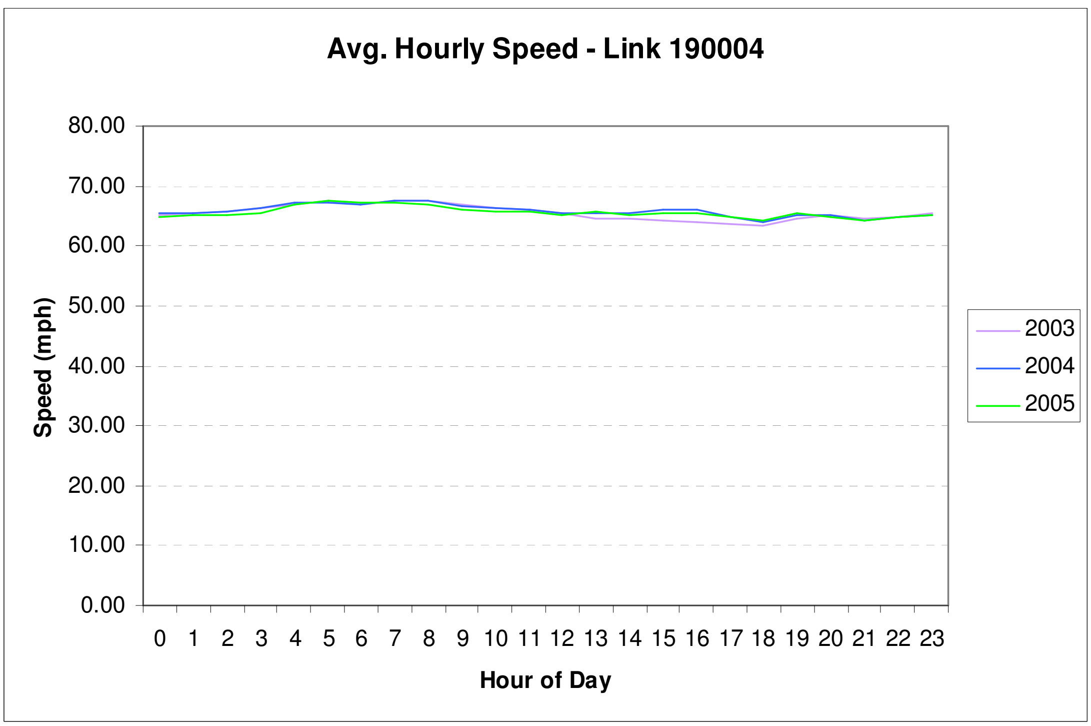


Figure A-16: Average Hourly Speed – Detector 190004

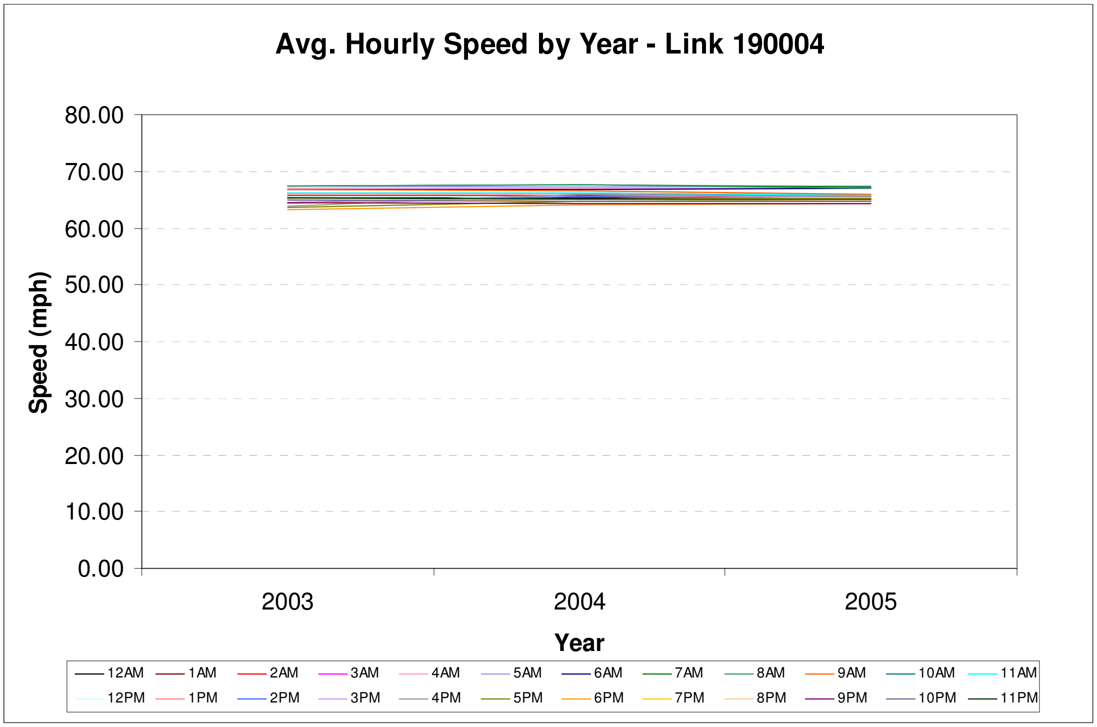


Figure A-17: Average Hourly Speed by Year – Detector 190004

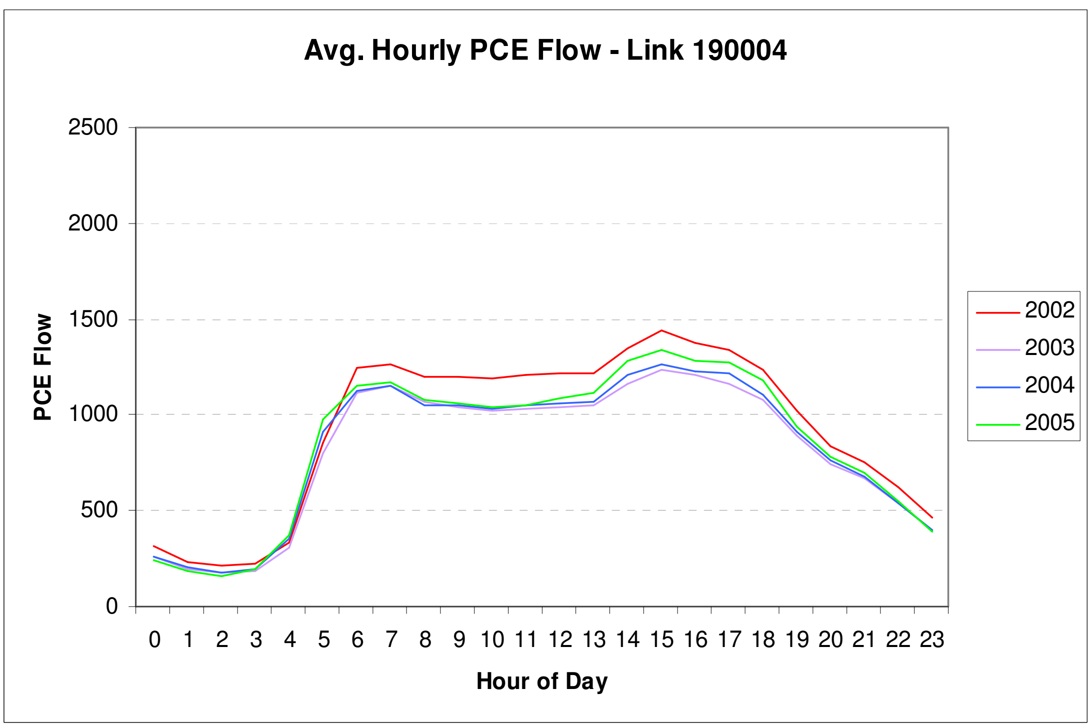


Figure A-18: Average Hourly Flow – Detector 190004

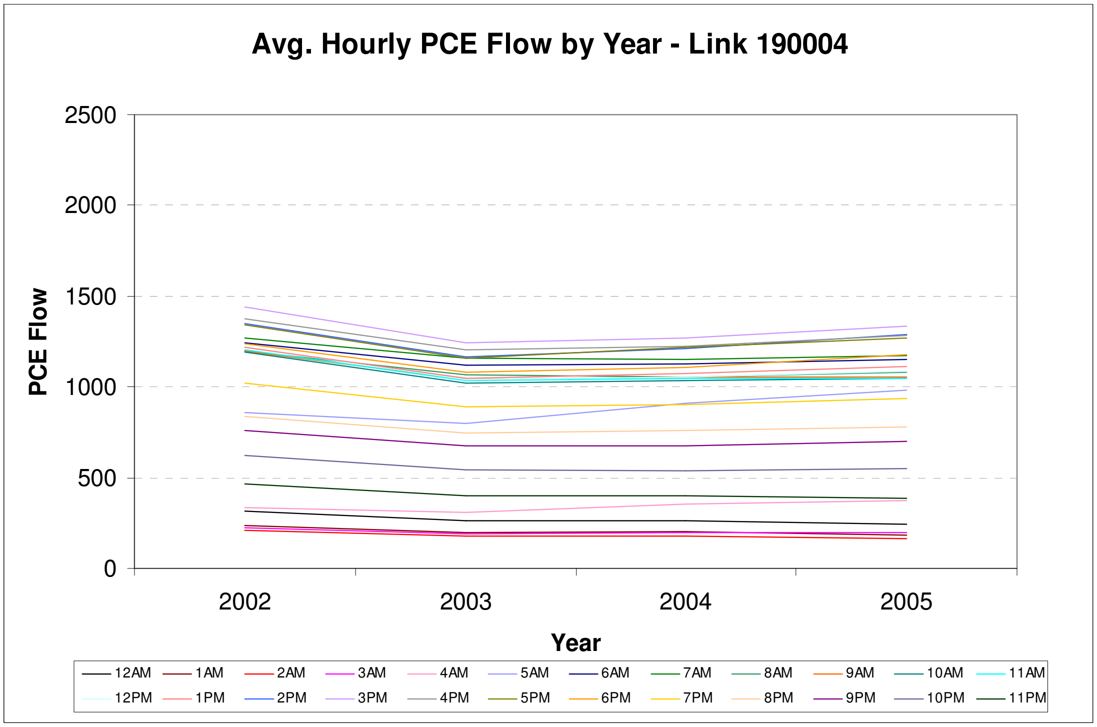


Figure A-19: Average Hourly Flow by Year – Detector 190004

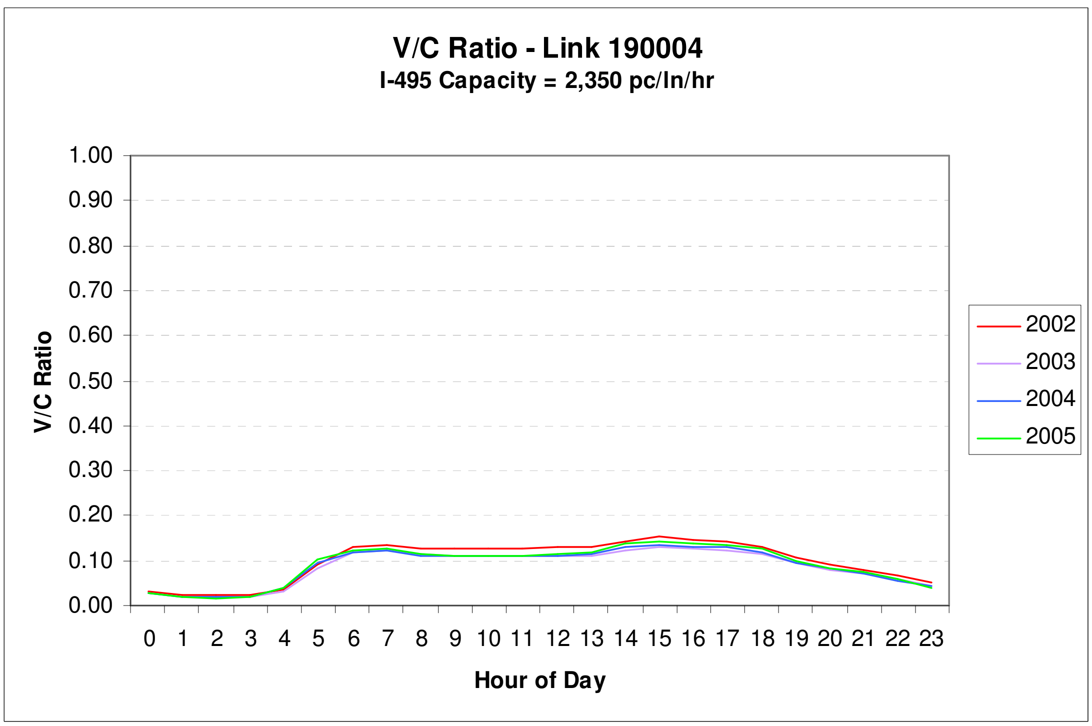


Figure A-20: Hourly Volume-to-Capacity Ratio – Detector 190004

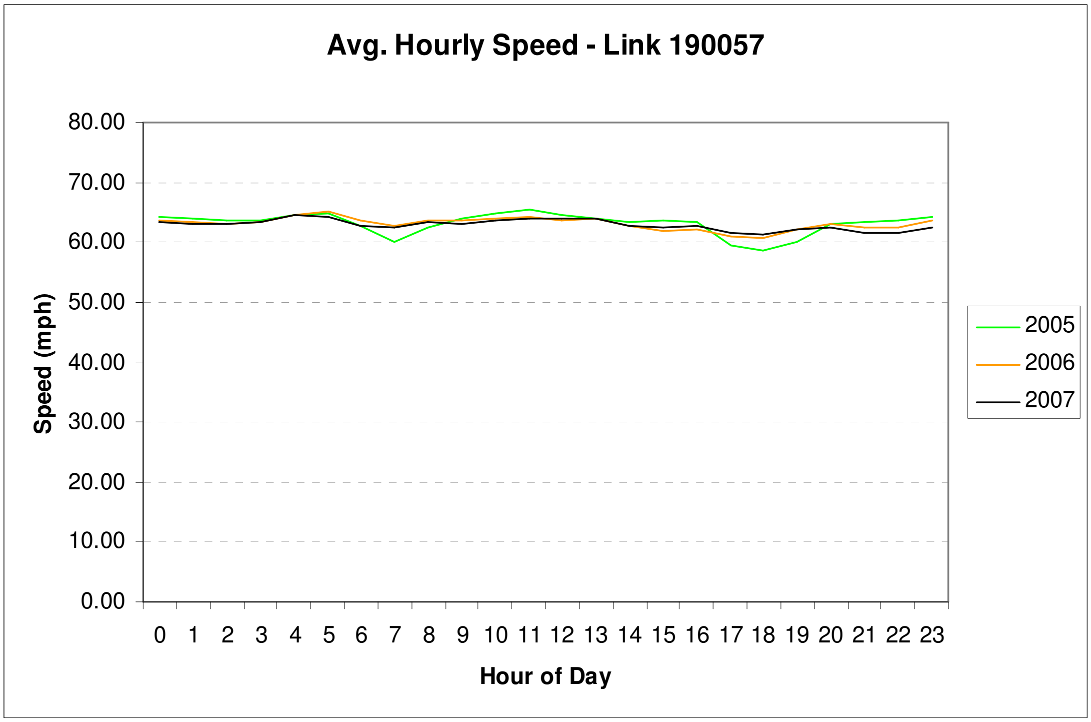


Figure A-21: Average Hourly Speed – Detector 190057

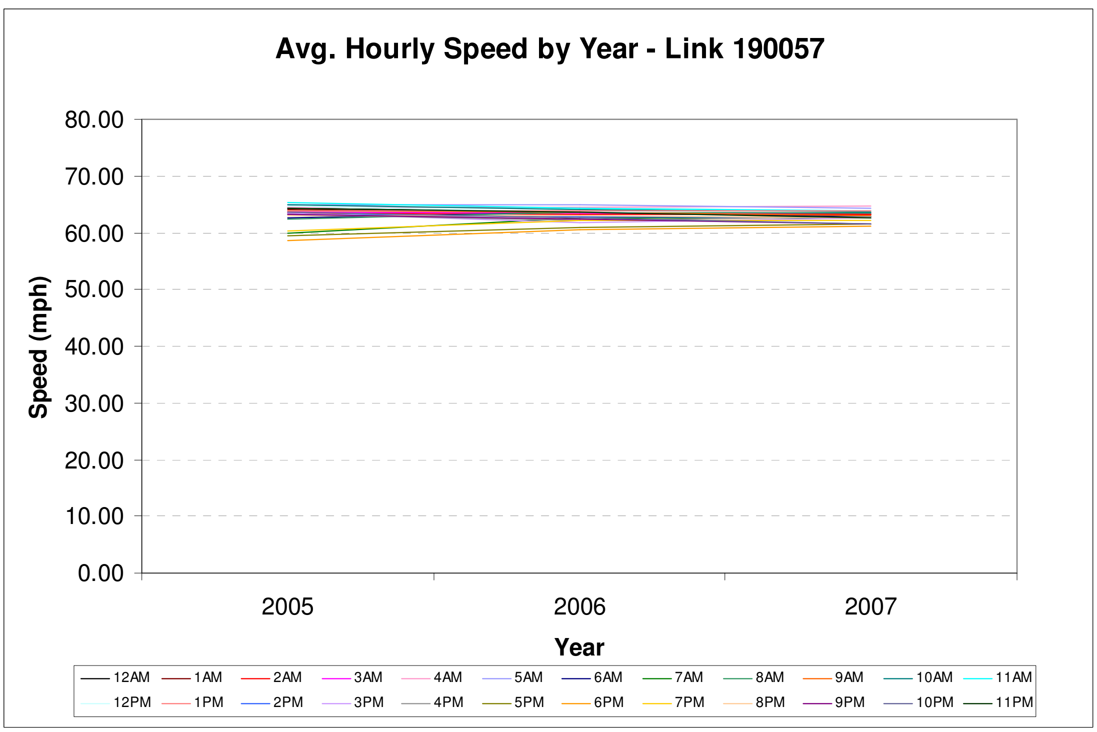


Figure A-22: Average Hourly Speed by Year – Detector 190057

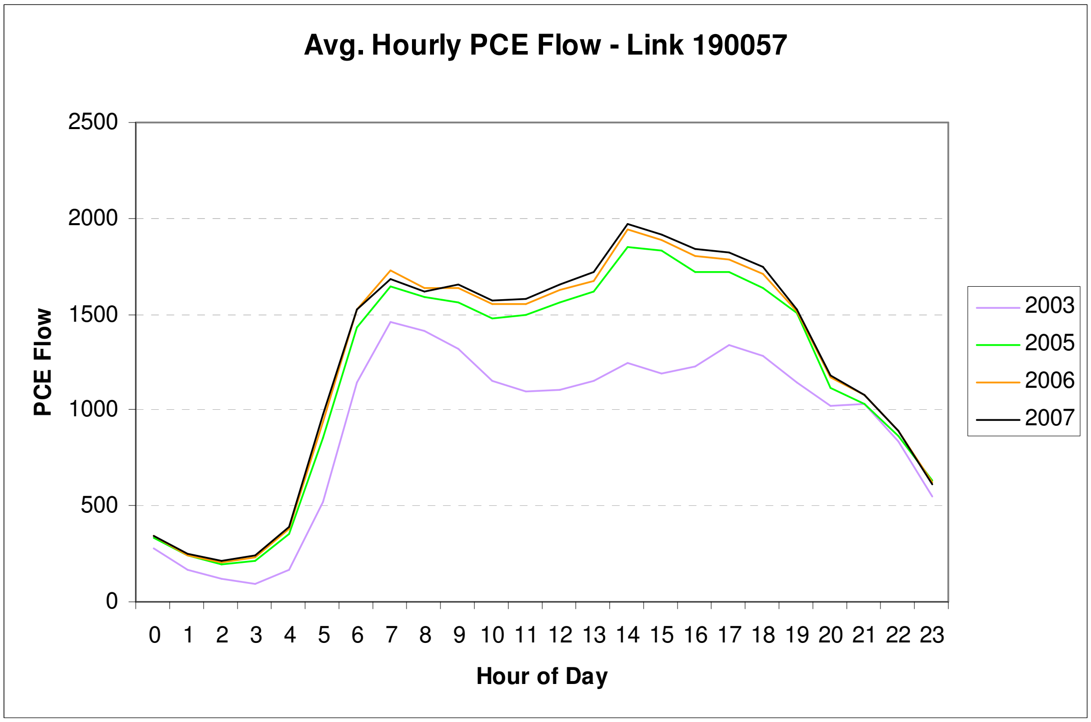


Figure A-23: Average Hourly Flow – Detector 190057

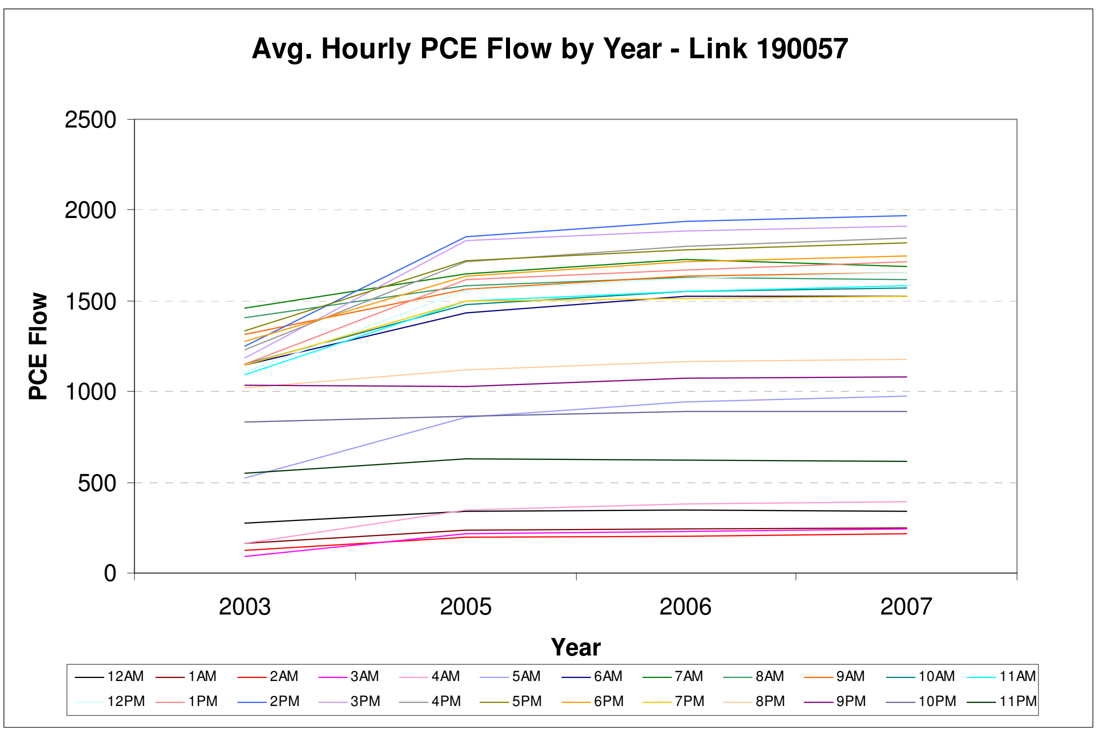


Figure A-24: Average Hourly Flow by Year – Detector 190057

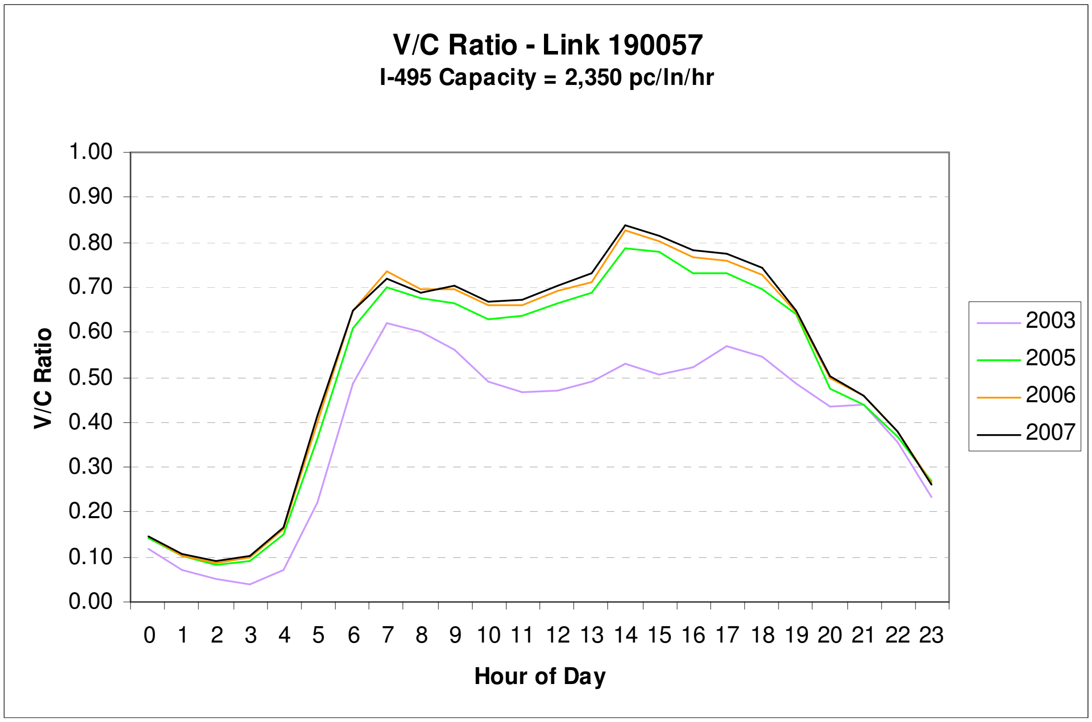


Figure A-25: Hourly Volume-to-Capacity Ratio – Detector 190057

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