

ENHANCEMENT AND EVALUATION OF DYNAMIC PRICING STRATEGIES  
OF MANAGED TOLL LANES

By

DIMITRA MICHALAKA

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I dedicate this dissertation to my amazing mom, dad, sister, and grandparents, who have always given me so much love, support, and advice.

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## LIST OF ABBREVIATIONS

AVC	Average Variable Cost
DST	Delta Settings Table
FHWA	Federal Highway Administration
GA	Genetic Algorithm
GP	General Purpose
HOT	High-Occupancy/Toll
HOV	High-Occupancy Vehicle
ITS	Intelligent Transportation Systems
LOS	Level of Service
SOV	Single-Occupancy Vehicle
SRMC	Short-Run Marginal Cost
TD	Traffic Demand
TTS	Travel Time Savings
VOT	Value of Time

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By

Dimitra Michalaka

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High-occupancy/toll (HOT) lanes are facilities that combine pricing and vehicle eligibility to maintain superior traffic conditions in the HOT lanes while maximizing freeway's throughput. Ideally, tolls should vary in real time in response to traffic conditions in order to achieve the above objective. Since the first HOT lanes were implemented in 1995, the concept has become quite popular and widely accepted by many transportation authorities. Currently, there are approximately ten HOT lane facilities in operation in the United States. Some of them are single-segment facilities, that is, they have essentially one entrance and one exit, plus one tolling point, while others consist of multiple segments, that is, they have multiple ingress or egress points that are located distantly from each other and more than one tolling point. Depending on the toll structure implemented and where motorists enter or exit, they may pay different tolls.

This dissertation enhances and evaluates dynamic pricing algorithms for HOT lane facilities that consist of a single or multiple segments. First, a genetic algorithm optimization procedure to enhance pricing strategies that are already implemented in practice is developed. The procedure is demonstrated on 95 Express in South Florida,

which is currently a single-segment facility. The experiments show that the procedure can yield improvements to the HOT lane operations. Then, the tolling practice for the multi-segment HOT lane facilities is outlined and recommendations for the future 95 Express, which will be expanded into a multi-segment facility, are made. This research also includes the enhancement of a microscopic simulation tool, CORSIM, to simulate HOT lane operations. Three main modeling components are developed, including three pricing strategies, a lane-choice module, and four toll structures for multi-segment HOT facilities. The enhanced software is demonstrated by simulating the current and future 95 Express. The result is that CORSIM enhancements are able to capture the primary characteristics of HOT lane operations and management.

## CHAPTER 1 INTRODUCTION

### 1.1 Background

Traffic congestion has become a severe problem in many societies. According to a well cited report (Schrank et al., 2010), United States (U.S.) congestion levels nationwide have risen significantly since 1982. As travel demand increases, existing infrastructure becomes more congested and alternative methods are required to manage the traffic flow. The construction of new facilities is very difficult due to environmental constraints and limited funding. This has led transportation agencies to explore other alternatives to manage traffic demand. Some of them include lane management strategies that can regulate demand, separate traffic streams, and utilize available but unused capacity on existing transportation facilities. In recent years, these operational strategies have come to be known as “managed lanes.” The Federal Highway Administration (FHWA) defines managed lanes as highway facilities or a set of lanes in which operational strategies are implemented to respond to changing conditions in real time. Managed lanes include high-occupancy vehicle (HOV) lanes, high-occupancy/toll (HOT) lanes, priced, and special-use lanes, such as express, bus-only, or truck-only lanes (Obenberger, 2004). HOT lanes are facilities that combine pricing and vehicle eligibility to maintain free-flow conditions on the HOT lanes while maximizing a freeway’s throughput. They provide a travel-time savings incentive for high-occupancy vehicles (HOVs), as these are allowed to enter the lanes at no monetary cost. HOV and special use lanes have been used for decades, but HOT lanes were implemented much later, the first in December, 1995 on California State Route 91. Currently, there are more than ten HOT lanes in operation in the U.S. Among other

factors, the popularity of the HOT lane concept is due to the underutilization of HOV lanes and the additional option it provides to motorists. Many have expressed concern about the wasted capacity resulting from a low utilization of HOV lanes (Dahlgren, 2002). Thus, converting underutilized HOV lanes to HOT lanes is likely to create a win-win situation for both HOT and regular lane users. Moreover, managed lanes provide motorists with the option to “buy in” or to pay to avoid congestion. The managed-lane operator must ensure a superior level of service in order to attract motorists to pay and use the lanes.

Ideally, tolls should vary in real time in response to changes in traffic conditions in order to achieve the aforementioned objective. Currently, there are at least six authorities pricing their toll lanes dynamically—the California Department of Transportation (Caltrans) on Interstate 15, the Florida Department of Transportation (FDOT) on Interstate 95, the Minnesota Department of Transportation (MnDOT) on Interstate 394, the Washington Department of Transportation (WSDOT) on State Road 167, the Utah Department of Transportation (UDOT) on Interstate 15, and the Georgia State Road and Tollway Authority (SRTA) on Interstate 85. Other HOT lane facilities such as Interstate 10 in Houston, Texas, implement time-of-day tolls. More specifically, the tolls vary by the time of day according to a predetermined schedule, which is usually designed based on historic traffic data.

## **1.2 Problem Statement**

Many HOT lane facilities are single-segment facilities, while others consist of multiple segments. A single-segment HOT facility has essentially one entrance and one exit. Sometimes more than one entrance or exit exists, but they are very close to each other and motorists still pay the same amount in tolls to use the facility no matter where

they enter or exit. In contrast, a multi-segment HOT lane has multiple ingress and egress points that are located distantly from each other and there are multiple tolling points in the facility. Depending on the toll structure implemented and where they enter or exit, motorists may pay different amounts in tolls.

Similar to the pricing of a single-segment facility, the pricing approach for a multi-segment HOT facility should provide superior traffic services on the HOT lanes while maximizing the utilization of the available capacity of the lanes. Moreover, the approach should avoid creating too much inequality between motorists entering at different points. For example, if not priced properly, those who access the HOT lanes via an entry point further downstream could end up paying much higher tolls for less time savings.

In the literature, many studies have been conducted to determine optimal dynamic tolls for congested freeway facilities, but many of them focus on idealized and hypothetical situations to derive solutions, while others require too many resources (e.g., much computational time) to be applied in practice. Conversely, the methods implemented in the field may not give the optimal toll rates for best managing a certain HOT lanes facility. Thus, the pricing strategies implemented in practice should be enhanced to be more robust. Also, there are no studies on how to price multi-segment HOT lane facilities.

In order to evaluate a proposed pricing scheme or the operation of managed lanes, microscopic simulation is very useful (e.g., Zhang et al., 2009). Unfortunately, few traffic simulation programs are able to simulate managed lanes, especially HOT lanes, and even those that do suffer limitations. For example, there are no software tools that

can simulate different toll structures for multi-segment HOT lanes. Therefore, there is a need to enhance the existing simulation software.

### **1.3 Research Objectives, Supporting Tasks and Validation**

The objectives of this research are first to enhance and evaluate dynamic pricing algorithms implemented in practice for single-segment and multi-segment HOT lane facilities, then to present the different toll structures that can be implemented on multi-segment HOT lanes and finally to enhance a microscopic traffic simulation software to simulate HOT lanes operations. The enhanced software will be validated by simulating an existing HOT lane facility.

The tasks conducted to achieve the objective are as follows:

- Conduct a thorough literature review in order to identify existing methods and procedures for managed lane operations.
- Develop a procedure to enhance pricing strategies that are already implemented in practice. This procedure is demonstrated by optimizing the pricing algorithm currently implemented on the 95 Express in South Florida.
- Outline the tolling practice for the multi-segment HOT lane facilities
- Make recommendations of how to select a tolling structure for a multi-segment HOT lane facility like the future 95 Express.
- Enhance the microscopic simulation tool, CORSIM, to simulate HOT lane operations.
- Validate the enhanced software by simulating the operations of the current 95 Express.
- Demonstrate CORSIM's ability to simulate the different toll structures for multi-segment HOT lanes by applying all the structures on the future 95 Express.

### **1.4 Document Organization**

Chapter 2 presents a literature review of the HOT lanes' operation components, including the pricing algorithms and current practice for single-segment and multi-

segment HOT lanes facilities. Chapter 2 also reviews the lane choice models used to determine the number of drivers that will choose to travel on the HOT lanes versus the general purpose (GP) lanes. One of the most important components that affect travelers' lane choice between HOT and GP lanes is the value of time (VOT). Literature on VOT is also provided. Also, Chapter 2 reviews simulation software used to simulate HOT lanes. Chapter 3 describes an optimization procedure to enhance pricing strategies for HOT lanes and then, as a case study, it presents the fine-tuning of parameters of the pricing algorithm that is currently implemented on the 95 Express in South Florida. Chapter 4 presents the toll structures for multi-segment facilities and recommends one to be implemented on the future 95 Express. Chapter 5 describes the new components incorporated into CORSIM that enable it to simulate HOT lane operations. Chapter 6 focuses on the evaluation of the CORSIM enhancements by simulating the current and future 95 Express and it validates the optimized 95 Express tolling algorithm using the enhanced CORSIM. Chapter 7 summarizes the research and presents some concluding remarks. Appendix A provides a user guide on how to simulate HOT lanes in the enhanced CORSIM.

## CHAPTER 2 LITERATURE REVIEW

This literature review focuses on methodologies and procedures used or proposed for HOT lane operations. It consists of four different sections: introduction to congestion pricing and HOT lanes practice, pricing models for determining toll rates, lane choice models predicting the number of users who will choose to travel on the HOT lanes versus the GP lanes, and simulation software that can be used to simulate HOT lane operations.

### **2.1 Congestion Pricing**

In many countries, including the U.S., toll roads, with fixed toll rates that every traveler has to pay, date back at least to the late eighteenth century. At that time, the purpose of tolling was to recover the construction cost or to gain revenue. In the early 1920s, economists and transportation researchers started to consider tolling as a measure to manage traffic demand and reduce congestion that had started to increase in many places (Morrison, 1986).

Congestion pricing, or value pricing, is a tool for mitigating traffic congestion because it has been observed that people tend to make more socially efficient choices when they face the cost of their actions and the social benefits (Lindsey and Verhoef, 2000). Congestion pricing usually leads rush-hour travelers to shift to off-peak periods or to other transportation modes. Removing even a small percentage of the peak-period volume from a congested facility through value pricing allows the system to perform much better (FHWA, 2006a). Congestion pricing involves setting tolls depending on real-time traffic conditions. This implies that tolls must vary according to time, location, vehicle type, occupancy of the vehicle, and current circumstances, such as bad

weather, accidents, and special events. Congestion pricing is also used in other practices besides traffic, such as determining rates for telephone lines, travel, hotels, electricity, other utilities, and other public services and facilities. The U.S. Federal Highway Administration (FHWA, 2006b) refers to four types of variable pricing strategies. The first involves priced lanes with variable tolls on separated lanes within a highway, such as express toll lanes and HOT lanes, while the second includes variable tolls on entire roadways (i.e., on toll roads, bridges, and existing toll-free roads) during rush hours. The third pricing strategy is applying cordon charges to drive into a congested area within a city and the fourth is implementing area-wide charges, which are charges per mile on all roads within an area that vary by the level of congestion.

The basic theoretical approach to congestion pricing was developed by Pigou (1920) and Knight (1924) who were the first people to propose pricing as a measure to alleviate congestion. Morrison (1986) further developed the theory of optimal congestion tolls based on Pigou's and Knight's work by using the speed-flow curve to derive the relationship between flow and cost per user. The most significant effect of congestion was considered to be the cost associated with increased trip travel times with an assumed traveler's VOT. If speed is inverted on the speed-flow curve, time per mile is obtained. Multiplying the VOT by the time per mile and adding operational vehicle costs gives the average variable cost (AVC). The extra cost of adding a vehicle to the flow is the short-run marginal cost (SRMC). The cost curves and the demand curve that represent the willingness to pay for various quantities of trips are shown in Figure 2-1. In this figure, the backward bending portion of the AVC curve is not illustrated because the

optimal flow will never occur in this region due to the fact that the same flow can be achieved at a lower cost.

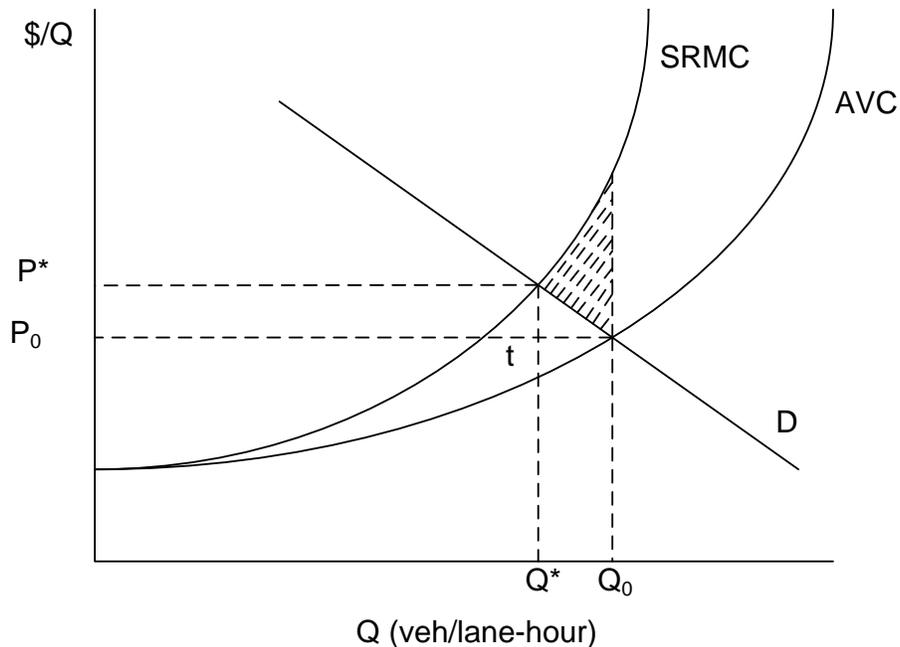


Figure 2-1. Optimal congestion toll (Morrison,1986).

If there are no tolls ( $t$ ), equilibrium will occur at  $Q_0$  which is the intersection point of the demand and AVC curves. At this point, the additional cost incurred from considering other users exceeds the benefit derived by the last traveler. This happens for all trips beyond point  $Q^*$ . The amount by which the extra cost of these  $Q_0 - Q^*$  exceeds the additional benefits represents the loss from non-optimal pricing. In order to have equilibrium, a toll,  $t$ , must be added to the optimal quantity,  $Q^*$ . This toll is equal to congestion externality, which is the difference between the cost a traveler affords (AVC) and the cost he imposes on the society (SRMC). In other words, externality is the congestion cost that each additional user of a congested road or other facility imposes

on other users, by slowing down, decreasing drivers' comfort, increasing the risk of accidents, and the like (Carey and Srinivasan, 1993).

Kraus et al. (1976) and Keeler and Small (1977) further analyzed the congestion problem from a long-run perspective. They argued that, in a long-run analysis, optimal tolls depend on highway capacity costs due to the fact that optimal highway capacity and congestion depend on the cost of the additional capacity. Kraus et al. estimated long-run peak tolls using "pseudo-empirical" analysis for a generic U.S. urban expressway. They found that tolls vary according to the capital cost and with the location of the expressway. Keeler and Small took into consideration speed-flow relationships for uninterrupted flow conditions and highway construction costs for the San Francisco Bay Area. Their results indicated that peak tolls vary greatly among the different types of roads.

## **2.2 HOT Lanes**

In this section, the general principles of HOT lanes, including definition, purpose, objectives, motivation, and current practice are summarized.

### **2.2.1 HOT Lane Concept**

HOT lanes are facilities that combine pricing and vehicle eligibility to maintain free-flow conditions while still providing a travel-time savings incentive for HOVs (Obenberger, 2004). This allows additional HOV lane capacity to be used while acting as a stimulant for mode shifting.

HOT lanes were first advocated by those who believed that congestion pricing can reduce the congestion levels on freeways because drivers have to pay a specific amount of money in order to use the congested facility. They posited that HOT lanes are the first step for more widespread pricing of congested roads (Dahlgren, 1999).

Dahlgren (2002) investigated when to implement HOT, HOV, and GP lanes, then suggested that a HOT lane seemed to perform as well as, or even better, than a HOV lane in any circumstance. More specifically, HOT lanes may offer a solution to the issue of under-utilization of HOV lanes.

The concept of HOT lanes combines two very effective highway management tools: lane management and value pricing. Lane management includes limited access to designated highway lanes, depending on the vehicle's occupancy and type. The desirable level of traffic service is maintained by limiting the number of vehicles on the designated lanes. The lane management can promote a range of policies, such as carpools and transit vehicles, to encourage higher occupancy, or low emission vehicles to improve air quality, or vehicles equipped for electronic toll collection to improve operational efficiency (FHWA, 2006b). Value pricing includes the introduction of road-user charges that vary over the time of day and according to the congestion level. During the peak periods when the volumes are high, even the shift of a small number of vehicles can reduce the overall congestion levels significantly and lead to more reliable travel times (FHWA, 2006b).

### **2.2.2 HOT Lane Benefits and Risks**

The implementation of HOT lanes is appealing to transportation authorities because it results in many advantages to traffic networks. First of all, implementing HOT lanes is an effective way to manage traffic demand during peak periods (FHWA, 2006a) and mitigate congestion by giving drivers a financial incentive to seek alternative modes of transportation, such as carpooling and public transit, or to drive during off-peak hours (Replogle, 2008). Second, HOT lanes offer travel options for saving time and enhance travel time reliability (Obenberger, 2004). Third, they improve transit speeds and service

reliability, and prevent the loss of vehicle throughput that comes from a breakdown of traffic flow. Also, they help commercial vehicles deliver more products per hour to their markets (FHWA, 2006a). In addition, converting HOV lanes that are underutilized to HOT lanes often reduces traffic in the free lanes by more efficiently utilizing the freeway's capacity (Replogle, 2008). Furthermore, HOT lanes can decrease turbulence among vehicles because they separate traffic streams, reducing the possibility of accidents (Sisiopiku and Cavusoglu, 2007). Another important benefit of congestion tolling is that it can take into consideration, not only congestion at traffic peak hours, but also, congestion that is caused by such special events as accidents, sporting events, parades, construction, maintenance, and severe weather conditions (Halem et al, 2007). Another significant benefit of imposing tolls on congested roads is the improvement of the quality of transportation services without an increase in taxes or large capital expenditures by providing additional revenues for funding transportation (FHWA, 2006b).

The implementation of HOT lanes has many advantages but, as in other traffic management strategies, there is always a risk of ineffective operation if tolls are not set appropriately, for instance, in the case of inaccurate traffic forecasts. If inaccurate traffic models are used to predict the tolls, the expectations of toll roads will not be met (Replogle, 2008). Inaccurate traffic forecasts were used, for instance, at Dulles Greenway in Virginia (U.S. DOT, 2006) creating problems in the toll lanes' operations. In addition, the construction of HOT facilities', including the toll collection infrastructure, requires funding resources. Moreover, consumers view tolls as a direct additional cost, or tax, for using the roads, spurring many of them to oppose the implementation of HOT

lanes (Smith, 2007). How much consumers are affected by the toll payment depends on their VOT and the travel time savings.

### **2.2.3 Current Practice of HOT Lanes in the U.S.**

Currently, there are approximately ten HOT lanes constructed in six different states in the U.S. One of them will open by the end of 2012. Each HOT lane facility is briefly described below:

- The State Route (SR) 91 HOT lanes in Orange County California opened in December 1995 and were the first ones implemented in the U.S. The facility is a four-lane, ten-mile toll road located on the median of SR-91 (OCTA, 2012). The tolls vary over the day to meet the traffic pattern and ensure that the toll lanes operate under free-flow conditions. The exact toll amount is set from a time-of-day toll schedule that includes the price for each hour on a particular day or holiday. HOVs with three or more commuters are allowed to use SR-91 for free during most hours, except between 16:00 and 18:00 on weekdays when they pay half of the posted toll. Priced lanes are separated from free lanes with plastic pylons on SR-91. Sullivan (2000) conducted a study to evaluate the impacts of the value pricing on SR-91. Some of his findings include that the toll lanes attracted a substantial share of the traffic using the SR-91 corridor, the congestion in the free lanes was reduced, and new trips, mostly for non-work purposes, were induced by the better travel conditions on the facility. Furthermore, the number of accidents in the express lanes decreased significantly after the implementation of the tolling.
- In San Diego, the I-15 HOT lanes opened in December 1996. The facility is sixteen miles long and has nine entrances and eight exits in the northbound direction and nine entrances and nine exits in the southbound direction. The facility was initially barrier-separated HOV lanes, but then solo drivers were allowed to gain unlimited access by purchasing a monthly permit (initially \$50, then \$70). In March 1998, time-of-day pricing was implemented. In March 2009, dynamic pricing was implemented on I-15 Express Lanes. Every few minutes, the system will recalculate the per-mile toll rate based on the traffic demand in the corridor, ensuring free-flow traffic conditions in the HOT lanes. When a motorist enters the facility, he or she needs to pay the minimum toll, regardless of his or her eventual exit location.
- In Houston, Texas, the Katy-managed lanes on the I-10 corridor replaced the HOV lanes in 1998 and became fully operational in 1999. They are thirteen miles long and consist of two lanes in each direction separated by barriers from the GP lanes. As specified by the Harris County Toll Road Authority (HCTRA), there are five entrances and three exits westbound and three entrances and five exits eastbound. In addition, there is one entrance and one exit to a park and ride lot in each direction where buses can enter and exit the managed lanes (HCTRA, 2010).

Vehicles with two or more people and motorcycles can enter the lanes for free from 5:00 to 11:00 and 14:00 to 20:00. For other times, all vehicles must pay a toll to access the managed lanes. The tolls are determined by a toll schedule and vary by time of day, tolling zone, vehicle occupancy, and axle count. Commercial vehicles with 3+ axles and vehicles towing trailers are allowed to use the HOT lanes by paying \$7.00 for each zone, regardless of the time of day and the traffic conditions (HCTRA, 2010). In November 2000, tolling was also implemented on US 290 HOV lanes in Houston. The average number of trips on the HOT lanes increased and the main source of the travelers on toll lanes were those who used to travel in single-occupancy vehicles (SOVs) in regular lanes (FHWA, 2006a).

- In Minnesota in May 2005, the MnPass program converted the HOV lanes on I-394 in Minneapolis into HOT lanes. The MnPass HOT lanes consist of three miles of reversible lanes that are barrier-separated and eight miles of previously HOV lanes that are separated with double white lines. The tolls vary dynamically every three minutes to maintain the target speed of 50-55 mph on the HOT lanes. The tolls are usually between \$0.25 and \$4.00, but sometimes can be as high as \$8.00. The average price during the peak period is \$1.00 to \$4.00. The reversible lanes are always tolled, running east between 6:00 and 13:00 and west between 14:00 and 5:00. The tolls on the HOT lanes are in effect between 6:00 to 10:00 and 14:00 to 19:00, Monday through Friday. For the other hours, HOT lanes are open to all traffic (MnDOT, 2010). In order to maintain the target speed for all vehicles, the algorithm that adjusts the toll rates is based on the detected traffic density on the HOT lanes, the level of service HOT lanes operate at during a certain time, the section type (diamond or reversible), and the time of day. When a change in the density is detected by the roadway sensors, the toll is determined from a “look-up” table and adjusted (Halvorson et al., 2006). The toll rates are calculated at each entry point according to the maximum traffic density downstream of each entry point. The rate calculation interval is adjusted so that traffic conditions that change rapidly can be measured. High differences between the toll rates in a single calculation interval are avoided. HOT lanes have also been implemented on I-35W in Minnesota.
- In Denver, Colorado, the I-25/US-36 managed lane facility opened in June 2006. It is a two-lane, seven miles long facility. Solo drivers have to pay a toll to use these lanes, while carpools, buses, and motorcycles do not. Prices vary by the time of day based on a predetermined toll schedule. One month after its opening, the usage of this facility had increased by more than 46% (Colorado Department of Transportation, 2006).
- In Salt Lake City, Utah, the I-15 express lanes opened in September 2006 (by converting HOV to HOT). The facility is forty miles long. There are two entrances and one exit in each direction, and eighteen access points in between where drivers can enter, exit, or overtake a slow-moving vehicle. Those access points, separated by white-dotted striping from the GP lanes, are 3,000 to 9,000 feet long and located at each I-15 interchange (UDOT, 2010a). Vehicles with two or more passengers, buses, clean-fuel vehicles, and motorcycles are allowed to use the

HOT lanes for free. Vehicles with a gross weight of 12,000 pounds or more are not allowed to use the lanes or the adjacent passing lane to the express lanes. When this system first opened, the SOVs had to buy a monthly decal for \$50 for unlimited access to the HOT lanes. In August 2010, the express lanes were divided into four payment zones and dynamic pricing was implemented.

- The Washington State Department of Transportation (WSDOT) opened the SR-167 HOT lanes in May 2008. The HOT lanes are ten miles long and separated by double white lines from the GP lanes. There are six access points northbound and four access points southbound where drivers can either enter or exit (WSDOT, 2008). SR-167 HOT lanes are designed to make the most efficient use of HOV lane capacity while providing fast and reliable trips for buses and carpools. Vehicles with two or more people, vanpools, transit, and motorcycles are allowed to travel for free on SR-167 HOT lanes. Vehicles that weight more than 10,000 pounds and slow-moving vehicles are not allowed to enter the HOT lanes. On SR-167, the tolls are adjusted every five minutes based on real-time traffic conditions to ensure that the traffic in the HOT lanes always flows smoothly and the speed does not drop below 45 mph. The toll ranges from \$0.50 to \$9.00. If the traffic on the HOT lanes increases significantly, the signs at the entrances of the HOT lanes will display “HOV only,” restricting access of all SOVs.
- In 2008, the Florida Department of Transportation (FDOT) opened the 95 Express in the Miami area by converting about seven miles of the HOV lanes on I-95 into HOT lanes. The HOT lane system is planned to be approximately twenty two miles long, extending from the I-95 interchange at SR-112 north to the Broward Boulevard Park-and-Ride lot (FDOT, 2008) and constructed in two phases. The current 95 Express extends from SR-112/I-195 to the Golden Glades Interchange and has two HOT lanes in each direction separated from the local traffic lanes with pylons. The northbound express lanes opened to traffic on July 11, 2008, and tolling began on December 5, 2008. The southbound express lanes opened to traffic in late 2009 and tolling began on January 15, 2010. Phase 2, currently under construction, will expand the HOT lanes from the Golden Glades to Broward Boulevard in Broward County. The tolls on the first part of 95 Express depend on traffic conditions and range from \$0.25 to \$2.65 during the average traffic conditions. During peak hours, tolls can be up to \$7.25 in order to provide operating speeds between 45-50 mph in the HOT lanes.
- In Georgia, I-85 HOV lanes in the northeast Atlanta area were converted to HOT lanes in October 2011. They are about sixteen miles long and have one lane per direction. The toll changes dynamically about every fifteen minutes to ensure uncongested traffic conditions on the HOT lanes. Transit vehicles, carpools with three or more occupants, motorcycles, emergency vehicles, and alternative fuel vehicles can access the lanes for free. All vehicles willing to use the HOT lanes should register with SRTA. There are five entries and six exits on the northbound direction and four entries and four exits on the southbound direction.

- In northern Virginia by the end of 2012, the Capital Beltway HOT lanes on the 495 Express lanes will open on the I-495/Capital Beltway. They will consist of two lanes in each direction and they will be fourteen miles long. There will be several access points to the lanes. More precisely, there will be six entry and seven exit points on the northbound direction and eight entry and nine exit points on the southbound direction. Vehicles with three or more occupants will use the lanes for free. Dynamic pricing will be applied on the HOT lanes to control the demand and to keep free-flow conditions. The prices will mainly be based on the traffic conditions, but it is expected that the toll rate will be from about \$0.20 to \$1.25 per mile with an average total trip cost between \$5.00 and \$6.00 (VDOT, 2012).

More HOT lanes are planned for Texas, California, Oregon, and North Carolina.

### **2.3 Determination of Dynamic Pricing Strategies**

In this section, the models that have been developed over the years to determine dynamic pricing strategies are summarized. More specifically, bottleneck, network, and self-learning control models are presented.

#### **2.3.1 Bottleneck Models**

The bottleneck model was introduced by Vickrey (1969) and further developed by Arnott et al. (1993). It focuses on the time at which motorists want to depart. Motorists in this model travel along a single road with a bottleneck or bottlenecks downstream of certain flow capacity. The bottleneck model often does not take into consideration route choice.

Vickrey (1969) was the first to consider trip costs with respect to desired arrival times. Travelers arriving later or earlier than the desired arrival time experience not only the travel time costs but also schedule costs. The simple bottleneck model is dynamic, deriving the time pattern of congestion over the peak hour (Arnott et al, 1999; Arnott, 1998). It assumes that, every morning, a fixed number,  $N$ , of individuals living in the suburbs would like to travel from home, which is the origin,  $O$ , to work, which is the destination,  $D$ , at the same time,  $t$ . Each person travels in his own car along a single

road connecting the origin and destination, which has a bottleneck downstream. Traffic conditions are uncongested, except at the bottleneck that has a deterministic capacity of  $s$  cars per unit time. Due to the bottleneck's capacity, it is not possible for all the motorists to be at their destination at the same time. As a result, travelers arrive at work at different times, some early and others late. Early or late arrivals entail a cost of delay. Furthermore, travelers incur expenses, including a fixed component, which can be set equal to zero for computational simplification, and a variable component, which depends on the time spent waiting at the bottleneck. The bottleneck model addresses individuals' decisions with regard to the time of departure from their homes. The basic insight is that the total trip cost, including the travel cost, the delay cost, and the toll, must be constant over the departure interval under equilibrium. For analysis simplification, in the model, total trip cost is assumed to be linear in its components as in equation 2-1:

$$C_i = \alpha(\text{queuing time}) + \beta(\text{time early}) + \gamma(\text{time late}) + (\text{toll}) \quad (2-1)$$

where  $C_i$  is the trip's cost when an individual arrives at time  $t$ ,  $\alpha$  is the shadow value of queuing time,  $\beta$  is the shadow value of time early, and  $\gamma$  is the shadow value of time late.

According to empirical results,  $\alpha > \beta$  (Small, 1982). It is also assumed that all individuals have the same desired arrival time,  $t^*$  (Small, 1982). Let  $t_f$  denote the time at which the first traveler arrives to work,  $t_1$  the time at which the last traveler arrives at work, and  $T(t)$  the variable travel time. During the peak hour, the capacity throughput of the bottleneck must be used because, in any other case, a traveler could depart in the middle of the peak hour incurring zero queuing cost and less delay cost than either the

first or the last person to arrive for the equilibrium consistency. This implies that  $t_1 - t_f = N/s$ , which means the first individual to arrive does not face a queue and experiences only a delay cost equal to  $\beta (t^* - t_f)$  and the last individual to arrive, who also does not face a queue, experiences only a delay cost equal to  $\gamma(t_1 - t^*)$ . Under equilibrium, delay costs of the first and last person to arrive must be equal so the equilibrium price,  $\bar{p}$ , is equal to  $\frac{\beta\gamma}{(\beta+\gamma)}N/s$ . Therefore, the travel cost function without toll is  $(N) = \frac{\beta\gamma}{s(\beta+\gamma)}N$ .

If a dynamic toll that equals the queuing cost component in the equilibrium without toll is introduced, the queue will be eliminated without changing the rush-hour interval. In this case, every traveler has the same trip cost as before (equilibrium without toll) and as the trip costs have become equal, no one wants to change his behavior. By imposing this toll, the social optimum is decentralized, the delay cost is minimized, the queuing costs are eliminated, and the bottleneck is used at capacity during the peak hour. The amount of travel does not change, while the total social cost is reduced by reallocating the traffic over the peak hour.

The bottleneck model presented above is simple and limited to homogeneous commuters. Therefore, many extensions are needed in order to make it more realistic. Over the years, many studies, have considered elastic demand, heterogeneous individuals, stochastic capacity and demand, simple networks, and alternative congestion treatments, to improve the simple bottleneck model.

Arnott et al. (1993) also used the 'bottleneck' approach to determine the time-varying tolls on the traffic network used by Vickrey (1969). They assumed individuals who travel through the network and all want to be at work at the same time, but because

the bottleneck limits the network capacity, this is not possible and delay costs are unavoidable. In this model, the social optimum and the distribution of travel delays, the scheduling costs at the peak period, and the duration of the peak are determined endogenously. The optimal toll depends on time and has its maximum value when drivers arrive at the desired arrival time. The most important thing in this approach is that private costs of the road use, which include the toll, the travel time cost, and the delay cost, should be constant over the peak period.

Iryo and Kuwahara (2000) considered that travelers choose their departure times to minimize their travel cost, which included the queuing delay at a bottleneck and schedule delay at the destination. They developed a mathematical model to analyze the traveler's decision, assuming one bottleneck with constant capacity and FIFO service between a residential area and a working area that must be used by all the commuters. At first, they derived the model without considering the congestion toll and then they applied it to evaluate a dynamic price. Their goal was to create a tool that can evaluate policies that have been proposed to mitigate congestion such as Traffic Demand Management (TDM) policies. Specifically, they considered a policy that disperses travel demand over time because individual variations in time are very important when a road pricing scheme is analyzed. Their conclusions after the application of their method to road pricing were that dynamic congestion tolls that reduce the waiting time are not proportional to waiting time without the existence of the tolls. Moreover, commuters are likely to change their departure times and that can cause different travel costs for them. This case will not be true if all travelers have the same willingness-to-pay. Finally, they concluded that even though individuals can have different VOTs, there is a dynamic

congestion toll that can reduce queuing delay to zero. In this case, a toll changes travelers' behavior and their costs.

Although the single bottleneck model that Vickrey (1969) used gives good insight for travel times, the optimal toll, and its benefits, it has an important deficiency. It does not consider the spatial extent of queues, which is a significant aspect in the analysis of extended networks because it gives more realistic patterns to avoid congestion.

Yperman et al. (2005) followed the same procedure as Vickrey (1969), but replaced the simple bottleneck model by a traffic flow model in order to take into consideration the road space that is occupied by the queues. Specifically, they used the Lighthill, Whitham and Richards (LWR) traffic flow model, which considers the spatial extent of queues and, at the same time, is not a very complicated model. The LWR model assumes that traffic is behaving as in a kinematic wave model. Yperman et al. (2005) used a simple multi-destination network in their study and tried to determine the advantages of congestion pricing and understanding the mechanisms of congestion. They used the traffic demand from Vickrey's bottleneck model and determined user equilibrium and system optimum network conditions using the LWR traffic model. After the analysis, they concluded that congestion can be mitigated if an optimal toll is imposed and that the benefits of introducing this time-varying optimal toll are higher than those expected by conventional point-queuing bottleneck models. The toll must be equal to the delay costs that commuters would experience if there were no toll.

After imposing the toll, commuters, who travel through the bottleneck, have the same travel costs as would be the case without tolls but their total travel time is less than when there was no toll imposed. The commuters that do not want to use the

bottleneck, but experience queues that spill over from the bottleneck, have reduced trip costs. Thus, travel demand will increase without an increase in congestion. Therefore, optimal tolling can lead to reduced trip costs for the travelers, more efficient use of the transportation network, and extra revenue for the government.

Verhoef (1997) considered a dynamic model of road congestion for the determination of time-varying tolls. The model is based on the bottleneck approach but considers elastic demand for the morning peak road usage. Such elasticity of demand could come from the presence of different transport modes. In this case, the optimal time-varying toll should include a time-invariant component when drivers share the same desired arrival time. This means that the regulator should have information about the distribution of travelers' desired arrival times in order to set the optimal tolls, because the underlying reason of the time-invariant component is the assumption that desired travel times are equal among the users. This time-invariant component is relevant only in studies of road traffic congestion with elastic demand. In this approach, the optimal toll is greater than zero, even in the case where congestion, in terms of travel time delays, has been reduced.

Although bottleneck models that take into consideration real-world complications give good insight into the amount of tolls to introduce for mitigating congestion levels, they do not incorporate route choice and they always consider a bottleneck on the road. Therefore, bottleneck models cannot be applied to large networks. That problem led researchers to develop models called network models that can include more parameters with regard to individual choices and can be used to determine pricing strategies on networks.

### 2.3.2 Network Models

In recent literature, network models have also been examined to find policies to alleviate the problem of congestion that is present on most transportation facilities. Network models, in contrast to bottleneck models, encompass the mode, departure time, route choice, and longer-run choices. The traffic models must be as realistic as possible in order to derive logical and effective policies. There are many types of network models, some of them consider fixed departure times, others variable demand, others many alternative modes, others destination choice, route choice, or combinations of the factors aforementioned. Some of them are presented in the next paragraphs.

De Palma et al. (1997) focused on the efficiency of use of private toll roads, assuming a simple network with two parallel routes that can have different free-flow travel times and capacity, which connects one origin and one destination. In addition, they assumed that congestion takes the form of queuing and that every traveler has three options: whether or not to travel by car, and if by car, which route and what time to travel. For the analysis, they considered three cases: free access on one of the routes and a private road with tolls on the other, private roads on both routes, and a public road with tolls competing with a private road. In each case, they measured the efficiency gain by determining the social surplus relative to the efficiency gain if both routes had first-best optimal tolls. The conclusion of the study was that the efficiency gain is much higher if tolls are imposed dynamically rather than using a fixed toll in each assumed case.

Time-dependent tolls on a general network are determined by Joksimovic et al. (2005a) using a dynamic traffic model to describe the network performance. They determined the time-varying road prices that minimize the total travel time in the

network, taking into account the time changes of the route and departure as a response to the prices with the formulation of a network design problem. For the analysis, they considered dynamic traffic flows and dynamic road pricing strategies. They formatted the problem using mathematical programming with equilibrium constraints and analyzed a small and simple network. In their research, they demonstrated that dynamic pricing can lead to savings in the total travel time in the network. Finally, they concluded that it was very difficult to find any simple solution to the dynamic toll design problem in real-size dynamic traffic networks because the objective function is non-linear and non-convex. Therefore, it is difficult to find a global optimal solution and optimal toll values. They suggested that in order to find a global solution to large networks, a global search algorithm should be developed. That was the reason they considered a small hypothetical network to analyze uniform and variable pricing.

Joksimovic et al (2005b) considered elastic demand and applied second-best tolling scenarios only to a subset of links on the network. They used the same methodology as Joksimovic et al (2005a) in order to determine the optimal toll.

Friesz et al. (2006) introduced a dynamic optimal toll problem with user equilibrium constraints (DOTPEC). They further presented and tested two algorithms for solving the optimal control representations of the DOTPEC. First, they studied a dynamic efficient toll problem by employing a form of dynamic user equilibrium model to compare the efficient tolls with DOTPEC, which is not equivalent to dynamic generalization of the static efficient toll problem. Then, they formulated DOTPEC in two different ways and solved it using both a descent in Hilbert space without time discretization and a finite dimensional approximation solved as a nonlinear program algorithm. In their approach,

the mathematical representation is detailed enough to capture the behavioral and technological considerations about dynamic tolling and it is considered as a computable theory.

### **2.3.3 Self-learning Control Approaches for Dynamic Tolling**

The models developed in previous studies always assume that the travel demand is known. These models are often not applicable for managing a HOT lane facility.

Yin and Lou (2009) proposed two practical approaches for the determination of pricing strategies for operating managed lanes. They considered dynamic tolls that change according to traffic conditions in order to maximize the throughput of a freeway and keep superior free-flow conditions for travelers. The first approach is a feedback-control approach where one loop detector station located downstream is required to detect the traffic condition along a facility segment. The second approach is a reactive self-learning approach that calibrates the willingness-to-pay using revealed preference information and then determines the optimal toll rate using the approaching flow rates, the estimated travel time, and the calibrated willingness to pay. For the implementation of this approach, two loop detectors are required, one before the toll entrance to detect approaching flows and one after the entrance to detect the flows on both the managed and the regular lanes. For the two approaches' validation, simulation experiments were conducted. The conclusions of this research were that, although both approaches are simple and easy to implement, they may lead to drastically varying toll patterns that can cause unstable traffic conditions. Moreover, the toll price is determined for each entry point without considering other entries, which may create inequality among motorists that enter the managed lane from different points.

Lou et al. (2011) further expanded the approach proposed by representing traffic dynamics more realistically and with an explicit formulation to optimize tolls. The impacts of the lane-changing before the entrance to the toll lanes on the freeway and the travel times are considered using the multi-lane hybrid traffic flow model that was proposed by Laval and Daganzo (2006). The optimal tolls were determined for specific time intervals solving a nonlinear optimization model in order to maximize the freeway's throughput and to ensure that the density of HOT lanes will not exceed the desired HOT lane operation density. They also further examined the conversion of HOV lanes to HOT lanes and presented some extensions to the approach that they proposed considering more realistic cell representations for differences in HOT lane slip ramp configurations. For the validation and demonstration of the approach, simulation experiments were conducted using data from loop detectors.

The self-learning framework proposed by Yin and Lou (2009) and Lou et al. (2011) is reactive in nature and may perform unsatisfactorily if there are substantial fluctuations in traffic demand. For this reason, Michalaka et al. (2012) enhanced that framework by developing a robust scenario-based toll optimization model that determines a proactive dynamic pricing strategy to accommodate traffic demand uncertainty and effectively manage HOT lanes under various conditions. The tolls were optimized to ensure free-flow conditions on HOT lanes while maximizing a freeway's throughput. Simulation experiments were conducted to validate the proposed approach. Then, the robust scenario-based approach was compared with the one currently implemented on the 95 Express. It was observed that the new, more robust model operates effectively on the HOT lane facility and produces a smoother toll pattern and better system performance

than the current 95 Express approach. Moreover, the robust approach responded more adaptively when there was a sudden demand surge.

Zhang et al. (2008) also developed a feedback-based dynamic tolling algorithm for HOT lane operations. They used a second-order control scheme to relax the complexity of the calculations. First, the optimal flow ratio for the HOT lanes was calculated using feedback control logic with an increment piecewise optimal function of traffic speed measured from the GP and HOT lanes. Then, the toll was estimated using a discrete route choice logit model. By decomposing the calculations, the tolling algorithm becomes more practical and effective. An external HOT lane module in Microsoft Visual Basic and VISSIM were used to examine the performance of the proposed algorithm. Five HOT lane sections on the southbound SR-167 corridor in Washington State were simulated and the results showed that the proposed method performs well under various traffic demand scenarios.

Currently, the approaches that are used to determine dynamic tolls depend on the availability of data, modeling software, model structure, and the objective of the study.

## **2.4 Lane-choice Models**

In the areas where HOT lanes exist, motorists have the choice of traveling on either the HOT or the GP lanes. Choosing the HOT lanes means that they have to carpool or pay a toll, but at the same time they will save some travel time and their trip will be more reliable. Sometimes the choice between HOT and GP lanes is referred to as a route choice because HOT lanes are basically an alternative parallel route to the GP lanes with different cost and travel time. Knowing how many vehicles will choose to travel on the HOT lanes in the presence of a specific toll and the factors that affect

drivers' choice is very important for effective HOT lane operation. Following are some studies that model travelers' lane choices between HOT and GP lanes.

Sullivan (2000) conducted an extensive study to evaluate the impacts of the implementation of HOT lanes on SR-91 in California. This study analyzed many aspects of travel behavior on the corridor, including traffic trends, driving conditions, transit, corridor travel behavior, assessing public opinion, modeling of travel choice and elasticities, collision trends and characteristics, and others. Here, the three models related to travel choice are presented. The first travel choice model included the route choice only, assuming other factors such as transponder choice, exogenous. The second one included route choice, mode choice, and transponder choice. The third one included route choice, transponder choice, and time of day. Many variables about travelers and trip characteristics were included in each model. The route choice model was a conditional multinomial logit model that showed that women, people 30 to 50 years old, and professionals are more likely to use the express lanes. The route choice, mode choice, and transponder model was a nested logit model with mode choice in the upper nest and joint transponder and route choice at the lower nest. That model indicated that getting a transponder in order to use the express lane was a barrier for males, people with lower education, and people younger than 30 and older than 50 years of age. The results were consistent with the route choice model. The route choice, transponder choice, and time of day model was also a nested logit model with time of day in the upper nest and joint transponder and route choice again in the lower nest. The results of this model were comparable with the results of the other models. An additional result was that travelers do not very commonly shift to traveling during

different times of day. The travel choice models described above are also published by Yan et al. (2002).

Lam and Small (2001) also modeled the route choice on SR-91 in Orange County, California, collecting data from surveys and traffic loop detectors. They developed a route choice only model and a route choice, mode choice, and transponder choice as Sullivan (2000) as well as models for route and time of day, route choice and mode choice, and route choice and transponder choice. Each model included many socio-economic and trip characteristics variables. More specifically, it was assumed that a traveler,  $n$ , chooses route,  $i$ , by maximizing the conditional utility function 2-2:

$$U_{in} = V_i(t_{in}, v_{in}, c_{in}, x_n) + \varepsilon_{in} \quad (2-2)$$

where  $t$ ,  $v$ , and  $c$  are the measures of travel time, variability in travel time, and cost, respectively, for each route,  $i$ , and traveler,  $n$ .  $x$  is a vector of observable socio-economic characteristics such as age, gender, annual household income, language spoken at home, wage rate, education, and other characteristics like flexibility of work arrival times and car occupancy; and  $\varepsilon_{in}$  is a random utility component.

The models with the route choice only were binomial logit models and suggested that people, who live in a high-income household, speak English at home, do not have route options other than SR-91, and females are more likely to use the HOT lanes. For the route and the time of day to work choice combination, multinomial, and logit models were run. The models showed that males and older workers are more likely to arrive early at work. For the models of route and mode choice, carpooling was assumed to be an endogenous factor and travelers could choose between three modes: driving alone, carpooling with one other person (HOV2), and carpooling with more than one other

person (HOV3+). In these cases, three models were run; one with mode choice alone and two with mode and route choice, a logit and a nested logit. The models indicated that long-distance trips, foreign-language speaking, and a large workplace favor HOV3, while low car ownership and low education levels favor HOV2. For the case of route and transponder choice, a transponder choice model, a transponder and route choice logit model, and a transponder and route choice nested logit model were estimated. The results showed that income, gender, and language influence the transponder choice more than the route choice. At the last logit model, transponder, route, carpool choice, gender, the distance of the trip, the number of workers in the household and the number of cars shared by the household seemed to affect people's choices.

Li (2001) also used survey data from SR-91 trying to explain the factors that influence motorists to use the HOT lanes. For this purpose, Li examined five nested multivariate logistic regression models. The first model tested the effects of travelers' travel characteristics, like trip purpose, trip length, vehicle occupancy, and travel frequency on SR-91 on HOT lane usage. The second model included travelers' financial capability, that is, level of household income in addition to the variables in the first model. Demographic characteristics such as gender, number of children in the household (indicating the household type), household size, and age were added to the variables of the first and second model. The fourth and fifth models included various variables representing different trip purposes. The only difference between the last two models was that the fourth model uses home-to-work trips as the reference category as opposed to the fifth model that uses work-to-home as the reference category. The results showed that as the age of the travelers increases so does the probability of them

choosing the HOT lanes. Income significantly influenced lane decision, with people with higher income being more inclined to use the HOT lanes. Interesting findings were that trip length, gender, household size, and household type did not seem to affect the lane decision and the fact that motorists were more likely to use the HOT lanes in the work-to-home trip than the home-to-work or an unrelated trip.

Small et al. (2005a) also modeled travelers' lane choice on SR-91 using both state and revealed preference data from three different surveys conducted in the area. The data included motorists' actual decisions for their morning commute and hypothetical choices motorists could make between express and GP lanes under different travel conditions. Small et al. simultaneously examined three choices motorists had to make. The first one was whether or not someone will install a transponder to have access to the express lanes, the second was to whether they will use the express lanes or the GP lanes and the third was whether they will travel with one, two, three, or more people in the vehicle. For the analysis, discrete choice modeling was applied and traveler's indirect utility,  $U$ , assumed to be random and equal to:

$$U_{jn} = X_{jn}(W_n\gamma + \mu_n) + \varepsilon_{jn} \quad (2-3)$$

where  $j$  indicates the alternative,  $n$  the traveler, and  $X_{jn}$  the attributes associated with alternative  $j$  including the toll, travel time, and trip reliability.  $(W_n\gamma + \mu_n)$  is a vector of parameters of traveler's  $n$  preferences,  $W_n$  is a vector of explanatory variables of traveler  $n$  including age, sex, household size, per capita income, and trip distance,  $\gamma$  is a vector of the parameters to be estimated statistically,  $\mu_n$  is a vector of random variables of traveler  $n$ , and  $\varepsilon_{jn}$  is the error term. Small et al. (2005a) examined more explanatory

travelers' variables like occupation, education, workplace size, and arrival-time flexibility, but they proved not to have much explanatory power.

The multinomial logit model results showed that toll, travel time, and reliability affect travelers' lane choice. Also, middle-aged women and all commuters were more likely to get a transponder and middle-aged women with large families were more likely to carpool which make sense as many family members may travel together. Another finding was that women, middle-aged motorists, and motorists in small households were more inclined to choose the express lanes.

Brownstone et al. (2003) studied travelers' choices of driving alone on the GP lanes, driving alone in the express lanes, and carpooling using revealed preference panel survey data at the I-15 in San Diego around the Express lanes area. Their model was a conditional logit model with all the choices available to all travelers. The results showed that households with income greater than \$100,000, women, persons 35 to 44 years old, persons with a graduate degree, and homeowners were more likely to choose the express lanes. Also, it seemed that the express lanes were chosen both for commuting and long-distance trips. As the number of workers in the vehicle increased for long trips, for non-commuting trips, and when there was a carpool bypass on ramp available, carpooling was preferred.

Burris and Xu (2006) conducted a study on the potential SOV demand for traveling on HOT lanes using state and revealed preference data from the travelers on the GP lanes at the Katy Freeway and Northwest Freeway corridors in Texas. Discrete choice modeling was implemented to analyze the data and, more specifically, a nested multinomial logit model was developed to predict travelers' mode choices. Nine potential

mode choices were assumed. Each of them was a combination of mode (SOV, HOV2, HOV3, transit), lane (GP, HOV), and on-off peak period choices. For example, one mode was SOV on the HOV lane in the off-peak period. Some of the variables used in the model were travel time savings, toll divided by the income, household size, vehicle ownership, traveler's occupation, age, gender, trip time, and education level. The results indicated that people with high income are more likely to use the HOT lanes and that motorists traveling on the Katy Freeway were willing to pay more than the ones traveling on the Northwest Freeway. This fact may be based on the differences in travelers' income levels.

As it can be seen from the above studies, there are many models that can be used to model travelers' lane/route choices. In addition, the factors that affect each choice are equally numerous, although not all of them are included in every model. However, travel time and cost are always considered in the lane choice models. These two factors indicate how much motorists value their time and how much they are willing to pay to switch lanes. A literature review on how much drivers value their travel time is presented in the following section.

## **2.5 Value of Time**

Value of time (VOT), often used in transportation studies and economics, is the cost travelers are willing to pay to save time or the amount of money they would accept for lost time; it is usually expressed in dollars per hour. Travelers' travel choices are highly affected by their VOT. There are several studies that estimate travelers' VOT and examine the factors that influence it. It should be mentioned that VOT can be different among roadway users and vehicle groups; SOVs, HOVs and commercial vehicles. The following literature mostly focuses on studies examining passenger cars' VOT.

Small (1992) used discrete choice modeling to specify a utility function that enables VOT calculation to include such socioeconomic characteristics as income. Then, he applied a technique to find the conditional indirect utility function and estimate travelers' VOT as the marginal rate of substitution between cost and time without having to solve the entire choice model. In the model, he assumed that the average VOT for work travel is 50% of the gross wage rate, but he mentioned that it can vary from 20 to 100% depending on the city and population group. It was concluded that the VOT is affected by the trip purpose, income or wage rate, and where the time is spent (in a vehicle or walking or waiting). The average estimated VOT was equal to \$4.80 per hour.

Brownstone et al. (2003) estimated travelers' VOT using revealed preference data from a congestion pricing project on I-15 in San Diego, California. The data used were obtained from a panel survey and loop detectors and included such trip characteristics as travel time, toll, mode choice and trip type, demographic characteristics by mode choice such as age, gender, education level, reason for travel, household income, home and vehicle ownership, and number of workers in the household. Assuming that each traveler had three mode alternatives: solo driving on GP lanes, solo driving on express lanes, and carpooling, they estimated a conditional logit model and computed the VOT using equation (2-4):

$$\frac{\beta_{time\ saving}}{\beta_{toll} + (\beta_{toll} \times reduction\ in\ variability)(reduction\ in\ variability\ for\ respondent)} \times (60\ min\ per\ hour) \quad (2-4)$$

where  $\beta_{time\ saving}$  is the coefficient of the travel time savings,  $\beta_{toll}$  is the coefficient of the toll value on the express lanes, and  $reduction\ in\ variability$  is the reduction in variability of time savings from express lane use measured as the difference between

the 90<sup>th</sup> percentile and median time savings. They found that the median VOT is \$30 per hour with the upper quartile of the distribution equal to \$43 per hour and the lower equal to \$23 per hour. In their study, VOT is not reported as a percentage of an hourly wage because individual income data were not available.

Lam and Small (2001) studied VOT using actual travel behavior data from SR-91 in Orange County, California. The data including both socio-economic and travel characteristics such as age, gender, income, education, flexibility of work arrival time, route, mode and transponder choice, travel time, and toll per person were collected from mail surveys and traffic loop detectors. Using the available data, they examined five choice combinations and for each combination they estimated three to four different models. The VOT was computed using formula (2-5):

$$VOT_n = \left(\frac{\partial V}{\partial t_n}\right) / \left(\frac{\partial V}{\partial c_n}\right) \quad (2-5)$$

where  $n$  indicates the traveler,  $V$  the utility,  $t_n$  the traveler's travel time, and  $c_n$  traveler's cost.

The computed VOT for the best fitting model in each of the five choice categories is presented in Table 2-1.

Table 2-1. VOT values for the different choice types

Type of choice	VOT (\$/hr)
Route	19.22
Route and time of day	4.74
Route and mode	24.52
Route and transponder	18.40
Route and transponder and mode	22.87

The route and time of day models gave much lower VOTs than the other models, which, as they claimed, could be a result of either upward-biased VOT estimations from the other models or inaccurate assumptions for a trip outside the study range. The other

models gave VOTs from \$18.40 to \$24.52 per hour. The best fitting model was the one that gave a VOT equal to \$22.87.

Small et al. (2005a) also used data from SR-91. The data, however, included not only actual travel behavior data, but also stated preference data. As mentioned in the previous section, a multinomial logit model was developed to try to examine the factors that affect travelers' choices between the express lanes and the GP lanes; obtaining a transponder or not; and how many people would travel in the vehicle. For this model, the VOT was computed for all road users and for the express lane users and free lanes users separately by dividing the coefficient of travel time by the coefficient of the cost for each group. The median VOT estimates, as well as the 5<sup>th</sup> and 95<sup>th</sup> percentiles for a 90% confidence level, are presented in Table 2-2. The median VOT value was \$19.63 per hour, which was about 85% of the wage rate. The average wage rate, estimated to be equal to \$23, was obtained by matching the data from the U.S Bureau of Labor Statistics for 2000 with the survey data using responder's occupation. Small et al. (2005b) in another study using the revealed preference data from Small et al. (2005a) found that the median VOT is \$21.46 per hour or about 93% of the wage rate.

Table 2-2. VOT estimates for user groups

	VOT (\$/h)		
	Median	90% confidence interval	
		5 <sup>th</sup> percentile	95 <sup>th</sup> percentile
All users	19.63	8.75	34.61
Express lane users	25.51	11.50	39.99
GP lane users	18.63	7.76	29.08

Outwater and Kitchen (2008) used Global Positional System (GPS) data collected from the Puget Sound Regional Council (PSRC) for 275 households to derive the revealed VOT for different auto market segments. The auto market segments under

analysis included single occupancy vehicles, carpools, vanpools, and trucks. During the survey, participants were given a financial incentive to avoid routes with high tolls, so their choices between paths with short travel times, but high tolls, and paths with longer travel times, but lower cost could be observed. The paths with short travel times and high tolls were defined as control paths while the others as actual or experimental paths. The VOT for each market segment was calculated as:

$$VOT = \frac{60}{100} \left( \frac{-\Delta P}{\Delta T} \right) \quad (2-6)$$

where  $\Delta P$  is the difference between the experimental and the actual toll in cents, and  $\Delta T$  is the difference between the experimental and the control travel time in minutes. Table 2-3 summarizes all the VOT results.

Table 2-3. VOT by market segment (Outwater and Kitchen, 2008)

Vehicle type	Income	VOT (\$/h)				
SOVs	Low Income	9.52				
Home-based work SOVs	Low-medium income	17.65				
	Medium-high income	26.09				
	High income	33.33				
Non-work SOVs	All income groups	15.68				
Carpool and Vanpool		AM Peak	Midday	PM Peak	Evening	Night
HOV2	All income groups	30.33	19.34	23.00	20.56	26.66
HOV3+	All income groups	38.34	21.35	27.01	21.35	34.57
Vanpools	All income groups	102.49	37.38	59.08	37.38	88.02
Trucks						
Light trucks		40.00				
Medium trucks		45.00				
Heavy trucks		50.00				

From Table 2-3 it can be seen that VOT varies significantly across the different auto market segments, income groups, and time of day.

In this paragraph, two VOT studies conducted in Sweden are presented. First, Algiers (1995) examined the national Swedish VOT, taking into consideration that the VOT may vary with the user, mode, and trip characteristics. He calculated the VOT for different modes (cars, air, long distance using regional train, and long distance using regional bus), trip type (business or private), household type (singles, two employed with children, and two employed without children), where the time is spent (in vehicle, transfer or frequency for the bus and train modes, and delay for long distance train only), and the trip distance (under and over 50 km). He analyzed state preference data collected as part of the 1994 Swedish VOTs study by phone survey using multinomial logit models. The VOT values in the original paper are given in Swedish kronas (SEK), so they are not presented here. Nonetheless, the VOT varied from approximately \$3.80 per hour for a non-commuting trip less than 50 km long to \$28.80 per hour for high income households with two employed people and children when traveling for 50 km or more. Second, Algiers et al. (1998) developed eight logit models to compute the VOT for long distance car trips using the same data as Algiers (1995). Their focus was to examine how VOT varies if instead of a traditional multinomial logit model, a mixed logit model is used. The difference between these two models was that in the mixed logit model, the user-specific parameters can vary across the population. Three main explanatory variables were used: cost, in-vehicle time, and an alternative-specific constant for the base alternative. By allowing possible combinations of normal and fixed parameters for the explanatory variables, eight different logit models were developed. From the results, they observed that VOT is highly dependent on how the models are specified and, more specifically, the values are lower when the model coefficients are

assumed to be normally distributed rather than fixed. In their best model, the median VOT was about \$7.96 per hour. However, when the parameters were fixed, the VOT was about \$12.40 per hour. The findings of Algiers et al. (1998) differ from Brownstone and Train (1999) and Train (1998), both of whom found that the estimates in a mixed logit specification were close to those in a traditional logit specification. Brownstone and Train (1999) stated that the insignificant differences in their results might be because the standard logit model they used captured the coefficients well.

Sullivan (2000) also conducted a VOT study as part of his project "Continuation Study to Evaluate the Impacts of the SR-91 Value-priced Express Lanes." SR-91 Express lanes, which opened in 1995 in San Diego, were the first HOT lanes to open in the U.S. Since the lanes opened, extensive amounts of data, including field observations, surveys, and other sources, were being collected to examine changes in the traffic patterns, drivers' behaviors, and public reactions. Five years later, the collected data were analyzed. The VOT was calculated in two ways. First, the travel time savings on SR-91 and the amount of toll travelers paid were considered. It was found that in 1997 the VOT per vehicle was at least \$13.75 per hour during the peak hour, but by 1999 only about \$6.00 at the same peak hour. These values assume that the data derived from loop detectors and the travel time savings estimated by the travelers were accurate. Next, the VOT was calculated from several multinomial and nested logit lane choice models as the ratio of the cost and time coefficients. The first group of multinomial models considered many choice specific variables and traveler and trip characteristics, including age, gender, number of children in the household, occupation type (professional, managerial, or otherwise), education, distance, time of

trip, flexibility in the working schedule, and others, but not income. These models gave VOTs from \$15.98 to \$17.16 per hour. Then, the income was added to the previously defined models to examine the effects on the route choice and VOT. The average VOT, from \$14.95 to \$17.89 per hour, included the VOT for the high-income people, which was from \$22.32 to \$29.22 per hour, and the VOT for low-income people, which was from \$10.20 to \$11.49 per hour. Further, nested logit models were estimated to simultaneously model the mode, transponder, and route choice. From these models, the VOT fell between \$14.74 and \$15.18 per hour. Also, the time of day, transponder, and route were modeled and the subsequent VOT was between \$13.31 and \$15.77 per hour. In the majority of the model estimates, VOT varied between \$13.00 and \$16.00 per hour.

In all the studies mentioned above discrete choice models were used to estimate travelers' VOT. On the other hand, Ozbay and Yanmaz-Tuzel (2008) took an analytical approach. They used data from the New Jersey Turnpike, where time-of-day pricing is implemented, to investigate commuters' routes and/or mode and departure-time choices under time of day pricing. In their model formulation, the objective function is to maximize motorists' utility, which includes the travel time, the time spent on other activities, travel cost, cost of other activities, income, available time, departure time, and early or late arrival time. Individuals' VOT was then calculated as the ratio of the partial derivative of the objective function with respect to travel time and the partial derivative of the objective function with respect to travel cost. Twelve models were estimated; six for the travelers using electronic device (in this case E-Zpass users) and six for the ones paying by cash. For each of these traveler groups, the models developed were based

on three departure time periods (pre-peak, peak, post-peak) and two trip purposes (work and leisure). The VOT was computed only for the E-Zpass holders because the toll-related parameters proved to be statistically insignificant for the cash users. For each individual, VOT was affected by the trip purpose, departure time choice, travel time, toll, income, departure time, and desired arrival time. Its average varied from \$15.33 to \$19.72 per hour across the different models. It is worth noting that the highest average VOT was for travelers who departed at the peak period and made work trips, while the lowest VOT was for travelers who departed after the peak period and were going for leisure.

In 1997, the U.S. Department of Transportation (USDOT) developed and published its first manual for the valuation of travel time in economic analysis to be used by analysts in studies related to travel time and cost. In the manual, it is mentioned that each VOT estimation depends on a large number of factors. Some of the factors can be measured and others not. Thus, in a study not every “measurable” parameter can be controlled. Some of the parameters included trip purpose, which was divided into business, personal, or leisure, and personal characteristics like age, sex, education, employment, hourly income, and mode characteristics like comfort, privacy, travel time, and travel cost. The manual recommended different VOTs for different trip purposes, transportation modes, trip lengths, and vehicle operators (e.g., car/SUV drivers, truck drivers, bus drivers, transit rail operators, locomotive engineers, and airline pilots and engineers). These VOTs were updated in 2003 and in 2011. In summary, Table 2-4 provides the recommended VOTs and their plausible ranges as presented in the latest version of the manual.

Table 2-4. USDOT 2011 recommended VOTs

Recommended Hourly VOT Savings (2009 U.S. \$ per person-hour)						
Category	Surface modes (except high-speed rail)			Air and high-speed rail travel		
	Low	Recommended	High	Low	Recommended	High
Local travel						
Personal	8.40	12.00	14.30			
Business	18.30	22.90	27.50			
All purposes	8.90	12.50	14.90			
Intercity travel						
Personal	14.30	16.70	21.50	27.40	31.90	41.00
Business	18.30	22.90	27.50	45.80	57.20	68.60
All purposes	15.20	18.00	22.80	34.80	42.10	52.20
Truck drivers	19.80	24.70	29.60			
Bus drivers	19.60	24.50	29.40			
Transit rail operators	32.30	40.40	48.50			
Locomotive engineers	27.40	34.40	41.20			
Airline pilots and engineers	60.90	76.10	91.30			

From the literature review on VOT, we can see that there is high variability in the VOT estimations. Depending on travelers' characteristics, trip characteristics, and even the modeling procedure, VOT can vary from a few dollars to more than \$70 per hour.

## 2.6 Traffic Simulation Software

Traffic simulation is very useful in designing and/or evaluating pricing schemes and other managed lane operational strategies (e.g., Zhang et al., 2009). The following paragraphs review the current practice of simulating HOT lane operations using traffic simulation software.

Traffic simulation software is a tool used by transportation engineers and planners to replicate real-world transportation situations and test different design and operation

strategies. There are three types of traffic simulation models based on the scale used to describe traffic conditions: microscopic, mesoscopic and macroscopic. Any of these can be used for the simulation of traffic conditions. In the transportation field, there are many simulation programs developed to accommodate the needs of the transportation industry. However, only a few of these programs are capable of simulating certain aspects of the HOT lane operations. Table 2-5 shows the most widely used traffic simulation software, the company/ university where they were developed, the scale used to describe the traffic conditions, and their ability to simulate HOT lane operations.

Table 2-5. Most widely used traffic simulation software

Software name	Developer	Scale	Ability to simulate HOT lanes
AIMSUN 6.1.3	Transport Simulation Systems (TSS)	Microscopic/ Mesoscopic/ Hybrid	Yes
TSIS 6.2 (CORSIM)	McTrans	Microscopic	No
DynaMIT	MIT	Microscopic	Under development
DYNASMART-P	UMD		Limited
DynusT	DynusT Team	Microscopic	Yes
MITSIMLab	MIT	Microscopic	Under development
Paramics	The Edinburgh Parallel Computing Centre and Quadstone Ltd	Microscopic	Limited
Synchro/ SimTraffic	Trafficware	Microscopic	No
TransModeler	Caliper Corporation	Microscopic/ Mesoscopic/ Macroscopic	Yes
VISSIM 5.4	PTV System Software and Consulting GMBH	Microscopic	Yes
WATSIM	KLD Associates	Microscopic	No

## 2.7 Software to Simulate HOT Lanes

This section describes the software programs that are able to simulate HOT lane operations to some extent, the procedures used to accomplish that and also the software that the simulation of HOT lanes is under development.

### **2.7.1 AIMSUN**

AIMSUN is a traffic simulation program developed and distributed by Transport Simulation Systems (TSS). It contains mesoscopic, microscopic and hybrid components that allow for traffic simulation on any scale and degree of complexity. According to TSS (2012), AIMSUN can be used for feasibility studies of HOT lanes. Unfortunately, a document that describes the components pertinent to HOT lane simulation could not be obtained.

### **2.7.2 DynaMIT and MITSIMLab**

DynaMIT is a real-time traffic microscopic simulation program developed by the Massachusetts Institute of Technology (MIT) Intelligent Transportation Systems (ITS) Program. It is based on dynamic traffic assignment and has two versions: DynaMIT-R, which refers to the “real-time” version, and DynaMIT-P, which refers to the “planning” version. It includes models of travel demand, travel behavior, network supply, and their interactions (Ben-Akiva et al., 2012).

MITSIMLab is a simulation program, also developed by the MIT ITS Program to evaluate the impacts of alternative traffic management system designs at the operational level and to assist in designing a system (MITSIMLab, 2010). It consists of three modules: the Microscopic Traffic Simulator (MITSIM) that has the ability to represent the road network and its components in a microscopic scale, the Traffic Management Simulator (TMS) that mimics the traffic control and route guidance systems and Graphical User Interface (GUI) for demonstrating the simulated models through animation.

In a presentation by Rathi and Koutsopoulos (2007), it was described how to simulate dynamic pricing using MITSIM and DynaMIT. Pricing is one component of a

closed loop framework. This framework uses network state information from DynaMIT and provides information as an input to the MITSIM traffic simulator. After MITSIM runs, the output surveillance sensor data are then used by DynaMIT to simulate the network state. This closed loop framework is illustrated in Figure 2-2. In the same presentation, Rathi and Koutsopoulos talked about the models and functionalities that should be implemented into DynaMIT and MITSIMLab in order to be able to simulate the operations of the HOT lanes. More precisely, they mentioned that models regarding the definition of classes of HOVs, the ability to specify HOV lanes in the network, the access type to HOT lanes (restricted or not), the pricing strategy, the mode choice, both the pre-trip and en-route route choice when HOT lanes exist, the users' response to pricing, the driving behavior (concerning merging and lane selection), and the availability of information to travelers should be incorporated into DynaMIT and MITSIM. Based on the information obtained from the MIT ITS Program website (MIT, 2011), all these modeling elements are not yet fully implemented within DynaMIT and MITSIMLab.

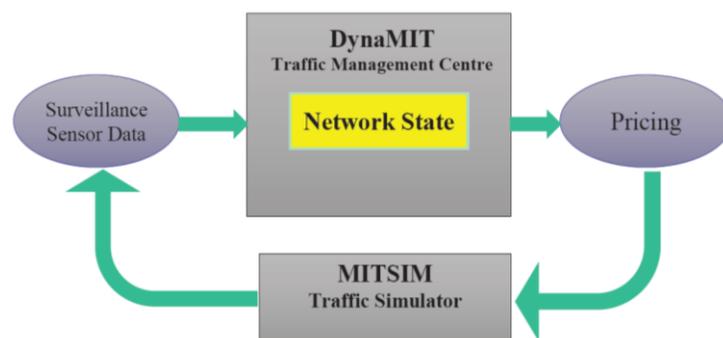


Figure 2-2. Dynamic Pricing Simulation using MITSIM and DynaMIT (Source: [http://www.trb-freewayops.org/sim\\_model/AnnualMeeting2007/HOT\\_Lanes\\_MITSIMLab.pdf](http://www.trb-freewayops.org/sim_model/AnnualMeeting2007/HOT_Lanes_MITSIMLab.pdf))

### **2.7.3 TransModeler**

TransModeler is a traffic simulator developed by Caliper Corporations to simulate transportation networks in microscopic, mesoscopic and macroscopic scale (Caliper Corporation, 2011). It provides the functionalities to simulate many types of facilities, networks and applications, including HOT lanes. TransModeler can simulate pricing schemes that vary tolls based on vehicle occupancy, prevailing demand, and time of day. In addition, TransModeler includes models that evaluate drivers' value of time (VOT), cost sensitivity in route choice decision making, economic and operational impacts of various toll lane pricing strategies, HOT lane revenue, and HOT lane utilization under different scenarios (Caliper Corporation, 2011). TransModeler has been used to simulate the HOT lane operations on the Capital Beltway (I-495) in Virginia.

### **2.7.4 DYNASMART-P**

DYNASMART-P is the planning version of a dynamic network assignment simulation model that was previously developed by researchers at the University of Maryland (UMD). It is supported by the FHWA and distributed through *McTrans*. It supports the evaluation of ITS options, network planning and traffic operations decisions, and production of policy-relevant traffic assignment results for planning analyses (*McTrans*, 2011). DYNASMART-P can be used to simulate networks with HOV lanes, HOT lanes, ramp metering, potential accidents, and other operation strategies. Basically, it is able to evaluate HOT lane operations, but it does not have any built-in feature to simulate the behavior of the travelers in the presence of HOT lanes.

### **2.7.5 DynusT**

DynusT is a dynamic network assignment simulation model (DynusT, 2012). It can be used to simulate networks with HOV lanes, HOT lanes, ramp metering, potential

accidents, and other operational strategies. Regarding HOT lane simulation, users have the choice of two different toll types: a distance based toll, and a link-based toll. These tolls can be updated dynamically based on congestion levels by an iterative algorithm, whose objective is to maintain the HOT target speed. The drivers' lane choice between GP and HOT lanes depends on congestion levels and their value of time, which is specified by the model user. This feature is useful for planning purposes but cannot be applied to simulate real-time operations, because of its iterative nature.

### **2.7.6 Paramics**

The commercial version of Paramics was developed by Quadstone, and is now maintained by Pitney Bowes Software. Paramics is capable of simulating HOT lanes with complex dynamic demand requirements or simple time-based schedules (Pitney Bowes Software, 2012). The HOT scenarios are combined with Paramics' built-in route choice modeling to simulate drivers' lane choice between the free and tolled facilities based on cost/benefit assessment.

### **2.7.7 VISSIM**

VISSIM is a microscopic traffic simulation tool part of the Vision Traffic Suite developed by the PTV Group. In the VISSIM product brochure, one of the features mentioned is the simulation of HOT lanes (PTV Vision – VISSIM, 2012). Based on a presentation during the Transportation Research Board (TRB) 86<sup>th</sup> Annual Meeting (Dale, 2007), there were three VISSIM HOT lane modeling options. The first is to define static routes between HOT and GP lanes prior to simulation; that is, the user predefines the demand percentage that will enter the HOT lanes at a specific time interval. The second option is to allow dynamic choice based on the downstream section toll price. The third option allows dynamic choice based on the downstream path cost. In the

second option, the user specifies where the traffic downstream of a HOT entrance would be monitored, the toll price model, and the choice model. However in the third option, where entire routes could be taken into account, HOT lane demand is based on the path costs by assigning OD matrices. When using a dynamic option (option two or three), toll price depends on the current traffic density. The user has to set a toll price for a certain traffic density interval. Whenever a certain traffic density is realized, the toll applied is the one that was specified for that certain traffic density. For example, in Figure 2-3, the traffic density detected was 36.6 vehicles per mile per lane (vpmpl) so the toll for the density interval 35 vpmpl to 40 vpmpl was implemented which was equal to \$3.50. VISSIM also provides a component object model interface (COM), allowing users to expand on its main built-in modules. For example, Zhang et al. (2009) built an external module in Microsoft Visual Basic, to enable the HOT lane simulation for evaluating the Washington State Route (SR) 167 HOT Lane Pilot Project.

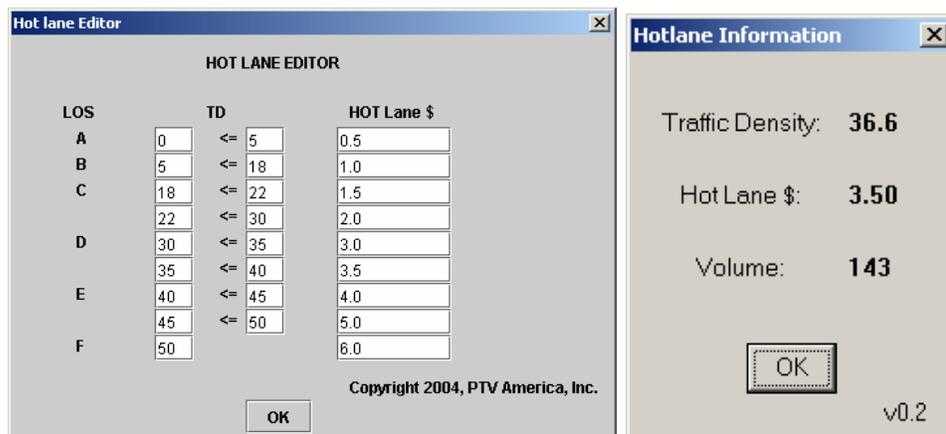


Figure 2-3. VISSIM HOT lane modules (Source: [http://www.trb-freewayops.org/sim\\_model/AnnualMeeting2007/HOT\\_Lanes\\_VISSIM.pdf](http://www.trb-freewayops.org/sim_model/AnnualMeeting2007/HOT_Lanes_VISSIM.pdf))

## 2.8 Summary

This literature review focuses on the different components of HOT lane operations and the tools that can be used to simulate them. Although a large number of studies

about HOT lanes that consider different aspects of dynamic tolling have been conducted, there are issues that have not yet been solved. For example, many studies consider idealized situations, make a large number of assumptions or require too much computational time to provide reliable and robust results. Therefore, the pricing algorithms implemented in practice are generally heuristic in nature that include many parameters that are determined using trial and error or engineering judgment. These algorithms could be optimized to better manage the HOT lane facilities. Also, even though there is some information available explaining the toll structure of the already implemented HOT lanes, no research has been found on the issue of pricing multiple segments in the same HOT facility.

Moreover, in the literature, there are many studies on drivers' lane choice between HOT and GP lanes that show that motorists make their lane choice considering many factors such as the purpose of the trip, the travel time savings, the cost of the trip, and the reliability of the trip. Furthermore, the literature indicates that drivers' VOT has high variability and depends on the drivers' and trips' characteristics

Additionally, among the existing traffic simulation programs, very few are capable of simulating certain features of HOT lanes. Therefore, additional modeling components should be added into the simulation software so that all the different characteristics of HOT lanes can be simulated.

Overall, this literature review indicates that there is a need for both the development of a method to optimize pricing strategies and more research on how to price multi-segment facilities. Also, simulation programs should be enhanced to be able to simulate all the functions of HOT lane operations.

## CHAPTER 3 ENHANCEMENT OF HOT LANE FACILITIES' PRICING STRATEGIES

In this chapter, a procedure to optimize the pricing algorithms implemented in practice is described. The procedure is based on genetic algorithms (GAs) that mimic natural selection, and are often used to generate optimal solutions to large-scale problems. The procedure is validated by optimizing the pricing algorithm currently implemented on the 95 Express in South Florida

### **3.1 GA Procedure**

In this section, the GA procedure is presented. The evolution of the GA procedure maintains a population of individuals, each of whom represents a potential solution to the optimization problem. Each potential solution is associated with a fitness value that is determined by the objective function value,  $S$ , for that individual. The individuals with the highest fitness values are preferentially selected by a randomized algorithm to create “offspring” using different transformations like mutations and crossovers. After a number of iterations, the procedure converges and the optimal solution is obtained. The GA procedure is illustrated in Figure 3-1. In the next subsections, each major step of the GA optimization procedure is presented in detail.

#### **3.1.1 Initialization**

An initial population of individuals is generated. The initial population is usually created randomly. In the GA procedure, an individual needs to be represented by a string of binary symbols.

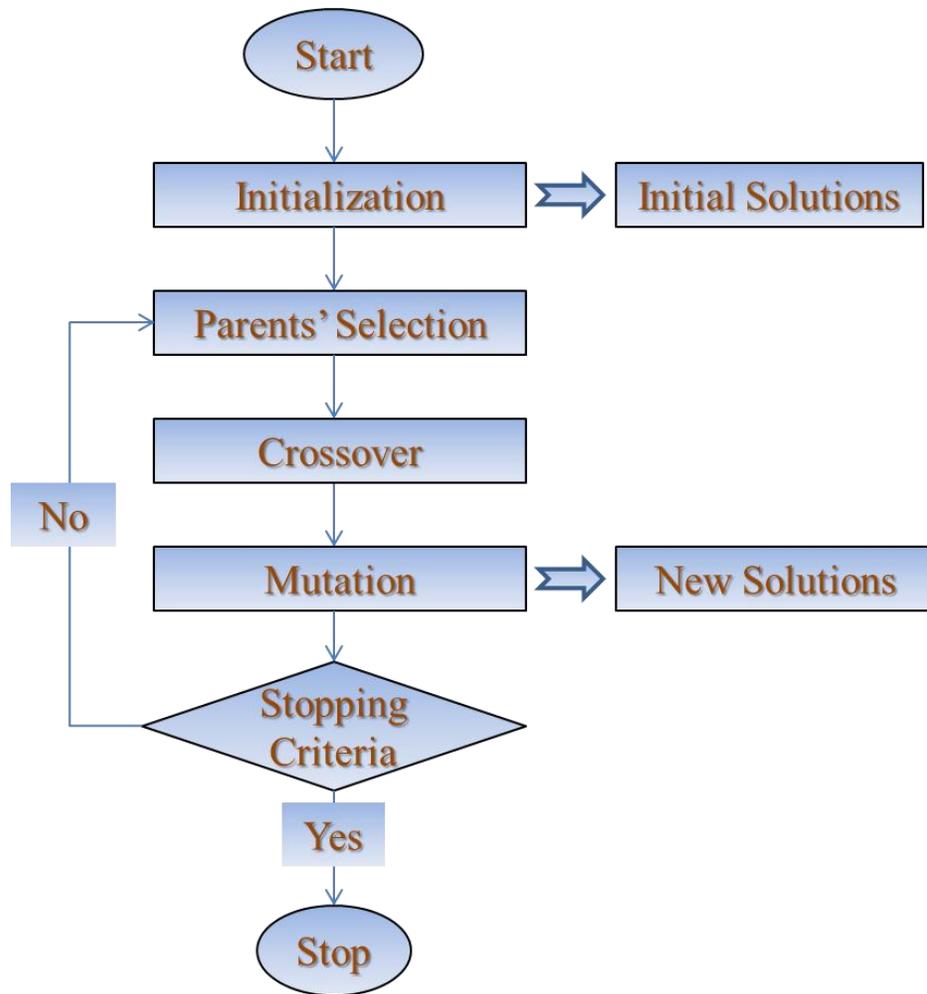


Figure 3-1. GA Procedure Flowchart

### 3.1.2 Selection of Parents

After generating the initial population of individuals, a number of iterations of GA operations is performed to obtain the optimal solution. At each iteration, a new set of individuals are created by combining the best performing individuals with their offspring, which are formed using mutations and crossovers. The “best” individuals are selected based on their fitness values. More precisely, the population is sorted in ascending order and the individuals with the highest fitness values are preferentially retained for the next generation. The number of selected individuals, who will become parents, can

be decided by the user. After all the parents are selected, they are combined into pairs. For this procedure, a random number is generated to determine the mate of the first parent listed. For example, if six parents are selected, five intervals (0-0.1999; 0.2000-0.3999; 0.4000-0.5999; 0.6000-0.7999; 0.8000-0.9999) are created in order to pair off the first parent. If the random number is 0.1248, which falls into the 0-0.1999 interval, the first parent should be paired up with the first of the remaining five parents. Then, to create the next couple, this procedure is repeated with four intervals rather than five and so on.

### **3.1.3 Crossover**

After the couples are created, there are several procedures used to create offspring for the next generation, including crossovers and mutations. For crossovers, when the two parents have the same feature of one gene, that feature will be transferred to the children. When the two parents have different features in one gene, the child will inherit that feature randomly. For instance, suppose that the two parents have the following genes: P1: 00111 and P2: 01011. In this case, the first, fourth, and fifth digits are the same, so the children will be C1: 0XX11 and C2: 0XX11, where X is an unknown digit. Random binary numbers are used to replace the unknown digits.

### **3.1.4 Mutation**

Next, mutation is used to finalize the genetic makeup of the offspring. The mutation occurs randomly by changing a small part of the genes, thus helping the optimization problem to avoid local optimum. However, the mutation rate of the GA should not be very great. Otherwise, the GA would generate too many random genes, slowing convergence.

### **3.1.5 Stopping Criteria**

The objective function value is recorded. When the value remains the same for several iterations, it is assumed that the objective function has reached its optimal value. The procedure can be terminated when the change in the objective value is under a particular number or when a certain number of iterations is reached.

## **3.2 Optimizing the 95 Express Tolling Algorithm**

In order to demonstrate the GA procedure described above, the 95 Express tolling algorithm is optimized. Before the GA is applied, the parameters in the procedure that are going to be optimized and the measure that will indicate the performance of the algorithm should be defined.

### **3.2.1 The 95 Express Dynamic Tolling Algorithm**

The GA procedure is used to fine-tune the parameters of the 95 Express tolling algorithm. The 95 Express is one of the HOT lane facilities currently in operation in the U.S. It has two HOT lanes and it was implemented by FDOT on I-95 in South Florida. The primary goal of the 95 Express is to safely and efficiently maximize the throughput of the facility while providing free-flow services on the HOT lanes. More specifically, the goal is to maintain travel speeds greater than or equal to 45 mph on the HOT lanes. To meet this goal, the toll changes every 15 minutes, varying from \$0.25 to \$7.25. The toll is determined by the traffic density currently detected on the HOT lane and the change in density from the previous interval. When an increase or decrease in the detected density occurs, the rate is adjusted upward or downward accordingly. The magnitude of the adjustment is based on a “look-up” table called a Delta Settings Table (DST), as reported in Table 3-1. Below is a description of the tolling algorithm of the 95 Express:

- 1) Calculate the average traffic density of the HOT lane segment, denoted as  $TD(t)$ . Adjust TD if necessary for specific geometric conditions, such as weaving areas.
- 2) Calculate the change in traffic density  $\Delta TD = TD(t) - TD(t - 1)$ , where  $TD(t)$  and  $TD(t - 1)$  are the traffic densities at time interval  $t$  and  $t - 1$ , respectively.
- 3) Determine toll adjustment,  $\Delta R$ , from the Delta Setting Table (DST) (Table 3-1), based on  $\Delta TD$  and  $TD(t)$ .
- 4) Calculate new toll amount as follows:  $R(t) = R(t - 1) + \Delta R$ , where  $R(t)$  and  $R(t - 1)$  are the toll amount for time interval  $t$  and  $t - 1$ , respectively.
- 5) Compare new toll amount with the minimum and maximum toll thresholds in the level of service (LOS) setting table (Table 3-2). If the toll is not within the toll thresholds corresponding to a specific  $TD(t)$ , either the maximum or minimum toll will be applied.

It can be seen that the toll at each time interval is highly dependent on  $\Delta R$  drawn from DST. In other words, DST plays a major role in determining the toll adjustment. Therefore, extra attention should be paid in designing the table and fine-tuning its parameters. The current pricing algorithm is effective in managing the traffic demand on the HOT lanes, but as traffic conditions on the I-95 corridor is expected to change in the future, the parameters will need to be updated. A macroscopic simulation tool developed in Matlab by Wu et al. (2011) will be incorporated in the GA procedure to compute the fitness values for the GA individuals. The simulation tool consists of two main modules: supply and demand. The supply module mainly consists of a traffic flow model that represents the characteristics of the facility and describes traffic dynamics along the facility and the toll determination process implemented on 95 Express, while the demand module describes users' behaviors.

Table 3-1. Delta setting table of the 95 Express (Source: FDOT, 2008)

LOS	Traffic density	Change in traffic density (TD)					
		-6	-5	-4	-3	-2	-1
A	0	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25
	1	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25
	2	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25
	3	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25
	4	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25
	5	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25
	6	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25
	7	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25
	8	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25
	9	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25
	10	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25
B	11	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25
	12	-\$0.50	-\$0.50	-\$0.50	-\$0.25	-\$0.25	-\$0.25
	13	-\$0.50	-\$0.50	-\$0.50	-\$0.25	-\$0.25	-\$0.25
	14	-\$0.50	-\$0.50	-\$0.50	-\$0.25	-\$0.25	-\$0.25
	15	-\$0.50	-\$0.50	-\$0.50	-\$0.50	-\$0.25	-\$0.25
	16	-\$0.50	-\$0.50	-\$0.50	-\$0.50	-\$0.25	-\$0.25
	17	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25
	18	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25
C	19	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25
	20	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25
	21	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25
	22	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25
	23	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25
	24	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25
	25	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25
	26	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25
	27	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25
	28	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25
	29	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25
D	30	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25
	31	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25
	32	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25
	33	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25
	34	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25
	35	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25
E	36	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25
	37	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25
	38	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25
	39	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25
	40	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25
	41	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25
	42	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25
	43	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25
	44	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25
	45	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25
F	>45	-\$2.00	-\$2.00	-\$2.00	-\$2.00	-\$1.00	-\$0.50

Table 3-1. Continued

LOS	Traffic density	Change in traffic density (TD)					
		+1	+2	+3	+4	+5	+6
A	0	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
	1	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
	2	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
	3	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
	4	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
	5	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
	6	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
	7	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
	8	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
	9	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
	10	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
B	11	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
	12	\$0.25	\$0.25	\$0.25	\$0.50	\$0.50	\$0.50
	13	\$0.25	\$0.25	\$0.25	\$0.50	\$0.50	\$0.50
	14	\$0.25	\$0.25	\$0.25	\$0.50	\$0.50	\$0.50
	15	\$0.25	\$0.25	\$0.50	\$0.50	\$0.50	\$0.50
	16	\$0.25	\$0.25	\$0.50	\$0.50	\$0.50	\$0.50
	17	\$0.25	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
	18	\$0.25	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
C	19	\$0.25	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
	20	\$0.25	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
	21	\$0.25	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
	22	\$0.25	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
	23	\$0.25	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
	24	\$0.25	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
	25	\$0.25	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
	26	\$0.25	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
	27	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	28	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	29	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
D	30	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	31	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	32	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	33	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	34	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	35	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
E	36	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	37	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	38	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	39	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	40	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	41	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	42	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	43	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	44	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	45	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
F	>45	\$0.50	\$1.00	\$2.00	\$2.00	\$2.00	\$2.00

Table 3-2. Toll range for the 95 Express (Source: FDOT, 2008)

LOS	Traffic density (vpmpl)	Toll range	
		Min	Max
A	0 - 11	\$0.25	\$0.25
B	> 11 - 18	\$0.25	\$1.50
C	> 18 - 26	\$1.50	\$3.00
D	> 26 - 35	\$3.00	\$5.00
E	> 35 - 45	\$3.75	\$6.00
F	> 45	\$5.00	\$7.25

### 3.2.2 Parameter to be Optimized

The parameters in DST that are most influential in determining the toll amount are first identified. The parameters corresponding to the LOS A (i.e., traffic density lower than 11 vpmpl), do not play any role in determining the toll amount because they are always equal to \$0.25 in accordance to Table 3-2. Also, when the traffic density change is small, that is, -1 and +1, the toll change is always the minimum, \$0.25. When LOS F is reached, the toll usually reaches its highest value to discourage motorists from entering the HOT lanes. Consequently, fine-tuning only the parameters associated with the LOS B to E and the change in traffic density ranging from -6 to -2 and from +2 to +6 is considered. In Table 3-3, the cells with numbers followed by (\*) represent the values that remain intact.

### 3.2.3 Optimization Objective

To be consistent with the operating objective of the 95 Express, the objective of the DST parameter optimization is to maximize the average speed on the GP lanes while ensuring the speed on the HOT lanes is higher than 45 mph.

Table 3-3. DST Parameters subject to fine-tuning

LOS	Traffic density	Change in traffic density (TD)					
		-6	-5	-4	-3	-2	-1
A	0	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*
	1	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*
	2	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*
	3	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*
	4	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*
	5	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*
	6	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*
	7	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*
	8	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*
	9	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*
	10	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*
B	11	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*	-\$0.25*
	12	-\$0.50	-\$0.50	-\$0.50	-\$0.25	-\$0.25	-\$0.25*
	13	-\$0.50	-\$0.50	-\$0.50	-\$0.25	-\$0.25	-\$0.25*
	14	-\$0.50	-\$0.50	-\$0.50	-\$0.25	-\$0.25	-\$0.25*
	15	-\$0.50	-\$0.50	-\$0.50	-\$0.50	-\$0.25	-\$0.25*
	16	-\$0.50	-\$0.50	-\$0.50	-\$0.50	-\$0.25	-\$0.25*
	17	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25*
	18	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25*
C	19	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25*
	20	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25*
	21	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25*
	22	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25*
	23	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25*
	24	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25*
	25	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25*
	26	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25*
	27	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25*
	28	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25*
	29	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25*
D	30	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25*
	31	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25*
	32	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25*
	33	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25*
	34	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25*
	35	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25*
E	36	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25*
	37	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25*
	38	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25*
	39	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25*
	40	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25*
	41	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25*
	42	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25*
	43	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25*
	44	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25*
	45	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25*
F	>45	-\$2.00*	-\$2.00*	-\$2.00*	-\$2.00*	-\$1.00*	-\$0.50*

Table 3-3. Continued

LOS	Traffic density	Change in traffic density (TD)					
		+1	+2	+3	+4	+5	+6
A	0	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*
	1	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*
	2	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*
	3	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*
	4	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*
	5	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*
	6	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*
	7	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*
	8	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*
	9	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*
	10	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*
B	11	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*	\$0.25*
	12	\$0.25*	\$0.25	\$0.25	\$0.50	\$0.50	\$0.50
	13	\$0.25*	\$0.25	\$0.25	\$0.50	\$0.50	\$0.50
	14	\$0.25*	\$0.25	\$0.25	\$0.50	\$0.50	\$0.50
	15	\$0.25*	\$0.25	\$0.50	\$0.50	\$0.50	\$0.50
	16	\$0.25*	\$0.25	\$0.50	\$0.50	\$0.50	\$0.50
	17	\$0.25*	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
	18	\$0.25*	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
C	19	\$0.25*	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
	20	\$0.25*	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
	21	\$0.25*	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
	22	\$0.25*	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
	23	\$0.25*	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
	24	\$0.25*	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
	25	\$0.25*	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
	26	\$0.25*	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
	27	\$0.25*	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	28	\$0.25*	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	29	\$0.25*	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
D	30	\$0.25*	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	31	\$0.25*	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	32	\$0.25*	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	33	\$0.25*	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	34	\$0.25*	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	35	\$0.25*	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
E	36	\$0.25*	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	37	\$0.25*	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	38	\$0.25*	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	39	\$0.25*	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	40	\$0.25*	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	41	\$0.25*	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	42	\$0.25*	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	43	\$0.25*	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	44	\$0.25*	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	45	\$0.25*	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
F	>45	\$0.50*	\$1.00*	\$2.00*	\$2.00*	\$2.00*	\$2.00*

Note: The values with (\*) indicate the values that remain intact

Mathematically, the objective function can be written as:

$$\max S = \sum_i [GP\_speed(i) + M \cdot \min(HOT\_speed(i) - 45, 0)] \quad (3-1)$$

where  $i$  is the tolling interval indicator;  $GP\_speed(i)$  is the speed on the GP lanes at the tolling interval  $i$ ;  $HOT\_speed(i)$  is the speed on the HOT lanes at tolling interval  $i$ , and  $M$  is a penalty parameter. If the speed on the express lanes is below 45 mph, the second component in the objective function will become negative. The larger the  $M$  is, the smaller the objective function value will be. However,  $M$  should not be too large. Otherwise, the optimization would lead to prohibitively high toll amounts, which is not beneficial to the overall performance of the system. In this task,  $M$  is set to be equal to 100.

### 3.2.4 GA Procedure

The steps of the GA procedure for the optimization of the 95 Express algorithm are explained in the following paragraphs.

#### 3.2.4.1 Initialization

A population of 10 different DSTs is randomly generated, each of which represents an “individual” in the procedure. These 10 individuals are then evaluated using the macroscopic simulation toll in Matlab (Wu et al., 2011) and the corresponding fitness values,  $S$ , are subsequently calculated. In the GA procedure, each DST needs to be represented by a string of binary symbols. Instead of directly converting each parameter in the DST into a binary variable, which would lead to a prohibitively long string, only the points where the price changes (or, in other words, jumps) are captured. From Figure 3-1, we observe that in the columns representing traffic density change from -6 to -3 and from +3 to +6, there are two price-jump points, implying that each column can have

three different prices. In the -2 and +2 columns, only one price-jump point exists and it yields two prices. In total, there are 18 price-jump points. Optimizing DST is equivalent to optimizing the locations of these 18 price-jump points. For the columns with one jump point, the location may be at any row from 14 to 45. For the columns with two jump points, the first point is located at any row from density 13 to 44, while the second can be at any row between 14 and 45. In all cases, there are 32 possible jump point locations. Thus, each location can take an integer value from 0 to 31, which can be represented as a five-digit binary substring (gene). For each DST, the corresponding binary string contains 18 genes and is 90 bits long. The coding process is illustrated in Figure 3-2, where column +3 contains two price jump points X1 and X2. The first jump point is at density 17, where the toll increases from \$0.50 to \$0.75 (the toll value is only allowed to change in increments of \$0.25). We thus have  $X1 = 17 - 13 = 4$ , and the substring or gene is coded as 00100. Similarly, the second jump point is at density 29, where the toll will change from \$0.75 to \$1.00. Therefore,  $X2 = 29 - 14 = 15$  and the substring or gene is 01111.

#### **3.2.4.2 Selection of parents**

After generating the initial population of 10 individuals, 100 iterations of GA operations are performed to obtain the optimal solution. At each iteration, a new set of 10 individuals is created by combining the best performing individuals with their offspring, which are formed using mutations and crossovers. As mentioned earlier, the “best” individuals are selected based on their fitness values.

#### **3.2.4.3 Crossover**

The crossovers are conducted to create the children or new individuals.

Traffic density	Change in traffic density +3
12	\$0.50
13	\$0.50
14	\$0.50
15	\$0.50
16	\$0.50
X1 → 17	\$0.75
18	\$0.75
19	\$0.75
20	\$0.75
21	\$0.75
22	\$0.75
23	\$0.75
24	\$0.75
25	\$0.75
26	\$0.75
27	\$0.75
28	\$0.75
X2 → 29	\$1.00
30	\$1.00
31	\$1.00
32	\$1.00
33	\$1.00
34	\$1.00
35	\$1.00
36	\$1.00
37	\$1.00
38	\$1.00
39	\$1.00
40	\$1.00
41	\$1.00
42	\$1.00
43	\$1.00
44	\$1.00
45	\$1.00
>45	\$2.00

Figure 3-2. Representation of price jump points

### 3.2.4.4 Mutation

There is a 10% mutation probability (flip the digit to the opposite value, for example, from 0 to 1) set in this model.

### 3.2.4.5 Stopping criteria

The GA procedure was set to terminate after a total of 100 iterations, so at that point the optimal algorithm solution was obtained.

### 3.2.5 Optimized DST

The DST parameters were optimized under two different traffic demand scenarios. Since the macroscopic traffic simulation tool used was calibrated against the traffic conditions on the 95 Express corridor in April 2010 by Wu et al. (2011), the travel demand of April 2010 was used as the base demand scenario. Then, the demand was increased by 5% to create an increased demand scenario.

#### 3.2.5.1 Base demand scenario

Table 3-4 compares the performances of the original and optimized DSTs. The performance measures include the average speed of the HOT lanes (HOT avg speed), the average speed of GP lanes (GP avg speed), and the percent time that the express lanes operate at more than 45 mph (reliability). The reported values in Table 3-4 were taken from the 95 Express performance report for April 2010 (FDOT, 2010a), while the other values were obtained from the macroscopic simulation tool. It can be observed that both the original and optimized DSTs provide satisfactory performance and the latter slightly outperforms the former. The optimized DST improves the speed reliability by 4.65%. A *t*-test was conducted to confirm that the improvements are statistically significant.

Table 3-4. Performance measures for base demand scenario

Performance measures	Reported	Original	Optimized	% Improvement
HOT avg speed (mph)	55.80	53.46	53.64	0.34%
GP avg speed (mph)	41.90	43.16	44.65	3.44%
Reliability	94.40%	95.56%	100.00%	4.65%

The optimized DST for the base demand scenario is shown in Table 3-5.

### **3.2.5.2 Increased demand scenario**

The performance measures for the increased demand scenario are presented in Table 3-6 and the optimized DST is illustrated in Table 3-7.

Table 3-6 shows that the current DST does not yield satisfactory results when there is a 5% demand increase. Conversely, the optimized DST improves the speed reliability by 16.60% without compromising the speed on the GP lanes.

The above demonstrates that the proposed GA optimization framework is able to fine-tune the DST parameters to adapt to the changes in traffic conditions. It should be noted that the GA procedure utilizes the macroscopic simulation tool due to its computational efficiency.

### **3.2.6 Conclusions**

The GA optimization procedure presented in this chapter can be used to optimize pricing algorithms that include a large number of parameters that are not produced from a closed-form function. Before applying the GA procedure, the most critical steps are to identify the parameters to be optimized and define the objective function. In the process of demonstrating the procedure, the 95 Express pricing algorithm was optimized. The most influential of the toll calculation parameters of the DST were optimized under two different traffic demand scenarios. In both scenarios, the objective was to maximize the speed on the GP lanes while maintaining speeds greater than 45 mph on the HOT lanes. The optimization of the 95 Express algorithm was conducted using Matlab and the results showed that the optimized algorithm gives much better network performance in the increased demand scenario. Overall, the proposed GA procedure provides a sensible approach to fine tune the DST parameters, avoiding trial and error.

The performance of the optimized algorithm was also tested using the enhanced CORSIM that is presented in Chapter 5. The results are provided in Section 6.2.

Table 3-5. Optimized DST for base demand scenario

LOS	Traffic density	Change in traffic density (TD)									
		-6	-5	-4	-3	-2	+2	+3	+4	+5	+6
B	12	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25	\$0.25	\$0.25	\$0.50	\$0.75	\$1.00
	13	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25	\$0.25	\$0.25	\$0.50	\$0.75	\$1.00
	14	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25	\$0.25	\$0.25	\$0.50	\$0.75	\$1.25
	15	-\$1.00	-\$0.75	-\$0.50	-\$0.50	-\$0.25	\$0.25	\$0.25	\$0.50	\$0.75	\$1.25
	16	-\$1.00	-\$0.75	-\$0.50	-\$0.50	-\$0.25	\$0.25	\$0.25	\$0.75	\$0.75	\$1.25
	17	-\$1.00	-\$0.75	-\$0.75	-\$0.50	-\$0.25	\$0.25	\$0.25	\$0.75	\$0.75	\$1.25
	18	-\$1.00	-\$0.75	-\$0.75	-\$0.50	-\$0.25	\$0.25	\$0.25	\$0.75	\$0.75	\$1.25
	19	-\$1.00	-\$0.75	-\$0.75	-\$0.50	-\$0.25	\$0.25	\$0.50	\$0.75	\$0.75	\$1.25
	20	-\$1.00	-\$1.00	-\$0.75	-\$0.50	-\$0.25	\$0.25	\$0.50	\$0.75	\$0.75	\$1.25
C	21	-\$1.00	-\$1.00	-\$0.75	-\$0.50	-\$0.25	\$0.25	\$0.50	\$0.75	\$0.75	\$1.25
	22	-\$1.00	-\$1.00	-\$0.75	-\$0.50	-\$0.25	\$0.25	\$0.50	\$0.75	\$0.75	\$1.25
	23	-\$1.00	-\$1.00	-\$0.75	-\$0.50	-\$0.25	\$0.25	\$0.50	\$0.75	\$0.75	\$1.25
	24	-\$1.00	-\$1.00	-\$0.75	-\$0.50	-\$0.25	\$0.25	\$0.50	\$0.75	\$0.75	\$1.25
	25	-\$1.00	-\$1.00	-\$0.75	-\$0.50	-\$0.25	\$0.25	\$0.50	\$0.75	\$0.75	\$1.25
	26	-\$1.00	-\$1.00	-\$1.00	-\$0.50	-\$0.25	\$0.25	\$0.50	\$0.75	\$0.75	\$1.25
	27	-\$1.25	-\$1.00	-\$1.00	-\$0.50	-\$0.25	\$0.25	\$0.50	\$0.75	\$0.75	\$1.25
	28	-\$1.50	-\$1.00	-\$1.00	-\$0.50	-\$0.25	\$0.25	\$0.50	\$0.75	\$0.75	\$1.25
	29	-\$1.50	-\$1.00	-\$1.00	-\$0.50	-\$0.25	\$0.25	\$0.75	\$0.75	\$0.75	\$1.25
D	30	-\$1.50	-\$1.00	-\$1.00	-\$0.50	-\$0.25	\$0.25	\$0.75	\$0.75	\$0.75	\$1.25
	31	-\$1.50	-\$1.00	-\$1.00	-\$0.50	-\$0.25	\$0.25	\$0.75	\$0.75	\$0.75	\$1.25
	32	-\$1.50	-\$1.00	-\$1.00	-\$0.50	-\$0.25	\$0.50	\$0.75	\$0.75	\$0.75	\$1.25
	33	-\$1.50	-\$1.00	-\$1.00	-\$0.50	-\$0.25	\$0.50	\$0.75	\$0.75	\$0.75	\$1.25
	34	-\$1.50	-\$1.00	-\$1.00	-\$0.50	-\$0.25	\$0.50	\$0.75	\$0.75	\$0.75	\$1.25
	35	-\$1.50	-\$1.00	-\$1.00	-\$0.50	-\$0.50	\$0.50	\$0.75	\$0.75	\$0.75	\$1.25
E	36	-\$1.50	-\$1.00	-\$1.00	-\$0.50	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.00	\$1.25
	37	-\$1.50	-\$1.00	-\$1.00	-\$0.50	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.00	\$1.25
	38	-\$1.50	-\$1.00	-\$1.00	-\$0.50	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.25	\$1.25
	39	-\$1.50	-\$1.00	-\$1.00	-\$0.50	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.25	\$1.25
	40	-\$1.50	-\$1.00	-\$1.00	-\$0.50	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.25	\$1.25
	41	-\$1.50	-\$1.00	-\$1.00	-\$0.75	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.25	\$1.25
	42	-\$1.50	-\$1.00	-\$1.00	-\$0.75	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.25	\$1.50
	43	-\$1.50	-\$1.00	-\$1.00	-\$0.75	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.25	\$1.50
	44	-\$1.50	-\$1.00	-\$1.00	-\$0.75	-\$0.50	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50
	45	-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50

Table 3-6. Performance measures for increased demand scenario

Performance measures	Original	Optimized	% Improvement
HOT avg speed (mph)	45.67	47.56	4.14%
GP avg speed (mph)	40.01	41.08	2.67%
Reliability	65.28%	76.11%	16.60%

Table 3-7. Optimized DST for increased demand scenario

LOS	Traffic density	Change in traffic density (TD)									
		-6	-5	-4	-3	-2	+2	+3	+4	+5	+6
B	12	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25	\$0.25	\$0.25	\$0.50	\$0.75	\$1.00
	13	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25	\$0.25	\$0.25	\$0.50	\$0.75	\$1.00
	14	-\$1.00	-\$0.75	-\$0.50	-\$0.50	-\$0.25	\$0.25	\$0.25	\$0.50	\$0.75	\$1.00
	15	-\$1.00	-\$0.75	-\$0.50	-\$0.50	-\$0.25	\$0.25	\$0.25	\$0.50	\$0.75	\$1.00
	16	-\$1.00	-\$1.00	-\$0.50	-\$0.50	-\$0.25	\$0.25	\$0.25	\$0.50	\$0.75	\$1.00
	17	-\$1.25	-\$1.00	-\$0.50	-\$0.50	-\$0.25	\$0.25	\$0.25	\$0.50	\$0.75	\$1.00
	18	-\$1.25	-\$1.00	-\$0.50	-\$0.50	-\$0.25	\$0.25	\$0.25	\$0.75	\$0.75	\$1.00
	C	19	-\$1.25	-\$1.00	-\$0.50	-\$0.50	-\$0.25	\$0.25	\$0.25	\$0.75	\$0.75
20		-\$1.25	-\$1.00	-\$0.50	-\$0.50	-\$0.25	\$0.25	\$0.25	\$0.75	\$0.75	\$1.00
21		-\$1.25	-\$1.00	-\$0.50	-\$0.50	-\$0.25	\$0.25	\$0.25	\$0.75	\$0.75	\$1.00
22		-\$1.25	-\$1.00	-\$0.50	-\$0.50	-\$0.50	\$0.25	\$0.25	\$0.75	\$0.75	\$1.00
23		-\$1.25	-\$1.00	-\$0.50	-\$0.50	-\$0.50	\$0.25	\$0.50	\$0.75	\$1.00	\$1.00
24		-\$1.25	-\$1.00	-\$0.50	-\$0.50	-\$0.50	\$0.50	\$0.50	\$0.75	\$1.00	\$1.00
25		-\$1.25	-\$1.00	-\$0.50	-\$0.50	-\$0.50	\$0.50	\$0.50	\$0.75	\$1.00	\$1.25
26		-\$1.25	-\$1.25	-\$0.50	-\$0.50	-\$0.50	\$0.50	\$0.50	\$0.75	\$1.00	\$1.25
27		-\$1.25	-\$1.25	-\$0.50	-\$0.50	-\$0.50	\$0.50	\$0.50	\$0.75	\$1.00	\$1.25
28		-\$1.25	-\$1.25	-\$0.50	-\$0.50	-\$0.50	\$0.50	\$0.50	\$0.75	\$1.00	\$1.25
29		-\$1.25	-\$1.25	-\$0.50	-\$0.50	-\$0.50	\$0.50	\$0.50	\$0.75	\$1.00	\$1.25
D	30	-\$1.25	-\$1.25	-\$0.75	-\$0.50	-\$0.50	\$0.50	\$0.50	\$0.75	\$1.00	\$1.25
	31	-\$1.25	-\$1.25	-\$0.75	-\$0.50	-\$0.50	\$0.50	\$0.50	\$0.75	\$1.00	\$1.25
	32	-\$1.25	-\$1.25	-\$0.75	-\$0.50	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.00	\$1.25
	33	-\$1.25	-\$1.25	-\$0.75	-\$0.50	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.00	\$1.25
	34	-\$1.25	-\$1.25	-\$0.75	-\$0.50	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.00	\$1.25
	35	-\$1.25	-\$1.25	-\$0.75	-\$0.50	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.00	\$1.25
	E	36	-\$1.25	-\$1.25	-\$0.75	-\$0.50	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.25
37		-\$1.25	-\$1.25	-\$0.75	-\$0.50	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.25	\$1.25
38		-\$1.25	-\$1.25	-\$0.75	-\$0.50	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.25	\$1.25
39		-\$1.25	-\$1.25	-\$0.75	-\$0.75	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.25	\$1.25
40		-\$1.25	-\$1.25	-\$0.75	-\$0.75	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.25	\$1.25
41		-\$1.25	-\$1.25	-\$0.75	-\$0.75	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.25	\$1.25
42		-\$1.25	-\$1.25	-\$0.75	-\$0.75	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.25	\$1.25
43		-\$1.25	-\$1.25	-\$1.00	-\$0.75	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.25	\$1.50
44		-\$1.25	-\$1.25	-\$1.00	-\$0.75	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.25	\$1.50
45		-\$1.50	-\$1.25	-\$1.00	-\$0.75	-\$0.50	\$0.50	\$0.75	\$1.00	\$1.25	\$1.50

## CHAPTER 4 PRICING OF MULTI-SEGMENT HOT LANE FACILITIES

Some of the HOT lane facilities currently implemented in the U.S. are single-segment, while others are multi-segment. Essentially, a single-segment HOT lane facility has one main ingress, one main egress, and includes one tolling point. Therefore, motorists who enter the facility during the same tolling interval pay the same toll amount. On the other hand, a multi-segment HOT lane facility consists of multiple entrances and exits that are located relatively far from each other. Downstream of every entrance there usually is a toll gantry and motorists will pay different tolls depending on where they entered and how far they traveled on the HOT lane facility. The exact toll amount a motorist has to pay when traveling on a multi-segment HOT lane depends on the toll structure implemented.

The pricing approach for a multi-segment HOT lane facility should provide superior traffic flow conditions on the HOT lanes while maximizing the freeway's throughput as the pricing for a single-segment HOT lane facility. Moreover, it should avoid creating inequality issues among motorists entering the facility at different ingress points. Therefore, pricing a multi-segment facility is more challenging than pricing a single-segment facility. The tolling algorithm and structure for a multi-segment facility must ensure similar traffic conditions within every segment of the facility without causing excessive lane changes before each HOT lane entrance or equity issues among motorists.

This chapter outlines the possible toll structures that can be implemented to manage a multi-segment HOT lane facility and the current practice of multi-segment facilities. It, also, presents the main advantages and disadvantages of each toll

structure. After all the different toll structures are described, the future 95 Express that will be a multi-segment facility is introduced and recommendations on how to price the future 95 Express are made.

#### **4.1 Multi-Segment HOT Lanes in the U.S.**

From the ten HOT lanes in operation in the U.S., the following six have multiple segments:

- I-15, Salt Lake City, Utah.
- I-10 (Katy Freeway), Houston, Texas.
- I-394, Minneapolis, Minnesota.
- SR-167 between Renton and Auburn, Washington.
- I-15, San Diego, California.
- I-85, Atlanta, Georgia.

##### **4.1.1 Toll Structures**

Although a multi-segment facility often has multiple tolling points, a motorist does not necessarily have to pay at each point. Where a motorist is charged depends on the toll structure implemented. In general, the toll structures for multi-segment facilities can be classified as zone-based, origin-specific, OD-based, and distance-based. All four structures have been implemented in practice. The following section describes each toll structure, reviews the tolling practice for the multi-segment HOT facilities in the U.S., and compares their advantages and disadvantages. In order to better explain each toll structure, the multi-segment HOT lane facility illustrated in Figure 4-1 is considered. In this facility, there are two HOT lanes and three GP lanes. The HOT lanes are separated from the GP lanes by double solid line. Motorists can access the HOT facility only at the access points that are indicated by dashed lines. I1, I2, and I3 represent the entrances from the GP lanes to the HOT lanes while O1, O2, and O3 show the exits from the HOT

lanes back to the GP lanes. A toll gantry is located downstream to each HOT lane entrance.

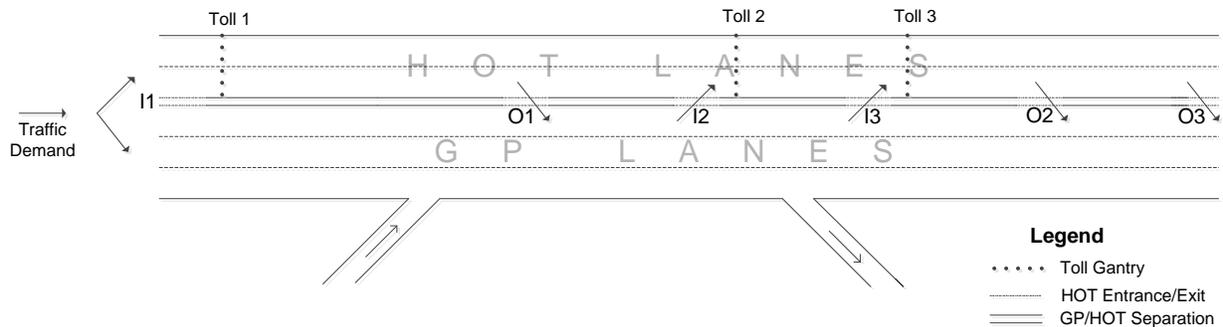


Figure 4-1. Example of a multi-segment HOT lane facility

#### 4.1.1.1 Zone-based tolling

In this approach, a HOT lane facility is divided into multiple zones. Whenever a motorist enters a new zone, he or she pays a specific toll. Consequently, the toll amount that a motorist pays depends on the numbers of zones he or she has traversed. Each zone can include multiple HOT lane entrances and exits. The toll at all the entrances that belong to the same zone is the same, however. For instance, suppose that the facility in Figure 4-1 is divided into two zones, one zone from I1 to O1 and one zone from I2 to O3. In this case, Zone 1 has one entrance and one exit while Zone 2 has two entrances and two exits. Zone 2 has also two tolling points, one downstream of I2 and one downstream of I3. The tolls charged at these points are equal, or in other words, toll 2 is equal to toll 3. Motorists who travel through Zone 1 will pay toll 1 and motorists who travel through the entire facility will pay toll 1 plus toll 2. Travelers who enter at either I2 or I3 and then exit at either O2 or O3 will pay the same toll, which is equal to the price of Zone 2.

The zone-based toll structure has been implemented on the I-15 Express lanes in Salt Lake City, the I-10 HOT lane corridor in Houston and the MnPass I-394 HOT lanes in Minneapolis.

**I-15 Salt Lake City, Utah.** I-15 express lanes in Salt Lake City, opened in September 2006, and in August 2010 the express lanes were divided into four payment zones and dynamic pricing was implemented. The toll rate at the entrance of each zone is determined by the real-time traffic condition in that particular zone, aiming to maintain a speed of at least 55 mph. Signs at the entrance of each zone and several other upstream locations display the price for traveling in that zone. A traveler who enters in the middle of a zone will have to pay the full amount for the entire zone. The price range for a solo driver is \$0.25-\$1.00 for each zone. It was determined based on public opinions and traffic analysis, with reference to the price ranges in other HOT lanes (UDOT, 2010b).

**I-10 (Katy Freeway), Houston, Texas.** The toll structure of the Katy managed lanes is zone-based and the tolls vary by time of day according to a pre-determined schedule. There are three tolling points along the facility and a driver who traverses the entire HOT facility needs to pay three separate tolls. Although time-of-day tolling is easier to implement, it may not be able to adequately manage the traffic demand when there are substantial demand fluctuations, such as during holidays or large sports events.

**I-394, Minneapolis, Minnesota.** The I-394 corridor is divided into two tolling zones. The price of each zone is determined independently from the others to manage the demand in that particular zone. A sign at each entry point lists the tolls by

destination, that is, the ending point of each zone. If a motorist exits anywhere before or at the first destination, he or she will pay only that first price for his or her trip. If the motorist continues beyond that point, he or she will also pay the second price posted on the sign at the entrance.

#### **4.1.1.2 Origin-specific tolling**

In origin-specific tolling, the toll a motorist will pay depends only on where he or she enters the facility. Regardless of how far the motorist travels, he or she pays the toll displayed at the entry point. In the example network in Figure 4-1, there are three origins, I1, I2, and I3. Motorists who enter at I1 will pay toll 1 regardless of which exit, O1, O2, or O3, they are going to take. In this case, a driver who travels from I1 to O1 will pay the same toll amount as someone who travels through the entire HOT facility. This can be unfair to the drivers who travel short distances on the HOT lanes. On the other hand, travelers can choose just once whether or not to use the HOT lanes and know in advance exactly how much they are going to be charged.

**SR-167, Washington State.** Origin-specific tolling was implemented on SR-167 HOT lanes, so users of the SR-167 HOT lanes pay the toll displayed at their entrances even if they traverse the entire facility. Sometimes, when traffic volume on the HOT lanes increases significantly, “HOV only” may be displayed at the HOT entrances indicating that SOVs cannot enter.

#### **4.1.1.3 OD-based tolling**

OD-based tolling implies that the toll rate a motorist will pay depends on where he or she enters and leaves the facility so there is a different price for motorists who travel through different OD pairs. In the example network (Figure 4-1), there are seven OD pairs (I1-O1, I1-O2, I1-O3, I2-O2, I2-O3, I3-O2, I3-O3) and drivers have to pay

depending on their OD. The toll per mile can be different for different OD pairs, thus creating some equality issues among drivers. The tolls displayed before each toll gantry show the price to major destinations, but do not indicate the exact amount a driver will finally pay. This toll structure is implemented on I-15 in San Diego.

**I-15, San Diego, California.** The sign at each entrance of the I-15 HOT lanes displays the minimum toll for entering the facility, the toll rate (i.e., toll per mile), and the toll amount for traveling to the end of the facility (i.e., the maximum toll). Transit riders, carpools, vanpools, motorcycles and permitted clean-air vehicles may access the lanes for free. For solo drivers, the toll depends on the distance traveled in the HOT lanes and the rate per mile at their entry location. The toll rate is calculated every few minutes but travelers pay the toll rate that was displayed at the time they entered the HOT lane facility. The system will recalculate the toll rate based on the level of traffic demand in the corridor, ensuring free-flow traffic conditions in the HOT lanes. When a motorist enters the facility, he or she needs to pay at least the minimum toll, regardless of his or her eventual exit location. The sign at each entrance also advises one or more possible fares for longer trips to upcoming freeway interchanges, such as SR-56 or 163. If the destination is somewhere after the first possible interchange, the expected toll will fall between the minimum and the toll for traveling all the way to the end of the facility (SANDAG, 2010).

#### **4.1.1.4 Distance-based tolling**

In this toll structure, the toll charge that a motorist will pay depends on the distance he or she travels on the HOT lanes. The rate, that is, toll per mile, is the same for all entry locations at a specific time interval. For example, in the network in Figure 4-1, the toll per mile for all the three entrances, I1, I2, and I3 will be the same at a certain time

interval. At each entrance, the toll per mile is displayed. Such a toll structure has been recently implemented on I-85 HOT lanes in Georgia.

**I-85, Atlanta, Georgia.** I-85 HOT lanes have multiple entrances in each direction. The sign at each entry location displays the toll rate to the first downstream exit, which is the minimum toll one has to pay when he or she enters the facility, and the toll rate to the last exit which is the maximum someone can be charged. A traveler who exits between the first and last exit, pays depending on the miles traveled on the HOT lanes.

#### **4.1.2 Summary**

Table 4-1 summarizes the characteristics and toll structures of the multi-segment HOT facilities in the U.S. The detailed description of each tolling algorithm is not available in the open literature.

#### **4.1.3 Pros and Cons of Toll Structures**

This section further compares the pros and cons of the above four toll structures. In the zone-based tolling, the toll charged for one zone is usually determined based on the traffic conditions in that particular zone. The toll rate will be displayed at the entrance to each zone. Therefore, the tolling algorithm for each zone is essentially the same as for a single-segment facility. In this sense, the zone-based toll structure is easier to implement. Motorists can make their decisions on whether to pay to access the HOT lanes multiple times and they know in advance exactly how much they will pay when they make those lane-choice decisions. One of the critical issues in implementing a zone-based toll structure is to determine the number and location of zones. If a zone is too long, pricing becomes less effective in managing demand. Conversely, many short zones will create additional lane changes, possibly yielding moving bottlenecks and disrupting the managed-lane operations.

Table 4-1. Summary of multi-segment HOT facilities in the U.S.

Facility	Length	Access points	Tolling points	GP/HOT separation	Toll structure
I-15 Salt Lake City, Utah	38 miles	18 access points <sup>1</sup> , 2 entrances and 1 exits at each direction	4 – one at the end of each zone	Double white line	Zone-based: dynamic pricing
I-10 Houston, Texas	13 miles	5 entrances and 3 exits WB and 3 entrances and 5 exits EB	3 – one at the end of each zone	Flexible “candlestick” barriers	Zone-based: time of day pricing
I-394 Minneapolis, Minnesota	11 miles	5 EB and 5 WB	5 EB and 5 WB	Double white line	Zone-based: dynamic pricing
SR-167 Renton & Auburn, Washington	10 miles	6 entrances and exits NB and 4 entrances and exits SB	6 NB and 4 SB	Double white line	Origin-specific: dynamic pricing
I-15 San Diego, California	8 miles	9 entrances and 8 exits NB and 9 entrances and 9 exits SB <sup>2</sup>	8 NB and 9 SB	Concrete barriers	OD-based: dynamic pricing
I-85 Atlanta, Georgia	16 miles	5 entrances and 6 exits NB and 4 entrances and 4 exits SB	6 NB and 4 SB	Double white line	Distance-based: dynamic pricing

<sup>1</sup>Access points are the points where drivers can either enter or exit the HOT lanes.

<sup>2</sup>Information provided by the I-15 Express Lanes Customer Service Center.

The origin-specific toll structure is also relatively easy to implement. Origin-specific tolling is convenient for users because they only need to make their lane choices once. However, this toll structure is likely to create inequity if the facility is long because the toll per mile at an upstream entrance may be less than that at a downstream entrance.

Otherwise, the capacity of HOT lanes upstream would be wasted. Consequently, users who enter midway or downstream of the HOT lanes may pay more for traveling a shorter distance, which may be viewed unfair to many. Similar to some ramp metering strategies, this toll structure tends to favor the long-distance travelers. If not designed properly, it may lead to public resistance, like the opposition to ramp metering in the Twin Cities, Minnesota, area where the state legislature passed a bill in the Spring of 2000 requiring a ramp meter shut-off experiment.

The OD-based toll structure, at least theoretically, can effectively manage demand and utilize available capacity on a long multi-segment HOT facility. The toll rates can be carefully designed to reduce inequality among users who access the facility via different entrances. It is, however, more sophisticated and thus more difficult to implement than the previous two structures. It can require a relatively high implementation cost because the system should keep track of where the vehicles enter and exit. Another downside of this structure is that, when users make their lane choices, they may not be sure of the exact amount of toll they will have to pay for their trips. In the current practice (i.e., I-15 in San Diego), when a motorist enters the facility, he or she needs to pay the minimum toll, regardless of his or her destination. A sign at each entrance advises one or more possible fares for longer trips to upcoming exits. If the destination is somewhere after the first possible exit, the expected toll can fall between the minimum and the toll for traveling all the way to the last exit of the HOT lanes.

Comparatively, the distance-based toll structure seems easier to implement than the OD-based tolling. From a software point of view, the implementation difficulty for both schemes is approximately the same. Distance-based tolling is more flexible than

the origin-based structure in managing the traffic demand and it may not create much equity concern as all travelers pay the same rate per-mile. However, it may still result in unused capacity in the network.

Table 4-2 summarizes the advantages and disadvantages of the different toll structures presented above.

Table 4-2. Pros and cons of toll structures

Toll structure		Pros	Cons
Zone-based	Easy to implement, particularly when expanded from a single-segment HOT facility		Additional lane changes at the beginning of each zone may cause disruptions; difficulty of balancing utilization of capacity and the disruptions caused by lane changes
Origin-specific	Easy to implement and convenient for users		Inefficient utilization of capacity; possible inequality concerns
OD-based	Effectively manage demand and utilize capacity		More costly to implement
Distance-based	No equity concern		More costly to implement; inefficient utilization of capacity

## 4.2 The Future 95 Express

The 95 Express will be deployed in two phases. Phase 1 has been completed, and includes express lanes between SR-836/I-395 and Miami Gardens Drive/NW 186th Street in Dade County. Phase 1 is the current 95 Express. Phase 2 will expand the express lanes northward to Broward Boulevard in Broward County. The future 95 Express includes the express lanes constructed during both Phase 1 and Phase 2. Figure 4-2 is a map of the current 95 Express and Figure 4-3 illustrates the future, completed, 95 Express. It can be seen that the current 95 Express is essentially a single-segment facility while the future 95 Express is slated to be a multi-segment facility. More specifically, the future 95 Express will have five entrances and four exits

southbound and four entrances and five exits northbound (Figure 6-3) and three tolling points in each direction. Some of these entrances and exits will be located very close to each other, while others will be at distances of approximately 10 miles. This implies that setting one toll amount may not be effective in managing traffic demand or be fair to all users. Therefore, the future 95 Express may better be managed as a multi-segment facility.

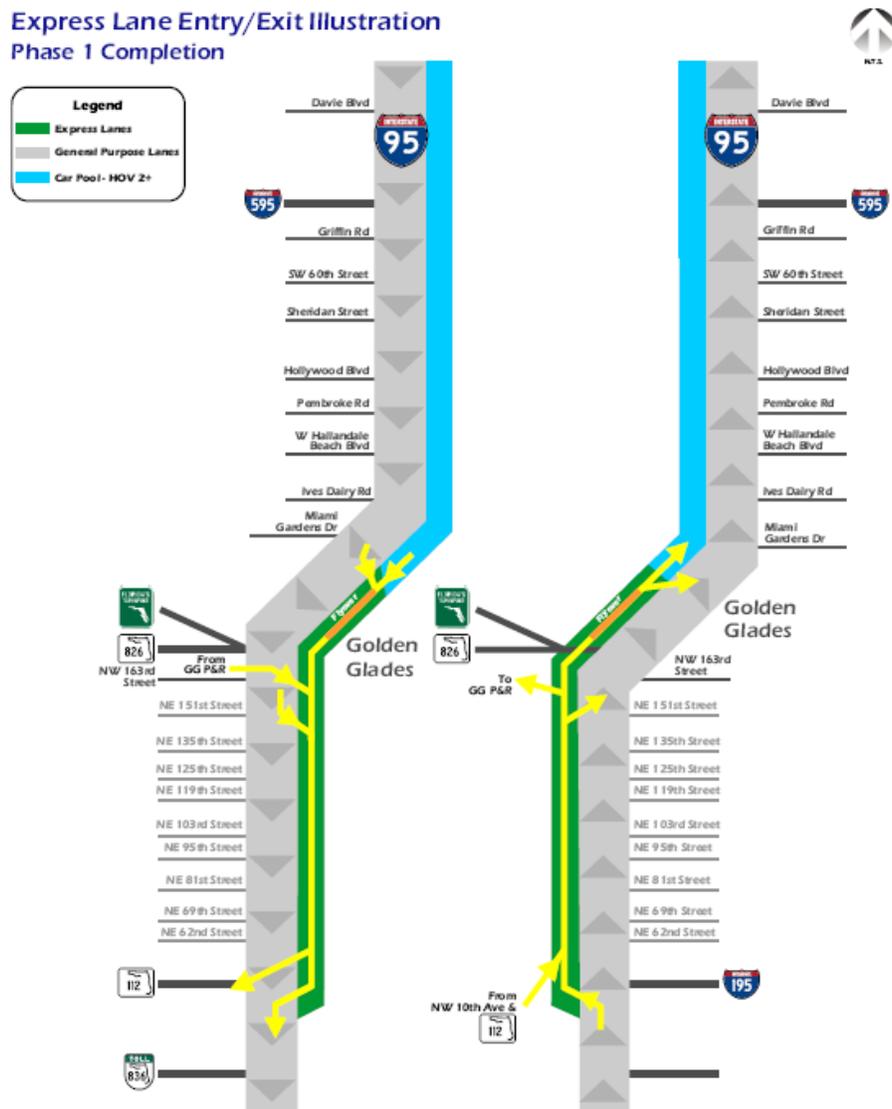


Figure 4-2. Map of the 95 Express after Phase 1 completion; left is southbound, right is northbound. (Source: [http://www.95express.com/PDF/2008-05-19\\_Entry-Exit%20Phase%201.pdf](http://www.95express.com/PDF/2008-05-19_Entry-Exit%20Phase%201.pdf))

### Express Lane Entry/Exit Illustration Final

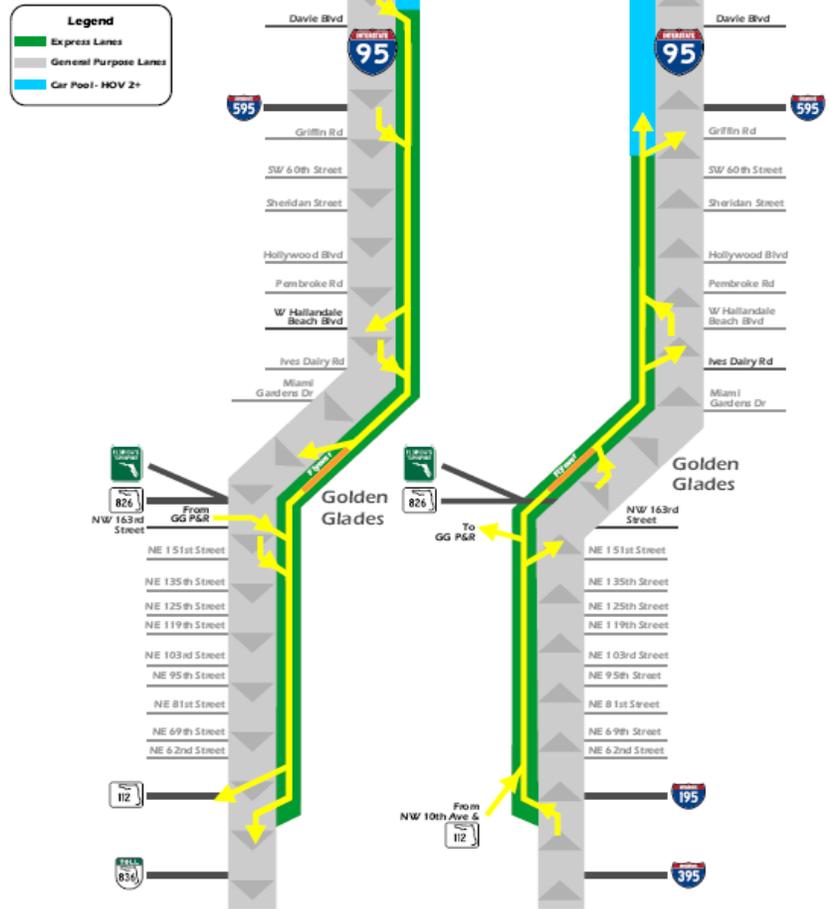


Figure 4-3. Completed 95 Express. Left is southbound, right is northbound. (Source: [http://www.95express.com/PDF/2008-05-19\\_Entry-Exit%20Phase%201.pdf](http://www.95express.com/PDF/2008-05-19_Entry-Exit%20Phase%201.pdf))

### 4.3 Recommendations for Pricing the Future 95 Express

As mentioned previously, the future 95 Express will have multiple entrances and exits and three tolling points in each direction which means that it will be better managed as a multi-segment facility. There are four different toll structures that can be applied to operate a multi-segment HOT lane facility but not all may be appropriate for the 95 Express. Taking into account the advantages and disadvantages of these toll structures, the design of the future 95 Express, and the number and location of its access and tolling points, zone-based tolling seems more appropriate for the 95

Express. In zone-based tolling, each zone is treated as a single-segment facility so the fact that the future 95 Express is an expansion of the current 95 Express provides an additional advantage to this tolling structure as there is already a pricing algorithm developed and implemented for the current 95 Express. This algorithm could be applied to manage the individual zones of the future 95 Express.

If the zone-based tolling is selected, the critical issue is to determine the zoning, or in other words, how to divide the facility into zones. One suggestion to determine the zoning is to ensure that each zone contains exactly one bottleneck. For this, once it is completed, the facility could be opened with free access for a certain period of time so that motorists' travel patterns can be observed and studied and the recurring bottlenecks in the facility be identified. If the above approach is not practical or feasible, we can rely on simulation studies to evaluate and compare multiple zoning designs.

Based on the design and location of the HOT lane entrances and exits (Figure 4-3), one possible zoning scenario is to treat Phase 1, that is, the current 95 Express, as one zone and the extended portion as another two zones, as shown in Figure 4-4. More specifically, the potential Zone 3 for the southbound direction and Zone 1 for the northbound direction are the current 95 Express while Zones 1 and 2 for southbound, and Zones 2 and 3 for northbound are the extension. These additional two zones in each direction can be combined into one zone, depending on the O-D demand pattern of the facility. The tolling algorithm to be implemented for each zone can be similar to the current one, but the parameters may need fine tuning.

Looking in the northbound direction, Zone 1 is the current 95 Express, which is about 7.3 miles long. In the first scenario, Zone 2 begins just downstream of the on-

ramp from Miami Gardens Drive and ends upstream of the on-ramp from Hallandale Beach Boulevard. Zone 2 is about 5 miles long, consisting of one extra exit upstream of the off-ramp to Ives Dairy Road. Zone 3 starts right after where Zone 2 ends and extends to the end of the completed 95 Express at Broward Boulevard. It has two more exits upstream of Stirling Boulevard and Davie Boulevard and is about 8.5 miles long. In the second scenario, Zones 2 and 3 are combined into one zone approximately 13.5 miles long with a total of two entrances and three exits.

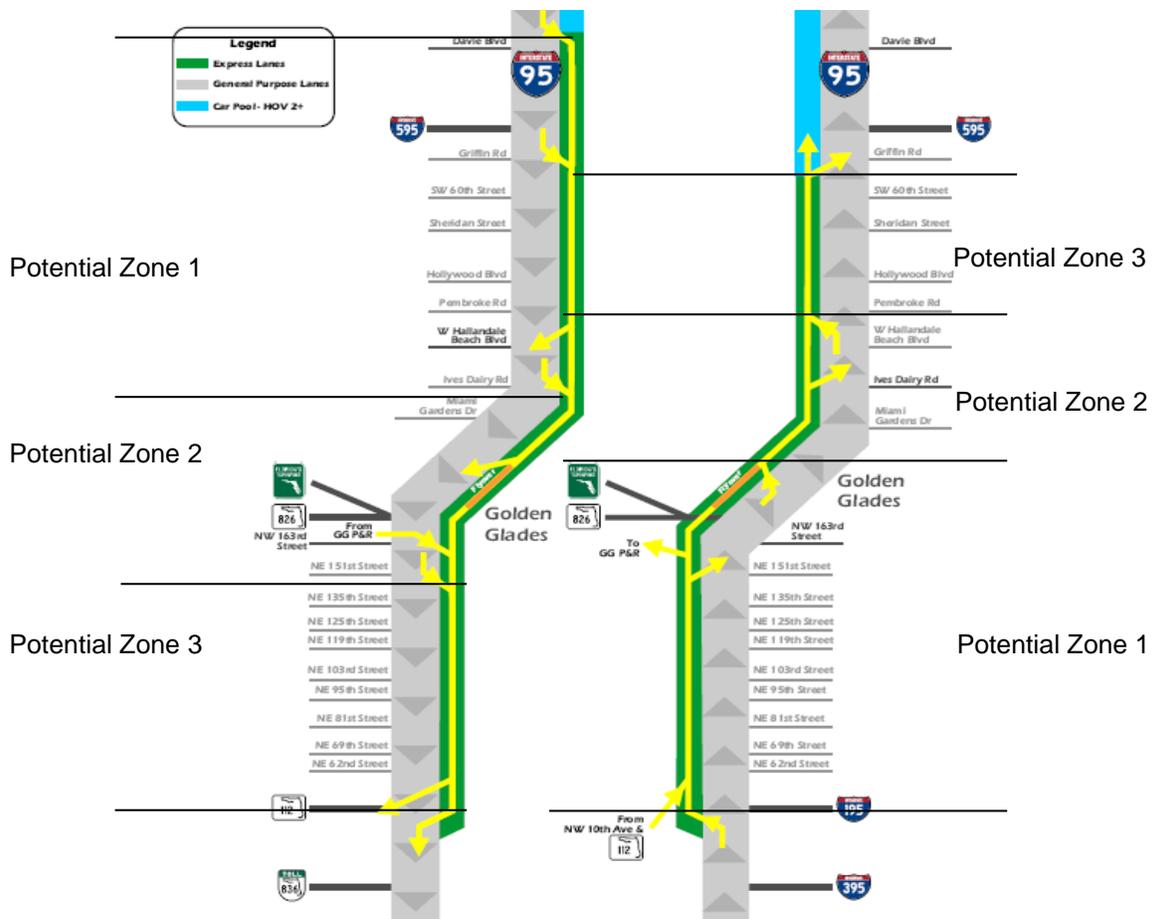


Figure 4-4. Potential zoning for the 95 Express. Left is southbound, right is northbound.

For determining the price of each zone, the 95 Express dynamic pricing algorithm or responsive pricing was used with the same DST parameters. However, the minimum

and maximum toll values in the LOS setting table (Table 3-2) for LOS D, E and F were increased to match the increased zone length, as shown in Table 4-3.

Table 4-3. Toll ranges for the zones of future 95 Express

Scenario 1, Zone 3				Scenario 2, Zone 2			
LOS	Traffic Density (vpmpl)	Toll Rate		LOS	Traffic Density (vpmpl)	Toll rate	
		Min	Max			Min	Max
A	0 - 11	\$0.25	\$0.25	A	0 - 11	\$0.25	\$0.25
B	> 11 - 18	\$0.25	\$1.50	B	> 11 - 18	\$0.25	\$1.50
C	> 18 - 26	\$1.50	\$3.00	C	> 18 - 26	\$1.50	\$3.00
D	> 26- 35	\$3.00	\$5.75	D	> 26- 35	\$3.00	\$9.25
E	> 35 - 45	\$4.75	\$7.00	E	> 35 - 45	\$8.75	\$11.00
F	> 45	\$6.25	\$8.50	F	> 45	\$11.25	\$13.50

The performance of the two different zoning designs for the northbound direction proposed above (Figure 4-4) is tested using the enhanced CORSIM. CORSIM is microscopic traffic simulation software that, until recently, had very limited capability in simulating the HOT lanes operations. However, as is described in detail in the next chapter, it was enhanced to simulate HOT lanes operations by implementing three different modeling components, including a variety of pricing algorithms, a lane choice model, and toll structures for managing multi-segment HOT lane facilities.

The simulated performance measures of the two zoning designs are summarized in Table 4-4. The data used for the calibration were obtained from the STEWARD database every 15 minutes for three weekdays, May 10-12, 2011, for all the detectors along the future 95 Express corridor.

As Table 4-4 indicates, the three-zone design produces similar performance as the two-zone design. The primary reason is that the freeway segment of Phase 2 (Zones 2 and 3) is not very congested in the CORSIM simulation. Thus, based on the network

performance measures, it is sufficient to treat Phase 2 as a single zone and use dynamic pricing to effectively manage the segment.

Table 4-4. Future 95 Express zoning performance measures

Zone designs									
Three-zone design									
Tolls	Zone 1		Zone 2		Zone 3		Facility		
Range	\$0.25 - \$2.75		\$0.25 - \$0.25		\$0.25 - \$0.50		\$0.75 - \$3.25		
Avg. peak period	\$1.41		\$0.25		\$0.27		\$1.93		
	HOT	GP	HOT	GP	HOT	GP	HOT	GP	
Avg speed (mph)	56	40	60	54	66	63	61	54	
HOT lanes operated above 45 mph	99.9%		100%		100%		99.9%		
Two-zone design									
Tolls	Zone 1		Zone 2		Facility				
Range	\$0.25 - \$2.25		\$0.50 - \$0.75		\$0.75 - \$2.75				
Avg. peak period	\$1.05		\$0.52		\$1.57				
	HOT	GP	HOT	GP	HOT			GP	
Avg speed (mph)	56	41	65	61	61			54	
HOT lanes operated above 45 mph	99.8%		100%		99.9%				

In the three-zone design each zone has one entrance and drivers are charged three times to travel along the entire HOT lane facility. This means that each time a car passes through a toll gantry, it gets charged. However, in the two-zone design, the second zone has two entrances and motorists who enter at the upstream entrance should not get charged when they are passing through the downstream entrance. This may require a different configuration of the second entrance of the second zone so only the motorists who enter the facility there get charged. If the same entry configuration is used at all entrances, then all the drivers entering the second zone need to be tracked and charged accordingly. This means that the two-zone design has a higher

implementation cost than the three-zone design. Also, the two-zone design will generally produce less revenue than the three-zone design.

Overall, from the operator's perspective, the selection of the number of zones highly depends on the implementation cost and the willingness to produce more revenue while from the user's perspective, it is preferable to have fewer zones so they get charged fewer times, the total of which is less.

## CHAPTER 5 ENHANCEMENT OF CORSIM

Microscopic simulation is very useful in evaluating pricing schemes and other managed lane operational strategies (Zhang et al., 2009). Unfortunately, there is not any software that is able to explicitly simulate the HOT lane operations. This chapter focuses on the effort to enhance a traffic simulation tool called CORSIM for simulating HOT lane operations. CORSIM was selected because it is a trustworthy traffic simulation tool and our ability to modify it through the *McTrans* Center.

### 5.1 Introduction

CORSIM is a widely-used and comprehensive microscopic traffic simulation program. It was initially developed by FHWA and is now being maintained and further developed by *McTrans* at the University of Florida. During recent years, CORSIM has been expanded to simulate signal pre-emption, two-lane rural highways, and new vehicle technologies, and has enabled large-scale network simulation. CORSIM has limitations, however. The current version of CORSIM is very limited in its ability to simulate dynamic tolling strategies, and drivers' lane choice behaviors in the presence of tolls. In order to incorporate HOT lane simulation into CORSIM, three modeling components were developed. The first set was to simulate a variety of pricing strategies. The second was to mimic drivers' choices between GP and HOT lanes in the presence of tolls based on a specific lane-choice model selected. The third was to allow for different toll structures or charging approaches for multi-segment HOT lane facilities. In the following paragraphs, these three components are described.

## 5.2 Pricing Strategies

In the literature, many studies have been conducted to develop pricing algorithms that can be potentially used for HOT lane operations. However, many of these studies (see, e.g., Morrison, 1986; Palma and Lindsey, 1997; Arnott et al., 1998) consider hypothetical and idealized situations to derive analytical solutions. For example, the travel demand function or travel demand is usually assumed to be known. For the CORSIM enhancement, practical and easy-to-implement pricing algorithms, including the one implemented for the 95 Express in South Florida, called here responsive pricing, and the approach proposed by Yin and Lou (2009) that determines time-varying tolls based on the concept of feedback control were selected. In addition, time-of-day pricing was implemented since it is being implemented at a few HOT lane facilities. The three pricing algorithms are presented below in detail.

### 5.2.1 Responsive Pricing

Responsive pricing is an approach to determine toll values based on the current HOT lane conditions to manage traffic demand and maintain free-flow conditions on HOT lanes. The algorithm is described in detail in section 3-2.

In CORSIM implementation, the tolling interval  $t$ , the parameter,  $\alpha$ , all values in DST (Table 3-1), and the minimum and maximum toll thresholds in Table 3-2 can be modified by a user.

### 5.2.2 Closed-loop-control-based Pricing Algorithm

A closed-loop-control-based algorithm is another method for adjusting the toll based on real-time traffic measurements. The toll for each subsequent time interval depends on the toll at the current interval, the current traffic density ( $TD$ ) and the critical or desired density ( $D_{cr}$ ). The procedure for determining the toll is described as follows:

- 1) Calculate average traffic density of the HOT lanes, denoted as  $TD(t)$ .
- 2) Calculate toll for the next time interval ( $R(t + 1)$ ) based on the following equation:

$$R(t + 1) = R(t) + K \times (TD(t) - D_{cr})$$

where  $R(t)$  is the current toll;  $K$  is a regulator parameter defined by a user. It is used to adjust the disturbance of the closed-loop control, that is, the effect of the difference between the measured traffic density and the critical density on the toll amount; and  $D_{cr}$  is the critical or desired density defined by a user.

- 3) Compare  $R(t + 1)$  with the minimum and maximum toll thresholds defined by the user. If  $R(t + 1)$  is less than the minimum threshold or greater than the maximum one, it takes the minimum or maximum threshold value.

In addition to those user-defined parameters mentioned above, the tolling interval  $t$  can also be specified by a CORSIM user.

### 5.2.3 Time-of-day Pricing Scheme

Time-of-day pricing is the third pricing scheme implemented in CORSIM for HOT lane operations. In this case, the toll is not determined based on real time traffic conditions. Instead, it follows a toll schedule predetermined by a user. This scheme is useful for freeway facilities that have stable traffic demand pattern during weekdays, for example.

In CORSIM implementation, multiple tolling periods (having different toll and durations) can be simulated. The number of tolling periods can be up to 24, and the duration of each tolling period varies from 3 to 60 minutes, with a toll amount ranging from \$0.00 to \$12.00. These values were selected based on the current practice where tolls are set based on the time-of-day pricing scheme. For instance, the toll on SR-91 in California changes every hour and its highest value is \$10.05.

### 5.3 Lane Choice

In the enhanced CORSIM, HOT and GP lanes are integrated as a single facility and lane-choice behaviors are simulated endogenously. Empirical studies (e.g., Sullivan, 2000; Lam and Small, 2001; Brownstone et al., 2003; Li, 2001; Burriss and Xu, 2006) showed that motorists' lane choice depends on many factors such as travel time saving, toll amount, travel time reliability, trip purpose, and travelers' characteristics (including income, age, gender and education). Implementing a sophisticated lane-choice model developed from those empirical studies (e.g., Lam and Small, 2001; Brownstone et al., 2003; Small et al., 2005a) in CORSIM is technically feasible. However, a model calibrated for one facility may not be transferable to another without calibration, which is often too costly to do for the new site. Even if the model is transferable, a CORSIM user would need to provide site-specific input data for many explanatory variables in the model, and such data are often not readily available. For these reasons, the lane-choice model selected for implementation within CORSIM is essentially based on a simple decision rule: motorists will pay to use HOT lanes if the benefit they perceive from travel time saving (TTS) is greater than the toll amount they are charged. The perceived benefit is the traveler's VOT multiplied by the perceived TTS, which is assumed to follow a truncated normal distribution whose mean is the real (actual) TTS (RTTS) and a standard deviation that can be customized by a CORSIM user. RTTS is the difference between travel times on GP and HOT lanes, averaged across a user-specified time interval and calculated internally by the software. The lane choice procedure for a particular vehicle, say  $j$ , that is approaching a warning sign upstream to a HOT lane entrance is illustrated in Figure 5-1.

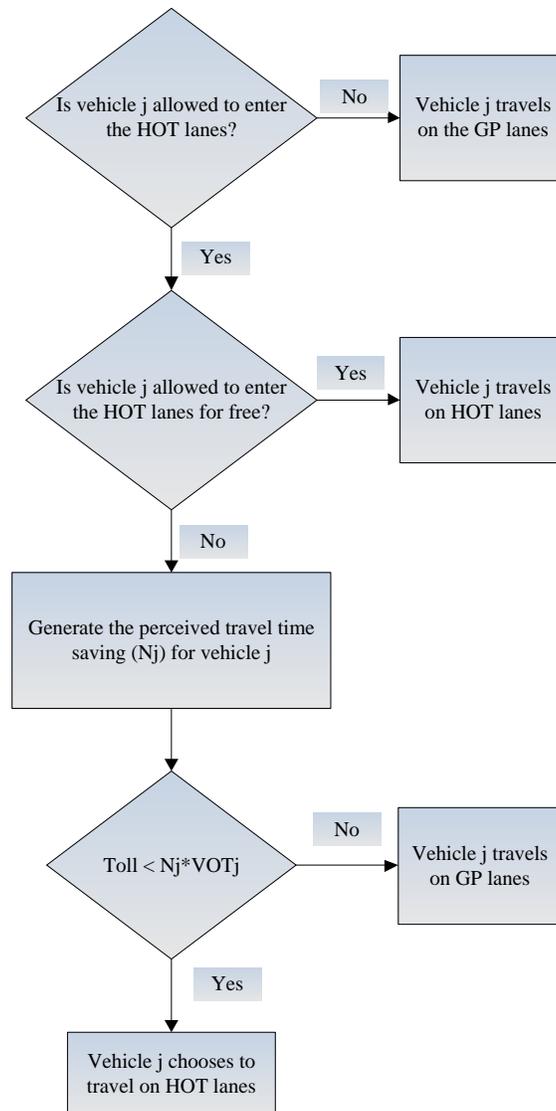


Figure 5-1. Drivers' lane choice in CORSIM

Previous studies (Miller, 1996; Small, 1982; Waters, 1982) suggested that the average VOT of an individual is about 50% of his or her wage rate while others (e.g., Small et al., 2005b; USDOT, 2003) pointed out that the VOT can be as high as 120% of the wage rate, depending on the length and type of travel. Moreover, Outwater and Kitchen (2008) suggested that the VOT of a vehicle representative increases as the vehicle occupancy increases. The increase of VOT between HOV 2 and HOV 3+ can range from 3.8% to 39.7%.

To capture variation of travelers' VOT in CORSIM, up to five different VOTs for each toll-paying vehicle type (including cars, HOV2, HOV3+ and trucks) can be specified by a user.

#### **5.4 Toll Structures**

Capturing different toll structures is very important in simulating multi-segment HOT lane facilities. Currently, all four toll structures implemented in practice; that is, zone-based, origin-specific, OD-based and distance-based, are fully implemented in CORSIM.

In a zone-based structure, the HOT lane facility is divided into zones. Each zone can have multiple entrances or exits. The toll is computed at the first entrance to a zone and will be assigned to all the entrances that belong to the same zone. When dynamic pricing (responsive or closed-loop-control-based) is implemented, the density used for toll calculation for a zone is the average of densities along the HOT lane segments in that zone. The total toll amount that a motorist pays will be the sum of toll amounts of the zones he or she traversed. Moreover, a driver will have to make a lane-choice decision every time he or she enters a new zone.

In an origin-specific structure, tolls are calculated for each entrance, and travelers simply pay the toll displayed upon first entering the HOT lanes. More precisely, a traveler pays the toll amount displayed on a sign at his or her entry point, regardless of how far the traveler intends to travel on the HOT lanes. Consequently, the traveler will only have to face the lane choice once. The toll at a specific HOT lane entrance is calculated based on the average of all densities on HOT lane segments between that entrance and the nearest HOT lane termination link (specified by the CORSIM user).

In an OD-based structure, the toll amount that motorists pay depends on where they enter and leave the HOT lanes; that is, it is based on their ingress and egress points. In this case, the prices to major exits are displayed at each entry point so that motorists can estimate approximately the price they have to pay. They can then decide whether they want to use the HOT lanes or not.

In a distance-based tolling, the toll a motorist is charged depends on the distance that he or she travels on the HOT lanes. The toll rate, that is, toll per mile, is the same for all HOT lane entry locations at a specific time interval. The entrance sign displays the minimum toll for entering the facility (the toll to the immediately downstream exit), the toll per mile, and the maximum toll for traveling to the end of the facility. In CORSIM, the toll calculation in distance-based tolling is similar to that within zone-based tolling. More specifically, a CORSIM user also needs to specify zones. Toll calculation also takes place at the first HOT entry link to each zone. To find the toll per mile, the toll is then divided by the length of the zone. The toll per mile is the same at all the entrances to the same zone, but can be different from zone to zone.

## **5.5 Summary**

CORSIM enhancement includes three HOT lane operations' components. The first includes three different pricing algorithms for the toll calculation. The second incorporates drivers' lane choice between the GP and HOT lanes after the toll is set. The third applies a toll structure to multi-segment HOT lanes facilities. The enhanced CORSIM evaluation is presented in the next chapter. Appendix A provides a user guide on how to simulate HOT lanes in CORSIM.

## CHAPTER 6 EVALUATION OF THE ENHANCED CORSIM

This chapter consists of two parts. In the first part, the northbound direction of the current (Phase 1) 95 Express is simulated to evaluate the accuracy of the enhanced CORSIM and the optimized 95 pricing algorithm presented in Chapter 3 is evaluated using the calibrated current 95 Express. In the second part, the future (Phases 1 and 2) 95 Express is simulated to test the ability of the enhanced CORSIM to simulate multi-segment HOT lanes and evaluate the performance of the different toll structures on the facility.

### **6.1 Simulating the Current 95 Express**

In order to demonstrate the ability of the enhanced CORSIM to simulate single-segment facilities, the northbound direction of the current 95 Express (Figure 4-2) was simulated. The data used in the simulation were obtained from the STEWARD database every fifteen minutes between May 10 and 12, 2011 (Tuesday, Wednesday, and Thursday). On those days, the data from most detectors were available and there were no special events. Based on the 95 Express Monthly Operations Report of May 2011 (FDOT, 2011), the peak period was 4:00-7:00pm for the northbound direction. We thus calibrated our model against this time period and an additional thirty minutes were used for initialization.

Table 6-1 compares the reported performance statistics of the northbound direction of the 95 Express (95 Express Monthly Operations Report of May 2011) with the simulated performance statistics obtained from the CORSIM simulation.

It can be observed that the simulation model replicates the major performance measures closely. In the simulation, the actual TTS were calculated by CORSIM every

minute and were then used for lane-choice decisions in the next minute. Also, the standard deviation of the perceived TTS distribution was assumed to be half of the actual TTS. In order to achieve the lane distribution between the HOT and GP lanes on the 95 Express network, drivers' VOT had to be calibrated. The calibrated VOT for the 95 Express network is shown in Table 6-2. The "percent of vehicles" columns represent the percentage of vehicles that have VOT equal to the value shown in the adjacent cell. For example, 10% of the cars have a VOT equal to \$8 per hour and 10% of the HOV2s have VOT equal to \$10 per hour.

Table 6-1. Comparison of performance statistics for northbound PM peak period

	Simulation model		Reported (May 2011)	
Tolls				
Range	\$0.25 - \$5.75		\$0.00 - \$5.50	
Avg. peak period	\$2.17		\$2.12	
	HOT	GP	HOT	GP
Avg speed (mph)	57	49	58	46
HOT Lanes operated above 45 mph	99.6%		99.7%	

The calibrated VOT values shown in Table 6-2 appear to be consistent with findings in the literature. The average VOT is about 75% of the average wage rate in the Miami/Fort Lauderdale area (Bureau of Labor Statistics, 2011), and is thus considered to be reasonable. An increase of 20% from HOV2 to that of HOV3+ also appears to be reasonable. It should be emphasized that another set of VOT values may also yield a good match. As Phase 1 of the 95 Express has been fully operational for almost two years, drivers of the corridor have become familiar with the system. A behavioral study can be conducted to better understand the factors that affect drivers' decisions whether or not to use the HOT lanes and estimate their travel time values for the I-95 corridor or

in South Florida. The study will provide much valuable information for the planning and operations of the future HOT network in the region.

The lane choice model in CORSIM was applied only to toll-paying vehicles; although there are some toll-exempt vehicles on the 95 Express, including public transit, hybrid vehicles, and vehicles registered as HOV 3+. The types and percentages of the toll-exempt vehicles can be specified in CORSIM. According to the 95 Express Monthly Operations Report of May 2011, approximately 11% of the HOT traffic is toll exempted.

## **6.2 Evaluation of Optimized DST for 95 Express Tolling Algorithm Using CORSIM**

A GA-based optimization procedure to optimize pricing algorithms for HOT lanes was presented in Chapter 3. The 95 Express tolling algorithm was used as a case to demonstrate the GA procedure and the optimized algorithm parameters were obtained by macroscopic simulation. In order to further examine and evaluate the performance of the optimized DSTs, described in section 3.2.5, as well as compare it to that of the original DST, the calibrated CORSIM simulation model of the current 95 Express was used. The simulation results for both the base and 5% increased demand scenario are summarized in Table 6-2.

The following observations can be made from the CORSIM simulation studies. The original and optimized DSTs give comparable performances in both demand scenarios. They both effectively achieve the operating objectives of the 95 Express. In the increased demand scenario, the optimized DSTs slightly increases the speed reliability, but charges a higher average toll. However, the highest toll value does not go beyond \$5.00, while the original DST charges up to \$7.00.

Table 6-2. Comparison of optimized and original DSTs

	Original		Optimized	
Base demand				
Tolls				
Range	\$0.25 - \$5.75		\$0.25 - \$5.50	
Avg. peak period	\$2.17		\$2.12	
	HOT	GP	HOT	GP
Avg speed (mph)	57.20	49.10	58.61	46.23
HOT lanes operated above 45 mph	99.6%		99.7%	
5% demand increase				
Tolls				
Range	\$0.25 - \$7.00		\$0.25 - \$5.00	
Avg. peak period	\$2.07		\$2.87	
	HOT	GP	HOT	GP
Avg speed (mph)	56.55	47.62	56.83	46.00
HOT lanes operated above 45 mph	95.3%		97.7%	

The optimized DSTs do not appear to produce much noticeable improvement in the CORSIM simulation. This is due to the discrepancy between the Matlab macroscopic simulation tool used for the optimization and CORSIM. If the latter is incorporated into the GA procedure, more substantial improvement can be expected, although a CORSIM-based GA optimization would be very time consuming, yet it remains feasible to utilize a parallel-computing framework to expedite the optimization process.

### 6.3 Simulating the Future 95 Express

The evaluation of CORSIM's ability to simulate multi-segment toll structures is presented in this section. For the demonstration, the northbound direction of the future 95 Express is simulated. The data used for the simulation and calibration were obtained

from the STEWARD database every fifteen minutes for three weekdays, May 10-12, 2011, for all the detectors along the future 95 Express corridor.

Figure 6-1 shows the major entrances from the GP lanes to the HOT lanes, and exits from the HOT lanes back to the GP lanes. Along the HOT lane network, there are nine input-output (I-O) pairs. The simulation results, including the toll range, average toll, GP and HOT lanes' average speeds, and reliability of the HOT lanes for each toll structure are presented for each I-O pair in Tables 6-4 to 6-7. I1-O4 represents the entire facility, extending from SR-836/I-395 to Broward Boulevard. In all toll structures that were tested, tolls were calculated from the tolling algorithm currently implemented on the 95 Express.

### **6.3.1 Zone-based Toll Structure**

Zone-based tolling, as described in Chapter 4, is one of the easiest toll structures to implement. The facility is divided into zones so that each zone includes only one main entrance to HOT lanes, and one toll gantry. This leads to three zones in the northbound direction. I1-O1 represents Zone 1 which is from SR-836/I-395 to the Golden Glades Interchange, I2-O2 represents Zone 2 which starts north of the Golden Glades Interchange and ends at Griffin Road, and I3-O4 is Zone 3 which extends from Ives Dairy Road to the end of the facility at Broward Boulevard. In Table 6-3 the facility performance measures under zone-based tolling are presented. Results indicate that the facility can be effectively managed using a zone-based toll structure. The average toll is \$1.41, \$0.25, and \$0.27 for the first, second, and third zone, respectively. The toll values for both Zone 2 and 3 are equal to the minimum toll for most time intervals, because these zones did not appear to be congested in CORSIM.



Figure 6-1. Entrances and exits of the Future 95 Express northbound direction (Source: [http://www.95express.com/images/2011\\_11\\_Phase%202\\_Alternative%201\\_EntryExit\\_Handout.jpg](http://www.95express.com/images/2011_11_Phase%202_Alternative%201_EntryExit_Handout.jpg))

On the other hand, there is some congestion in Zone 1, with the average speed on the GP lanes being approximately 40 mph. A toll for Zone 1 can reach up to \$2.75. A motorist who travels through the entire HOT lane facility will have to pay on average a total of \$1.93.

### **6.3.2 Origin-specific Toll Structure**

Table 6-4 presents the performance measures of the origin-specific tolling on the future 95 Express. The HOT lanes can be effectively managed with this type of charging, but there are equality issues among the motorists. A motorist who is traveling from I1 to O1, a 7.3 mile stretch, will pay the same amount of toll as someone who is traveling through the entire facility, I1-O4, which is about 21.0 miles long. This implies that the driver who travels from I1 to O1 will pay a toll rate of \$0.42/mile while the driver who travels from I1 to O4 will pay a rate of \$0.15/mile. However, this structure, is easy to implement and convenient for users, because they pay just once to use the facility. In this structure, the average toll a motorist pays to travel the entire facility is \$3.13, which is about \$1.00 higher than under the three-zone toll structure. In the latter, each zone is managed as a single HOT lane facility, and thus each toll is not very high. In contrast, with origin-based tolling, tolls at the first entrance need to be much higher, to ensure superior flow conditions on HOT lanes along the entire facility.

Table 6-3. Value of time (\$/hr)

	percent vehicles	VOT	Weighted Average								
Cars	10	8	15	10	50	16	15	18	10	22	15.2
HOV 2	10	10	15	12	50	19	15	22	10	26	18.2
HOV 3+ not registered	10	12	15	14	50	23	15	26	10	31	21.8

Table 6-4. Performance measures of Future 95 Express under zone-based tolling

	I1-O1		I1-O2		I1-O3		I1-O4/ facility		I2-O2		I2-O3		I2-O4		I3-O3		I3-O4	
Toll range (\$)	0.25 - 2.75		0.50 - 3.00		0.75 - 3.25		0.75 - 3.25		0.25 - 0.25		0.50 - 0.75		0.50 - 0.75		0.25 - 0.50		0.25 - 0.50	
Avg. peak Period toll	\$1.41		\$1.66		\$1.93		\$1.93		\$0.25		\$0.52		\$0.52		\$0.27		\$0.27	
Avg speed (mph)	HOT	GP	HOT	GP	HOT	GP	HOT	GP	HOT	GP	HOT	GP	HOT	GP	HOT	GP	HOT	GP
	56.1	40.1	56.9	43.0	60.6	52.3	61.1	54.1	60.0	53.8	64.4	60.8	64.6	61.3	66.0	62.9	65.8	62.8
HOT lanes operated above 45 mph	99.9%		99.9%		100%		100%		100%		100%		100%		100%		100%	

Table 6-5. Performance measures of Future 95 Express under origin-based tolling

	I1-O1		I1-O2		I1-O3		I1-O4/ facility		I2-O2		I2-O3		I2-O4		I3-O3		I3-O4	
Toll range (\$)	1.00 - 6.25		1.00 - 6.25		1.00 - 6.25		1.00 - 6.25		0.50 - 0.50		0.50 - 0.50		0.50 - 0.50		0.25 - 0.25		0.25 - 0.25	
Avg. peak Period toll	\$3.13		\$3.13		\$3.13		\$3.13		\$0.50		\$0.50		\$0.50		\$0.25		\$0.25	
Avg speed (mph)	HOT	GP	HOT	GP	HOT	GP	HOT	GP	HOT	GP	HOT	GP	HOT	GP	HOT	GP	HOT	GP
	56.1	42.7	56.9	45.0	60.6	53.5	61.2	55.2	59.9	53.9	64.5	61.1	64.6	61.6	65.7	63.0	65.6	62.9
HOT lanes operated above 45 mph	99.9%		99.9%		99.9%		99.9%		100%		100%		100%		100%		100%	

Table 6-6. Performance measures of Future 95 Express under OD-based tolling

	I1-O1		I1-O2		I1-O3		I1-O4/ facility		I2-O2		I2-O3		I2-O4		I3-O3		I3-O4	
Toll range (\$)	0.50 - 4.00		1.50 - 5.00		1.50 - 5.00		1.75 - 5.25		0.75 - 0.75		1.00 - 1.00		1.00 - 1.00		0.25 - 0.25		0.25 - 0.25	
Avg. peak Period toll	\$2.08		\$3.08		\$3.25		\$3.39		\$0.75		\$1.00		\$1.00		\$0.25		\$0.25	
	HOT	GP	HOT	GP	HOT	GP	HOT	GP	HOT	GP	HOT	GP	HOT	GP	HOT	GP	HOT	GP
Avg speed (mph)	56.1	38.6	56.8	41.8	60.7	51.7	61.2	53.7	60.1	53.8	64.7	60.8	64.8	61.3	66.0	63.0	65.8	62.8
HOT lanes operated above 45 mph	99.8%		99.8%		99.9%		99.9%		100%		100%		100%		100%		100%	

Table 6-7. Performance measures of Future 95 Express under distance-based tolling

	I1-O1		I1-O2		I1-O3		I1-O4/ facility		I2-O2		I2-O3		I2-O4		I3-O3		I3-O4	
Toll range (\$)	0.75 - 2.25		1.00 - 3.00		1.50 - 5.00		2.25 - 6.50		0.25 - 0.50		0.75 - 2.50		1.25 - 4.00		0.50 - 1.25		0.75 - 2.50	
Avg. peak Period toll	\$1.09		\$1.41		\$2.45		\$3.13		\$0.27		\$1.23		\$1.00		\$0.63		\$1.18	
	HOT	GP	HOT	GP	HOT	GP	HOT	GP	HOT	GP	HOT	GP	HOT	GP	HOT	GP	HOT	GP
Avg speed (mph)	56.0	43.2	56.9	45.4	60.2	53.7	61.1	55.3	59.7	53.9	64.4	61.1	64.6	61.7	65.7	63.0	65.6	63.0
HOT lanes operated above 45 mph	99.8%		99.8%		99.9%		99.9%		100%		100%		100%		100%		100%	

### **6.3.3 OD-based Toll Structure**

In an OD-based structure, the tolls are calculated for each different OD pair. The results for this structure are given in Table 6-5. As stated earlier, the responsive tolling algorithm was applied when testing all toll structures. However, ideally, a more sophisticated tolling algorithm should be developed to charge users based on their origins and destinations. This would help to maintain desired traffic conditions on the express lanes, and would help to fully utilize express lanes' available capacity, without creating excessive inequality among different OD pairs. In this case, the toll per mile is different for every OD pair. More precisely, the average toll per mile is \$0.28, \$0.38, \$0.20, \$0.16, \$ 0.49, \$0.12, \$0.08, \$0.07, and \$0.03 for I1-O1, I1-O2, I1-O3, I1-O4, I2-O2, I2-O3, I2-O4, I3-O3, and I3-O4, respectively, which may also cause some equity concerns among the drivers.

### **6.3.4 Distance-based Toll Structure**

In the distance-based structure, a toll rate for the entire HOT lane facility is set. Drivers are charged that rate multiplied by the number of miles they have traveled on the facility. This should result in less equity concern, but the structure might fail to maintain desired traffic conditions on the HOT lanes. Table 6-6 shows the results when distance-based tolling is implemented to the future 95 Express. The average toll rate for the simulated period is \$0.15 per mile, and the toll for traveling between each OD pair is different as each OD has a different length. Because the facility is not very congested, the distance-based structure was able to maintain superior LOS on the HOT lanes.

### **6.3.5 Toll Variation**

The toll variation for the entire facility for each toll structure is illustrated in Figure 6-2. In the zone-based model, the toll a motorist has to pay to travel through the entire

HOT lane facility is calculated as the summation of the tolls for each individual zone. In the origin-specific structure, the toll to travel the entire facility is equal to the toll at the first entrance. In the OD-based structure, it is equal to the toll per mile at the first entrance multiplied by the total number of miles of the facility, while in the distance-based structure, it is also calculated by multiplying the toll per mile at the first entrance by the entire length of the HOT lane facility. The toll pattern is the same for all the structures except for the origin-specific structure. The origin-specific toll pattern has high fluctuations at some time intervals. For example, at time interval 7, the toll increases from \$1.25 to \$6.25, while in the next time interval the toll drops from \$6.25 to \$2.25. This could be caused by the increased number of travelers who choose to enter the HOT lanes at the first entrance and travel through the entire facility as they have to pay only once. In general, motorists pay less total toll amount when the zone-based structure is applied.

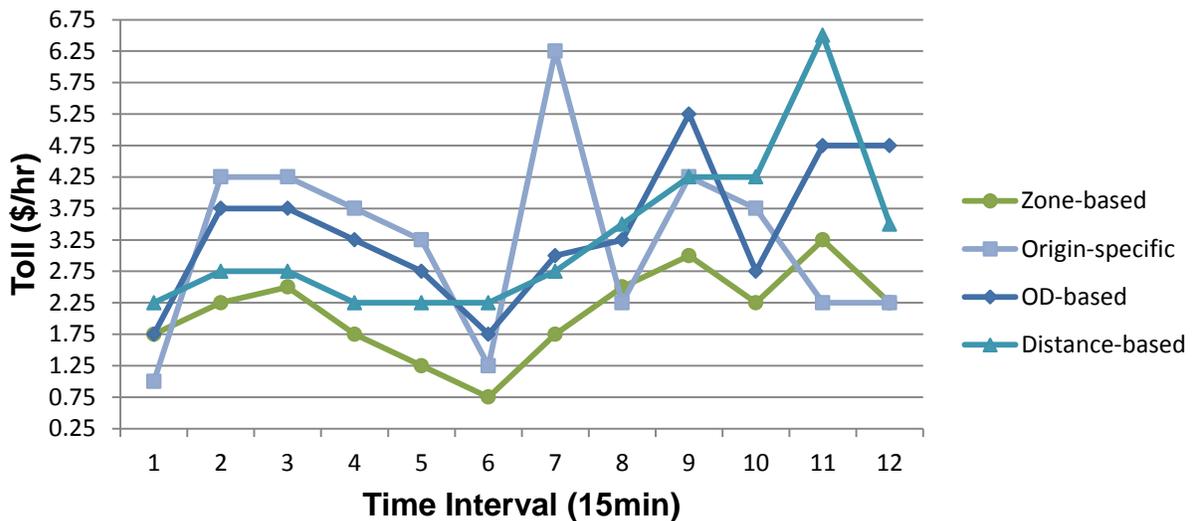


Figure 6-2. Average toll by toll structure

## 6.4 Summary

In summary, CORSIM was enhanced to simulate both single-segment and multi-segment HOT lane facilities. The current 95 Express was simulated to demonstrate CORSIM's ability to replicate the operations of a single-segment HOT lane facility while the future 95 Express was simulated to show that CORSIM can adequately simulate the HOT lane operation components and different toll structures for multi-segment HOT lanes. All four toll structures for multi-segment HOT lanes were simulated. In addition, the zone-based toll structure was recommended for the future 95 Express. The recommendation was made based on the advantages and disadvantages of the toll structures. However, one should not use the results presented in this chapter to compare toll structures and draw a conclusion on which particular toll structure outperforms the other. This is because the toll rates are not optimized against each structure, and the results could differ with the type and design of each HOT lane facility.

## CHAPTER 7 SUMMARY AND CONCLUSIONS

This dissertation focuses on enhancing and evaluating dynamic pricing strategies for managed lane facilities. Initially, a thorough literature review of the managed lanes operation components, including pricing algorithms, current practice of single-segment and multi-segment HOT lane facilities, and lane choice models, was conducted. Different simulation programs that can be used to simulate HOT lanes were also reviewed.

The majority of the pricing algorithms currently implemented in practice are heuristic, so the toll rates they produce can be further optimized against the network traffic conditions. For this purpose, a GA-based optimization framework for fine-tuning practical pricing algorithms was developed in this dissertation. In order to validate the optimization framework, the pricing algorithm currently implemented on the 95 Express in South Florida was optimized. The GA optimization procedure was implemented in Matlab. The simulation experiments demonstrated that the procedure produces good results and yields improvements. In order to achieve more noticeable improvements, it will be necessary to incorporate a microscopic simulation platform that is able to simulate HOT lane operations, like CORSIM, into the GA procedure. Further research is needed to improve the computational efficiency of the microscopic simulation-based GA optimization procedure.

The current practice of managing multi-segment HOT lanes facilities showed that there are four different methods (i.e., zone-based, origin-specific, OD-based, and distance-based) to charge the low occupancy vehicles that use the HOT lanes. Each toll

structure has advantages and disadvantages and the selection of one over the others highly depends on the local conditions and the goals of the HOT lanes operator.

As the implementation of HOT lanes is becoming more accepted and popular in the U.S., a traffic simulation tool that can replicate the HOT lane operations is very useful in designing and evaluating managed lanes operation strategies. Our literature review indicates that there is not any software presently on the market that can fully simulate the different components of HOT lanes. Therefore, this research also enhanced microscopic simulator CORSIM to simulate all the functions of HOT lanes. More specifically, three main components were developed. They comprise three pricing strategies, a lane-choice module, and four toll structures for multi-segment HOT facilities. The CORSIM enhancements were demonstrated by simulating the current and future 95 Express in South Florida. Using data from the current 95 Express, the simulation was calibrated to provide a good match with the actual operation performance measures. The experiments showed that the CORSIM enhancements appear to be able to capture the primary characteristics of HOT lane operations and management. Then, CORSIM's ability to simulate multi-segment HOT lane facilities was demonstrated by simulating all four toll structures on the future 95 Express which will be a multi-segment facility by the end of 2014.

## APPENDIX A SIMULATING HOT LANES IN CORSIM

This appendix provides a guide on how to use CORSIM to simulate a HOT lane network. It describes all the steps in coding a network, selecting a pricing algorithm, inputting drivers' lane-choice parameters and specifying the toll structure for multi-segment HOT lane facilities. When drafting this appendix, it was assumed that readers are already familiar with using CORSIM to simulate a regular freeway network.

The steps for simulating HOT lanes in CORSIM are shown in Figure A-1 and are described in detail in the following sections.

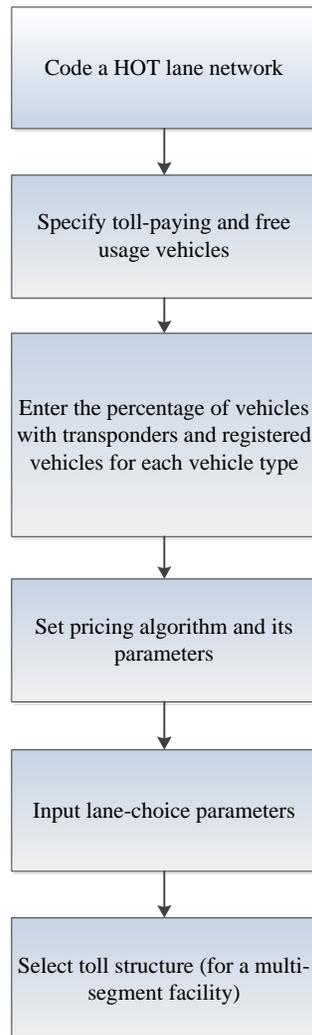


Figure A-1. HOT lane simulation in CORSIM

## A.1 Coding HOT Lane Network

The first step in simulating a HOT-lane facility in CORSIM is to code a HOT lane network, that is, specify the links of a freeway network where HOT lanes are present. There are three HOT lane use codes that can be placed on a link, as shown in Figure A-2. A HOT entry link is placed to represent a HOT-lane entrance where vehicles first enter the HOT lanes; HOT continuation links are then placed downstream to a HOT entry link; and a HOT termination link is used to indicate the end of the HOT-lane segment or facility. The HOT termination link also indicates the last link whose density will be used for the average density calculation for toll determination, as explained later in this appendix. For each HOT lane use code, Figure A-1 presents two types of HOT lanes: non-exclusive/concurrent and exclusive. Exclusive HOT continuation links can be placed along the links/sections where vehicles are neither allowed to enter nor to exit the HOT lanes, while the non-exclusive counterparts are to indicate that vehicles are allowed to exit, but not enter, the HOT lanes. Apparently, even though the two types of HOT lanes are available for all the HOT lane use codes, the only type that is reasonable for HOT entry and HOT termination links is the non-exclusive one. Finally, HOT lanes can be placed either at the left or the right side of the freeway.

After specifying the lane-use code for each HOT lane link, the lane characteristics should be input. The HOT lane characteristics introduced in the following paragraphs, including toll-paying and free usage vehicles, pricing algorithm, and all the parameters associated with the selected pricing algorithm, are specified only for HOT entry links.

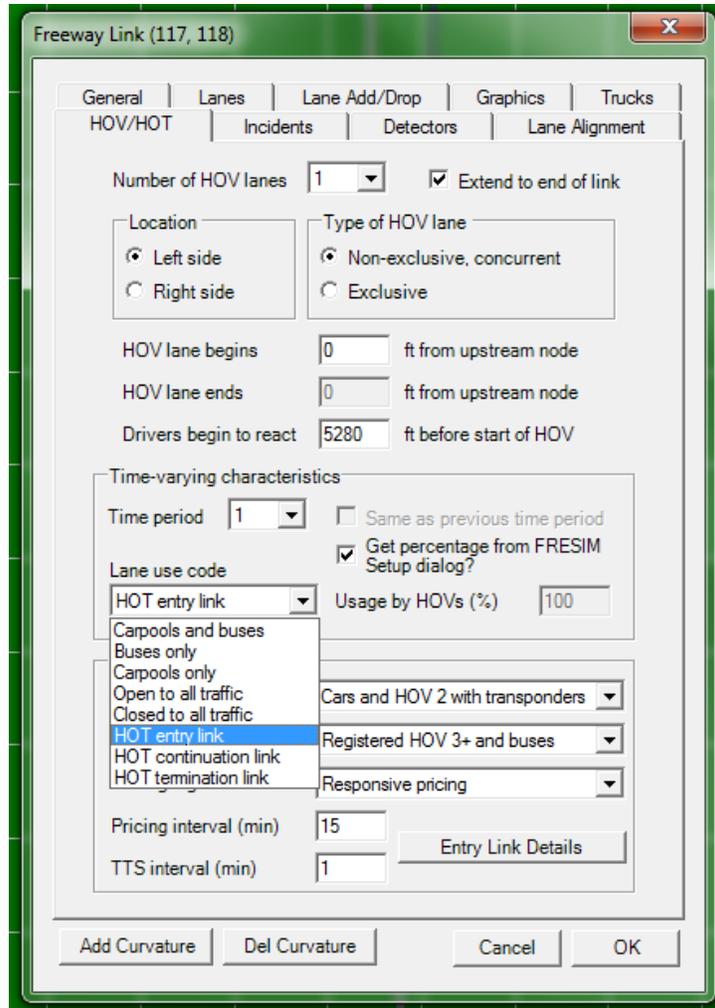


Figure A-2. HOT/HOV lane use codes

First, the vehicles that are allowed to access the HOT lanes either by paying or for free should be specified. CORSIM has the following options for these vehicle groups

(See Figure A-3 and Figure A-4):

- Toll-paying vehicles
  - Cars with transponders
  - Cars and HOV 2 with transponders
  - All vehicles with transponders
  - All traffic
  - Closed to all traffic
- Free usage vehicles
  - Registered HOV 2, Registered HOV 3+ and Buses
  - Registered HOV 3+ and Buses
  - All HOV 2, all HOV 3+ and Buses

- All HOV 3+ and Buses
- Only registered HOV 3+
- Only Buses
- All traffic except trucks
- All traffic
- Closed to all traffic

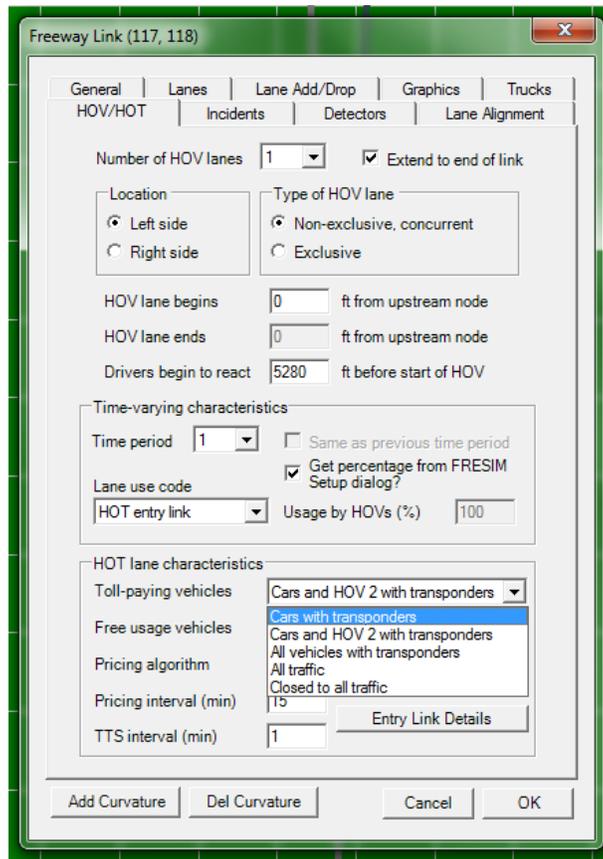


Figure A-3. Toll-paying vehicles

Since toll collection on the HOT lanes is conducted electronically, among toll-paying vehicles, only those equipped with a transponder can legally enter the HOT lanes. The percentage of such vehicles for each vehicle type can be entered in CORSIM. The free usage vehicles are not required to have a transponder to use the HOT lanes but they may need to register. Registered vehicles are those that are registered to the HOT-lane authority to use the facility without paying a toll. The HOT

lane authority specifies which vehicles are eligible for registration and also the registration process and requirements. Eligible vehicles for registration can be cars with two or more occupants, buses, and others. Not every HOT lane operator requires vehicles to register in order to be toll-exempt. However, if the HOT lane authority has such requirement, all non-registered vehicles are expected to pay to enter the HOT lanes.

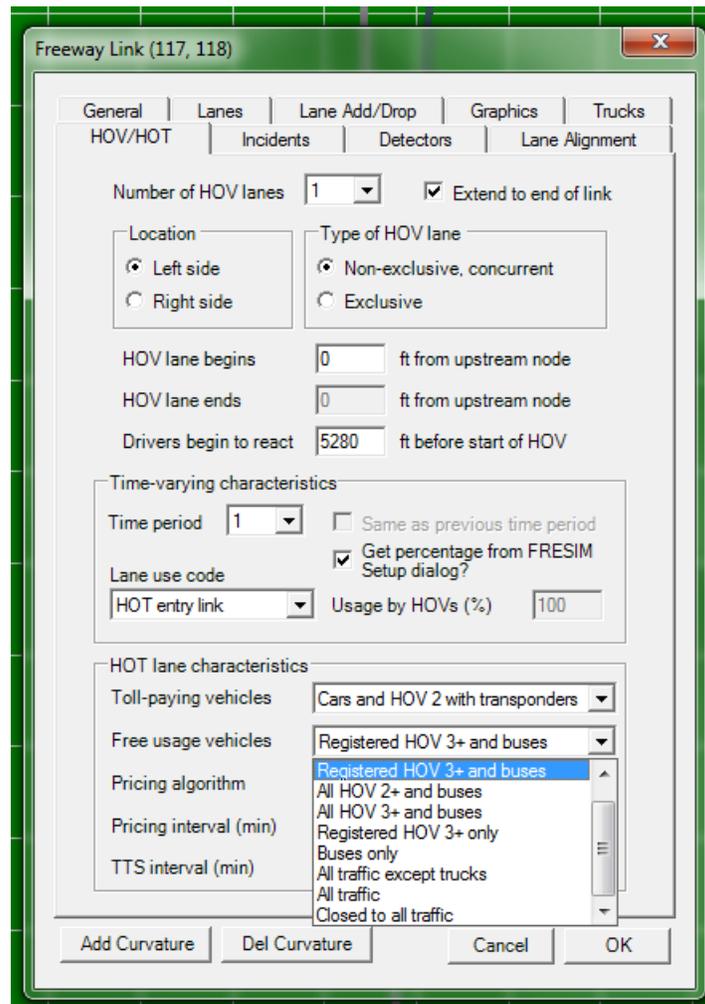


Figure A-4. Free usage vehicles

Both the percentage of vehicles with transponders and registered vehicles for each vehicle type can be input under Edit -> Global -> Network Properties -> Vehicle Types, as illustrated in Figure A-5 and Figure A-6.

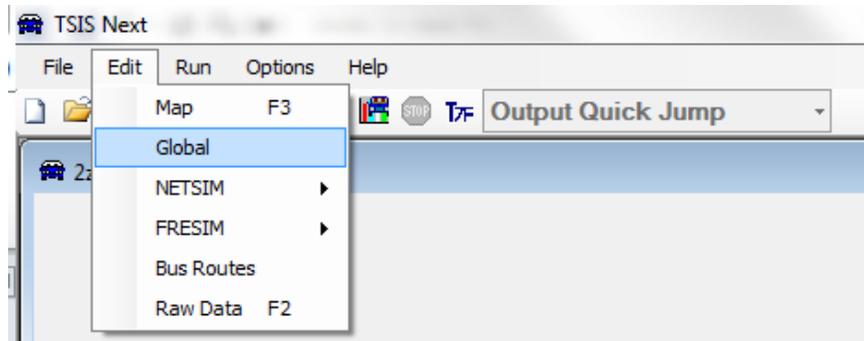


Figure A-5. Specifying network properties in TSIS Next

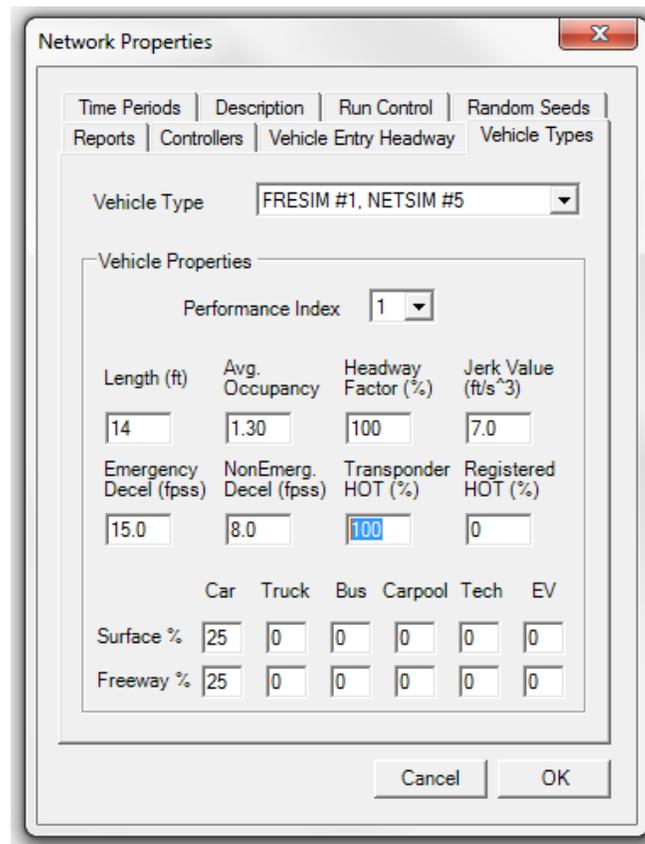


Figure A-6. Transponder and registered percentage input

### A.2 Setting the Pricing Algorithm

After all the parameters mentioned above are set, the pricing algorithm and the corresponding pricing interval (in minutes) for toll calculation should be selected. The former specifies how a toll amount is computed, while the latter indicates how often the

toll amount will be calculated and updated. In CORSIM, three different pricing algorithms are implemented, as shown in Figure A-7.

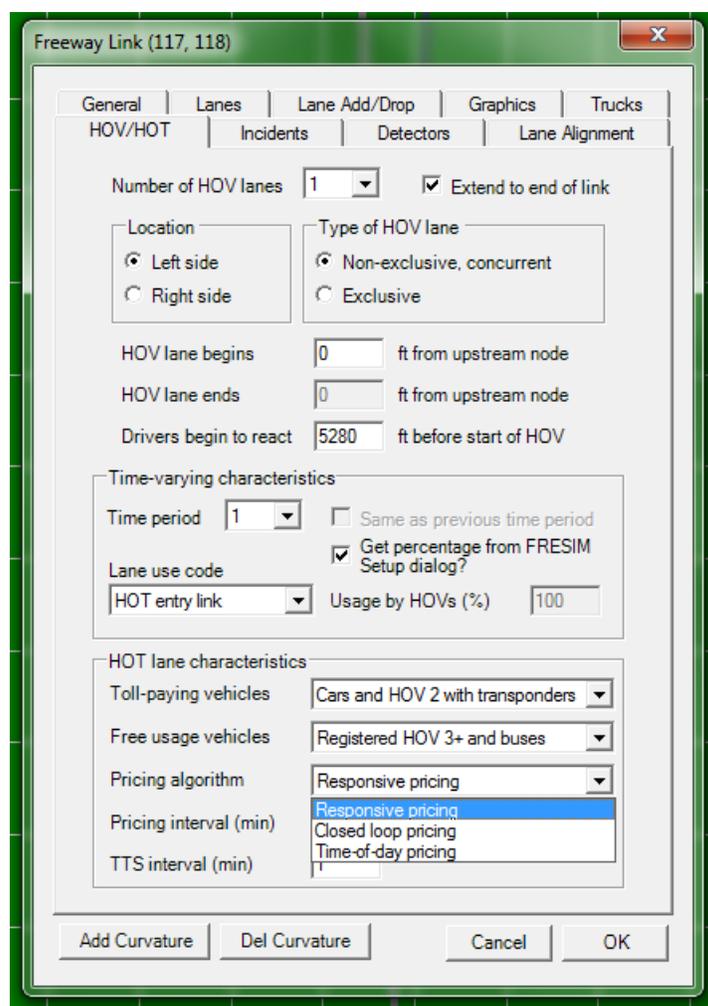


Figure A-7. Pricing algorithms available in CORSIM

The first is a so-called responsive pricing, which is a methodology for determining toll amounts based on the current HOT lane conditions to manage the HOT traffic demand and maintain free-flow conditions on HOT lanes. In responsive pricing, the performance measure used to calculate the toll is traffic density ( $TD$ ). The steps for the toll determination are the following:

- 1)  $TD$  is calculated for each HOT lane link and further averaged for each HOT lane segment for every toll interval.  $TD$  is then rounded to an integer and multiplied by an alpha parameter, which adjusts the calculated  $TD$  to reflect segment-specific

conditions, such as weaving areas and geometric conditions. The default alpha parameter is set to one, implying no impact on the  $TD$  calculation. The alpha value can be specified under the model parameters tab (Figure A-10);

- 2)  $TD$  calculated for the previous time interval is subtracted from  $TD$  of the current interval to determine the change in  $TD$  ( $\Delta TD$ );
- 3) Using the Delta Settings Table (Figure A-8), a toll change is determined. The toll change is either added or subtracted to the toll of the previous interval to calculate the current toll. All the parameters in the Delta Settings Table are user modifiable;
- 4) The toll is compared with the minimum and maximum toll values in the LOS setting table (table on the left in Figure A-9). If the toll is outside the acceptable toll range for the corresponding  $TD$ , the maximum or minimum toll is applied correspondingly. Again, the toll intervals for each LOS are user modifiable.

	-6	-5	-4	-3	-2	-1	+1	+2	+3	+4	+5	+6
0	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
1	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
2	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
3	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
4	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
5	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
6	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
7	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
8	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
9	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
10	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	-\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
11	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25	\$0.25
12	-\$1.25	-\$1.00	-\$0.75	-\$0.50	-\$0.25	-\$0.25	\$0.25	\$0.25	\$0.25	\$0.50	\$0.50	\$0.50

Figure A-8. Delta settings table for responsive pricing

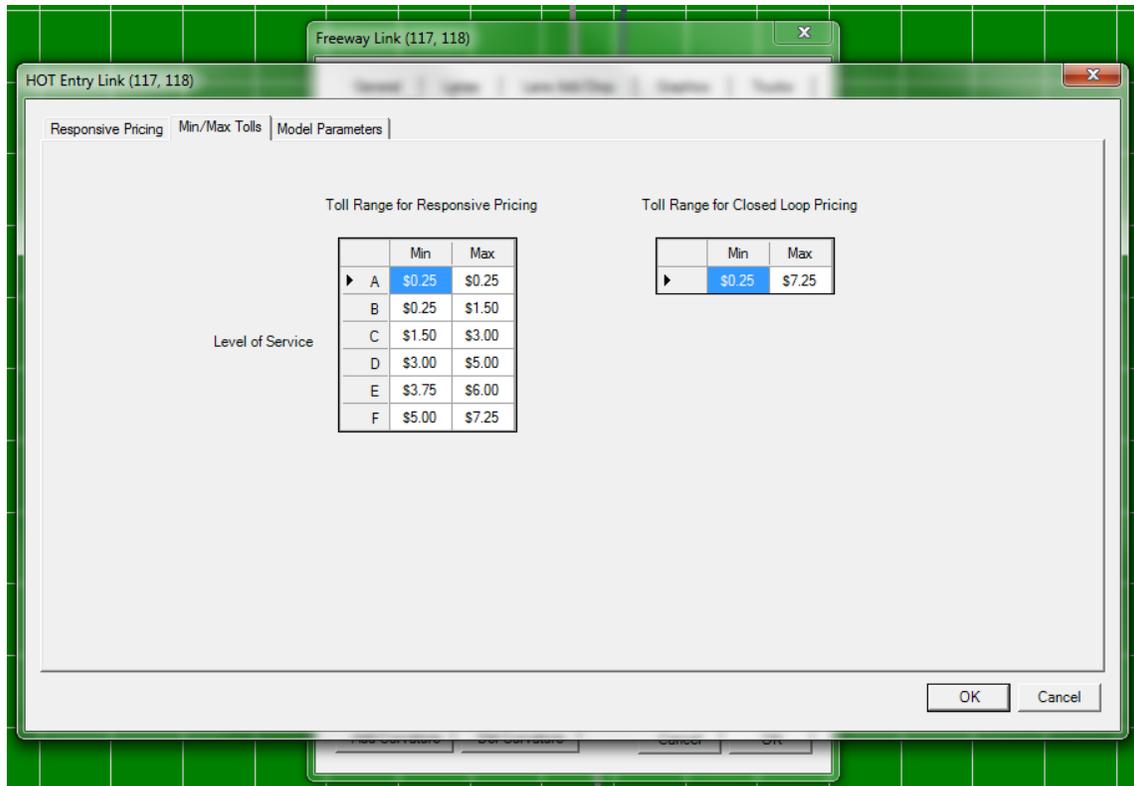


Figure A-9. Minimum and maximum toll values for responsive and closed-loop-control-based pricing algorithms

The second pricing algorithm is a so-called closed-loop-control-based approach that also determines toll values based on real-time traffic conditions. In this approach, the toll value at the current time interval depends on the toll at the previous interval, the traffic density ( $TD$ ) at the current time interval and the critical or desired density, denoted as  $D_{cr}$ . The steps for the toll determination are described below:

- 1) Calculate  $TD$  as in responsive pricing;
- 2) The toll for the next time interval is calculated as follows:
- 3)  $R(t + 1) = R(t) + K \times (TD(t) - D_{cr})$

where  $R(t)$  is the current toll; and  $K$  is a regulator parameter defined by the user under the model parameters tab (Figure A-10).  $K$  is used to adjust the disturbance in the closed-loop control, that is, the effect of the difference between the measured traffic density and the critical density on the toll amount.  $D_{cr}$  is the critical or desired density defined also by the user under the model parameters tab (Figure A-10).  $R(t + 1)$  is rounded to the closest quarter.

- 4) Compare  $R(t + 1)$  with the minimum and maximum toll values defined by the user (table on the right in Figure A-9). If  $R(t + 1)$  is less than the minimum value or greater than the maximum value, then it takes the minimum or maximum value respectively.

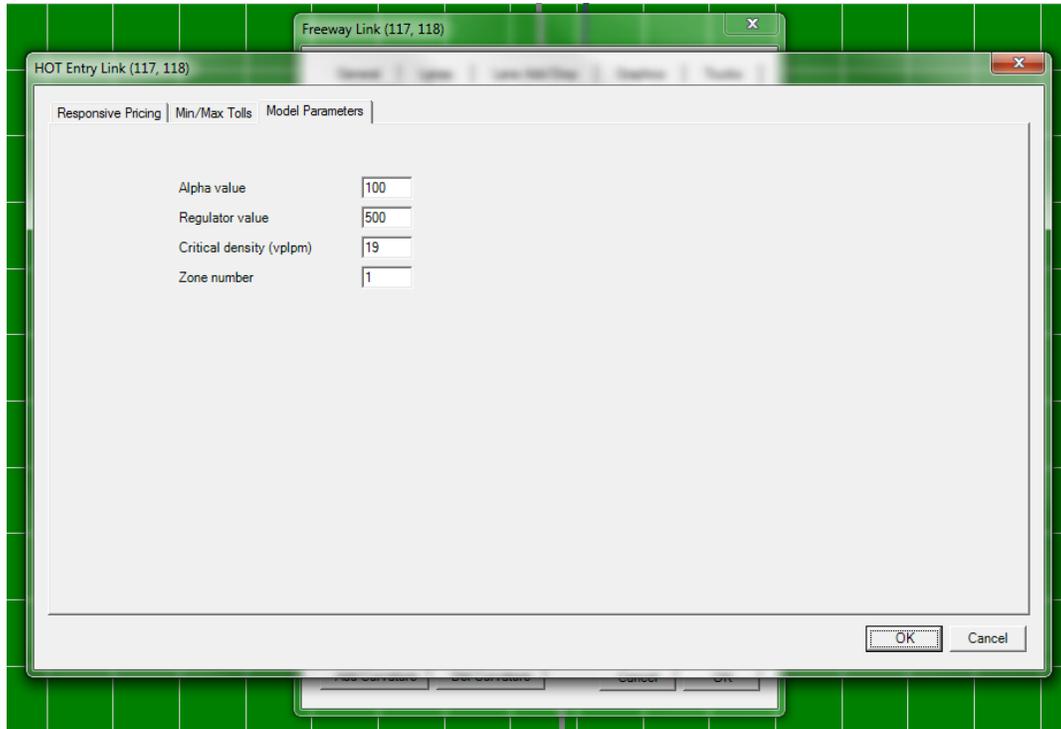


Figure A-10. Model parameters for pricing algorithms

The third pricing scheme that can be selected in CORSIM is time-of-day pricing. As its name suggests, the toll value is not determined in real time in this approach. Instead, it varies according to a toll schedule pre-defined by users. This scheme is useful for freeway facilities that have similar traffic pattern, for example, on weekdays. In CORSIM, the number of tolling intervals can be up to 24, and the duration of each interval varies from 3 to 60 minutes, with a toll amount varying from \$0.00 to \$12.00. The inputs for time-of-day pricing are shown in Figure A-11:

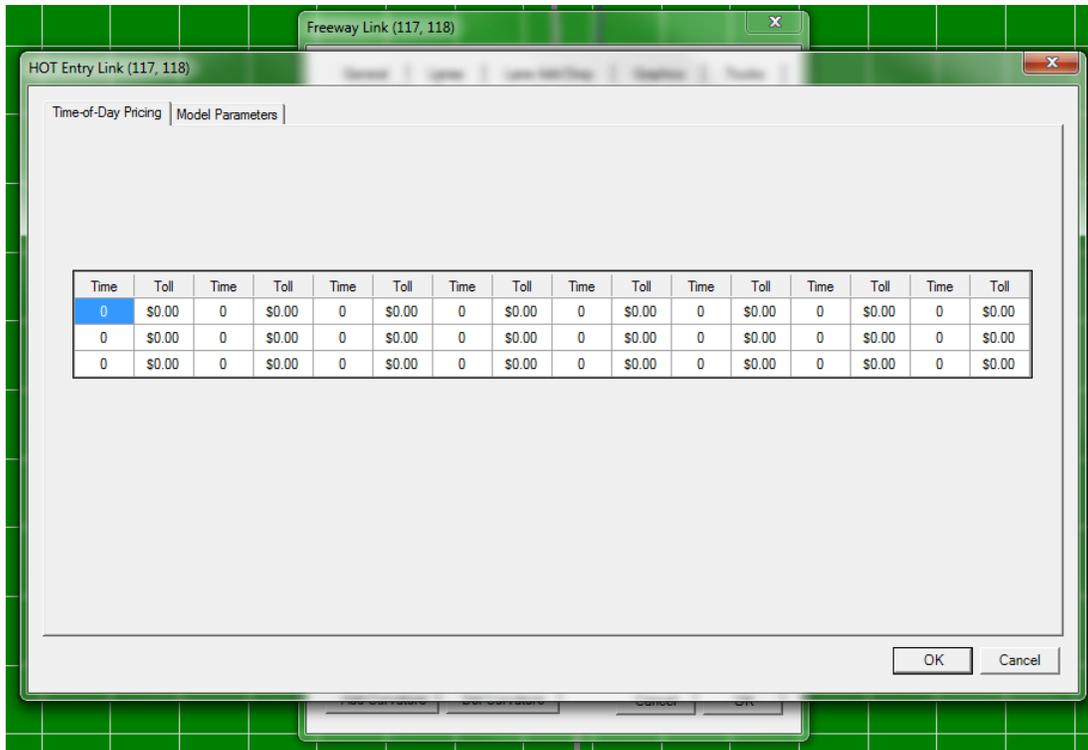


Figure A-11. Time-of-day pricing

### A.3 Lane Choice Parameters

After the toll amount is calculated using one of the pricing algorithms, drivers' lane choice between the HOT and the GP lanes is simulated in CORSIM. The lane-choice model implemented is based on a decision rule that motorists will pay to use the HOT lanes if the benefit they perceive from the travel time savings (TTS) is greater than the toll they are charged. The perceived benefit is the value of time (VOT) of the traveler multiplied by the perceived TTS, which is assumed to follow a truncated normal distribution whose mean is the real (actual) TTS (RTTS) and standard deviation customized by a software user. The RTTS is the difference between travel times on GP and HOT lanes, averaged across a user-specified time interval. The RTTS interval in minutes can be input in the HOV/HOT lane tab (see Figure A-7), which determines how often RTTS will be evaluated. For example, if it is 10 minutes, RTTS will be evaluated

every 10 minutes, and all decisions made in the next 10 minutes will be based on the average of the previous 10 minutes. Decisions made during the first 10 minutes are based on the value of average RTTS at time 0. Decisions made during minutes 11 to 20 will be based on the average RTTS calculated at time 10. The lane choice decisions are made whenever a vehicle encounters a HOT lane entry warning sign. The locations of the warning signs are specified by the user (Figure A-7).

Drivers' VOT (\$/hr) can be input under Edit -> FRESIM -> Calibration -> Value of Time tab, as shown in Figure A-12 and Figure A-13.

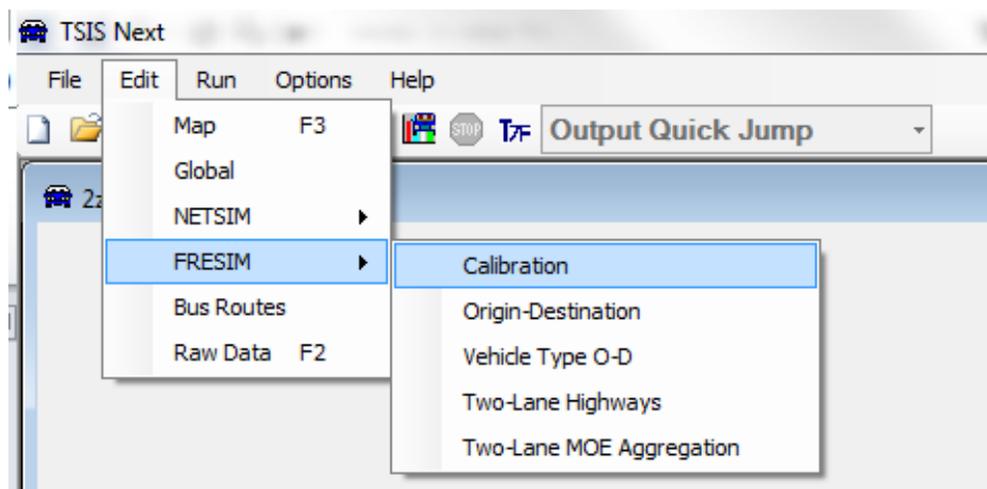


Figure A-12. FRESIM calibration

#### A.4 Toll Structures

When a HOT lane facility has multiple segments, motorists can be charged in different ways based on the toll structure implemented by a user. There are four basic toll structures for multi-segment facilities: zone-based, origin-specific, distance-based, and origin-destination (OD)-based. The toll structure can be selected in the Value of Time tab under FRESIM Setup (Figure A-13). Also the option "HOT lanes charge individually" is provided, which means that each HOT segment functions as a stand-alone single-segment HOT lane facility.

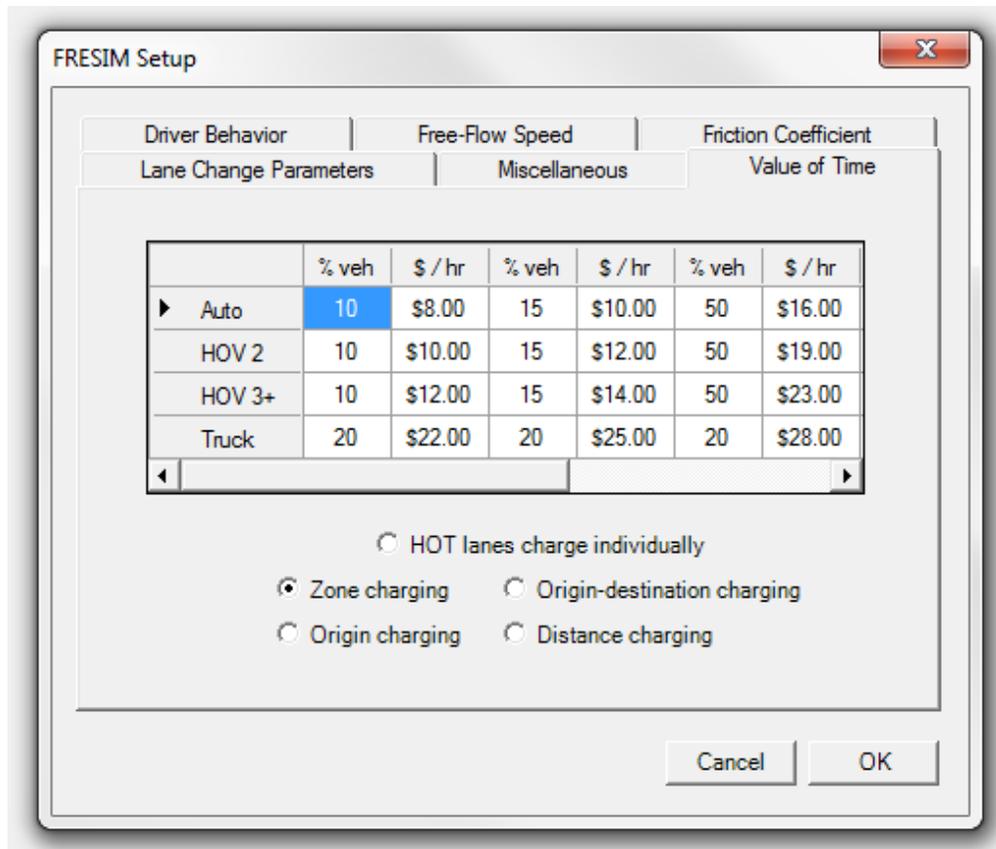


Figure A-13. Value of Time Tab under FRESIM Setup

#### A.4.1 Zone-based Tolling

The HOT-lane facility is divided into multiple zones. Each zone can have multiple entrances (HOT entry links) or exits (HOT continuation non-exclusive or HOT termination links). To specify in which zone a HOT entry link belongs, a zone number can be input for each HOT entry link, as illustrated in Figure A-10. The toll amount is the same for all entrances that belong to the same zone. The toll amount is calculated at the first HOT entry link into a zone and is assigned to be associated with all the downstream HOT entry links in the same zone. The total toll amount a motorist pays depends on the numbers of zones he or she traverses. A vehicle has to make a lane choice decision at every warning sign upstream of a HOT entry link. Note that when

each zone consists of only one HOT entry link, the zone-based tolling essentially functions the same as the “HOT lanes charge individually” option.

#### **A.4.2 Origin-based Tolling**

In origin-based tolling, the toll is calculated at every HOT entry link and the toll amount that travelers pay depends only on their origins. More precisely, the traveler pays the toll that is displayed on a sign at their entry point regardless of how far they intend to travel on the HOT lanes. Consequently, they will only have to face the lane choice between HOT and GP lanes once. The toll at a specific HOT entry link is calculated based on the average density of all HOT lane segments between that HOT entry link and the nearest HOT termination link.

#### **A.4.3 Distance-based Tolling**

In this toll structure, the toll charged to a motorist depends on the distance that he or she travels on the HOT lanes. The toll rate, that is, toll per mile, is the same for all entry locations at a specific time interval. The sign at the entrance displays the minimum toll for entering the facility (i.e., the toll amount to the immediately downstream exit), the toll per mile, and maximum toll for traveling to the end of the facility. In CORSIM, the toll calculation in distance-based tolling is similar to that in zone-based tolling. More specifically, a user also needs to specify zones. Toll calculation also takes place at the first HOT entry link to each zone. Then, to find the toll per mile, the toll is divided by the length of the zone. The toll per mile is assigned to every HOT entry link that belongs to the same zone. The toll per mile for each zone can be different and drivers are charged based on the miles they traveled on each zone.

#### **A.4.4 OD-based Tolling**

In OD-based tolling, the toll that motorists pay depends on where they enter and leave the HOT lanes. In this case, the prices to major destinations are displayed at each entry point so that motorists can estimate approximately the price they have to pay.

They can then decide whether they want to use the HOT lanes or not.

All four tolling structures are fully implemented in CORSIM.

#### **A.5 Example**

Below, an example for coding a multi-segment facility in CORSIM is provided.

Assuming that a HOT lane network consists of the following links:

5a-6a-6b-5b-6c-7a-5c-6d-6e-6f-7b

where 5a, 5b, and 5c are entry links, 6a, 6c, 6d and 6f are continuation exclusive links, 6b and 6e are continuation non-exclusive links, and 7a and 7b are termination links.

The different toll structures as well as the “HOT lanes charge individually” implementation for the example network are described below.

##### **A.5.1 HOT Lanes Charge Individually**

When the “HOT lanes charge individually” option is selected, there will be three different toll calculations. These calculations can be done using any of the three pricing schemes available in CORSIM, including responsive, closed-loop-control-based, or time-of-day. If either of the first two is chosen dynamic pricing is used:

- 1) The toll amount at entrance 5a will be calculated based on the average density of segments 5a-7a;
- 2) The toll amount at entrance 5b will be calculated based on the average density of segments 5b-7a;
- 3) The toll amount at entrance 5c will be calculated based on the average density of segments 5c-7b.

Drivers make the lane choice decision upstream of every HOT entry link and they are charged each time they travel through a HOT entry link.

### **A.5.2 Zone-based Tolling**

If we assume that the network has two zones: 5a-7a and 5c-7b, the toll displayed at 5a and 5b should be the same and drivers who travel from 5a to 7b need to pay two tolls: the one displayed at entrance 5a and the one displayed at entrance 5c. Drivers traveling from 5b to 7b will also have to pay two tolls.

If dynamic pricing is implemented, we have the following:

- 1) The toll amount at entrance 5a will be calculated based on the average density of segments 5a-7a;
- 2) The toll amount at entrance 5b is the same as the toll at entrance 5a as these two entrances belong to the same zone;
- 3) The toll amount at entrance 5c will be calculated based on the average density of segments 5c-7b.

### **A.5.3 Origin-based Tolling**

In this case, vehicles that enter at entrance 5a will pay the toll amount displayed at that entrance regardless of where they exit. Thus, vehicles traveling from 5a to 7b and those traveling from 5a to 6b will pay the same toll. For this specific example network, toll calculation in dynamic pricing is the same with the “HOT lanes charge individually” option.

### **A.5.4 Distance-based Tolling**

As mentioned above, the distance-based tolling is similar to the zone-based tolling in the sense that zones should be specified for both structures. If we assume that there are two zones, that is, 5a-7a and 5c-7b, the toll rate displayed on 5a and 5b will be the same. The toll calculation is the same as in the zone-based tolling. However, in

distance-based tolling, a driver who exits before the end of a zone will be charged less than in zone-based tolling.

#### **A.5.5 OD-based Tolling**

In the example network, there are the following OD pairs:

5a-6b

5a-7a

5a-6e

5a-7b

5b-7a

5b-6e

5b-7b

5c-6e

5c-7b

Consequently, there will be nine toll calculations. A more complicated pricing algorithm will be developed and implemented in the future.

#### **A.6 HOT-Lane Simulation Outputs**

When HOT lanes are simulated, CORSIM generates an additional .csv output file that includes the basic HOT lane inputs and outputs. There are eighteen columns in this file (see, Figure A-14 (A) and (B)). The first nine columns summarize the basic input information and the last nine provide the outputs generated by the software.

All these columns are further explained in Table A-1

Table A-1. HOT output explanation

Column No	Column name	Explanation
Inputs		
1	TIME	Simulation time when the toll is calculated and updated.
2	UPSTREAM NODE	Upstream node of the HOT entry link.
3	DOWNSTREAM NODE	Downstream node of the HOT entry link.
4	PRICING ALGORITHM	Pricing algorithm selected for toll calculation.
5	ORIGIN	Origin (applies only to OD-based tolling to be implemented).
6	DESTINATION	Destination (applies only to OD-based tolling to be implemented).
7	ZONE	Zone number (applies only to zone- and distance-based tolling).
8	MIN TOLL	Minimum toll set by the user (applies only to responsive and closed-loop-control-based pricing)
9	MAX TOLL	Maximum toll set by the user (applies only to responsive and closed-loop-control-based pricing)
Outputs		
10	DENSITY	Average density calculated over a zone or segment (applies only to responsive and closed-loop-control-based pricing)
11	DELTA DENSITY	Difference in density between two tolling intervals (applies only to responsive pricing)
12	PRICE	Toll
13	TOLL PER MILE	Toll rate, i.e., toll per mile (applies only to distance-based tolling)
14	MIN CHARGE	Minimum toll for entering the facility (applies only to distance-based tolling)
15	MAX CHARGE	Toll amount for traveling to the end of the facility (applies only to distance-based tolling)
16	RTTS	Real or actual travel time saving
17	REVENUE	Revenue
18	ZONE REVENUE	Revenue for each zone (applies only to zone and distance-based tolling)

	HOT Entry Link				Inputs			
	UPSTREAM	DOWNSTREAM	PRICING					
TIME	NODE	NODE	ALGORITHM	ORIGIN	DESTINATION	ZONE	MIN TOLL	MAX TOLL

A

			Distance-based charging outputs					
DENSITY	DELTA DENSITY	PRICE	TOLL PER MILE	MIN CHARGE	MAX CHARGE	RTTS	REVENUE	ZONE REVENUE

B

Figure A-14. HOT lane output. A) Summary of Inputs. B) Output.

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## BIOGRAPHICAL SKETCH

Dimitra Michalaka was born and grew up in Papados, a small Greek village (population 1,500) at the Lesvos island. In 2001, after she passed the national general exams, she enrolled as a student at the National Technical University of Athens, where she received a Bachelor of Science in civil engineering in 2006. In August 2007, she moved to Gainesville to pursue graduate studies at the University of Florida (UF). In 2009, she earned a Master of Science in civil engineering and won the Pikarsky Award for Outstanding M.S. Thesis in Science and Technology from the Council of University Transportation Research Centers. After she graduated with the M.S. degree, she was hired as a transportation engineer at the UF Transportation Research Center. Then, in Spring 2010, she enrolled at UF in the Ph.D. program in civil engineering with a focus on transportation engineering.

In addition to her studies, Dimitra has been involved with several professional organizations and groups such as the UF Women's Transportation Seminar (WTS) student chapter, the UF Institute of Transportation Engineers (ITE) student chapter, the Tau Beta Pi (the honorary engineering society), the International Student Speakers' Bureau (ISSB), and the Civil and Coastal Engineering (CCE) Graduate Student Advisory Group, in which she has often taken leadership positions.

Dimitra is looking forward to what the life after graduation has to bring.