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THE FLORIDA DEPARTMENT OF TRANSPORTATION
RESEARCH CENTER

on Project

"Managed Lane Operations –
Adjusted Time of Day Pricing vs. Near-Real Time Dynamic Pricing"

FDOT Contract BDK77 977-04 (UF Project 00081551)

Volume I: Dynamic Pricing and Operations of Managed Lanes

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The University of Florida

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METRIC CONVERSION CHART

U.S. UNITS TO METRIC (SI) UNITS

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

METRIC (SI) UNITS TO U.S. UNITS

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

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16. Abstract

The Florida Department of Transportation recently implemented high occupancy/toll (HOT) lanes (known as 95 Express) in the Miami regional area on Interstate 95. This report investigates three aspects relevant to the operations and management of HOT lanes such as 95 Express. First, two questions concerning the impact and effectiveness of dynamic tolling are investigated. One is whether a managed-lane system exhibits hysteresis-like behavior that motorists periodically shift their departure times to cope with the volatility of the toll being charged. The other is whether dynamic pricing necessarily performs better than static or time-of-day pricing. Second, this report examines whether and how the reduced lane, shoulder widths, delineators, and designs of ingress/egress points have affected the capacity and operations of the toll lanes and the general-purpose lanes of 95 Express. Lastly, the report focuses on enhancement and evaluation of the tolling algorithms for the current and future 95 Express.

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EXECUTIVE SUMMARY

High-occupancy/toll (HOT) lanes refer to high-occupancy-vehicle (HOV) facilities that allow lower-occupancy vehicles to pay a toll to gain access. Since the first HOT lane was implemented in 1995 on State Route 91 in Orange County, California, the concept has been becoming popular among governors and transportation officials, in state legislatures and the media. Among other factors, the popularity and wide acceptance of the HOT lane concept are due to the additional option it makes available to motorists and the low utilization of HOV lanes. More specifically, HOT lanes provide motorists an option to "buy in" or to pay to avoid congestion. On the other hand, many have expressed concern about the wasted capacity resulting from a low utilization of many HOV lanes. Thus, converting underutilized HOV lanes to HOT lanes likely creates a win-win situation for both HOT and general-purpose (GP) lane users.

The Florida Department of Transportation (FDOT) implemented HOT lanes, known as 95 Express, in the Miami and Fort Lauderdale regional area on I-95. The system will eventually be approximately 22 miles long, extending from I-95 interchange at SR-112 north to the Broward Boulevard Park and Ride lot. It is constructed in two phases. Phase 1 extends from SR-112/I-195 to the Golden Glades Interchange. The northbound express lanes opened to traffic on July 11, 2008, and tolling began on December 5, 2008. The southbound 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 primary goal of 95 Express is to safely and efficiently maximize the throughput of the facility while providing free-flow services, more specifically, travel speeds greater than or equal to 45 mph, on the HOT lanes. To achieve these objectives, dynamic tolling is implemented. For the current 95 Express, the toll amount is updated every 15 minutes, varying from $0.25 to $7.25.

There is little research on the overall benefit of dynamic tolling on the management and operations of managed lanes. To help ensure the operational success of and protect the significant investment in these managed lanes projects, this project attempts to answer a variety of questions relevant to the operations and management of managed lanes. The final report is organized into two volumes. This volume (Volume I) discusses three aspects of managed lane operations, including the impacts, enhancement and evaluation of dynamic tolling and the capacities of managed lanes.

We first investigated the two questions concerning the impact and effectiveness of dynamic tolling on managed lane operations. One is whether a managed-lane system exhibits hysteresis-like behavior that motorists periodically shift their departure times to cope with the volatility of the toll being charged. The other question is whether dynamic pricing necessarily performs better than static or time-of-day (TOD) pricing. Both questions may be best answered by analyzing empirical data from different facilities in different settings. Due to the lack of empirical data to make a meaningful comparison, we developed a behavior-based simulation tool that captures the interactions between motorists' departure-time and lane choices and a variety of pricing strategies on a managed-lane system. Using 95 Express of Florida as a testbed, simulation experiments were conducted. The simulation results show that at the current demand level of 95 Express, the system achieves a certain degree of equilibrium. However, if the demand increases to a certain level that leads to severe congestion, the system may exhibit hysteresis-like behavior where travelers are constantly shifting their departure times on day-to-day basis. The system performance is unstable and volatile. Our experiments also confirm that the dynamic tolling algorithm of 95 Express is able to manage the traffic demand and maintain a superior performance of the express lanes. However, when the demand pattern is predictable, TOD or even static tolling could perform as well as dynamic tolling, provided that the toll profiles are optimized against the demand pattern. However, since dynamic tolling is adaptive to demand fluctuations, its performance is more robust and stable. Recognizing that the dynamic tolling is beneficial but more costly to implement, we further conducted a cost-benefit analysis to examine whether the benefits from dynamic tolling can justify its additional implementation cost or not. The additional travel time saving incurred by dynamic tolling was considered as the primary benefit. Based on different estimates of the value of travel time, we estimated the breakeven implementation cost for dynamic tolling to be from $1.0M to $3.4M. Compared with the TOD tolling, if the additional cost is more than the breakeven cost, it may not be advisable to implement dynamic tolling.

The second aspect we investigated is the operational capacity of 95 Express. The HOT lanes were constructed by separating them from the GP lanes by a physical barrier, most commonly called delineators, and by reducing the lane-widths of all the lanes from 12 to 11 feet. We examined whether and how the reduced lane, shoulder widths, delineators, and designs of ingress/egress points have affected the capacity and operations of the toll lanes and the GP lanes. A detailed capacity analysis was performed for several sites located along 95-Express, SR-826 (Palmetto Expressway) and I-95 corridor that are outside the 95Express lanes zone. These analyses were performed by comparing the capacities of the freeway sections before the toll lanes were constructed with the capacities after the toll lanes were constructed depending on the availability of the data which was obtained from Florida's Central Data Warehouse (aka STEWARD). Based on the analyses of the data available, it cannot be concluded that the narrowing of the lanes on 95 Express from 12 to 11 feet, or the narrowing of the shoulders as well, has had a negative impact on the capacity of the GP lanes in this section of I-95. The configuration of the entrance to the HOT lanes and the close proximity of the delineators to the GP lane adjacent to the HOT lanes do appear to be limiting the utilization of this GP lane, however.

The third part of this report focuses on enhancing the dynamic tolling algorithm of the current 95 Express and making recommendations for tolling of the future 95 Express. In the implemented dynamic tolling algorithm, the toll amount is determined based on traffic density currently detected on the HOT lanes and the change in density from the previous interval. When an increase or decrease in the detected density occurs, the toll amount is adjusted upward or downward according to a Delta Settings Table (DST). The table plays a key role in determining the adjustment in toll amount. It is thus imperative to update the parameters of the table if traffic demand or conditions in the corridor have changed. This report presents a sensible approach to fine-tune the DST parameters, avoiding trial and error. The approach is a genetic-algorithm (GA) procedure that encapsulates the aforementioned macroscopic simulation tool for this project. The optimized DSTs were evaluated using an enhanced CORSIM, which implemented a variety of tolling algorithms and simulated the lane-choice behaviors endogenously. The CORSIM simulation experiments confirmed that the current 95 Express tolling algorithm yields satisfactory system performances. At the same time, the optimized DSTs presented similar good results, demonstrating that the proposed GA procedure can be potentially applied to fine-tune parameters to adapt to future increases in traffic demand. To achieve further improvement, the report also suggests incorporating CORSIM into the GA procedure.

The current 95 Express is a single-segment HOT facility. However, the system, once completed, is slated to be a multi-segment facility. Similar to pricing of a single-segment facility, the pricing approach for a multi-segment HOT facility should induce superior traffic conditions on the HOT lanes while utilizing the available capacity of the lanes. Moreover, the approach should avoid unbalanced toll per usage among motorists. In general, the toll structure for multi-segment facilities can be classified into zone-based, origin-specific, OD-based and distance-based. The former three have been implemented in practice. Given the implementation of dynamic tolling on the current 95 Express, it will be relatively easier and more cost-effective to implement the zone-based dynamic tolling approach on the future 95 Express. In this approach, the facility is divided into multiple zones. Whenever a motorist enters a new zone, he or she pays a specific toll. Consequently, the toll that a motorist pays depends on the numbers of zones he or she has traversed. The report recommends two zoning designs and evaluates them using the enhanced CORSIM. Given its potential of more effectively managing traffic demand and utilizing available capacity on a long multi-segment HOT facility, the report also recommends the OD-based tolling approach for the future 95 Express. In this approach, the toll amount a motorist will pay depends on where he or she enters and leaves the facility. However, the approach is more costly and difficult to implement. Future research is needed to develop a more sophisticated OD-based tolling algorithm for 95 Express and then conduct a CORSIM simulation study to compare the OD-based toll structure with the zone-based one.

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1 INTRODUCTION

Congestion pricing has been advocated as an efficient way to reduce congestion for over eighty years. However, it has been adopted only recently in part due to the advent of electronic tolling and the pressing need for alternative funding sources to finance transportation projects. One prevalent form of congestion pricing in the U.S. is express toll lanes, which can be viewed as a first step towards system-wide pricing of congested roads. In a typical setting, lanes on a particular freeway are designated either as regular or managed toll lanes. There is no toll on the former while the latter can only be accessed by paying a toll. In the case where high-occupancy vehicle (HOVs) need not pay, the lane is widely known as high-occupancy/toll (HOT) lane. Ever since the first HOT lane was implemented in 1995 on State Route 91 in Orange County, California, the concept has become quite popular and widely accepted by many transportation authorities. Among other factors, the popularity and wide acceptance of the HOT lane concept are 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 likely creates a win-win situation for both HOT and regular lane users. Moreover, managed lanes provide motorists an 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. Currently, there are approximately 12 managed-lane facilities in operation around the country and many others are either under construction or in planning.

The Florida Department of Transportation (FDOT) implemented HOT lanes, known as 95 Express, in the south Florida on I-95. The system will eventually be approximately 22 miles long, extending from I-95 interchange at SR-112 north to the Broward Boulevard Park and Ride lot. It is constructed in two phases. Phase 1 extends from SR-112/I-195 to the Golden Glades Interchange. The northbound express lanes opened to traffic on July 11, 2008, and tolling began on December 5, 2008. The southbound 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 primary goal of 95 Express is to safely and efficiently maximize the throughput of the facility while providing free-flow services, more specifically, travel speeds greater than or equal to 45 mph, on the HOT lanes. To achieve these objectives, dynamic tolling is implemented. For the current 95 Express, the toll amount is updated every 15 minutes, varying from $0.25 to $7.25. Similar to FDOT, quite a few other authorities price their HOT lanes dynamically, such as California Department of Transportation (Caltrans) on I-15 and Minnesota Department of Transportation (MnDOT) on I-394.

There is little research on the overall benefit of dynamic tolling on the management and operations of managed lanes. To help ensure the operational success of and protect the significant investment in these managed lanes projects, this project attempts to answer a variety of questions relevant to the operations and management of managed lanes. The final report is organized into two volumes. This volume (Volume I) discusses three aspects of managed lane operations, including the impacts and enhancement of dynamic tolling and the capacities of managed lanes.

Chapter 2 investigates two questions concerning the impact and effectiveness of dynamic tolling on managed lane operations. One is whether a managed-lane system exhibits hysteresis-like behavior that motorists periodically shift their departure times to cope with the volatility of the toll being charged. The other is whether dynamic pricing necessarily performs better than static or time-of-day (TOD) pricing.

Chapter 3 focuses on the capacity analysis of 95 Express lanes. More specifically, it examines whether and how the reduced lane, shoulder widths, delineators, and designs of ingress/egress points have affected the capacity and operations of the toll lanes and the general-purpose (GP) lanes for 95-Express lanes.

Lastly, Chapter 4 discusses dynamic tolling algorithms for single- and multi-segment HOT lane facilities. The former 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 of toll to use the facility no matter where they enter or exit. In contrast, the latter has multiple ingress or egress points that are located distantly from each other. Depending on where they enter or exit, motorists may pay different amounts of toll. This report focuses on enhancement and evaluation of the tolling algorithms for the current and future 95 Express. The former is a single-segment facility while the latter consists of multiple segments.

2 IMPACTS OF DYNAMIC PRICING ON MANAGED LANE OPERATIONS

2.1 Background

This chapter attempts to investigate two questions often raised by researchers and practitioners concerning the impact and effectiveness of dynamic pricing schemes on managed-lane operations. One is whether a managed lane system exhibits hysteresis-like behavior under dynamic pricing. A system with hysteresis can be described as having outputs that are dependent on the path taken, or history of its inputs. This dependency causes the system to generate outputs as though it had a memory of the nature of its previous inputs. Hysteresis-like behavior of demand in the context of managed lanes could, if it exists, present itself as shifts in the demand for the managed lanes over a time series of commutes. For example, if in the first morning, the maximum toll rate was reached by 8:00 AM, at which point the general-purpose (GP) lanes had become unstable, the memory of unstable operation in the vicinity of 8:00 AM may cause, in the following morning, motorists to shift earlier into the managed lanes such that the maximum toll is reached by, say, 7:50 AM. Subsequent morning commute periods could be characterized by further shifts in time in either direction, causing oscillation in travel demand and system performance. This phenomenon, if it exists, would be of interest to managed-lane operators and researchers as it could provide insight into how the managed-lane system should be operated.

The other question is whether dynamic tolling necessarily performs better than static or TOD tolling. When operating traditional traffic control signal systems, there is a point of diminishing returns associated with dynamic control. Often a more effective approach is to develop TOD timing plans that optimize signal operations for well-defined and relatively predictable time-dependent patterns of traffic demand. One naturally wonders whether this applies to the tolling strategies for managed lanes.

Although previous studies (e.g., Yang and Huang, 1997; Supernak et al., 2003; Burris and Sullivan, 2006) have examined many aspects of managed-lane operations, to our best knowledge, none has investigated the above two questions. The key to both questions involves understanding drivers’ responses to different tolling strategies, more specifically, how they learn from their day-to-day driving experiences and incorporate the knowledge into their departure time and lane choices. The questions are best answered by analyzing empirical data from different facilities in different settings. Due to the lack of empirical data to make a meaningful comparison, we adopted a simulation approach to investigate the issues. A behavior-based simulation tool is developed in Matlab to capture the interactions between commuters' departure-time and lane choice behaviors and a variety of pricing strategies on a managed-lane system. Simulation experiments based on the current configuration of 95 Express in Florida are conducted.

The remainder of this chapter is organized as follows. Section 2.2 describes the behavior-based simulation tool. Section 2.3 presents the simulation results related to the first question of analyzing travel demand of managed-lane systems. Section 2.4 compares dynamic tolling with the TOD and static tolling for managed-lane systems. Finally, Section 2.5 provides the concluding remarks.

2.2 Behavior-Based Simulation Tool

Several simulation models in the literature may be used to investigate the raised issues. De Palma et al. (2005) studied congestion pricing using a dynamic equilibrium simulator named METROPOLIS (De Palma et al., 1997). The model is able to treat endogenously individuals' mode, departure-time and route choices over a road network. However, the pricing scheme in the model is pre-determined and the model does not take into consideration the stochastic nature of traffic condition. DYNASMART (Jayakrishnan et al., 1994) is another competent simulation model, but does not provide flexibility needed in our research to simulate a variety of tolling strategies. Therefore, a behavior-based simulation model is developed in Matlab to address the research needs. The model represents commuters' day-to-day learning and adjustment behaviors and captures the interactions between commuters' departure-time and lane choice behaviors and dynamic pricing strategies under different operating conditions.

2.2.1 Framework of the simulation model

The developed simulation model consists of two major modules: demand and supply. The demand module describes users' behaviors, including day-to-day learning of travel time and toll and choices of departure time and lane. The learning mechanism determines the role of travelers' past experience and other historical information in their current choices and describes how travelers form their own perceptions of travel costs. The components of departure-time and lane choice capture travelers' decision processes, based on their perceptions of travel costs. The supply module mainly consists of a traffic flow model and toll determination procedures. The former represents the characteristics of the facility and describes traffic dynamics along the facility while the latter, e.g., mimics the toll determination process implemented on 95 Express. The framework of the simulation model is shown in Figure 2.1.

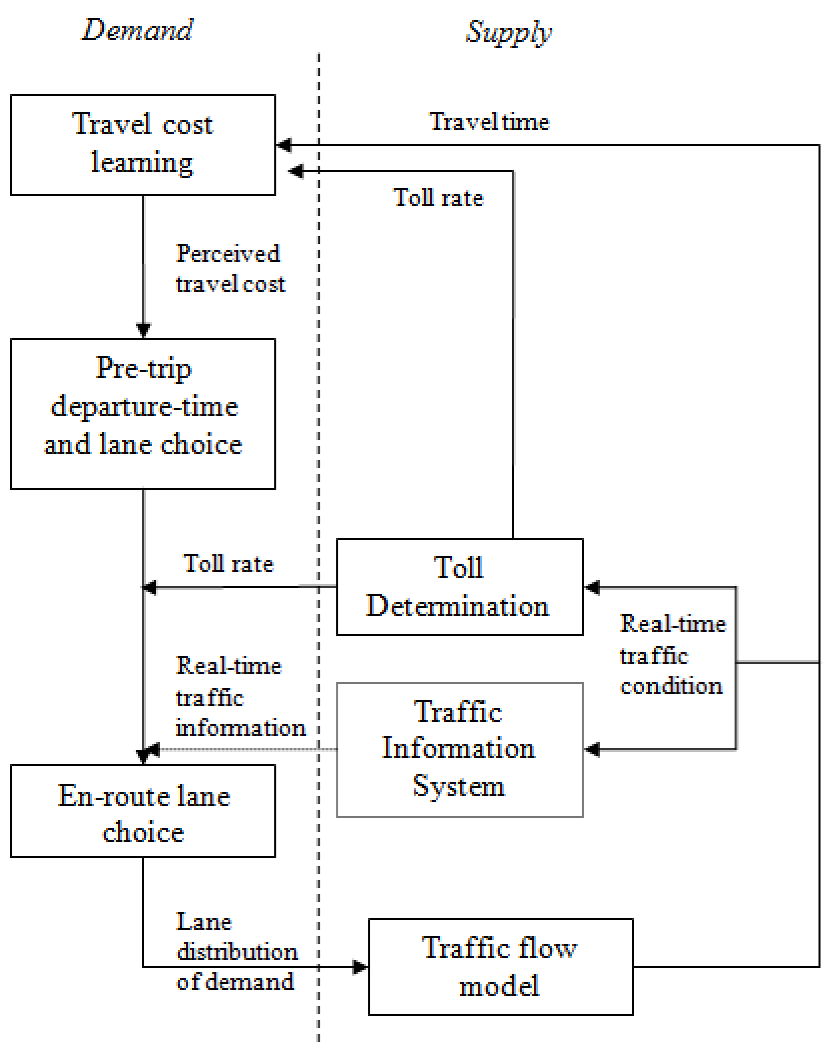


FIGURE 2.1 Framework of the Simulation Tool

2.2.2 Demand module

We adopt a microscopic approach to model individual travelers' behaviors in the simulation model, i.e., each individual's behavior is explicitly considered.

2.2.2.1 Day to Day Learning

Since travelers are not able to foresee the outcome (e.g., travel time and toll amount) of their trips before departure, they make their travel decisions based on their own understanding of the traffic condition and the associated cost, which may be obtained from their own travel experience or other information sources through a learning process. One of the pioneering studies on travelers' learning mechanism is Horowitz (1984), in which a weighted average approach was proposed to describe travelers' learning from their actual travel times of previous days. The approach can be represented as follows:

$$\hat{t}_i^k(y) = \sum_{j=1}^{k-1} w_j(k-1)(t_i^k(y) + \varepsilon_i^j) \text{ , } k \geq 2$$

where $\hat{t}_i^k(y)$ is the perceived travel time on link i for departure time y in day k; $t_i^k(y)$ is the previous travel time on link i at departure time y in day j; ε_i^j is a random variable associated with travel time $t_i^k(y)$, representing the reliability and accuracy of the information. More specifically, the variable captures the error in users' perception of travel time through their own experiences or based on other information sources; $w_j(k-1)$ is a non-negative weight corresponding to the previous travel time on each link, which should satisfy the following equation:

$$\sum_{j=1}^{k-1} w_j(k-1) = 1 \text{ .}$$

The weighted average approach has been a dominating learning model in the literature of modeling day-to-day traffic dynamics (e.g., Mahmassani and Chang, 1998; Iida et al., 1992; Cantarella and Cascetta, 1995; Avineri and Prashker, 2006).

Another commonly used method for travelers' learning mechanism is Bayesian learning (e.g., Jha et al., 1998; Chen and Mahmassani, 2008; Nakayama, 2009).Bayesian learning can be considered as a special type of the aforementioned weighted average model. Instead of being predetermined, the “weight” for each sampled past experience or historical information is dependent upon the variance of the data. The Bayesian updating can be conducted as per the following equations:

$$\hat{t}_i^k(y) = \frac{\hat{t}_i^{k-1}(y) \cdot Var(t_i^{k-1}(y)) + t_i^{k-1}(y) \cdot Var(\hat{t}_i^{k-1}(y))}{Var(\hat{t}_i^{k-1}(y)) + Var(t_i^{k-1}(y))},$$

$$Var(\hat{t}_i^k(y)) = \frac{Var(\hat{t}_i^{k-1}(y)) \cdot Var(t_i^{k-1}(y))}{Var(\hat{t}_i^{k-1}(y)) + Var(t_i^{k-1}(y))}.$$

where $\hat{t}_i^k(y)$ and $\hat{t}_i^{k-1}(y)$ are the perceived travel time on link i for departure time y in day k and $k-1$, respectively; $t_i^{k-1}(y)$ is the actual experienced travel time on link i at departure time y in day k and Var denotes the variance.

Reinforcement learning is another learning model recently introduced into the transportation field (e.g., Selten et al., 2003; Chen and Mahmassani, 2008). The basic idea of the reinforcement learning is that people “appear to be more sensitive to past outcomes when the payoff framing involves losses” (Erev et al., 1999). More specifically, travelers under the reinforcement learning scheme tend to deviate from their current choices when they suffered from losses in travel costs. For example, Chen and Mahmassani (2008) proposed a reinforcement learning model where, among the experienced travel costs, only those with a loss are used to update perceived travel costs.

In this study, we assume that users traveling on a tolled facility form their perceptions on both travel time and toll amount via a learning process. The learning mechanism adopted for the simulation model is an implementation of the weighted average approach, written as follows:

$$\hat{t}_i^k(y) = \frac{\sum_{j=1}^{k-1} \beta^{(k-j)} t_i^j(y)}{\sum_{j=1}^{k-1} \beta^{(k-j)}} + \varepsilon_{i,t}^j, \forall k > 1$$

$$\hat{\tau}_i^k(y) = \frac{\sum_{j=1}^{k-1} \beta^{(k-j)} \tau_i^j(y)}{\sum_{j=1}^{k-1} \beta^{(k-j)}} + \varepsilon_{i,\tau}^j, \forall k > 1$$

where $\beta^{(n)}$ is the *n*th exponent of β; $\hat{\tau}_i^k(y)$ is the perceived toll amount for link i at departure time y in day k; $\tau_i^j(y)$ is the actual toll amount on link i at departure time y in day *j*, and lastly $\varepsilon_{i,t}^j$ and $\varepsilon_{i,\tau}^j$ are random variables used to capture the users' perception errors during the learning process for travel time and toll.

Travelers in this model are assumed to treat travel time and toll separately during the learning process. However, the same learning mechanism is used for both aspects. Although the mechanism is simple in the mathematical formulation, it has been demonstrated to be able to capture most characters of human's learning and judgment process (Hogarth, 1987), e.g., human beings have a selective perception of information, limited memory and usually use heuristics or simple rules. In the above learning model, previous information (travel time and toll amount) is exponentially discounted, implying that the most current information is valued the most by the travelers.

2.2.2.2 Pre-Trip Choice of Departure Time and Lane

Based on their perceptions of traffic condition and their desired arrival times, travelers will evaluate different combinations of departure times and lanes, and then make their choices accordingly. The perceived travel cost for each combination can be written as follows (Mahmassani and Chang, 1986):

$$\hat{C}_i^k(y) = \alpha \hat{t}_i^k(y) + \hat{\tau}_i^k(y) - b_e \min\left(\hat{E}_i^k(y), 0\right) + b_l \max\left(\hat{E}_i^k(y), 0\right)$$

where $\hat{C}_i^k(y)$ is the perceived travel cost on route i in day k with departure time y. It consists of four components: the first is the cost of the perceived travel time, i.e., $\alpha \cdot \hat{t}_i^k(y)$ where α is the traveler's value of travel time (VOT); the second is the perceived toll amount while the last two are the penalty for early or late arrival. $\hat{E}_i^k(y)$ is the perceived schedule delay on route i in day k with departure time y. Since each traveler is assumed to have a desired arrival time, say, A, $\hat{E}_i^k(y) = y + \hat{t}_i^k(y) - A$. Neither early nor late arrival to the destination is considered to be preferable to the traveler, therefore incurring a disutility. b_e and b_l are parameters representing traveler's attitude toward early or late arrival respectively. Typically, $b_l >> b_e$.

The traveler chooses his or her departure time to minimize the perceived travel cost. As there are two possible routes (GP for general purpose lanes and EL for express lanes), the traveler's pre-trip departure time choice will be:

$$y^* = \arg\min_y \left(\min\left(\hat{C}_{GP}^k(y), \hat{C}_{EL}^k(y)\right)\right),$$

where y^* is the selected departure time.

2.2.2.3 En-Route Lane Choice

The pre-trip choice of departure time and lane is made by a traveler with previous information. However, the traveler will be able to revisit his or her lane choice after he or she has departed. Given that the toll amount is displayed ahead of the entrance to the managed lanes and the real-time travel time information may be available from a traveler information system or simply through traveler's own observation when he or she is approaching to the entrance, the traveler will decide whether to pay to use the express lanes. The preferred lane may not be the same as the one pre-selected by the traveler at the time of departure.

Based on the new travel time information, travelers will form a new projection of travel time $\tilde{t}_i^k(y^*)$. The new projected travel time is calculated as follows:

$$\tilde{t}_i^k(y^*) = t_i^k(y^*) + \tilde{\varepsilon}$$

where $t_i^{k*}(y^*)$ is the current travel time for link i; $\tilde{\varepsilon}$ is an error term to represent the perception error or inaccuracy of the travel time information. $\tilde{\varepsilon}$ is assumed to follow the normal distribution with a standard deviation of one tenth of the travel time $t_i^k(y^*)$.

If the real-time travel time information is not available to travelers, they will have to use their original perceived times. In this case, the new projected travel time is calculated as:

$$\tilde{t}_i^k(y^*) = \hat{t}_i^k(y^*)$$

where $\hat{t}_i^k(y^*)$ is the perceived travel time obtained from the learning mechanism, as previously described.

With the actual toll amount replacing the perceived value and the new projected travel time, the perceived travel cost is now updated as:

$$\tilde{C}_i^k(y^*) = \alpha \cdot \tilde{t}_i^k(y^*) + \tau_i^k(y^*) - b_e \min\left(\tilde{E}_i^k(y^*),0\right) + b_l \max\left(\tilde{E}_i^k(y^*),0\right)$$

where $\tau_i^k(y^*)$ is the actual toll charge for link i on the chosen departure time y^*.

We again assume that the traveler will make en-route lane choice to minimize his or her perceived travel cost

2.2.2.4 User's Preferred Arrival Times

The travelers' preferred arrival times are estimated according to the probability density function shown in Figure 2.2. In order to replicate fluctuations in travel demand, a random variable is added to the distribution function of the preferred arrival time. So travelers may have different preferred arrival times at different days. Consequently travel demand will fluctuate to a certain degree on a day-to-day basis. The magnitude of the randomness is adjustable in the model to represent different levels of demand fluctuations.

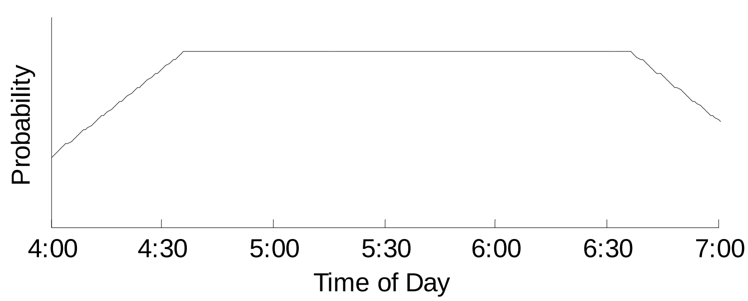


FIGURE 2.2 Probability Density Function of Users' Preferred Arrival Times

2.2.2.5 User Classes

The users of the managed-lane facility are divided into four classes according to their abilities of accessing the toll lanes. The first class is the users whose vehicles are registered as toll exempt vehicles. These users will not be charged to use the express lanes. The second class is those who are not able to access the express lanes. This is either due to the fact that their vehicles are not equipped with an electronic tolling device required or some other restrictions. These users will only use the GP lanes. The third class of users is the ones who can access the express lanes by paying the displayed toll. The fourth class includes those who are able to make a choice on which car to drive: one is an electronic-tolling-enabled vehicle, and the other is not. For example, a family may have more than two cars shared among the family members with one of the cars equipped with an electronic tolling device. A family member may decide not to use the toll lanes one day prior to his or her departure, and thus chooses to drive the unequipped car. Consequently, this traveler will not able to adjust his or her lane choice en route even if he or she found the HOT lanes more attractive.

We assume that 300 of the total peak demand are toll exempt vehicles (class 1); 12000 vehicles cannot access the HOT lanes (class 2) and 1000 vehicles belong to class 4. The rest can freely choose between HOT and GP lanes.

2.2.2.6 Choice of Parameters

Discount rate in the learning model ($\boldsymbol{\beta}$). The experimental results from Iida et al. (1992) show that the actual and perceived travel times on day $k-1$carry roughly the same weight for estimating the travel time on day k. The weight of the actual travel time ranges from 0.413 to 0.576 in two experiments they conducted. When using the exponential form of the learning model, the corresponding discount parameter is close to 0.5. Therefore, 0.5 is selected as the value of β in the simulation and all travelers are assumed to have the same discount rate in the learning.

Perception errors in the learning model: $\boldsymbol{\varepsilon_{i,t}^{j}}$ and $\boldsymbol{\varepsilon_{i,\tau}^{j}}$. The perception errors are assumed to follow normal distributions among all travelers with a mean value of 0. The standard deviation of $\varepsilon_{i,t}^{j}$ is assumed to be 0.6 minute, which is one tenth of the free-flow travel time of the freeway segment and the standard deviation of $\varepsilon_{i,\tau}^{j}$ is set to be \$0.25, which is the minimum toll amount for the express lane.

Value of travel time (α). The VOT for each traveler is randomly generated in the beginning of the simulation process. Although different travelers may have different VOT, the value for the same traveler will remain constant throughout the simulation process. Several studies have used empirical data from existing HOT or express lane projects to calibrate travelers' VOT (e.g., Lam and Small, 2001; Steimetz and Brownstone, 2005). The estimated VOT ranges from \$7 to \$65 with a median varying from \$18 to \$33 per hour. In the simulation, we assume that VOT is log-normally distributed among travelers with a mean of 25 and standard deviation of 5, respectively. Both values fall in the range of results from previous empirical studies.

Early and late arrival penalty parameters b_e and b_l. Previous studies, e.g., Small (1982) and Hendrickson and Plank (1984) have calibrated the early and late arrival penalty parameters. However, the results differ substantially. One consistent conclusion is that for work trip in the morning peak hours, the weight for the late arrival is significantly higher than that for the early arrival. The values of b_e and b_l are set to be $N(0.6,0.12)\alpha$ and $N(3,0.6)\alpha$, respectively. The selected values are close to the estimates by Hendrickson and Plank (1984),and appear reasonable for the setting of the simulation model.

2.2.3 Supply module

The supply module consists of tolling algorithms that determine the toll amount and a traffic flow model that captures traffic dynamics along the freeway segment.

2.2.3.1 Toll Determination

The toll determination component calculates the toll amount based on the traffic flow condition. This component can be programmed to follow different tolling algorithm to represent different dynamic tolling or time-of day or flat tolling schemes. The dynamic tolling algorithm implemented in this model is the one used for 95 Express. The toll is determined based on the current traffic density and the change in the density of the express lanes (FDOT, 2008).The toll amount is displayed prior to the entrance of the express lanes so that drivers can decide whether to pay the price to use these lanes. Except registered toll exempt vehicles, all vehicles need to pay a toll to access the express lanes.

The toll determination procedure of 95 Express is as follows:

1) Calculate the change in density $\Delta D = D_t - D_{t-1}$, where D_t and D_{t-1} are the density at time interval t and $t-1$.
2) Find the corresponding toll amount adjustment $\Delta\tau$ from Table 2.1based on D_t and ΔD.
3) Calculate toll amount $\tau_t = \tau_{t-1} + \Delta\tau$, where τ_t and τ_{t-1} are the toll amount for period t and $t-1$, respectively.
4) Finalize the toll amount according to the following:

$$\tau_t = \begin{cases} \tau_{\max}(D_t), if \tau_t > \tau_{\max}(D_t) \\ \tau_{\min}(D_t), if \tau_t < \tau_{\min}(D_t) \\ \tau_t, otherwise \end{cases}$$

where $\tau_{\max}(D_t)$ and $\tau_{\min}(D_t)$ are the maximum and minimum toll amounts respectively, determined as per Table 2.2.

TABLE 2.1 Toll Setting Table of 95 Express

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
	11	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25
B	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 2.1.Toll Setting Table of 95 Express (cont'd)

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
	11	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
B	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 2.2 Toll Range for 95 Express

Level of Service	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

2.2.3.2 Traffic Flow Models

Although a microscopic approach is used to describe users' departure-time and route choice behaviors, we adopt a macroscopic approach to represent traffic dynamics in order to expedite the simulation process. The approach does not model each individual traveler's driving behavior such as car following and lane changing. Instead, it attempts to capture collectively the characteristics of the vehicular flow. The approach has a much simpler structure but provides sufficient accuracy and information for toll determination and traffic analysis.

The macroscopic model used in the simulation is the cell transmission model (Daganzo, 1994 and 1995). In the model, a road is divided into homogeneous cells, and the length of each cell is determined such that all vehicles in one cell will flow into the downstream cell in one time step under the free-flow condition. The relation between the time step Δt and the cell length Δx is as follows:

$$\Delta x = v_f \cdot \Delta t \ .$$

where v_f is the free-flow speed.

The traffic condition of each cell is updated every time step in the simulation. The occupancy (number of vehicles) in each cell at time $t+1$ can be calculated as:

$$n_i(t+1) = n_i(t) + y_i(t) - y_{i+1}(t)$$

where the cell occupancy $n_i(t+1)$ of cell i at time $t+1$ is equal to the cell occupancy $n_i(t)$ at time t plus the inflow $y_i(t)$ of cell i at time t minus the outflow $y_{i+1}(t)$, which is also the inflow of downstream cell $i+1$. The inflow $y_i(t)$ is determined by the following equations:

$$y_i(t) = \min\{n_{i-1}(t), Q_i(t), \delta \cdot [N_i(t) - n_i(t)]\},$$

$$\delta = w / v_f .$$

where $Q_i(t)$ is the maximum number of vehicles that can flow into cell i in one time step; $N_i(t)$ is the capacity of cell i at time t and w is the speed with which disturbances propagate backward when traffic is congested (the backward wave speed).

Let $q_{\max}$ be the maximum flow and d_j be the jam density. The fundamental diagram of the freeway facility under the cell transmission model is illustrated in Figure 2.3.

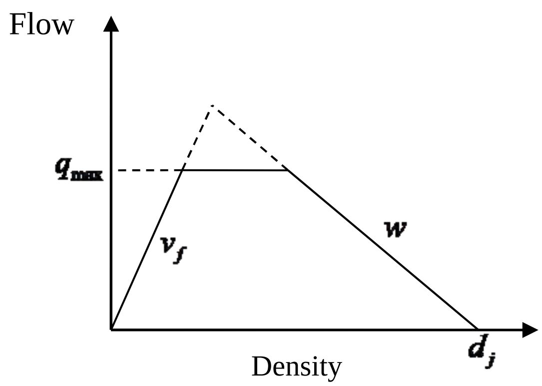


FIGURE 2.3 Flow Density Relationship of Cell Transmission Model

In order to better replicate the fluctuation of travel time observed in the field, the capacities of the managed and GP lanes are considered to be fluctuating over time instead of being constant or deterministic. The capacity in the model is assumed to follow the Weibull distribution (Brilon et al., 2005). The scale and shape parameters are 7 and 2000 per lane for the managed lanes and 11 and 2100 per lane for the GP lanes, respectively. The parameters are chosen by analyzing the data from 95 Express.

Figure 2.4 shows the cell representation of the freeway segment of interest. It is assumed that there is only one entrance and one exit for the express lanes. The toll amount and real-time traffic information, if any, are displayed prior to the entrance of the freeway segment. Drivers at the entrance can decide to enter either the express or GP lanes. After they entered the segment, travelers cannot switch lanes because the express lanes are separated from the GP lanes by plastic delineators. There are two exits at the end of the freeway segment and their capacities are set to be 1500 and 1700 vphpl for express and GP lanes respectively. The values are determined by analyzing the data available from the STEWARD database (http://cdwserver.ce.ufl.edu/steward/index.html).

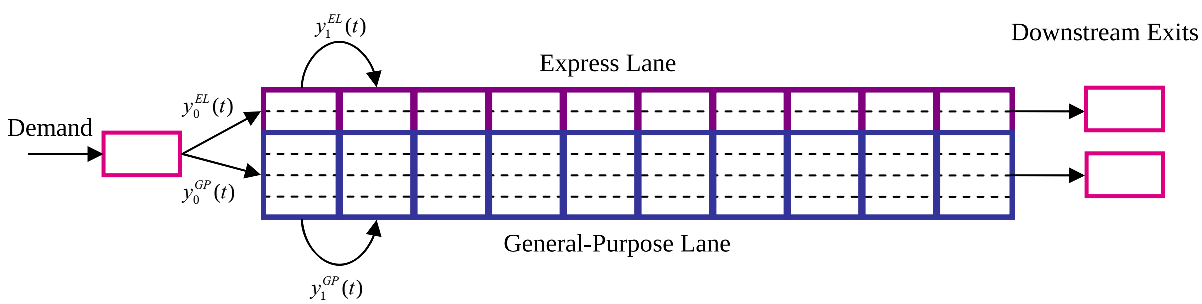


FIGURE 2.4 Cell Representation of 95 Express

2.2.3.3 Real-Time Travel Time Estimation

The actual travel time that a traveler experienced can only be calculated after the traveler has completed his or her trip. Therefore, the real-time travel time information provided to travelers in the simulation will only be an estimate. The estimation is based on the density of the HOT or GP lanes as shown below:

$$t_i^k(y) = fft + \theta_i \,(d_i\,(y) - d_{i,0})$$

where fft is the free-flow travel time; $d_i\,(y)$ is the density of lane i at time y, and θ_i and $d_{i,0}$ are parameters to be calibrated based on the characteristic of the facility.

2.2.3.4 Choice of Parameters

The total length of the freeway segment analyzed in this project is 7 mile. The free-flow speed is 70 mph and the free-flow travel time is 0.1 hour. The parameters of the cell transmission model are set as below:

- Time step $\Delta t = 0.01$ hr;
- Cell length $\Delta x = 0.7$ mile;
- Jam density $d_j = 148$ vpmpl;
- Free flow speed $v_f = 70$ mph;
- Backward wave speed $w = 14$ mph(Munoz et al., 2003);
- Maximum inflow for each cell $Q_i\ (t) = c_i(t)/100$ veh, where $c_i\ (t)$ is the capacity cell *i* at time *t*;
- $\delta = 0.2$;
- $\theta_{EL} = 1/4000$, $\theta_{GP} = 1/9000$, and
- $d_{EL,0} = 200$, $d_{GP,0} = 500$

2.2.4 Model calibration

Evidently, the simulation model is constructed upon many assumptions. Whenever possible, the assumptions are adopted from previous empirical studies. The relevant parameters are either taken from the literature or estimated based on the actual condition of 95 Express. After varying, in their corresponding reasonable ranges, multiple parameters associated with the supply and demand side of the managed lane system, we produced the simulated performance measures that match closely the ones reported in the 95 Express monthly operations report for April 2010.

The system performance measures we chose for the calibration process include, the average speed of express lanes (AvgSpeedEL), the average speed of GP lanes (AvgSpeedGP), and the percent of time express lanes are operated above 45 mph (EL Operated above 45 mph). We simulated for 100 days. However, the results of initial days may not represent stable conditions of traffic because travelers do not have enough information of the facility. Therefore, we only used the data from the last 50 days to compute the performance measures in the following way:

AvgSpeedEL and AvgSpeedGP. Speed for each user can be obtained as a model output from the simulation tool. The average speeds were then calculated across all users for the last 50 days during the peak period.

EL Operated above 45 mph. Average speed of express lanes for every 15 minute interval was calculated. We then counted the number of intervals within the peak period for day 51 to 100 where the average speed was above 45 mph. The percent time is the ratio of the number of those intervals to the total number of intervals.

The performance measures obtained from the simulation model and the reported ones are presented in Table 2.3.

TABLE 2.3 Comparison of Performance Measures for Calibration

Performance Measures	Simulation Model	Reported (April 2010)
AvgSpeedEL (mph)	55.8	55.0
AvgSpeedGP (mph)	41.9	42.0
EL Operated above 45 mph	94.4%	93.5%

2.3 Analyzing Travel Demand of Managed Lane System

In order to analyze travelers' behaviors in the managed-lane system and investigate whether hysteresis-like behavior exists under dynamic pricing, two scenarios were simulated using the developed simulation tool.

2.3.1 Base-demand case

In the base-demand case, the total demand during the three-hour peak period was assumed to be 25,300 vehicles, which is similar to the actual traffic demand in the I-95 corridor. We simulated 100 days and the results are summarized in Figure 2.5 to Figure 2.15.

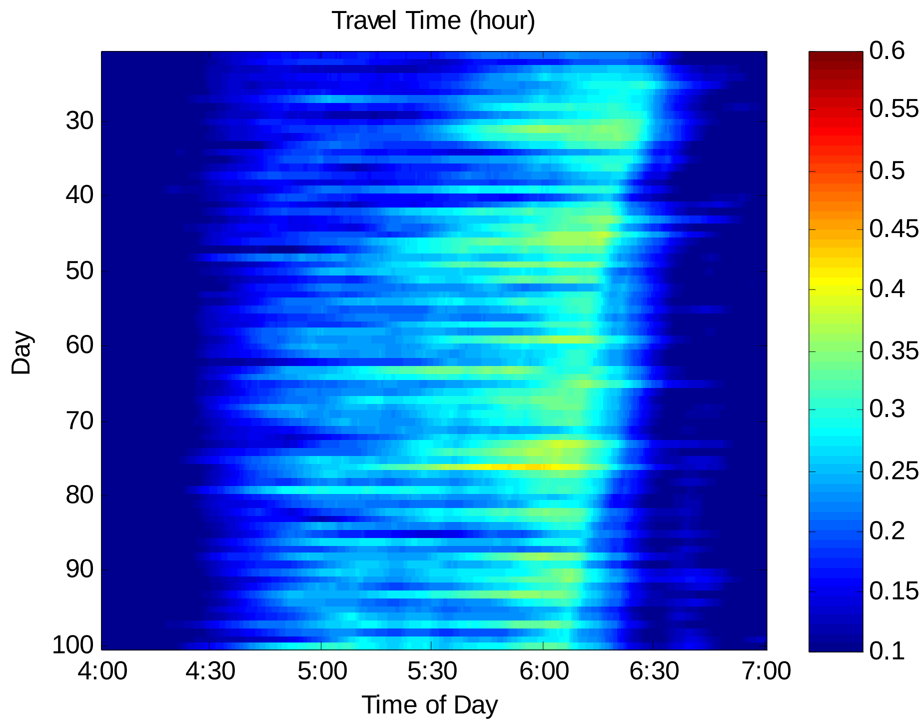


FIGURE 2.5 Travel Time of GP Lanes under Base Demand

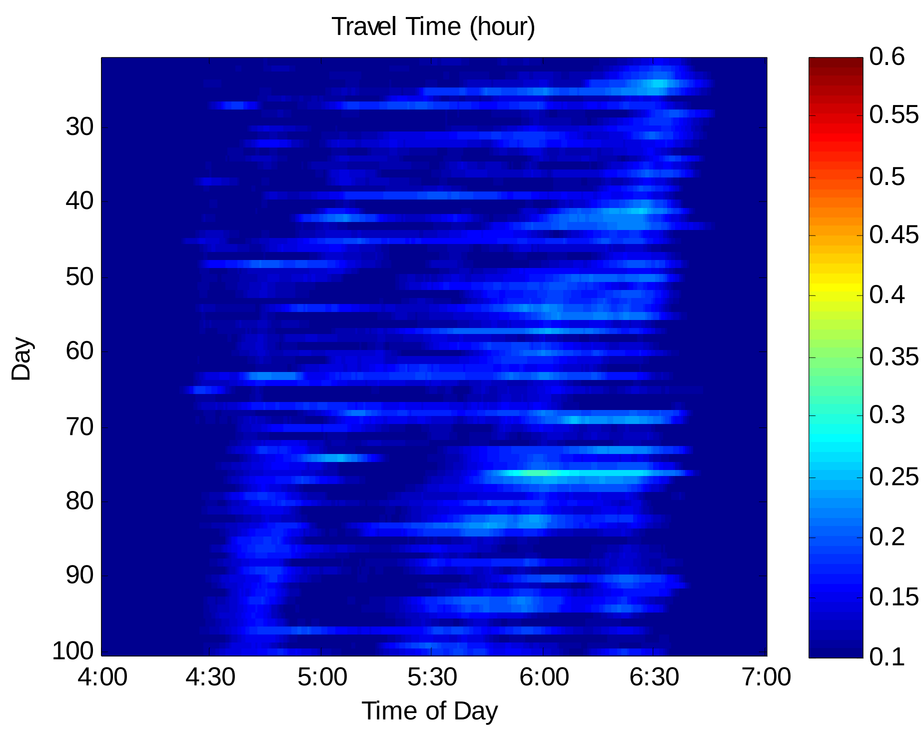


FIGURE 2.6 Travel Time of Express Lanes under Base Demand

Figure 2.5 and Figure 2.6 show the average travel times for different departure times from Day 21 to Day 100 of the simulation. The first 20 days are treated as a transition period for the simulation and the results for this period are thus omitted from the analysis. It is obvious from comparing these two figures that the travel times of express lanes are significantly lower than those of GP lanes for the same departure time, especially during the most congested hour (5:30 to 6:30pm). It is also observed that the travel time pattern for both GP and express lanes are relatively stable. For the GP lanes, the travel time starts to increase around 4:30pm every day and reaches its peak between 6:00 and 6:30pm, and gradually decreases to the free-flow travel time after that. For express lanes, although the travel time also increases, the magnitude of the increase is much smaller. For most of the time, travel times on express lanes are close to the free-flow travel time.

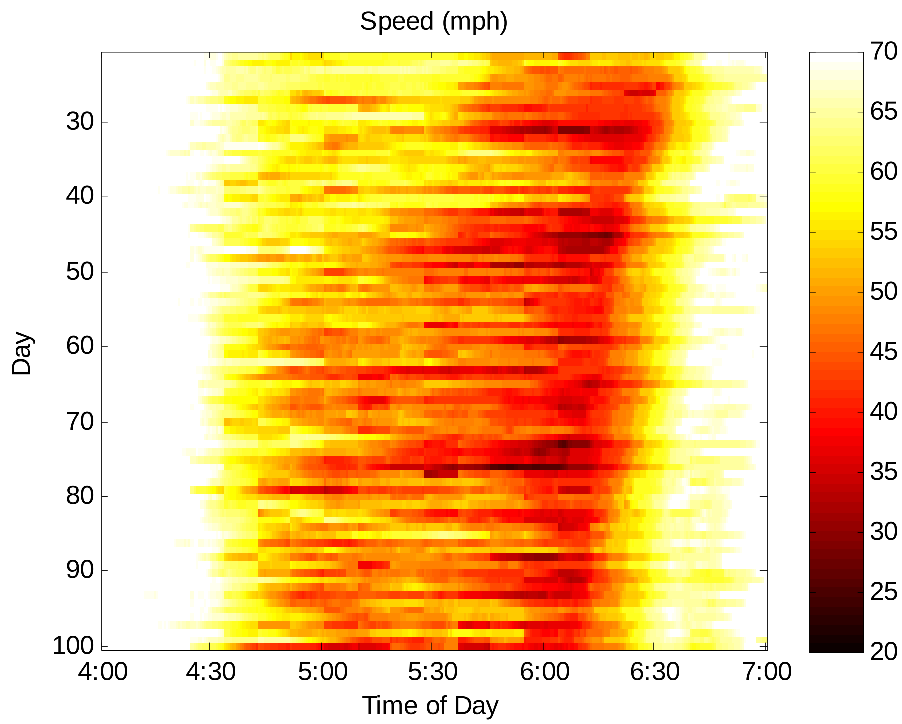


FIGURE 2.7 Speed on GP Lanes

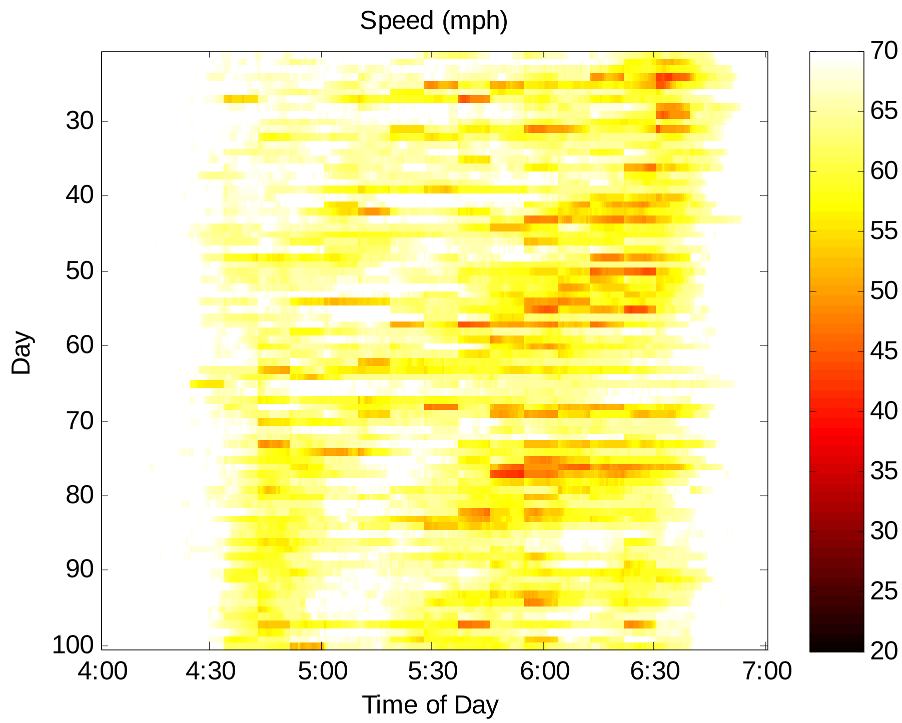


FIGURE 2.8 Speed on Express Lanes

Figure 2.7 and Figure 2.8 present the average speeds for GP and express lanes across different times of day respectively. The speed is the average across all locations along the corridor for the same period of time. It can be observed that the express lanes are operated at a superior condition than the GP lanes. For the majority of time, the average speed is above 45 mph while the speed for GP lanes can be as low as 20 to 25 mph.

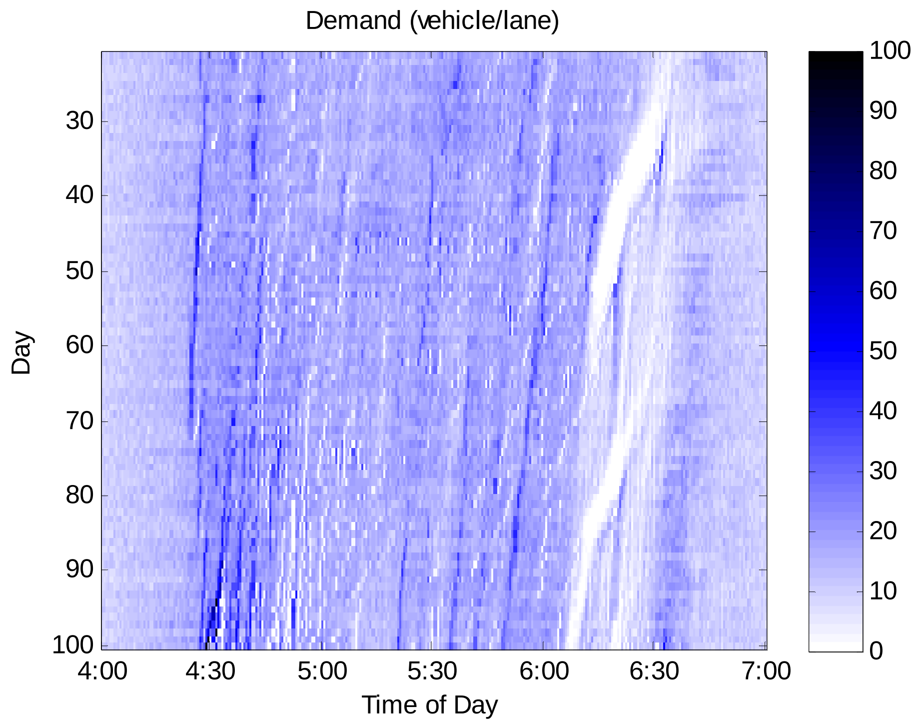


FIGURE 2.9 Demand for GP Lanes Based on Preferred Departure Time

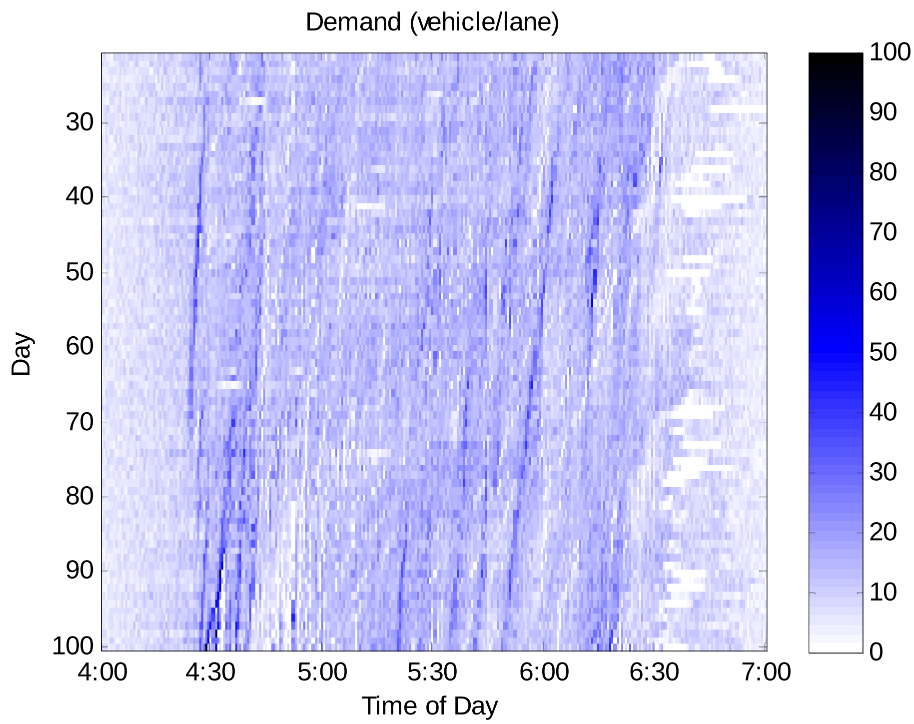


FIGURE 2.10 Demand for Express Lanes Based on Preferred Departure Time

Figure 2.9 and Figure 2.10 illustrate the distribution of traffic demand for GP and express lanes. Again, although the demand is fluctuating over time due to the stochastic nature of the simulation model, the distribution remains relatively stable over the days being simulated. In general, the GP lanes carry higher demand than the express lanes on a per lane basis, as shown in Figure 2.11 for one typical day.

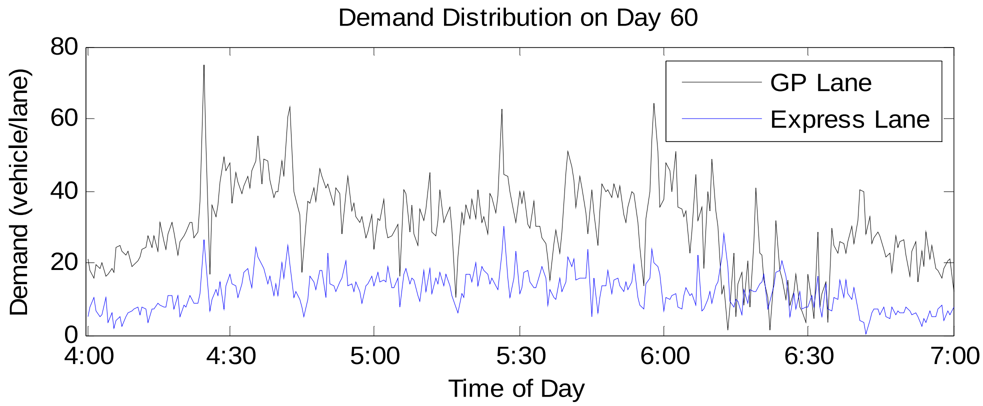


FIGURE 2.11 Demand Distribution for GP and Express Lanes on Day 60

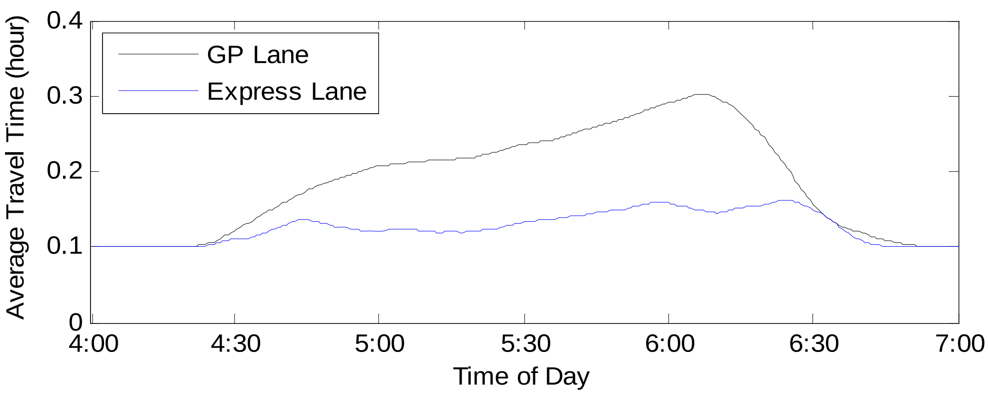


FIGURE 2.12 Average Travel Time on GP and Express Lanes from Day 21 to 100

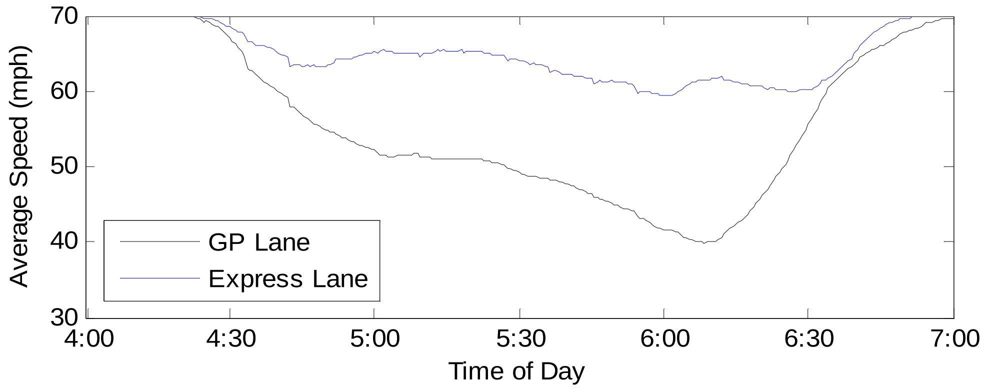


FIGURE 2.13 Average Speed on GP and Express Lanes from Day 21 to 100

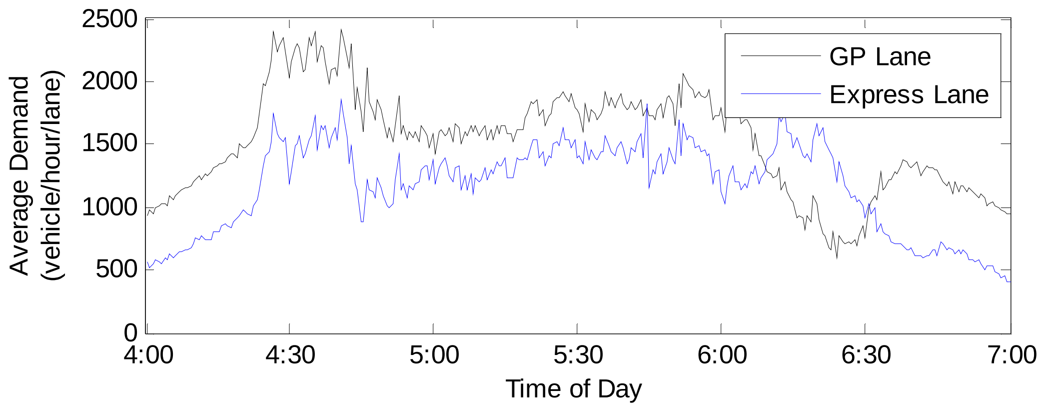


FIGURE 2.14 Average Demand on GP and Express Lanes from Day 21 to 100

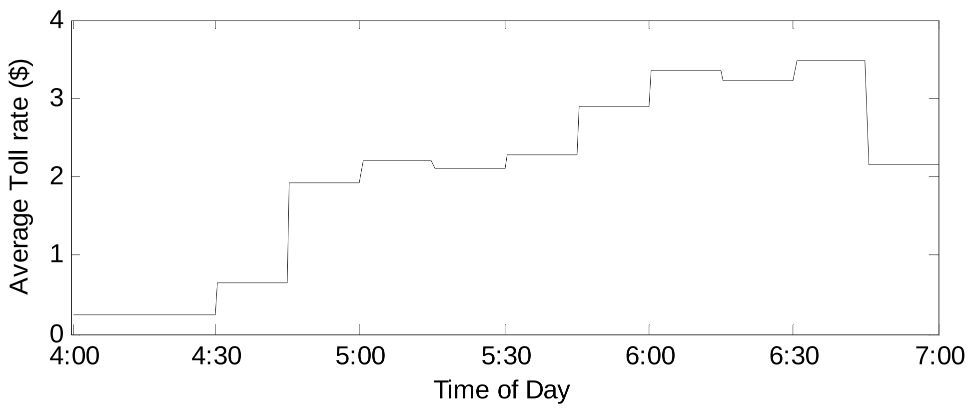


FIGURE 2.15 Average Toll Amount for Express Lanes from Day 21 to 100

Figure 2.12 to Figure 2.15 present the average travel time, speed, demand and toll amount on both GP and express lanes from Day 21 to 100. It can be concluded that under the dynamic tolling scheme, the express lanes are operated close to the free-flow condition, and the capacity of the express lanes can be fully utilized with a peak flow at about 1500 veh/hr/ln.

2.3.2 High-demand case

We further increased the total demand by roughly 20% to examine the performance of the managed-lane system. The results are summarized in Figure 2.16 to Figure 2.20.

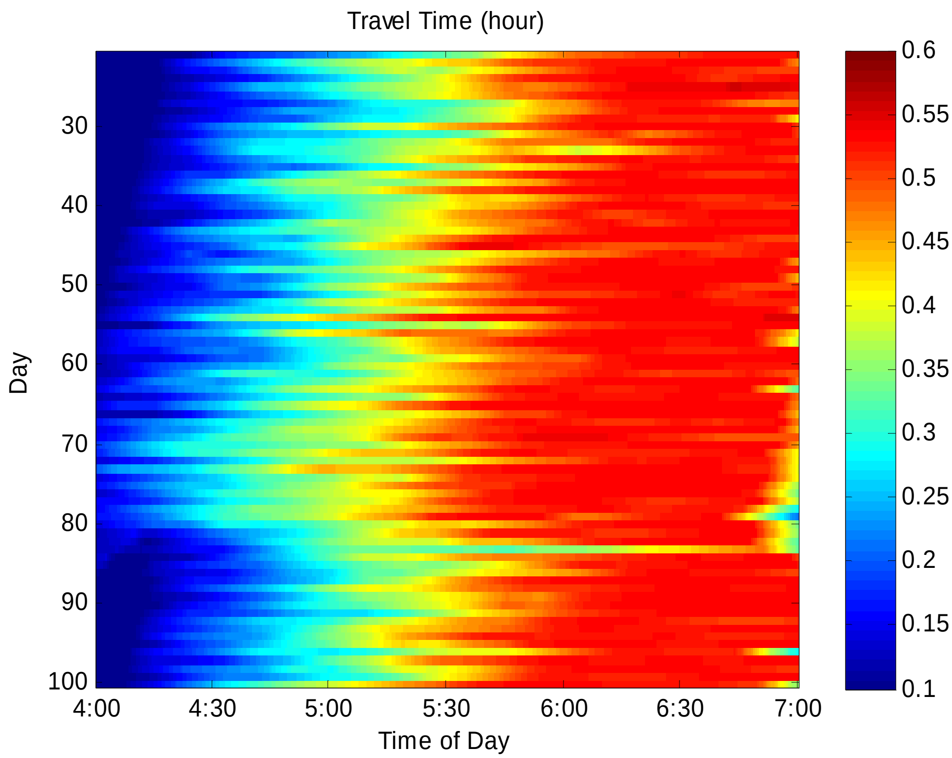


FIGURE 2.16 Travel Time for GP Lanes under High Demand

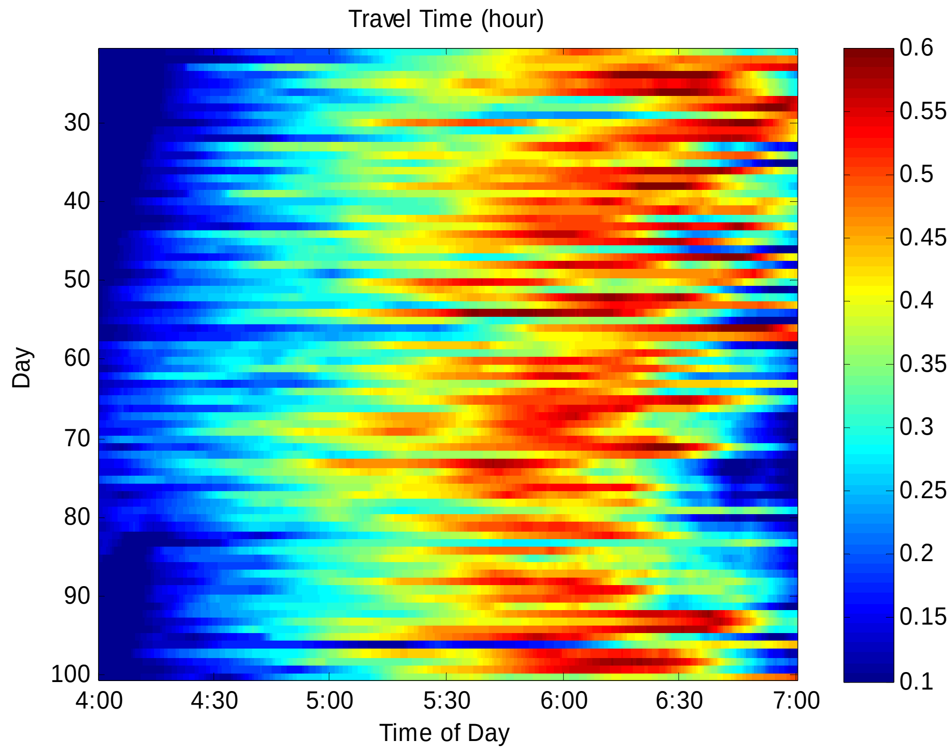


FIGURE 2.17 Travel Time for Express Lanes under High Demand

Figure 2.16 and Figure 2.17 show the travel times under high demand scenario for GP and express lanes respectively. As the demand increases, both lanes experience severe congestion. The express lanes still perform better, but the travel time increases substantially. This suggests that although dynamic tolling is able to maintain a superior level of service on express lanes, its effectiveness becomes limited when the level of total demand increases. It thus becomes necessary to refine the procedure and adjust some key parameters of the algorithm to accommodate high demand in the future.

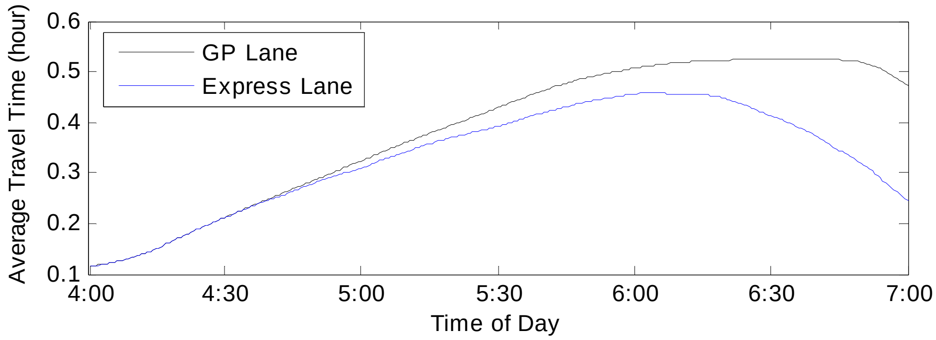


FIGURE 2.18 Average Travel Time on GP and Express Lanes under High Demand from Day 21 to 100

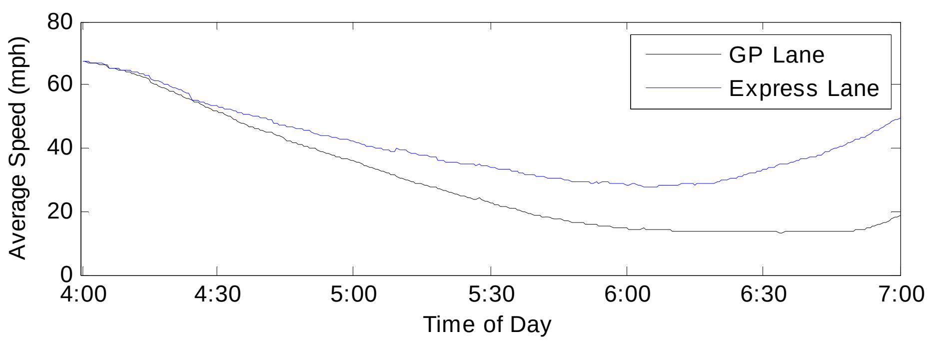


FIGURE 2.19 Average Speed of GP and Express Lanes under High Demand from Day 21 to 100

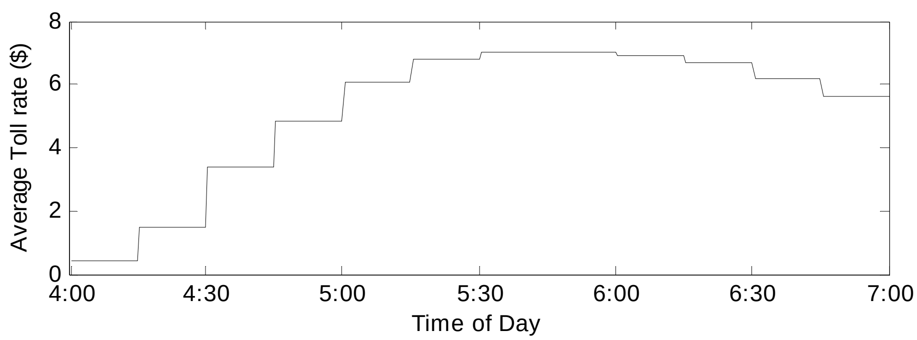


FIGURE 2.20 Average Toll Amount on Express Lanes under High Demand from Day 21 to 100

The average travel time and speed maps in Figure 2.18 and Figure 2.19 also confirm the above observation. Although the express lanes outperform the GP lanes, the pricing algorithm fails to maintain an acceptable traffic condition on the express lanes. More specifically, the average speed of the express lanes falls below 45 mph between 5:30 and 6:30 PM. The high toll amount shown in Figure 2.20 is also an indication of severe congestion in the express lanes. However, because the GP lanes are even more congested, motorists are still willing to pay to access the express lanes.

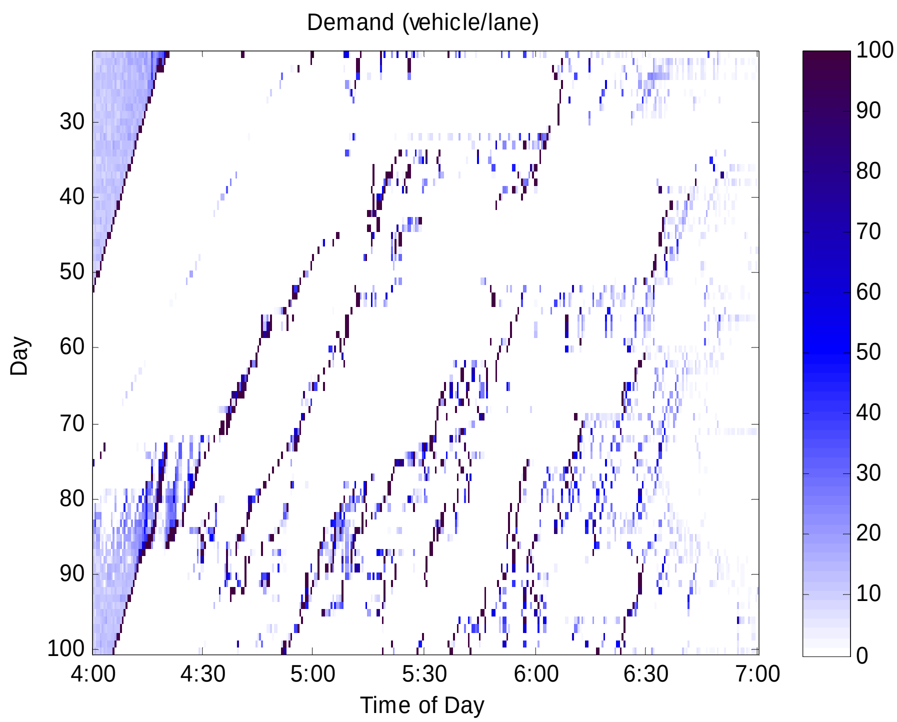


FIGURE 2.21 Demand for GP Lanes Based on Preferred Departure Time under High Demand

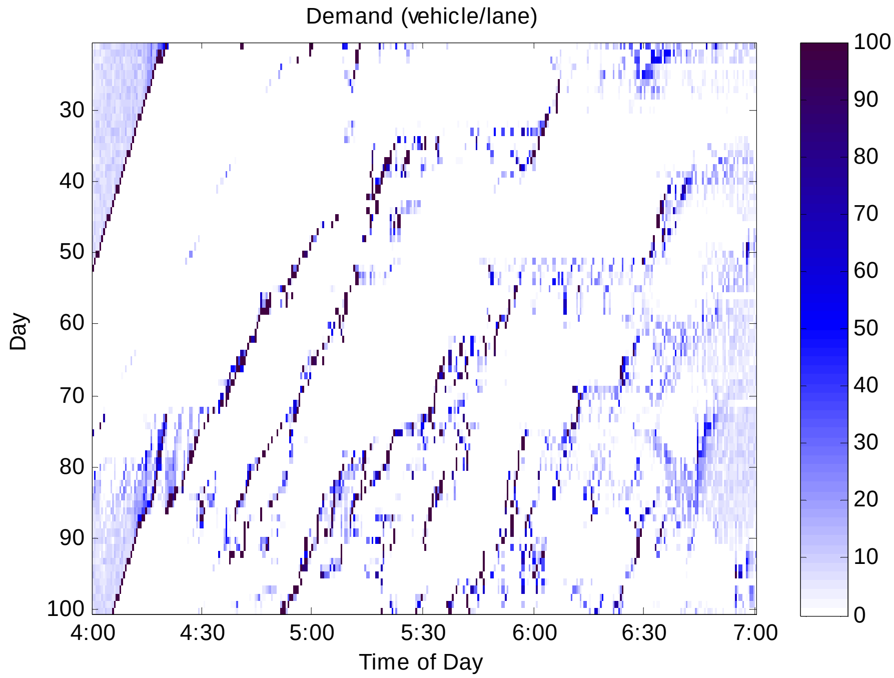


FIGURE 2.22 Demand for Express Lanes Based on Preferred Departure Time under High Demand

The demand distributions are presented in Figure 2.21and Figure 2.22. Compared to the case of base demand, commuters' departure times under the high demand scenario tend to concentrate on a few intervals. This leads to demand surge for certain short periods of day and very low demand for the others. The reason for this phenomenon is that in the high demand case, the total demand for the corridor exceeds its capacity, thus a queue will form at the entrance of the managed-lane system. When the demand reaches a certain level, the queuing delay rises dramatically. In order to avoid the queuing delay, most travelers tend to depart before the formation of queue. As many travelers face the same situation and make similar departure time adjustment, the demand of both lanes become highly concentrated on a few small intervals. This phenomenon is apparent when comparing Figure 2.21 and Figure 2.22 to Figure 2.9 and Figure 2.10. In the latter, the demands for both GP and express lanes are more spread out through the whole peak period.

More interestingly, the demands in the high demand case exhibit hysteresis-like behavior, i.e., travelers shift their departure time choices on day-to-day basis. As shown in Figure 2.21 and

Figure 2.22, the peaks of demand for both GP and express lanes are shifting from day to day. More specifically, an individual traveler keeps moving his or her departure time forward until it is too early for him or her, and then the traveler starts to adjust backward. The pattern is repeated again and again. For example, on day 50, most travelers depart at 5:00pm, and thus the freeway becomes highly congested after that. Given that the travel time is much less before 5:00, on the following day, many choose to depart several minutes earlier than 5:00, resulting in an earlier activation of congestion, which forces many travelers to depart even earlier the next day. Figure 2.23 illustrates this situation.

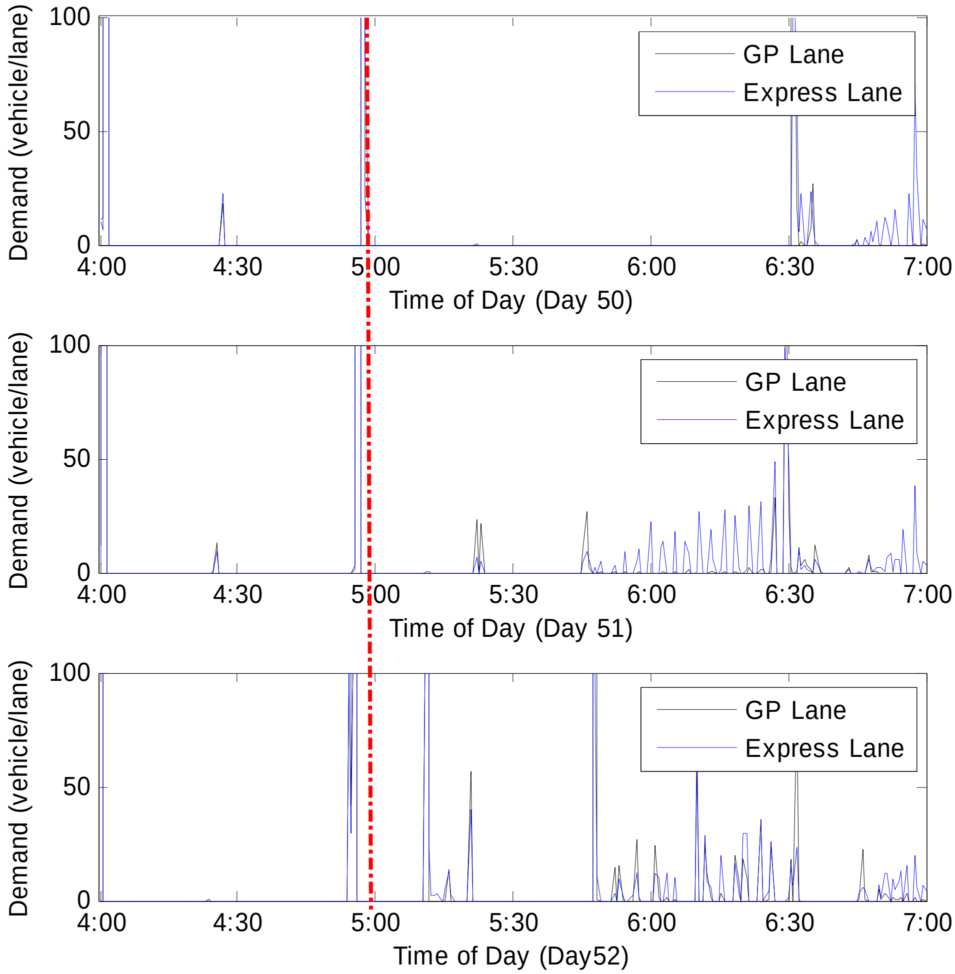


FIGURE 2.23 Demand Distribution for Day 50 to 52 under High Demand

2.3.3 Findings

By examining the results of our simulation experiments, we have the following observations:

- In the base scenario when the demand is relatively low (25300 vehicles from 4 to 7pm, a demand level comparable to the one with 95 Express), the demand distribution and the resulting traffic condition are in a relatively stable state and the system achieves a certain degree of equilibrium. However, when the demand is high (20% more than the current demand level), the system exhibits hysteresis-like behavior, i.e., travelers periodically shift their departure times and lane choices on day-to-day basis.

- The tolling algorithm for 95 Express is able to manage traffic demand and maintain a superior level of service on the express lanes. However, when the traffic condition on the GP lanes becomes severe, the effectiveness of the current tolling algorithm is limited. This is partly due to that the algorithm determines tolls only based on the traffic density of the managed lanes without considering that of the GP lanes. When the traffic condition on the GP lanes is severe, the toll amount will not be high enough to discourage travelers from using the express lanes.

2.4 Analyzing TOD and Static Tolling Versus Dynamic Tolling

In order to answer the other question, i.e., whether dynamic tolling necessarily performs better than TOD or static tolling, we conducted another simulation experiment using the developed simulation tool. The focus was to analyze how the frequency of toll adjustment and the volatility of toll amount impact the system performance. Based on the simulation results, we further investigated whether or not the benefit from dynamic tolling justifies the additional cost of its implementation.

2.4.1 Simulation description

In the analysis, we first determined static and TOD tolling plans to be compared with the dynamic tolling algorithm. Static tolling implies a constant toll amount for the whole peak period while in TOD tolling, the toll amount varies by time of day according to a pre-determined toll schedule. As previously described, dynamic pricing does not employ a toll schedule. The toll reacts to the prevailing traffic condition and varies every 15 minutes.

A total demand of 25,300 vehicles was considered between 4 to 7 pm, i.e., the evening peak. As aforementioned, this demand level matches closely the current peak-period demand on 95 Express, and thus this scenario is called as the base demand scenario. For this scenario, we implemented the 95 Express tolling algorithm and the resulting toll profile is presented in Figure 2.24.

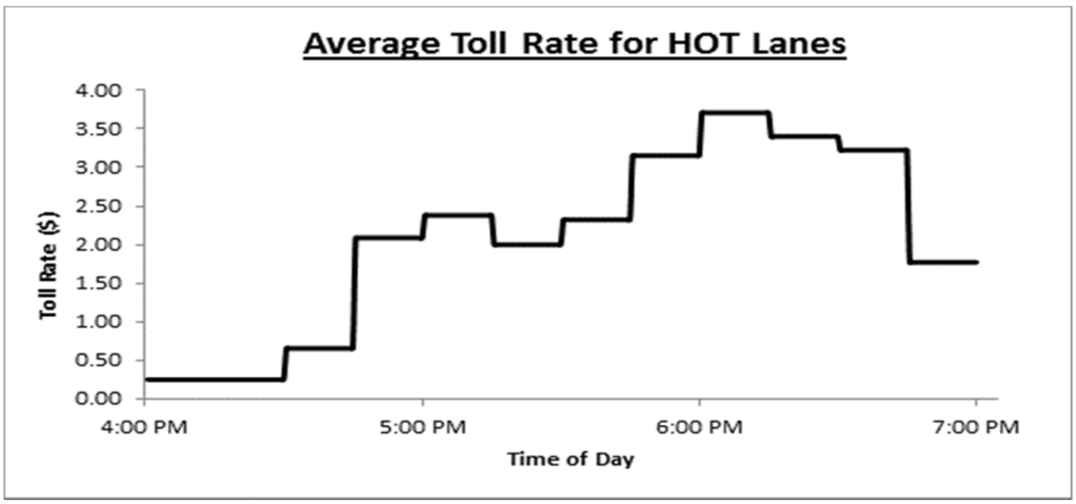


FIGURE 2.24 Average Toll Profile in Dynamic Tolling for the Base Demand Scenario

Using a trial-and-error method, static and TOD tolling plans were obtained, which achieve similar performance as dynamic tolling. The performance measures include the average speed of express lanes (AvgSpeedEL), the average speed of GP lanes (AvgSpeedGP), and the percent time that the express lanes are operated more than 45 mph (Operating SpeedEL> 45mph). The resulting tolling plans are shown in Table 2.4and their corresponding performance measures are presented in Table 2.5.

TABLE 2.4 Selected Static and TOD Tolling Plans for Base Demand

Static Toll ($)	Time-of-day Toll ($)	Time of Day
2.50	1.00	4:00 - 5:00 PM
	2.75	5:00 - 6:00 PM
	2.50	6:00 - 7:00 PM

TABLE 2.5 Summary of Performance Measures of Different Tolling Approaches under Base Demand

Tolling Plan	Total Peak Demand (veh)	AvgSpeedEL (mph)	AvgSpeedGP (mph)	EL Operated above 45 mph (percent)
Dynamic	25,300	55.8	41.8	94.4
TOD Tolling		55.9	41.9	94.4
Static Tolling		56.6	41.0	94.9

2.4.2 Simulation results

To investigate how a static or TOD tolling plan determined for one specific demand scenario performs under other demand scenarios, three future demand scenarios were created, representing 2%, 5%, and 10% increase from the base demand. The resulting performance measures under different future demand scenarios are compared in Table 2.6.

TABLE 2.6 Comparisons of Tolling Approaches under Future Demand Scenarios

Tolling Plan	Demand Scenario (Change from Nominal Demand)	Total Demand (veh)	AvgSpeedEL (mph)	AvgSpeedGP (mph)	EL Operated above 45 mph (percent)
Dynamic	2% Increase	25,805	47.1	35.3	88.6
TOD Tolling			45.5	36.4	85.3
Static Tolling			45.9	35.7	86.8
Dynamic	5% Increase	26,565	41.3	31.5	79.7
TOD Tolling			37.0	31.6	75.1
Static Tolling			36.9	30.7	73.3
Dynamic	10% Increase	27,830	34.9	26.4	69.9
TOD Tolling			29.9	26.0	61.7
Static Tolling			29.8	24.7	60.9

When there is a slight increase, i.e., 2%, in travel demand, dynamic tolling results in slightly better performance, but all three tolling approaches still produce comparable performance. The average speed of express lanes is above 45 mph in all three tolling approaches. Since the travel demand has increased, express lanes are operated above 45 mph for less duration of time. However, when the increase in demand is as high as 5%, dynamic tolling produces better performance than the other two approaches, with a higher speed in express lanes and longer duration over 45 mph. When the demand is increased by 10%, the overall condition of the segment is worse in all three approaches with static and TOD tolling performing more poorly as compared to dynamic tolling. The scenarios with less demand were also considered in the analysis. However, all the three tolling approaches produced very good and comparable performance, and consequently those scenarios are not reported here.

We further conducted a Monte Carlo simulation to investigate the system performance under different tolling approaches for day-to-day varying demand. Assuming that the demand follows a uniform distribution between 0% to 10% increases in the base demand level, we generated 50 demand samples and conducted the simulations accordingly. The resulting average performance measures across these 50 simulations/samples under different tolling approaches are shown in Table 2.7.

TABLE 2.7 Comparisons of Average Performance Measures for Day-to-Day Varying Demand

Tolling Plan	AvgSpeedEL (mph)	AvgSpeedGP (mph)	EL Operated above 45 mph (percent)
Dynamic Tolling	43.2	32.5	82.1
TOD Tolling	40.0	33.1	77.4
Static Tolling	41.1	32.6	77.9

It can be observed that dynamic tolling performs better as compared to other two tolling approaches. The comparison shows that dynamic tolling is more adaptive to the day-to-day demand variation. On the other hand, TOD and static tolling plans determined for one particular level of demand may perform unsatisfactorily under another demand level.

2.4.3 Findings

The simulation results further verify that the dynamic tolling algorithm is able to manage the traffic demand and maintain a superior performance of the express lanes. The performance comparison suggests that when travel demand is predictable, TOD or even static tolling can perform as well as dynamic tolling, provided that the toll profiles are optimized against the demand level. However, since dynamic tolling is adaptive to different level of traffic demand and condition, its performance is more robust and stable. In contrast, the performance of the static and TOD tolling plans may deteriorate substantially if there is an increase in travel demand.

2.4.4 Cost-benefit analysis

The last section reveals that it is beneficial to implement dynamic tolling. On the other hand, dynamic tolling is more costly to implement. This section presents a cost-benefit analysis to examine whether the benefit can justify the additional implementation cost or not.

2.4.4.1 Benefit Estimation

The benefit of dynamic tolling can be multifaceted, but we focus on travel time saving, the major component of the benefit. The estimation of this benefit requires a key parameter, i.e., the value of time or VOT. A reliable estimate of VOT is extremely important for transportation project evaluation.

Different ways of estimating VOT have been suggested in the literature, and the use of certain percent of average wage rate to represent VOT is prevalent. Many studies (e.g., Small, 1982; Waters, 1982; Miller, 1996) have recommended the average VOT as approximately 50 percent of the wage rate. A recent synthesis of research on VOT by Concas and Kolpakov (2009) provides an overview of the empirical estimates of VOT in the literature. The report also suggests that 50 percent of the prevailing wage rate is a good approximation of VOT for personal travel (including commute travel).

On the other hand, some recent studies point out that people often value their travel time higher than 50 percent of wage rate. A study by Small et al. (2005) suggests using a much higher VOT for pricing policies and estimates the median VOT as 93 percent of the average wage rate. The U.S. DOT recommends various VOT to be used for evaluating transportation projects. The estimate varies vary from 50 to 120 percent of the wage rate, depending on the length and the type of travel (USDOT, 2003).

Based on the review of the literature, we selected two different estimates of VOT as 50% and 90% of the average wage rate in our analysis. The former represents the traditional wisdom while the latter reflects the results from some recent studies on tolling projects.

2.4.4.2 Breakeven Implementation Cost

For the wage rate, we used the estimate provided by Bureau of Labor Statistics for the Miami/Fort Lauderdale area (Bureau of Labor Statistics, 2011). Our analysis considers the difference in total system travel time under dynamic and TOD tolling as the benefit of dynamic tolling. Based on the life cycle of project and the discount rate, the present value of the total benefit was calculated to estimate the breakeven implementation cost for dynamic tolling.

Two different scenarios were considered in our analysis to cope with the uncertainty of future demand growth. In the first scenario (Scenario 1), it is assumed that the growth in the future demand is unknown and any value between 0% to 10% increases in the base demand can be realized for future years. We simulated the future demand and computed the total benefits for both tolling approaches. In second scenario (Scenario 2), it is assumed that the there is a linear growth up to 5% increase in the current demand level over the project life cycle. The benefits of the future years were calculated accordingly and then converted to the present value using the discount rate.

The parameters used for estimating the breakeven implementation cost are summarized as follows:

- Project life cycle–10 years;
- Discount rate – 3%;
- Working days in a year – 250 days;
- Average hourly wage rate – $19.85
- VOT – 9.93 or 17.87 $/hr.

The resulting breakeven implementation costs under different considerations are shown in Table 2.8. The cost varies from $1.0M to $3.4M. It implies that if the additional implementation cost for dynamic tolling is higher than the value presented, it is not worth implementing dynamic tolling over TOD tolling.

TABLE 2.8 Breakeven Implementation Cost

	Value of Time ($/hr)	
	$9.93 (50 % of avg wage rate)	$17.87 (90 % of avg wage rate)
Scenario 1	$1,003,832	$1,806,492
Scenario 2	$1,882,124	$3,387,064

2.5 Conclusions

A simulation model was developed based on the current configuration of the existing 95 Express in Florida to analyze the performance of a managed-lane system under a variety of tolling strategies. The model incorporates travelers' day-to-day learning processes and travel choice behaviors. It also represents the traffic flow characteristics of the freeway facility. The model was used to investigate: 1) whether a managed lane system exhibits hysteresis-like behavior under dynamic pricing and 2) whether dynamic pricing necessarily performs better than static or TOD pricing.

The simulation results show that at the current demand level of 95 Express, the system achieves a certain degree of equilibrium. However, if the demand increases to a certain level and congestion becomes severe, the system may exhibit hysteresis-like behavior where travelers constantly shift their departure time on day-to-day basis. The results also confirm that the dynamic tolling algorithm is able to manage the traffic demand and maintain a superior performance of the express lanes. However, when the demand pattern is predictable, TOD or even static tolling could perform as well as dynamic tolling, provided that the toll profiles are optimized against the demand level. However, since dynamic tolling is adaptive to variations in traffic demand and condition, its performance is more robust and stable. Compared to TOD tolling, a breakeven implementation cost for dynamic tolling was estimated to be from \$1.0M to \$3.4M. If the additional implementation cost is more than the value, it is not worth implementing dynamic tolling over TOD tolling.

3 CAPACITY ANALYSIS OF 95 EXPRESS

3.1 Background

As the primary concept of express lanes is to provide access to the vehicles by paying tolls, the HOT lanes in Miami were constructed by separating the GP lanes with the toll lanes via physical barriers, commonly referred as delineators. Though evident that these delineator separated lanes will help in reducing the congestion along the freeway, it thus becomes necessary to analyze and study the effects of these barriers on the operations of other lanes on a facility. As these facilities are generally built within the urban areas, the widths of the lanes or the shoulders/medians are reduced in order to accommodate the extra lanes due to space constraints. For the 95 Express, the lane widths of the adjacent GP lanes and the newly built HOT lanes were reduced to 11 feet from 12 feet.

The objective of this task is to examine whether and how the reduced lane, shoulder widths, delineators, and designs of ingress/egress points have affected the capacity and operations of the toll lanes and the GP lanes for 95 Express lanes. To accomplish this task of the project, a detailed capacity analysis was performed for several sites located along 95 Express, SR-826 (Palmetto Expressway) and I-95 corridor that are outside the 95Express lanes zone. These analyses are performed by comparing the capacities of the freeway sections before the toll lanes were constructed with the capacities after the toll lanes were constructed depending on the availability of the data. The following section describes the traffic data used for these analyses with information on all the sites selected. Section 3.2 provides the detailed capacity analysis, and Section 3.3 provides a summary of the findings and concluding remarks. Finally, recommendations for future study are provided in Section 3.4.

3.1.1 Site selection

To perform the data analyses, detector locations along the 95Express northbound (NB)/southbound (SB) directions, SR-826 (Palmetto Expressway) and on I-95 (sites that are outside of 95 Express zone, referred to as ‘I-95 Other’ thereafter) were selected. In all, three sites were selected for each of the 95 Express northbound and southbound directions, four sites from SR-826 and four sites from I-95 Other. The sites from SR-826 and I-95 were selected because the data were not available for the time periods when the lane widths along 95 Express were 12-ft. This is further discussed in the data section of this chapter (Table 3.5). Thereafter, all the sites within the 95 Express lanes zone will be referred to as 95 Express and all the other sites on I-95, but not the express lanes, will be referred to as I-95 Other. These sites were selected on the basis of the data availability and that they meet the criteria for basic freeway segments.

The three sites along the 95 Express northbound/southbound directions were: one that is close to the entry point of the express lanes (referred as Site 1 for SB, Site 4 for NB); one that is further downstream of the first site and roughly in the middle of the entry and exit points of the express lanes (referred as Site 2 for SB, Site 5 for NB); and one that is near to the exit point of the express lanes (referred as Site 3 for SB, Site 5 for NB). The details for these sites on the 95 Express lanes are provided in Table 3.1 and Table 3.2. Satellite maps for these sites are shown in Figure 3.1and Figure 3.2.

TABLE 3.1 Selected Sites on 95 Express along Southbound Direction

Sites	Description	# Lanes HOT	# Lanes GP	Lat.	Long.	Milepost	Speed Limit
Site 1	I-95 S of NW 143 St	2	4	25.904265	-80.21042	11.1	55 mi/h
Site 2	I-95 at NW 112 St	2	4	25.877547	-80.20928	9.29	55 mi/h
Site 3	I-95 S of NW 68 St	2	4	25.836399	-80.20634	6.48	55 mi/h

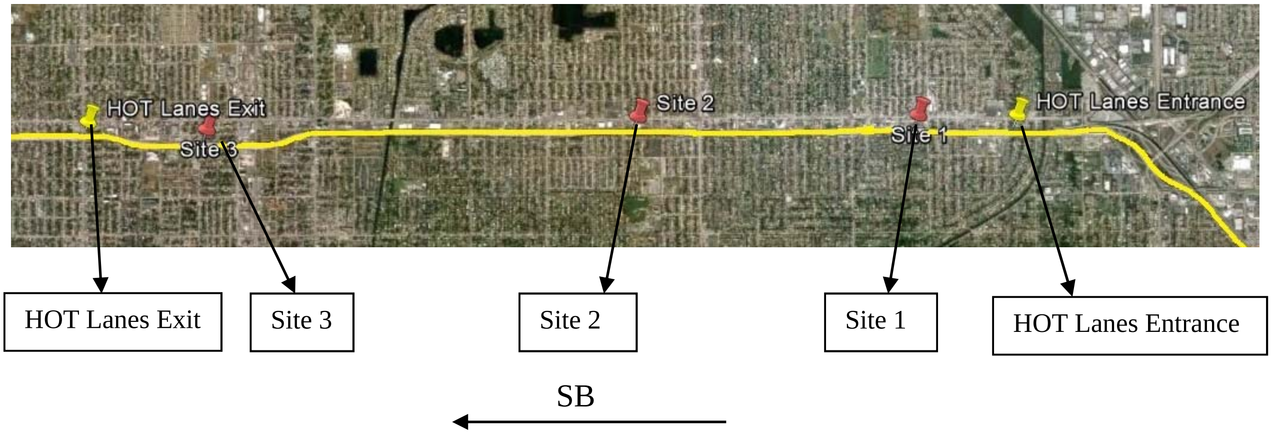


FIGURE 3.1 Detector Locations along 95 Express Southbound Direction (Source: Google Earth)

TABLE 3.2 Selected Sites on 95 Express along Northbound Direction

Sites	Description	# Lanes HOT	# Lanes GP	Lat.	Long.	Milepost	Speed Limit
Site 4	I-95 at NW 69 St	2	4	25.83773	-80.20618	6.56	55 mi/h
Site 5	I-95 N of NW 103 St	2	4	25.8718	-80.20874	8.89	55 mi/h
Site 6	I-95 N of Opa-Locka Blvd	2	4	25.90039	-80.21044	10.8	55 mi/h

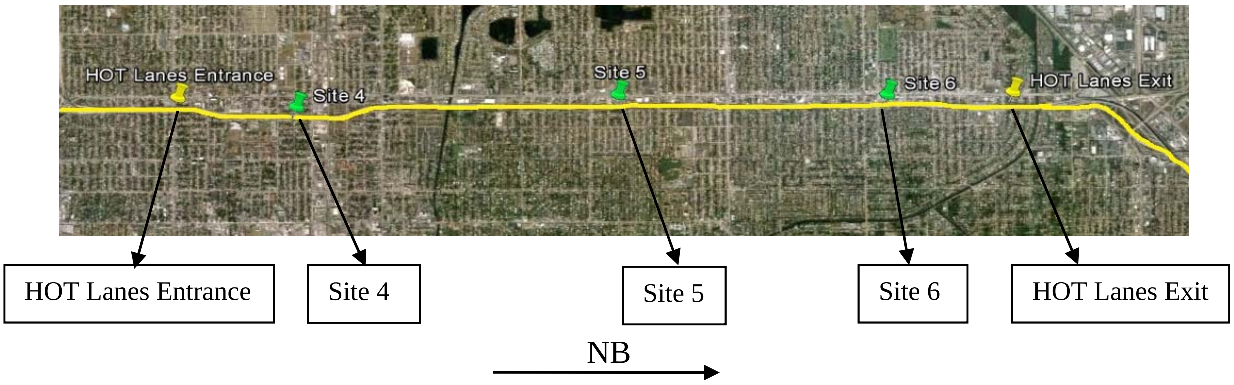


FIGURE 3.2 Detector Locations along 95 Express Northbound Direction (Source: Google Earth)

The sites that are selected along SR-826 (Palmetto Expressway) are described in Table 3.3. A satellite map with the locations of all the sites is also provided in Figure 3.3.

TABLE 3.3 Selected Sites on SR-826 in Miami Regional Area

Sites	Description	# Lanes GP	Lat.	Long.	Milepost	Speed Limit
Site 7	SR-826 WB South of W 60 St.	4	25.8733	-80.3238	13.16	55 mi/h
Site 8	SR-826 WB East of NW 57 Ave	3	25.9256	-80.2855	19.06	55 mi/h
Site 9	SR-826 EB East of NW 57 Ave	3	25.9251	-80.2855	19.06	55 mi/h
Site 10	SR-826 WB East of NW 47 Ave	3	25.9257	-80.2692	20.14	55 mi/h

FIGURE 3.3 Detector Locations along other Facilities in Miami Regional Area (Source: Google Earth)

The sites that are selected along on I-95 (excluding the express lanes zone) are described in Table 3.4. A satellite map with the locations of all the sites is also provided in Figure 3.4.

TABLE 3.4 Selected Sites with 12-ft Wide GP Lanes, SB Direction

Sites	Description	# Lanes HOV	# Lanes GP	Lat.	Long.	Milepost	Speed Limit
Site 12	I-95 SB At NW 19th St	1	5	26.1510	-80.1683	29.6	65 mi/h
Site 13	I-95 SB South of Sheridan St	1	5	26.0256	-80.1675	20.8	65 mi/h
Site 14	I-95 SB North of Miami-Dade Co/Ln	1	4	25.9764	-80.1677	17.4	65 mi/h
Site 15	I-95 North of Miami Gardens Dr	1	3	25.9513	-80.1804	15.2	55 mi/h

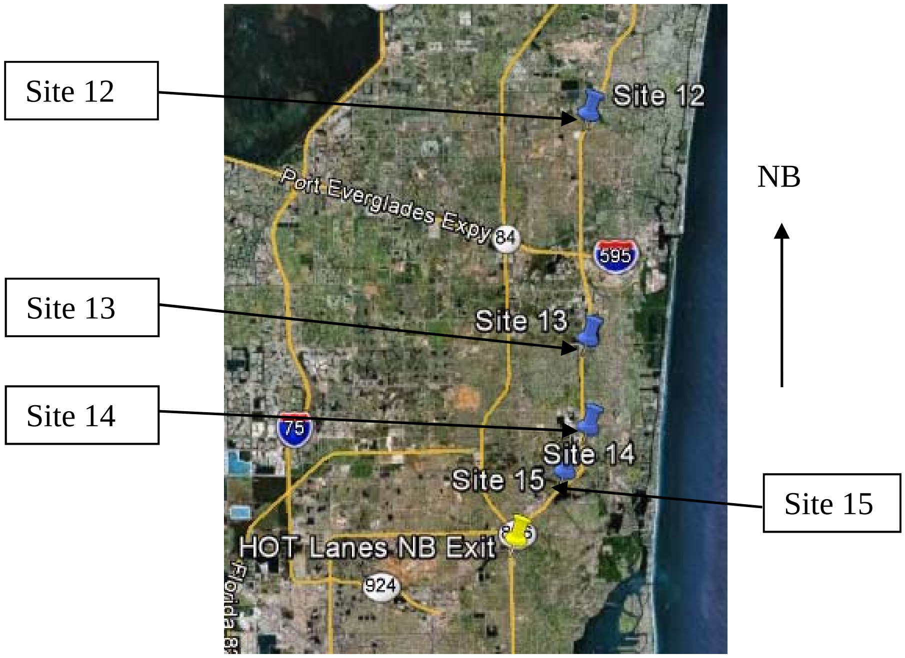


FIGURE 3.4 Detector Locations along I-95 Other that are outside the 95 Express Lanes Facility (Source: Google Earth)

3.1.2 Data

Florida's Central Data Warehouse (aka STEWARD) was used to obtain the 5-minute aggregated station and lane data. The speeds were plotted with the hourly flow rates (calculated from aggregated 5-minute intervals) to obtain the speed-flow plots. To ensure that the erroneous entries (during night hours) are avoided, the data points were considered only from 5 AM to 10 PM. Also, all the flow rates above 2700 veh/h/ln were excluded from the analyses (as these are likely a result of erroneous measurements). For calculating the average vehicle speeds, the AM Peak was considered as 6 AM to 9 AM and the PM Peak was considered as 4 PM to 7 PM.

Three time periods were chosen for performing the analyses: 1) pre-delineator installation, 2) post-delineator installation but pre-tolling, and 3) post-tolling. The data for these time periods were selected on the basis of the construction timeline of the 95 Express lanes. This is provided briefly in Table 3.5.

TABLE 3.5 Construction Timeline for the 95 Express Northbound and Southbound

	Northbound	Southbound
*Re-striping of the mainlines	March - July 2008	April - August 2009
Detector Calibration	June 2008	August 2009
Delineators Installation	July 2008	December 2009
Last STEWARD available data	November 2008	September 2009
Tolling Implementation	December 2008	January 2010

*Reduction of lane-widths from 12-feet to 11-feet

The data availability, data constraints, and the quality of data were taken into account to select the following days for all the analyses:

95 Express southbound direction:

Pre-delineator installation: 09/14/2009 – 12/05/2009, 81 days

Post-delineator installation but pre-tolling: 12/21/2009 – 01/14/2010, 25 days

Post-tolling: 01/20/2010 – 06/30/2010, 160 days

Pre re-striping of mainlines data: Not available (detectors were not calibrated)

95 Express northbound direction:

Pre-delineator installation: Not Available

Post-delineator installation but pre-tolling: 11/01/2008 – 11/30/2008, 30 days

Post-tolling period: 09/01/2009 – 11/30/2009, 90 days

Pre re-striping of mainlines data: Not available (detectors were not calibrated)

SR-826:

Only post-tolling period: 01/20/2010 – 06/30/2010, 160 days

I-95 Other (outside of 95 Express lanes zone):

Only post-tolling period: 03/01/2010 – 08/30/2010, 180 days

Lane widths:

95 Express SB/NB: All GP lanes and HOT lanes are 11-ft wide for all three time periods

I-95 Other (outside of 95 Express lanes): All GP lanes and HOV lanes are 12-ft wide for post-tolling period

SR-826: All GP lanes are 12-ft wide for the post-tolling period

3.2 Data Analysis

To accomplish the objective of this task, the capacity analysis was performed by estimating the freeway capacities for all the selected sites. At first, the capacities were estimated by a mathematical model that is based on a simple car-following model developed by Van Aerde (1995), and second, the capacities were estimated by using an "average capacity" methodology developed by Washburn et al (2010). These methods, along with their findings are briefly described in the following sections.

3.2.1 Preliminary data analysis

To estimate the capacity of the freeway segments, a mathematical model developed by Van Aerde (1995) was used that provides a good fit to speed-flow data points. This mathematical model is based on a simple car-following model which is based on the minimum headway distance between consecutive cars. The regression analysis as suggested is implemented in the software program Traffic Stream Calibration Software, SPD_CAL.exe, by Rakha (2007). This software program calibrates the four parameters, free-flow speed, speed at capacity, capacity, and jam density, for a given data set. The software uses a heuristic hill-climbing technique to determine the optimum parameters. For these models, the flow-rate value that represents the apex of the mathematical model fitted to the speed-flow data points is considered as the capacity estimate for the freeway segment.

The speed-flow models were run separately for both HOT lanes and GP lanes for only two times periods: 1) post-delineator installation but pre-tolling, and 2) post-tolling period, because the data in the northbound direction were not available for the pre-delineator installation period. The 5-minute station data were used to plot the respective speed-flow data points at the three sites in northbound direction of 95 Express. The Van Aerde model fitted function to speed-flow data points for the time periods along with the calibrated capacity parameters were obtained from the

Traffic Stream Calibration Software program. An example of the Van Aerde model fitted function to speed-flow data points for the post-tolling condition is provided in Figure 3.5and the calibrated parameters, obtained from the Traffic Stream Calibration program, for all sites, is shown in Table 3.6.

TABLE 3.6 Station Capacity Values at Sites in NB Direction for GP and HOT Lanes in veh/h/ln from the Van Aerde Model Method

	Post-Delineator but Pre-Tolling Period		**Post-Tolling Period**	
	GP Lanes	HOT Lanes	GP Lanes	HOT Lanes
Site 4	1524	1524	1605	1426
Site 5	1600	1503	1659	1333
Site 6	1558	1543	1623	1568

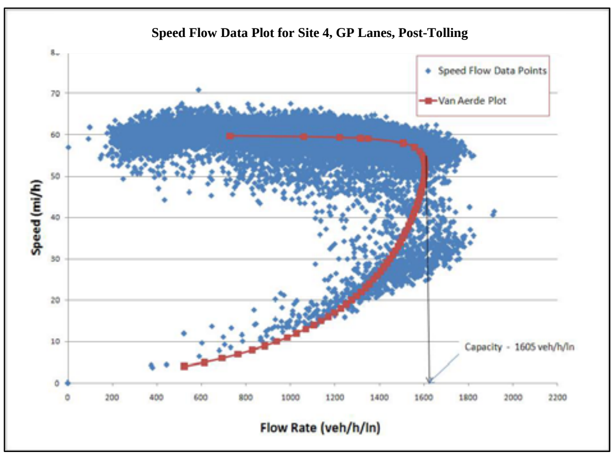


FIGURE 3.5 Speed-Flow Data Points and Van Aerde Model Curve Fit for GP Lanes for Site4 during Post-Tolling Period

The following observations were made from the calibrated capacity estimates of GP and HOT lanes, and the speed-flow plots using the station data at the three selected sites:

- The capacity estimates for the HOT and GP lanes were found to be comparable during the pre-tolling period. However, during the post-tolling period, the capacity estimates for the GP lanes appeared to be higher as compared to HOT lanes.
- The capacity estimates for the HOT lanes are found to be lower during the post-tolling

period as compared to the pre-tolling period. However, the capacities of HOT lanes at site 6 are found to be fairly similar during post-tolling and pre-tolling period.

- It is also observed that the HOT lanes at sites 4 and 5 do not appear to be congested whereas, site 6 is found to be congested.
- The vehicle speeds on the HOT lanes are found to be higher as compared to their respective GP lanes at the same site location.

After further consideration, it was felt that the capacity estimates from the Van Aerde model capacity estimation method were found to be too low, as these estimates were observed to be at the lower end of the region containing the highest flow-rates from the respective speed-flow plots. These findings were shared with FDOT Central Office and FDOT's District 6 personnel and it was decided by the research team that an alternate approach should be considered for calculating the capacity estimates for these sites. As a result, not all of the results are tabulated and not all of the speed-flow plots are provided in this report. Also, since the data were unavailable for the pre-delineator installation period for the 95 Express northbound direction, all of the other analyses presented in this report were performed only for the 95 Express southbound direction. The next section describes the alternate approach used by the researchers to estimate the capacities of the GP and HOT lanes.

3.2.2 Percentage of maximum flow-rates estimation method

After examining the results from the Van Aerde model capacity estimation method, another approach was considered for estimating the capacity values. This method is based on concept of breakdown by Brilon (2005), commonly referred to as the stochastic capacity estimation method. Using this method, the capacity estimates for all the sites along southbound direction were determined, and they were generally found to be unreasonably high for any percentile value, except for small percentile values as suggested by Geistefeldt (2008). Therefore, an alternate approach was used to determine "reasonable" capacity estimates that seek to find a compromise in the estimated values between the Van Aerde model and the stochastic capacity estimation method.

The approach as suggested by Washburn et al. (2010) is a simple methodology that determines an hourly flow-rate, corresponding to a selected percentile value within a subset of observed highest flow rates. The flow-rate from the most appropriate percentile value is considered as the capacity value for a given facility. The lower boundary of this subset is taken as the average of the top 6.5% of highest flows and the upper boundary is taken as the highest flow rate observed on a facility. Based on the upper bound value and the lower bound value, the flow rate at the 75th percentile value within this subset of flow rates (value for which 75% of flow rate values in this subset are less than) is taken as the capacity estimate. After careful observations and comparisons, the averaging methodology was found to provide reasonable and acceptable capacity values. This methodology was developed after analyzing and estimating capacities for 22 basic freeway segments in Florida. The development of this method is described next in brief.

In this alternate methodology, the lower bound of the set of data points containing the highest flow-rates was determined by selecting a flow-rate that corresponded to a certain percentile of a subset of the total number of flow-rate values. However, given that the selection of this percentile value can be subjective, the percentile value was based on the Van Aerde model estimated capacity values. The data were sorted from highest to lowest flow rates, and the average of the top x% highest flow rates was calculated for 5- and 15-min aggregated hourly flow rates. For all 22 sites, the x value was calculated such that the average of the top x% highest flow rates corresponded to the respective Van Aerde model capacity estimates. On the basis of the range and average of these x values, two specific values of x, 5% and 6.5% were chosen. Using these x values, the lower boundaries for two different sets containing the highest flow-rates were determined. For both sets, flow rates were estimated for the 55th percentile value up to 85th percentile value (in increments of 5%) within these sets. These flow rates were tabulated and given to FDOT Systems Planning Office (SPO) for their review. After discussing these values/tables with FDOT, it was decided that the capacity estimates could be best determined from a set containing the highest flow rates where the lower boundary is the average of the highest 6.5% flow rates and the upper boundary is the maximum flow rate. From this set, the flow rate at the 75th percentile value is chosen as the capacity estimate (as decided upon by the FDOT SPO and the research team). Therefore this method was chosen as the primary method for all the analyses presented in this chapter and within the scope of this task.

3.2.3 Effect of delineators/tolling on GP lanes of 95 Express

The following analysis is performed to understand/capture the effect of delineators and tolling on the capacity of the GP lanes along 95 Express. For this, the capacity analysis is performed for all the three time periods as mentioned earlier. Due to data limitations and availability, only the sites along the southbound direction were considered. The method of percentile of highest flow rates was used to obtain the capacity estimates for all the GP lanes, i.e., GP Lane 1, GP Lane 2, GP Lane 3 and GP Lane 4. A schematic diagram of the lane numbering convention used for the lanes on GP lanes is provided in Figure 3.6. The capacity estimates from this method are provided in Table 3.7, Table 3.8 and Table 3.9 for the three time periods respectively. The speed flow plots are obtained for all the lanes at all the selected sites for all three time periods. Figure 3.7, Figure 3.8 and Figure 3.9 provide the speed-flow plots for only GP lane 1 and GP lane 2 for all the three time periods at all three locations respectively.

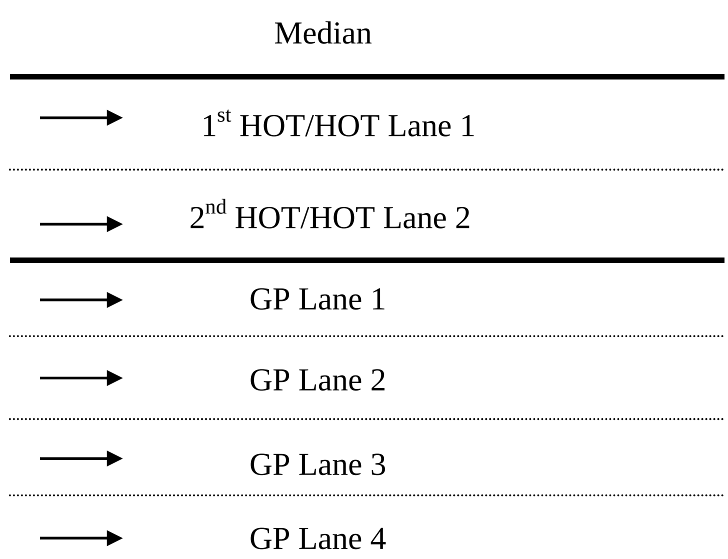


FIGURE 3.6 Lane Numbering Convention

3.2.3.1 Capacity Analysis

The following observations are made on the basis of the capacity estimates from the above mentioned capacity estimation method:

- The capacity estimates are found to be higher for all the GP lanes during the post-delineator installation but pre-tolling period and post-tolling period as compared to the pre-delineator installation time period, except for GP lane 1 the location near to the entry point. The reason behind this observation could be the increase in demand for GP 2 -4 lanes. As the demand on the GP lane 1 decreases (because drivers may not feel comfortable driving next to delineators), the downstream vehicles start using GP lanes 2-4. Also, the induction of tolls could have reduced the demand on HOT lanes that were GP lanes during pre-tolling period and subsequently, the demand on the current GP lanes increased. Thus, the capacity estimates for the pre-delineator period may have been demand-limited.
- It is observed that the capacity, or possibly demand-limited capacity, for GP lane 1 at the entry-point or site 1 decreased significantly after the delineators were installed on the 95 Express lanes. This "capacity" value appears to be a function of reduced demand. Drivers likely prefer to not drive in the lane next to the delineators, and will use other lanes if they are not congested. That appears to be the case at this location; thus, this capacity value actually represents the upper limit of demand rather than a true capacity.
- The capacity of the GP lane 1 is observed to be higher as compared for the GP lane 2 during the pre-delineator installation period at sites 2 and 3. But during the post-tolling period, the capacity of GP lane 1 is observed to be lower as compared to the GP lane 2. This means that the GP lane 1 is utilized less as compared to the GP lane 2 because of the presence of delineators. The delineators make the drivers shy away from the lane next to delineators, hence the GP lane 1 capacity decreases during the post-tolling period.
- The capacity estimates for GP lane 1 during the pre-delineator installation period are found to be comparable at all three locations, but during the post-delineator installation period the capacity estimates increase along the flow of direction. The reason behind this observation could be the initial reluctance of drivers to drive next to the delineators, but as they travel further downstream there is a probable shift of demand from GP lanes 2-4 to GP lane 1, so the vehicles start using the lane next to the delineators.

TABLE 3.7 Lane-by-Lane Capacity Analysis for SB GP Lanes Using the Percentile of Highest Flow Rates Method for the Pre-Delineator Installation Period

	Capacity Estimates (veh/h/ln)			
Sites	GP Lane 1*	GP Lane 2*	GP Lane 3*	GP Lane 4*
Site 1	1884 (2040)	2100 (2292)	2136 (2292)	1752 (1980)
Site 2	2004 (2160)	1980 (2136)	2100 (2256)	2004 (2160)
Site 3	2016 (2304)	1788 (2076)	1992 (2172)	2088 (2292)

*() is the maximum flow-rate observed during the time period.

TABLE 3.8 Lane-by-Lane Capacity Analysis for SB GP Lanes Using the Percentile of Highest Flow Rates Method for the Post-Delineator Installation but Pre-Tolling Period

	Capacity Estimates (veh/h/ln)			
Sites	GP Lane 1*	GP Lane 2*	GP Lane 3*	GP Lane 4*
Site 1	1176 (1332)	2040 (2208)	2196 (2316)	1848 (1980)
Site 2	1632 (1884)	2172 (2364)	2208 (2400)	2424 (2604)
Site 3	2004 (2316)	2148 (2280)	2088 (2292)	2124 (2388)

*() is the maximum flow-rate observed during the time period.

TABLE 3.9 Lane-by-Lane Capacity Analysis for SB GP Lanes Using the Percentile of Highest Flow Rates Method for the Post-Tolling Period

	Capacity Estimates (veh/h/ln)			
Sites	GP Lane 1*	GP Lane 2*	GP Lane 3*	GP Lane 4*
Site 1	1236 (1548)	2100 (2364)	2220 (2400)	2136 (2364)
Site 2	1908 (2220)	2280 (2532)	2268 (2520)	2304 (2556)
Site 3	2160 (2424)	2196 (2460)	2208 (2412)	2220 (2412)

*() is the maximum flow-rate observed during the time period.

3.2.3.2 Speed Analysis

This set of analysis is performed to study/capture the effects on the average vehicle speeds due to delineator installation/tolling on 95 Express GP lanes. The average vehicle speeds are calculated for all the three selected sites along the 95 Express southbound direction for all the three time periods. The 5-minute speed data were averaged for the entire data analysis period during the AM peak and PM peak period. The AM peak covers all the speed points from 6 AM to 9 AM and PM peak covers speed points from 4 PM to 7 PM. The average vehicle speeds for the GP lanes for all the three time periods are tabulated in Table 3.10, Table 3.11 and Table 3.12 respectively. As a simple comparison of average vehicle speeds between different time periods would not prove to be useful, a detailed statistical analysis of the speed data is performed to determine if there is a significant change in the average vehicle speeds over the three time periods. For this statistical testing, the analysis of variance (one-way ANOVA) test was performed. The details of the statistical analysis are provided next:

The dataset for this test contains the per-lane average vehicle speeds of GP lanes 1, 2, 3 and 4 grouped together by all three time periods across the lanes and along the direction of traffic flow. For these ANOVA tests, the following null and alternative hypotheses are assumed:

H_o: The means of the groups within the datasets containing the average vehicle speeds are equal. Hence, there are no statistically significant differences among the groups.

H_A: The means of the groups within the datasets containing the average vehicle speeds are not equal. Hence, there are statistically significant differences among the groups.

To test the respective hypotheses, the *F*-test was performed for all the experiment sets. The $F_{\text{statistic}}$ was calculated for all the experimental sets and was compared with the F_{critical} value. The F_{critical} value is calculated for the 95% confidence level. If the $F_{\text{statistic}}$ value from the experiment is found to be less than the F_{critical} value, the null hypothesis is accepted and vice-versa.

For the cases where the null hypothesis is accepted, no further tests are performed and all the groups within the datasets are considered to have equal means. For the cases, where the alternative hypothesis is accepted, the means of the groups within the datasets are considered to be different. In this case, it is useful to determine which groups are different from each other. For this task, the Tukey's *W* procedure is applied, which provides information on the groups that differ from each other. For all three experiments above, the *F*-test is applied and the Tukey's *W* procedure is applied wherever it is necessary. The following are some of the observations from this experiment.

For the AM peak period, when the vehicular traffic is traveling towards downtown Miami:

- It is observed that the average vehicle speeds on the 95 Express GP lanes were significantly higher during the post-tolling period as compared to the pre-delineator installation period at sites 1 and 3. However at site 2, the average vehicle speeds were found to be significantly lower during the post-tolling period which could be due to the increasing number of breakdown events after the tolling started (refer Figure 3.8 C).
- It is also observed that the differences in the average vehicle speeds between the GP lanes 1 and 2 are not significantly different during the post-tolling period as compared to the pre-delineator installation period. Also, the GP lanes 1 and 2 speeds are significantly lower than the average vehicle speeds on the adjacent HOT lanes 1 and 2 except for HOT lane 2 at site 1.
- The average vehicle speeds on GP lanes 1 and 2 are significantly higher than the vehicle speeds on GP lanes 3 and 4 at sites 1 and 2. The interaction of the merging vehicles from the on-/off-ramps with the outer lanes could be one of the reasons for this observation.

For the PM peak period, when the vehicular traffic is traveling away from downtown Miami:

- It was observed that the average vehicle speeds were significantly higher during the post-tolling period at site 1, whereas at site 2, the speeds were found to be significantly lower during the post-tolling period. The increasing number of breakdown events at site 2 could be the reason for lower average vehicle speeds during post-tolling period.
- GP lanes 1 and 2 appear to be slower as compared to HOT lanes 1 and 2 for all the time periods at all the sites except for the site 1 HOT lane 2.
- The average vehicle speeds on GP lanes 1 and 2 are significantly higher than the vehicle speeds on GP lanes 3 and 4 at sites 1 and 2. The interaction of the merging vehicles from the on-/off-ramps with the outer lanes could be one of the reasons for this observation.

From the speed-flow plots in Figure 3.7 A) & C) and Figure 3.8 A) & C), it is observed that GP lanes 1 and 2 do not have congested speed-flow data points during the pre-delineator installation period at site 1, but during the post-tolling period, GP lanes 1 and 2 are found to have congested speed-flow data points. This is due to the vehicles trying to enter/use the express lanes.

TABLE 3.10 Average Vehicle Speeds Observed for all the SB GP Lanes during the Pre-Delineator Installation Period

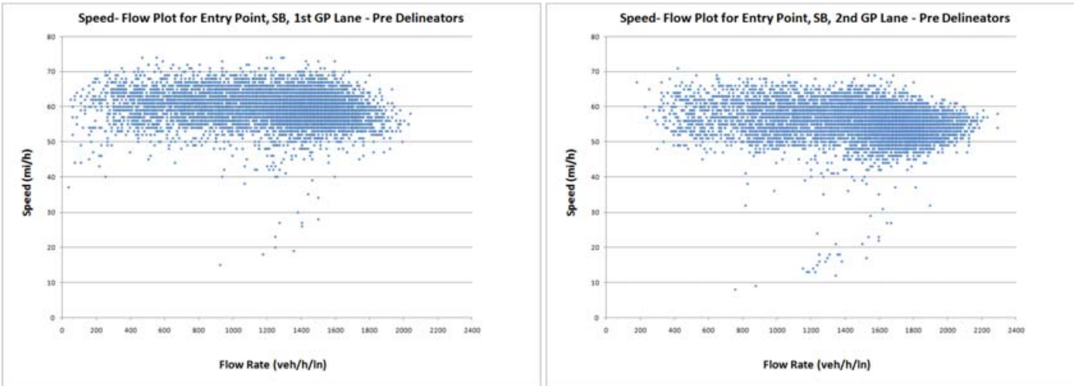
	Average Vehicle Speeds (mi/h)							
	GP Lane 1		GP Lane 2		GP Lane 3		GP Lane 4	
Sites	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak
Site 1	54.4	55.9	52.1	51.3	51.6	50.0	45.8	45.2
Site 2	55.9	59.7	55.6	58.1	55.1	57.9	48.1	49.9
Site 3	45.8	59.2	55.1	61.3	48.8	59.2	46.2	53.7

TABLE 3.11 Average Vehicle Speeds Observed for all the SB GP Lanes during the Post-Delineator Installation but Pre-Tolling Period

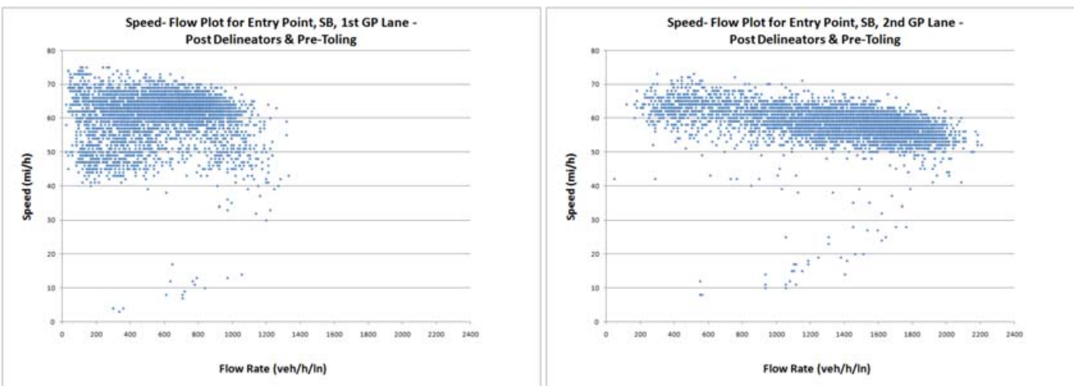
	Average Vehicle Speeds (mi/h)							
	GP Lane 1		GP Lane 2		GP Lane 3		GP Lane 4	
Sites	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak
Site 1	50.5	59.2	53.8	53.8	51.3	51.5	43.9	45.4
Site 2	60.0	60.9	61.8	58.5	61.3	57.6	54.2	50.1
Site 3	59.7	60.0	59.6	59.4	58.7	58.0	55.7	53.9

TABLE 3.12 Average Vehicle Speeds Observed for all the SB GP Lanes during the Post-Tolling Period

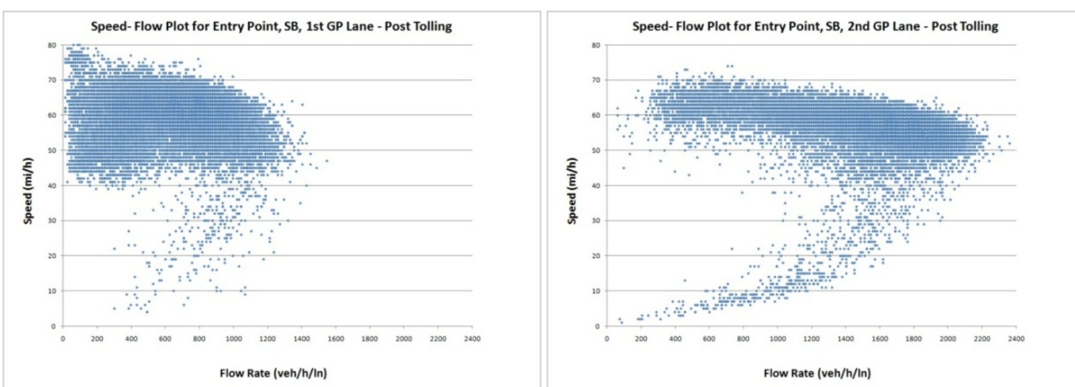
	Average Vehicle Speeds (mi/h)							
	GP Lane 1		GP Lane 2		GP Lane 3		GP Lane 4	
Sites	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak
Site 1	55.1	60.6	55.8	54.7	54.0	52.6	48.6	47.9
Site 2	53.2	58.7	51.7	56.3	51.4	55.9	45.9	48.2
Site 3	56.0	58.9	55.5	58.9	53.6	57.2	51.2	53.2



A) Speed-flow plots for site 1 or entry point for GP lane 1 and GP lane 2 at SB for pre-delineator installation period

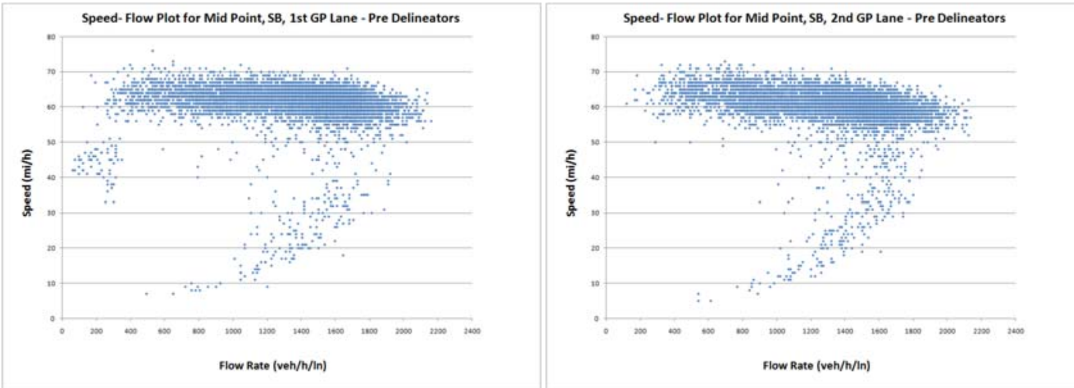


B) Speed-flow plots for Site 1 or entry point for GP lane 1 and GP lane 2 at SB for post-delineator installation and pre-tolling period

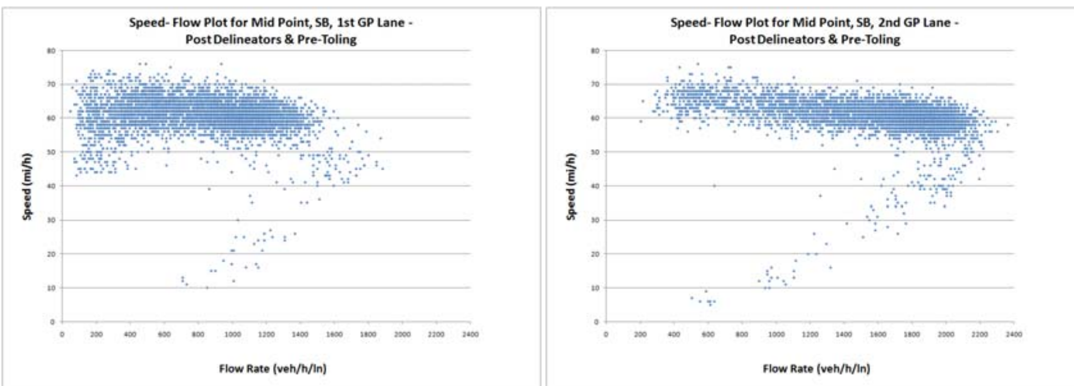


C) Speed-flow plots for Site 1 or entry point for GP lane 1 and GP lane 2 at SB for post-tolling period

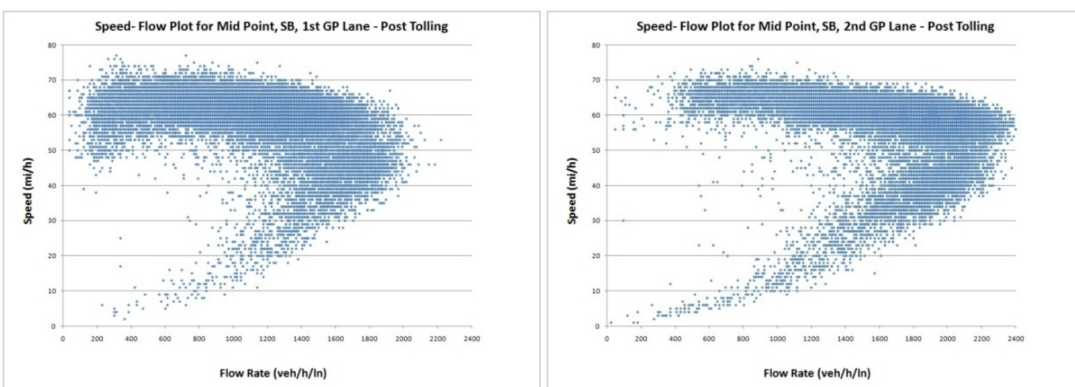
FIGURE 3.7 Lane-by-Lane Comparisons of Speed-Flow Plots of GP Lane 1 and GP Lane 2 for the SB Site 1 for the Three Time Periods



A) Speed-flow plots for Site 2 or mid point for GP lane 1 and GP lane 2 at SB for pre-delineator installation period

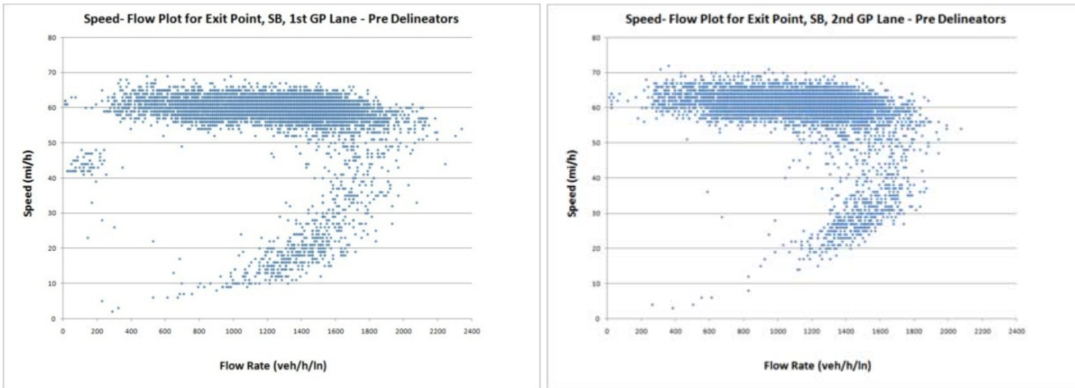


B) Speed-flow plots for Site 2 or mid point for GP lane 1 and GP lane 2 at SB for post-delineator installation and pre-tolling period

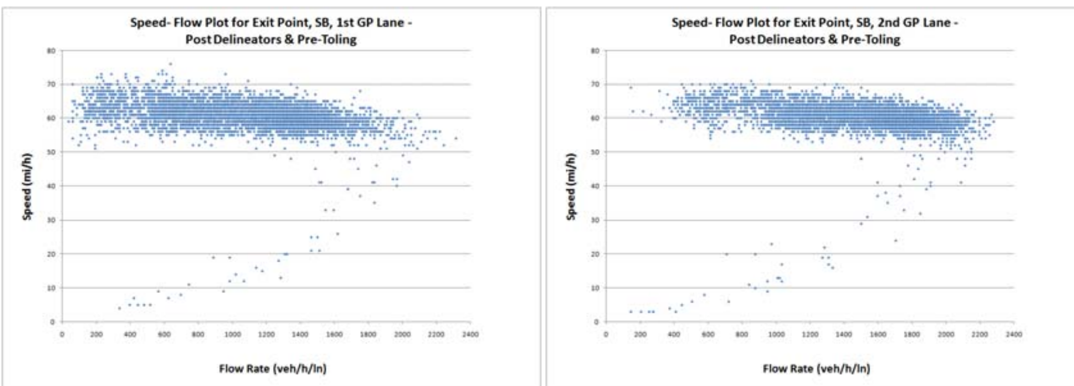


C) Speed-flow plots for Site 2 or mid point for GP lane 1 and GP lane 2 at SB for post-tolling period

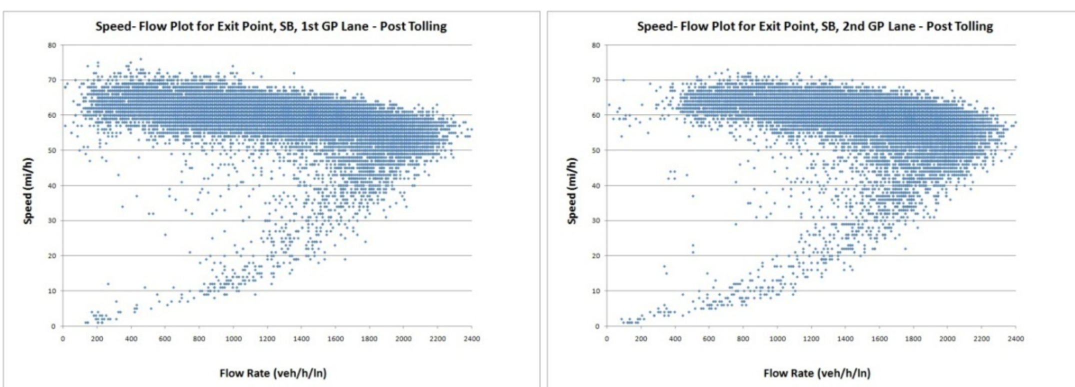
FIGURE 3.8 Lane-by-Lane Comparisons of Speed-Flow Plots of GP Lane 1 and GP Lane 2 for the SB Site 2 for the Three Time Periods



A) Speed-flow plots for Site 3 or exit point for GP lane 1 and GP lane 2 at SB for pre-delineator installation period



B) Speed-flow plots for Site 3 or exit point for GP lane 1 and GP lane 2 at SB for post-delineator installation and pre-tolling period



C) Speed-flow plots for Site 3 or exit point for GP lane 1 and GP lane 2 at SB for post-tolling period

FIGURE 3.9 Lane-by-Lane Comparisons of Speed-Flow Plots of GP Lane 1 and GP Lane 2 for the SB Site 3 for the Three Time Periods

3.2.4 Effect of delineators/tolling on HOT lanes of 95 Express

The following analysis is performed to understand/capture the effects of delineator installation and tolling on the 95 Express HOT lanes. For this, the capacity analysis is performed for all the three time periods from the method of percentile of highest flow rates to obtain the capacity estimates for both the HOT lanes, i.e., HOT lane 1 and HOT lane 2. Due to data limitations and availability, only the locations along the southbound direction were considered. A schematic diagram of the lane numbering convention used for the HOT lanes is provided in Figure 3.6. The capacity estimates for this analysis are provided in Table 3.13, Table 3.14 and Table 3.15for the three time periods respectively. The speed-flow plots are obtained for the HOT lanes at all selected sites for the three time periods and are provided in Figure 3.10, Figure 3.11 and Figure 3.12 respectively.

3.2.4.1 Capacity Analysis

The following observations are made on the basis of the capacity estimates from the percentile of highest flow-rates capacity estimation method:

- It is observed that the capacity estimates and the highest hourly flow-rates are lower during the post-tolling period as compared to the pre-delineator installation time period and the post-delineator but pre-tolling time period. The tolls are intended to reduce demand flow rates in the HOT lanes, and since the capacity estimates are influenced by the magnitude and quantity of high flow rates in the capacity estimation method used in this study, this result is as expected. It should be also noted that these capacity estimates may not reflect ‘true’ capacity value as higher flow rates (in range of 2000 veh/h/ln) are not observed consistently. Therefore, technically, these estimates are demand driven capacity values or otherwise ‘maximum throughput’.
- It is also interesting to note that at site 1 which is near to the entry point of the express lanes, the capacity or maximum throughput and demand flow rates for HOT lane 2 are higher than the HOT lane 1 for all the time periods. This is due to the merging traffic from the GP lanes and adjacent ramp that wish to enter/use the HOT lanes. Also, this is because of lower vehicles/traffic volume coming from upstream of HOT lanes entrance as the HOT lane 1, i.e., upstream of the HOT lanes entrance is an overpass/flyover coming from I-95 further upstream.

- The capacity or the demand driven flow rates of HOT Lane 1 is higher than the capacity of HOT lane 2 for locations 2 and 3 during the post-tolling period. This is observed because the traffic traveling downstream along the SB direction tends to change lanes from HOT lane 2 to HOT lane 1, possibly due to presence of delineators (drivers may feel more comfortable driving on lane next to an open shoulder rather than the delineators). This behavior is not seen during the pre-delineator installation period because the HOT lanes essentially act as GP lanes with no delineators.
- The maximum flow rates on the HOT lane 2 are observed to be very high at site 1 during the post-delineator installation but pre-tolling period. Since this value is the maximum 5-minute converted hourly flow-rate (observed for 25 days) and not the estimated capacity value, this particular flow rate could be the result of "ideal" traffic flow conditions for 5-minute duration, or could be the result of erroneous raw data. However, as explained in the last bullet, a higher flow rate is expected due to the merging traffic from the GP lanes and the adjacent ramp that wish to enter the HOT Express lanes.

TABLE 3.13 Lane-by-Lane Capacity Analysis for SB HOT Lanes Using the Percentile of Highest Flow Rates Method for the Pre-Delineator Installation Period

	Capacity Estimates (veh/h/ln)	
Sites	HOT Lane 1*	HOT Lane 2*
Site 1	1512 (1740)	2016 (2400)
Site 2	1788 (2136)	2088 (2340)
Site 3	2064 (2412)	2244 (2436)

*() is the maximum flow-rate observed during the time period.

TABLE 3.14 Lane-by-Lane Capacity Analysis for SB HOT Lanes Using the Percentile of Highest Flow Rates Method for the Post-Delineator but Pre-Tolling Installation Period

	Capacity Estimates (veh/h/ln)	
Sites	HOT Lane 1*	HOT Lane 2*
Site 1	1608 (1932)	2412 (2616)
Site 2	1644 (1908)	2172 (2460)
Site 3	2052 (2280)	1956 (2328)

*() is the maximum flow-rate observed during the time period.

TABLE 3.15 Lane-by-Lane Capacity Analysis for SB HOT Lanes Using the Percentile of Highest Flow Rates Method for the Post-TollingPeriod

	Capacity Estimates (veh/h/ln)	
Sites	HOT Lane 1*	HOT Lane 2*
Site 1	1512 (1818)	2208 (2568)
Site 2	1860 (2232)	1728 (2292)
Site 3	1872 (2220)	1764 (2136)

*() is the maximum flow-rate observed during the time period.

3.2.4.2 Speed Analysis

This set of analysis is performed to study/capture the effects on the average vehicle speeds due to delineator installation/tolling on 95 Express HOT lanes. The average vehicle speeds are calculated for all the three selected sites along the 95 Express southbound direction for all the three time periods. The 5-minute speed data were averaged for the entire data analysis period during the AM peak and PM peak period. The AM peak covers all the speed points from 6 AM to 9 AM and PM peak covers speed points from 4 PM to 7 PM. The average vehicle speeds for the HOT lanes for all the three time periods are tabulated in Table 3.16, Table 3.17 and Table 3.18 respectively. As a simple comparison of average vehicle speeds between different time periods would not prove to be useful, a detailed statistical analysis of the speed data is performed to determine if there is a significant change in the average vehicle speeds over the three time periods.

For this statistical testing, a similar analysis of variance (one-way ANOVA) test was performed as was performed for the GP lanes. For the details of the statistical tests, refer section 3.2.3.2. From these tests, the alternative hypothesis was accepted for all the experimental sets, therefore the Tukey's *W* procedure was applied to further study the differences in the means of the groups within this experiment. The following are some of the observations from this experiment.

- It was observed that the average vehicle speed of the HOT lanes increased significantly during the post-tolling period and post-delineator but pre-tolling period as compared to the pre-delineator installation period except for the HOT lane 2 at site 1. This means that after the first two lanes (the present HOT lanes) were separated from the other GP lanes, the HOT-lane vehicle speeds were significantly improved.

- The average vehicle speed at site 3 is however similar during the post-delineator installation but pre-tolling period and post-tolling period indicating that the construction of delineators have led to the increase in vehicle speeds on HOT lanes.
- For the AM peak period, the average vehicle speed on both HOT lanes were found to be significantly higher during the post-tolling period as compared to the pre-delineator installation period at all the sites except for HOT lane 2 at the entry location. This is due to the merging traffic from the GP lanes at the entrance of the HOT lanes, and the incoming traffic from upstream of HOT lane 1 that possibly makes the driver less comfortable to change lanes.
- For the PM peak period, the average vehicle speed on HOT lane 1 did not change significantly at any of the sites. For HOT lane 2, the average vehicle speeds were found to be significantly higher during the post-tolling period at sites 1 and 2.

TABLE 3.16 Average Vehicle Speeds Observed for all the SB HOT Lanes during the Pre-Delineator Installation Period

	Average Vehicle Speeds (mi/h)			
	HOT Lane 1		HOT Lane 2	
Sites	AM Peak	PM Peak	AM Peak	PM Peak
Site 1	63.3	64.5	60.2	62.4
Site 2	65.4	70.1	62.0	64.9
Site 3	52.5	66.4	49.0	63.2

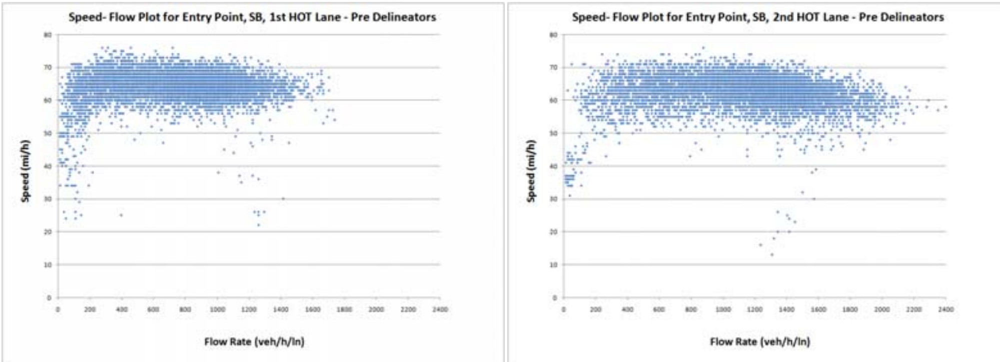
TABLE 3.17 Average Vehicle Speeds Observed for all the SB HOT Lanes during the Post-Delineator Installation but Pre-Tolling Period

	Average Vehicle Speeds (mi/h)			
	HOT Lane 1		HOT Lane 2	
Sites	AM Peak	PM Peak	AM Peak	PM Peak
Site 1	65.3	64.2	58.2	59.6
Site 2	69.0	69.9	65.3	66.3
Site 3	66.1	67.2	63.1	63.8

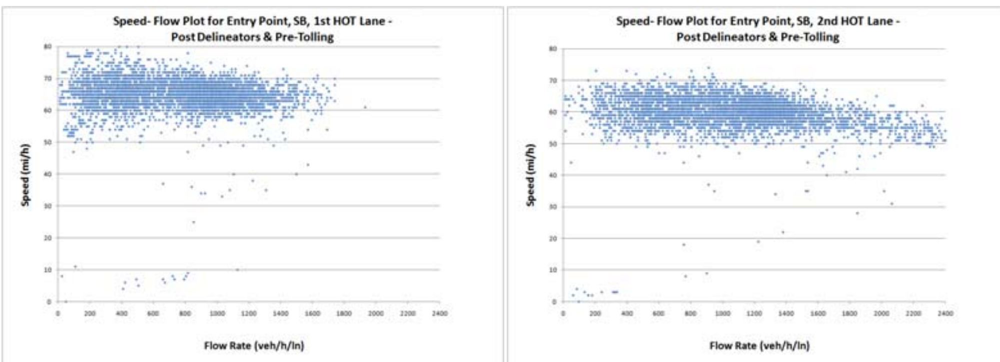
TABLE 3.18 Average Vehicle Speeds Observed for all the SB HOT Lanes during the Post-Tolling Period

	Average Vehicle Speeds (mi/h)			
	HOT Lane 1		HOT Lane 2	
Sites	AM Peak	PM Peak	AM Peak	PM Peak
Site 1	65.0	65.6	55.3	58.2
Site 2	67.3	70.2	64.9	66.7
Site 3	65.1	66.9	62.9	64.8

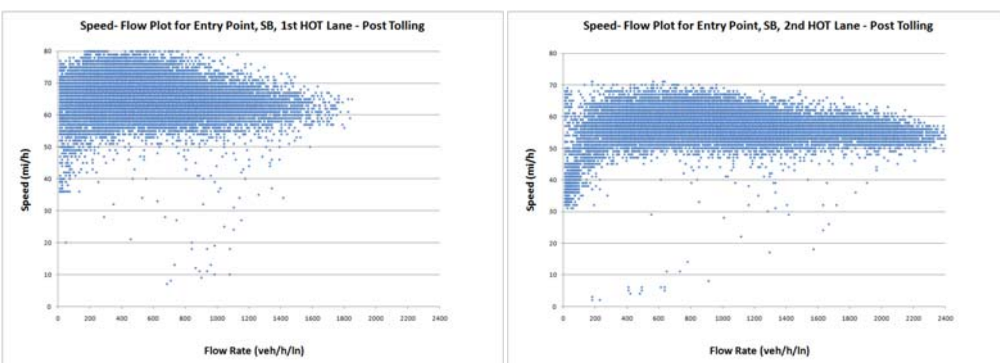
From the speed-flow plots, Figure 3.11 A) & C) and Figure 3.12 A) & C), it is observed that the HOT lanes do not get congested during the post-tolling period as compared to the pre-delineator construction period at the sites 2 and 3.



A) Speed-flow plots for Site 1 or entry point for 1st HOT and 2nd HOT lane, SB during pre-delineator installation period

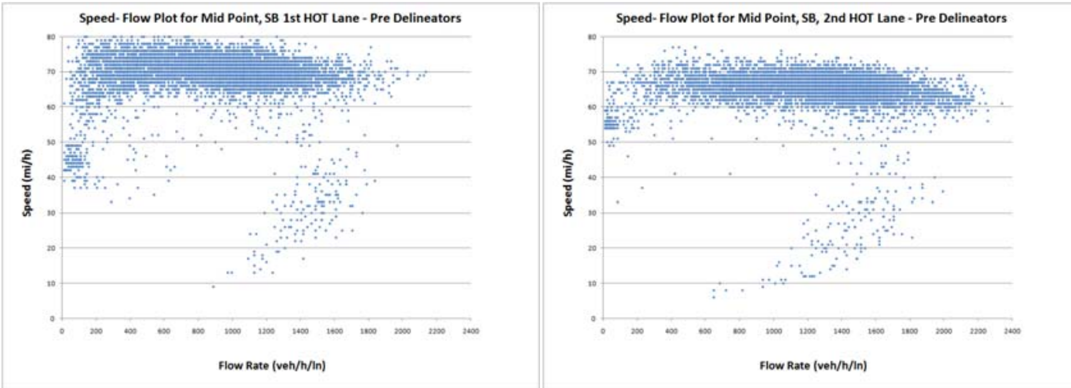


B) Speed-flow plots for Site 1 or entry point for for 1st HOT and 2nd HOT lane, SB during post-delineator installation and pre-tolling period

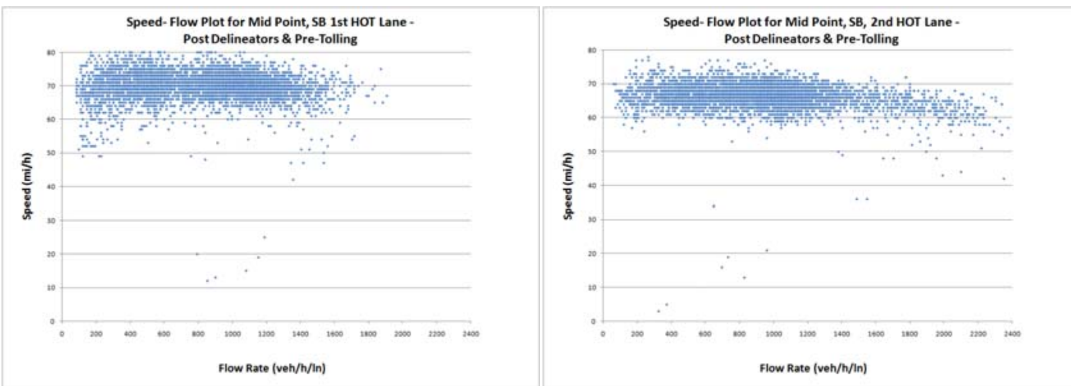


C) Speed-flow plots for Site 1 or entry point for for 1st HOT and 2nd HOT lane, SB during post-tolling period

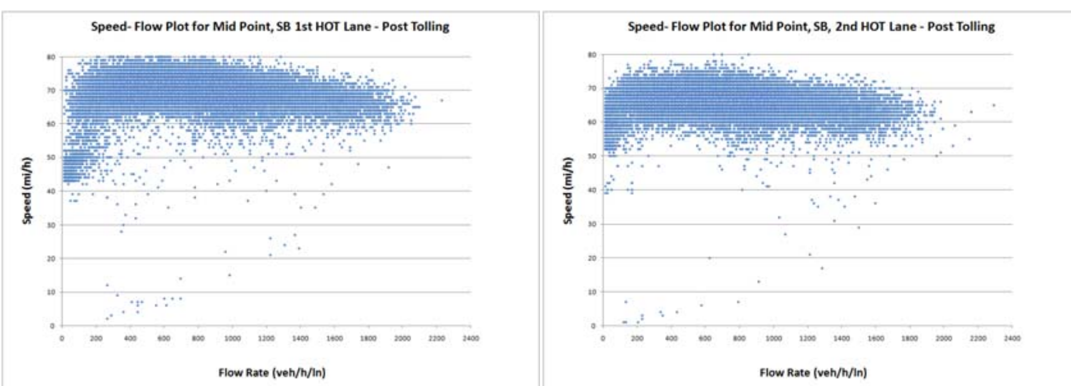
FIGURE 3.10 Lane-by-Lane Comparisons of Speed-Flow Plots of HOT Lane 1 and HOT Lane 2 for the SB Site 1 for the Three Time Periods



A) Speed-flow plots for Site 2 or mid for 1st HOT and 2nd HOT lane, SB during pre-delineator installation period

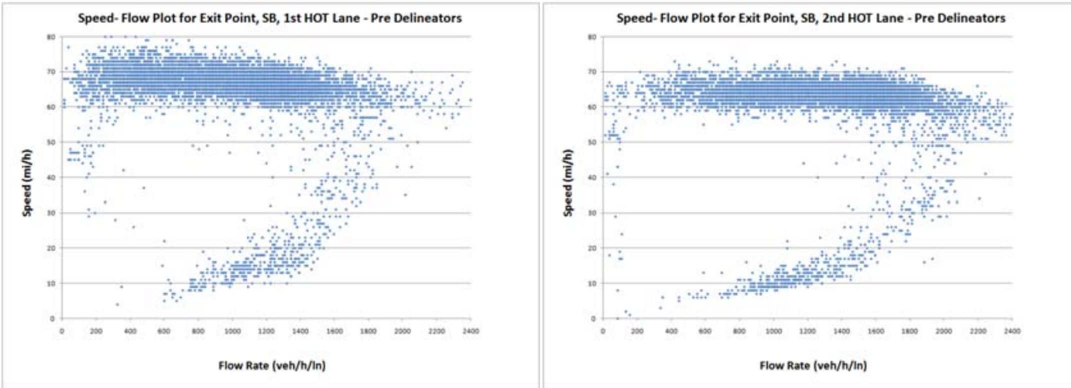


B) Speed-flow plots for Site 2 or mid point for 1st HOT and 2nd HOT lane, SB during post-delineator installation and pre-tolling period

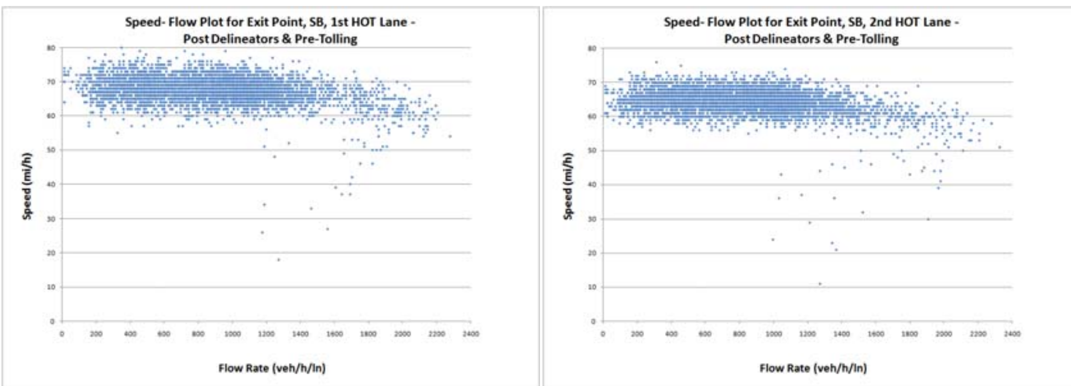


C) Speed-flow plots for Site 2 or mid point for 1st HOT and 2nd HOT lane, SB during post-tolling period

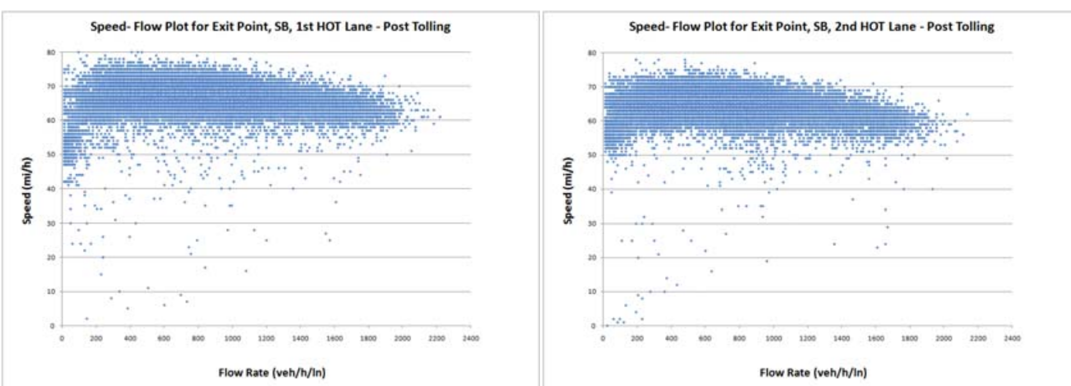
FIGURE 3.11 Lane-by-Lane Comparisons of Speed-Flow Plots of HOT Lane 1 and HOT Lane 2 for the SB Site 2 for the Three Time Periods



A) Speed-flow plots for Site 3 or exit point for 1st HOT and 2nd HOT lane, SB during pre-delineator installation period



B) Speed-flow plots for Site 3 or exit point for 1st HOT and 2nd HOT lane, SB during post-delineator installation and pre-tolling period



C) Speed-flow plots for Site 3 or exit point for 1st HOT and 2nd HOT lane, SB during post-tolling period

FIGURE 3.12 Lane-by-Lane Comparisons of Speed-Flow Plots of HOT Lane 1 and HOT Lane 2 for the SB Site 3 for the Three Time Periods

3.2.5 Effect of reduced lane/shoulder widths on 95 Express

The following sets of analyses were performed to identify the potential effects of reduced lane widths on the capacity values and the average vehicle speeds of the 95 Express GP lanes. In general, the standard lane width of a freeway lane is 12 feet. However, when the 95 Express HOT lanes were constructed, the lane widths of the adjacent GP lanes and the newly built HOT lanes were reduced to 11 feet. Thus, an impact analysis is performed to observe the potential effects of reduced lane widths on 95 Express operations. To accomplish this, the capacity and speed analyses were performed for sites with 12-ft and 11-ft wide lanes.

As described earlier in the data section 3.1.2 of this chapter, the data were not available for the 95 Express when the lanes were 12-ft wide; thus, a before-and-after comparison of capacity and speed values for the same selected sites was not possible. Therefore, the research team identified sites from other freeway facilities in/around Miami regional area for these comparisons. These sites were selected from SR-826 and from I-95 Other (outside of 95 Express zone). Although selecting these sites will not have identical geometric characteristics (excluding the lane widths) with the 95 Express GP lanes, choosing sites in/around the Miami region will likely provide similar traffic flow characteristics and driver behavior. For these analyses, three sites from the 95 Express lanes southbound direction, four sites from SR-826 and four sites from I-95 Other were chosen. The description of all these sites is provided in Table 3.1, Table 3.3 and Table 3.4, and aerial photos are provided in Figure 3.1, Figure 3.3 and Figure 3.4 respectively.

3.2.5.1 Comparison of 11-ft wide lane sites on 95 Express with 12-ft wide lane sites on SR-826

For the capacity analysis, the percentile of highest flow rates estimation method is used to estimate the capacity values. Table 3.19provides the capacity values along with the calculated average vehicle speeds (provided for both AM and PM peak periods) for all the selected sites that are based on the 5-minute station data (i.e., data aggregated across all lanes).The speed-flow plots for these sites are provided in Figure 3.13 and Figure 3.14. As only the effect of the reduced lane-widths needs to be studied, these analyses were performed for the post-tolling time period only.

TABLE 3.19 Comparison of Capacities and Average Vehicle Speeds for GP Lanes on 95 Express with GP Lanes on Other Facilities

GP Lanes on 95 Express				GP Lanes on SR-826			
Sites	Capacity (veh/h/ln)	Avg. Speed (mi/h) AM Peak	Avg. Speed (mi/h) PM Peak	Sites	Capacity (veh/h/ln)	Avg. Speed (mi/h) AM Peak	Avg. Speed (mi/h) PM Peak
Site 1	1785 (1914)	52.42	53.49	Site 7	2175 (2367)	57.77	56.91
Site 2	2094 (2268)	47.39	55.49	Site 8	1804 (1968)	57.11	50.44
Site 3	2145 (2304)	52.24	57.87	Site 9	1888 (2124)	57.18	56.91
-	-	-	-	Site 10	1860 (2028)	72.65	67.63

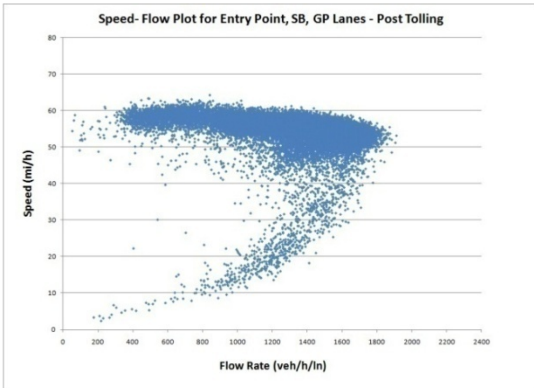
*() is the maximum flow-rate observed during the time period.

The following observations were made on the basis of the above-described capacity and speed analyses:

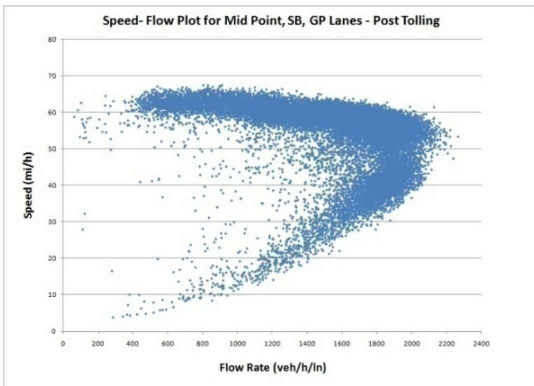
- It is observed that the per-lane capacity values of the GP lanes on the 95 Express (sites 2 and 3) appear to be higher as compared to the sites on SR-826 (sites 8, 9 and 10). This result, however, could be demand related, as the highest flow-rates during the data analysis period are considerably lower on SR-826 as compared to 95 Express. Similarly, due to higher demand, the GP lanes on the 95 Express appear to be more congested (Figure 3.13 B & C and Figure 3.14 B, C & D).
- For the sites with similar posted speed-limits on 95 Express and SR-826, the congestion or probable breakdown events[1] appear to occur at similar speeds. This might mean that there is no obvious effect of lane-width on the flow rate at which congestion or breakdown occurs. This is evident from Figure 3.13 and Figure 3.14 A & C.
- For the AM peak period, when the traffic is headed in the direction of downtown Miami, it is observed that the average vehicle speed on SR-826 is significantly higher as compared to the sites on 95 Express. This could also be due to the lower demand on SR-826 as compared to 95 Express.

The following section provides the comparisons of the capacity and speed analyses for the sites from the 95 Express lanes and the other sites from I-95.

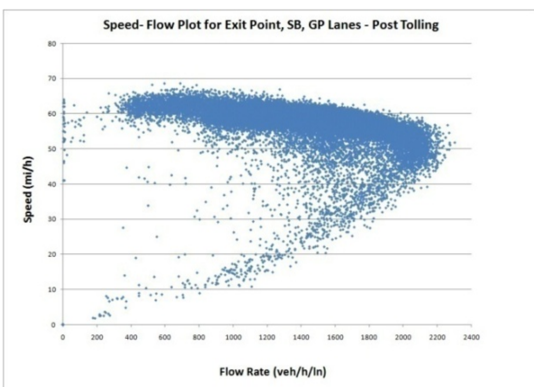
[1]The congestion identification is generally based on the density of the data points from speed-flow plots in saturated traffic condition that represents congestion (data points on the lower right hand side of the speed-flow curve/plots).



A) Speed-flow plots of GP lanes for Site 1 in SB direction

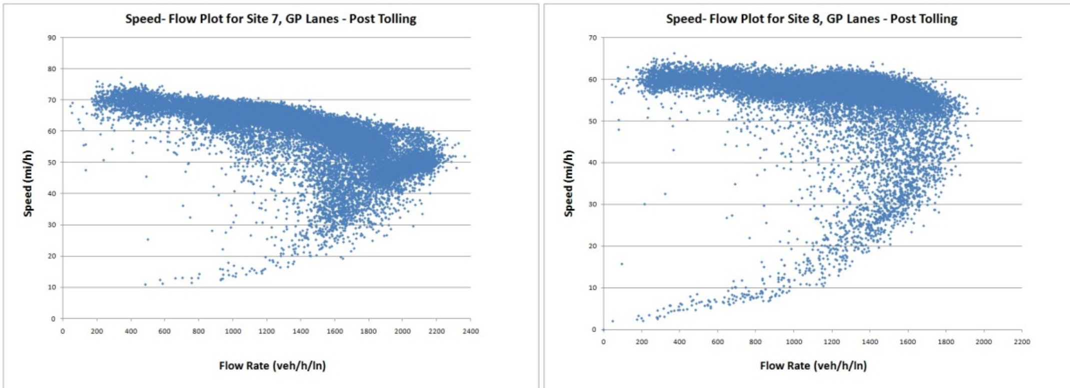


B) Speed-flow plots of GP lanes for Site 2 in SB direction

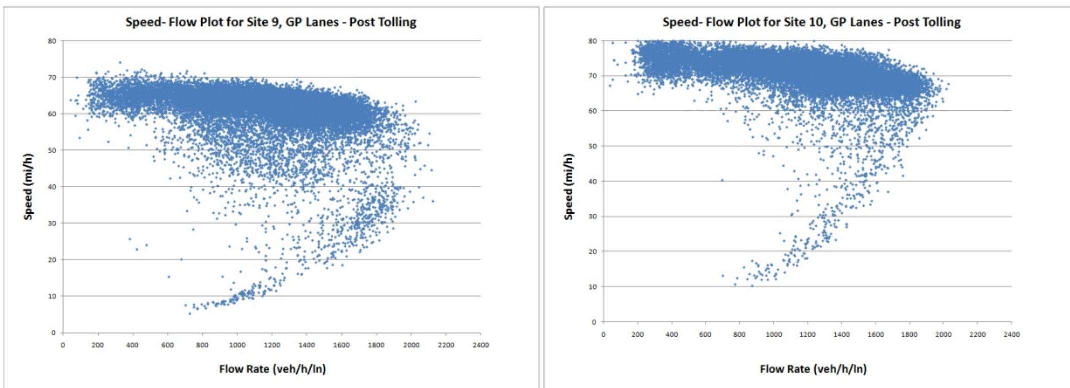


C) Speed-flow plots of GP lanes for Site 3 in SB direction

FIGURE 3.13 Speed-Flow Plots of GP Lanes for Location on 95 Express along SB Direction



A) Speed-flow plots of GP lanes for sites 7 and 8 respectively.



B) Speed-flow plots of GP lanes for sites 9 and 10

FIGURE 3.14 Speed-Flow Plots of GP Lanes for Sites along SR-826

3.2.5.2 Comparison of 11-ft wide lane sites on 95 Express with 12-ft wide lane sites on I-95

Similar to the previous set of analyses, the station level capacities and speeds were also compared between 11-ft wide lane sites from 95 Express with 12-ft wide lane sites from I-95. The percentile of highest flow rates estimation method was used to calculate the capacity values. These analyses were only performed for the post-tolling period with data ranging from March 2010 to June 2010. Due to the presence of HOV lanes on I-95 sites, the data from 7 AM to 9 AM and 4 PM to 6 PM were filtered and used for all of the following analyses. The average vehicle speeds for these sites were also calculated for these time periods. It should be noted that the freeway capacities at these locations were estimated on the basis of the station data (i.e., data aggregated across lanes). Table 3.20 summarizes the estimated capacity values and the average vehicle speeds for all the sites from 95 Express and I-95 Other.

TABLE 3.20 Comparison of Capacities and Average Vehicle Speeds for GP Lanes on 95 Express with I-95 Other GP Lanes

11-ft GP Lanes on 95 Express				12-ft GP Lanes on I-95 Other			
Sites	Capacity (veh/h/ln)	Avg. Speed (mi/h) AM Peak	Avg. Speed (mi/h) PM Peak	Sites	Capacity (veh/h/ln)	Avg. Speed (mi/h) AM Peak	Avg. Speed (mi/h) PM Peak
Site 1	1785 (1914)	52.42	53.49	Site 12	1963 (2090)	63.97	59.91
Site 2	2094 (2268)	47.39	55.49	Site 13	1805 (1913)	68.05	65.67
Site 3	2145 (2304)	52.24	57.87	Site 14	1878 (1980)	64.19	48.95
-	-	-	-	Site 15	1956 (2091)	55.19	50.07

*() is the maximum flow-rate observed during the time period.

- It is observed that the capacities of the 95 Express GP lanes were found to be higher than the capacities for the I-95 Other GP lanes except for site 1.
- For the sites with comparable speed limits (sites 1, 2, 3 and 15), it was observed that during the AM peak period, when the traffic is headed towards downtown Miami, the GP lanes on the 95 Express are found to be slower indicating that they may be more congested. As sites 12, 13 and 14 have higher posted speed limits, the comparisons with the lower posted speed limits were not performed as they could have proved of little value to this research.
- The maximum flow-rates observed for the sites from I-95 Other are lower than the maximum flow-rates on 95 Express (except for the site 1). Two reasons that might explain this observation are one, the demand on the freeway mainlines for the sites from I-95 Other are lower, or second, one of the GP lanes from these sites are highly under-utilized. A detailed discussion for this observation is provided next.

To study whether the low maximum flow rates for the sites from I-95 Other are due to lower traffic demand or due to an under-utilized GP lane, a detailed lane-by-lane analysis was performed for the sites from 95 Express and I-95 Other. The percentile of highest flow rates method was used to calculate the individual lane capacities. These results are tabulated in Table 3.21 and Table 3.22. The speed-flow plots of all the lanes for these sites are provided in Figure 3.15, Figure 3.16, Figure 3.17, and Figure 3.18.

TABLE 3.21 Comparison of Lane Capacities of GP Lanes on 95 Express with I-95 Other GP Lanes

	I-95 Other (north of 95 Express zone), SB Capacity Estimates (veh/h/ln)						
Sites	HOV Lane 1	HOV Lane 2	GP Lane 1	GP Lane 2	GP Lane 3	GP Lane 4	GP Lane 5
Site 12	-	1824 (2076)	2556 (2700)	2148 (2316)	2088 (2292)	2148 (2364)	1488 (1812)
Site 13	-	1656 (2052)	2436 (2652)	1932 (2088)	1896 (2040)	1776 (1992)	1392 (1644)
Site 14	-	2028 (2280)	2556 (2700)	1776 (2520)	1740 (1896)	1896 (2304)	-
Site 15	-	1884 (2124)	2544 (2688)	2112 (2280)	1980 (2064)	-	-

Versus

	95 Express Lanes SB Capacity Estimates (veh/h/ln)						
Sites	HOT Lane 1	HOT Lane 2	GP Lane 1	GP Lane 2	GP Lane 3	GP Lane 4	GP Lane 5
Site 1	1512 (1818)	2208 (2568)	1236 (1548)	2100 (2364)	2220 (2400)	2136 (2364)	-
Site 2	1860 (2232)	1728 (2292)	1908 (2220)	2280 (2532)	2268 (2520)	2304 (2556)	-
Site 3	1872 (2220)	1764 (2136)	2160 (2424)	2196 (2460)	2208 (2412)	2220 (2412)	-

*() is the maximum flow-rate observed during the time period.

- It is observed that the capacities of the GP lanes (except GP Lane 1) on the 95 Express are higher than the capacities on the GP lanes for the sites from I-95 Other. The lower demand on the GP lanes of I-95 Other could possibly be the reason for this observation.
- The capacities of GP Lane 1 for the sites on I-95 Other are found to be significantly higher than the sites on 95 Express. This is observed because the probability of lane-changing maneuvers on the lane next to the non-delineator separated HOV lane is higher as compared to the lane changing maneuvers on the 95 Express GP lanes.
- It is interesting to note that the capacities of the right-most lanes for the sites 12 and 13 are highly under-utilized. It was later investigated that the right-most lane is not a 'true' GP lane and is an auxiliary lane (i.e., on-ramp connected directly to off-ramp). This was also confirmed from the speed-flow plots of these sites as shown in Figure 3.15 C and Figure 3.16 C. Therefore, the inclusion of these lanes, even for long auxiliary lanes, probably influenced the lower station capacity values for these locations.

From the above mentioned observations and analyses, it was felt that a simple comparison of the station level capacities or individual lane capacities between the two sets of sites would not be useful until a detailed statistical analysis is performed. The challenge to performing a statistical analysis of the capacity measures from multiple sets of sites is because the capacity value is a single data point for a respective group, whereas multiple data points are required for any statistical testing/analysis. After further reviewing the data sets, it was decided that a detailed analysis of the station level throughput values should be performed instead of just the station level capacity statistic. The throughput statistic, here, is defined as the highest flow-rate that is observed on a particular day at the respective detector station or site on the basis of the station data.

For creating a dataset with multiple throughput data points, the highest flow-rates were obtained for the data analysis period for the all the respective sites. The data period was considered from March 2010 to June 2010 and only the weekdays were considered for this analysis. After the daily highest flow-rates were obtained for all the sites within the data analysis period, the analysis of variance (ANOVA) tests were performed. To check whether these datasets are significantly different from each other, Tukey's *W* test (as explained earlier in this report) was performed. The results of these tests are tabulated in Table 3.22. In these tables, the sample size refers to the number of days or data set points that were considered for each site, and the variable *Gx* (x denotes numerical group 1, 2, 3, 4, and 5) refers to the group under which they fall from the statistical tests. Group 1 or *G*1 refers to the set with smallest mean of throughput values and Group 5 or *G*5 refers to the set with the highest mean of throughput values.

TABLE 3.22 Analysis of 12-ft GP Lanes with 11-ft GP Lanes

		Tukey's *W* Test - Maximum Throughput comparisons (veh/h/ln)				
Sites	Sample Size	*G*1	*G*2	*G*3	*G*4	*G*5
Site 13	84	1753.11				
Site 1	82	1788.51				
Site 14	84		1835.32			
Site 15	73			1905.16		
Site 12	83			1915.49		
Site 2	81				2099.33	
Site 3	82					2140.24

(11-ft wide lane-width sites marked in bold)

From these analyses, it was found that the mean of the daily throughput or the daily highest flow-rates were significantly higher for the sites on 95 Express as compared to the sites from I-95 Other except for site 1. These findings are generally consistent with previous observations. Therefore, it could be concluded that the capacities or the mean of the daily highest flow-rates, from the 95 Express lanes are higher than the sites from I-95 Other.

However, it was also observed that the right-most GP lane on sites 12 and 13 was under-utilized as compared to the right-most GP lanes on the 95 Express. Since these lanes usually have lower demand, even for long auxiliary lanes such as these, it was felt that the observation for lower capacity values on I-95 Other GP lanes could have been biased for this reason. Therefore, another statistical analysis was performed without including the right-most (i.e., auxiliary lane) in the station data for sites 12 and 13. These results are tabulated in Table 3.23.

TABLE 3.23 Analysis of 12-ft GP Lanes (Excluding GP Lane 5) with 11-ft GP Lanes

		Tukey's *W* Test - Maximum Throughput comparisons (veh/h/ln)				
Sites	Sample Size	*G*1	*G*2	*G*3	*G*4	*G*5
Site 1	82	1788.51				
Site 14	84		1835.32			
Site 13	84			1898.21		
Site 15	73			1905.16		
Site 2	81				2099.33	
Site 12	83				2122.88	2122.88
Site 3	82					2140.24

(11-ft wide lane-width sites marked in bold)

From this analysis, it was observed that the throughput values, or the mean of highest daily flow-rates, for site 12 on I-95 Other were not significantly different from site 3 on 95 Express. Also, the throughput statistic for site 1 from 95 Express was found to have the lowest maximum throughput value. This could be because the GP lane 1 in the close vicinity of the HOT entrance lanes or the ingress point is highly under-utilized and the throughput statistic for this specific lane may have influenced the lower aggregated/station throughput value. In general, all the other observations and the comparisons were found to be consistent with previous findings.

Apart from the capacity/maximum throughput analysis, a speed analysis was also performed. Since the posted speed-limits of the sites on 95 Express and I-95 Other (excluding site 15) were different, detailed statistical testing was not performed. However, the following observations were made from the speed analyses:

- From the speed-flow plots of these sites, it was observed that the sites from I-95 Other appear to be less congested as compared to the 95 Express.
- For the sites with similar posted speed-limits, the average vehicle speeds on all the 95 Express sites were found to be significantly lower as compared to site 15 from I-95 Other during the AM peak period.
- During the PM peak period, the average vehicle speeds on the 95 Express lanes were higher than the sites from I-95 Other.

TABLE 3.24 Comparison of Lane Average Vehicle Speeds of GP Lanes on I-95 Other with 95 Express GP Lanes for Both AM and PM Peak Periods

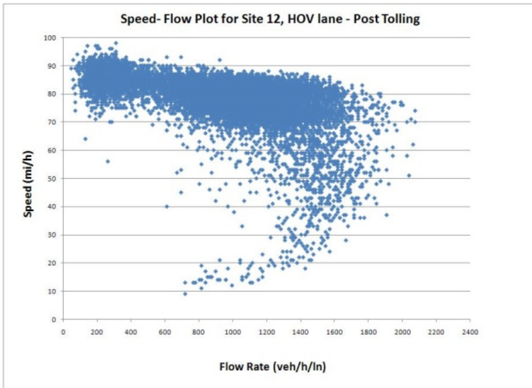
I-95 Other (north of 95 Express zone), SB Average vehicle speeds (mi/h)														
	HOV Lane 1		HOV Lane 2		GP Lane 1		GP Lane 2		GP Lane 3		GP Lane 4		GP Lane 5	
	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak
Site 12	-	-	77.48	73.38	72.43	67.56	66.68	63.56	65.07	62.04	64.80	62.47	62.32	60.91
Site 13	-	-	68.47	65.73	75.18	70.76	71.09	67.23	70.55	66.64	70.10	65.92	69.80	66.54
Site 14	-	-	73.48	64.35	73.95	58.40	68.99	54.26	67.90	52.52	68.63	52.87	-	-
Site 15	-	-	66.09	60.93	60.81	52.44	59.53	51.56	52.99	45.91	-	-	-	-

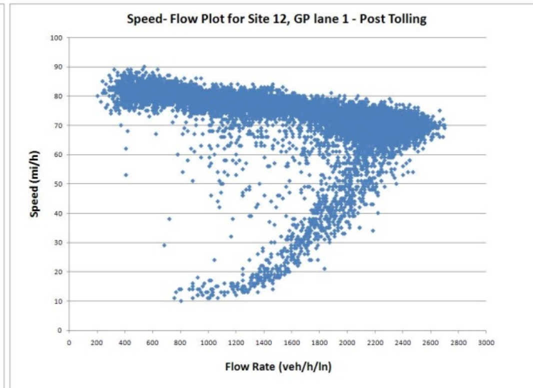
Versus

95 Express Lanes, SB Average vehicle speeds (mi/h)														
	HOT Lane 1		HOT Lane 2		GP Lane 1		GP Lane 2		GP Lane 3		GP Lane 4		GP Lane 5	
	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak
Site 1	65.00	65.60	55.30	58.2	55.10	60.60	55.80	54.70	54.00	52.60	48.60	47.90	-	-
Site 2	67.30	70.20	64.90	66.70	53.20	58.70	51.70	56.30	51.40	55.90	45.90	48.20	-	-
Site 3	65.10	66.90	62.90	64.80	56.00	58.90	55.50	58.90	53.60	57.20	51.20	53.20	-	-

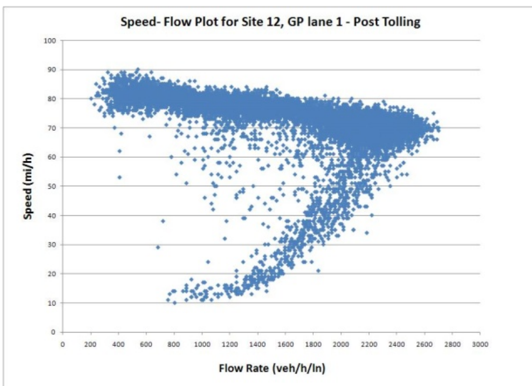
In general, it is observed that capacities, or the daily highest flow-rates, are found to be higher on the 11-ft wide GP lanes as compared to the 12-ft wide GP lanes, and the average vehicle speeds on the 12-ft wide GP lanes are found to be higher than the sites with 11-ft wide GP lanes. This is primarily due to the more frequent occurrence of congestion or probable breakdown on the 95

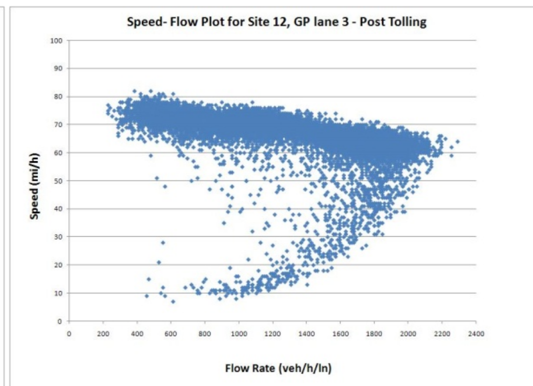
Express GP lanes than on I-95 Other. However, it is not possible to conclude from just the detector data that the higher occurrence of breakdown events on the 95 Express GP lanes is due to narrower lanes. At a minimum, a study investigating driver behavior differences on 11-ft versus 12-ft lanes would be required. Of course, if before data (i.e., before the lanes were narrowed from 12 ft to 11 ft) were available, more insight on this issue would have been possible. Based on the analyses of the data available for this project, it cannot be concluded that the narrowing of the lanes on 95 Express from 12 ft to 11 ft, or the narrowing of the shoulders as well, has had a negative impact on the capacity of the GP lanes in this section of I-95. The configuration of the entrance to the HOT lanes and the close proximity of the delineators to the GP lane adjacent to the HOT lanes do appear to be limiting the utilization of this GP lane, however.



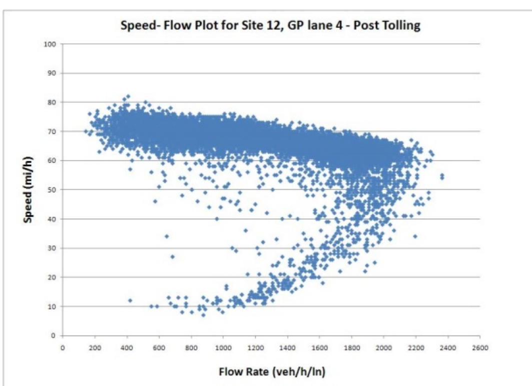


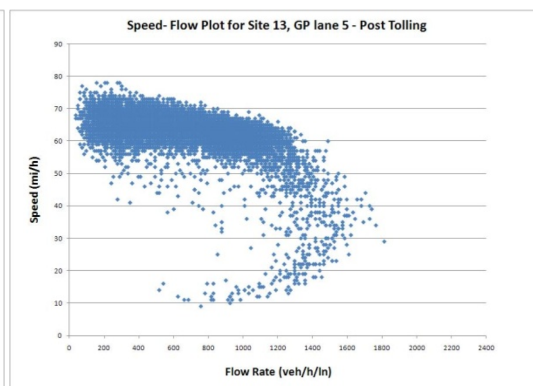
A) Speed-flow plots of HOV lane and GP lane 1 for Site 12





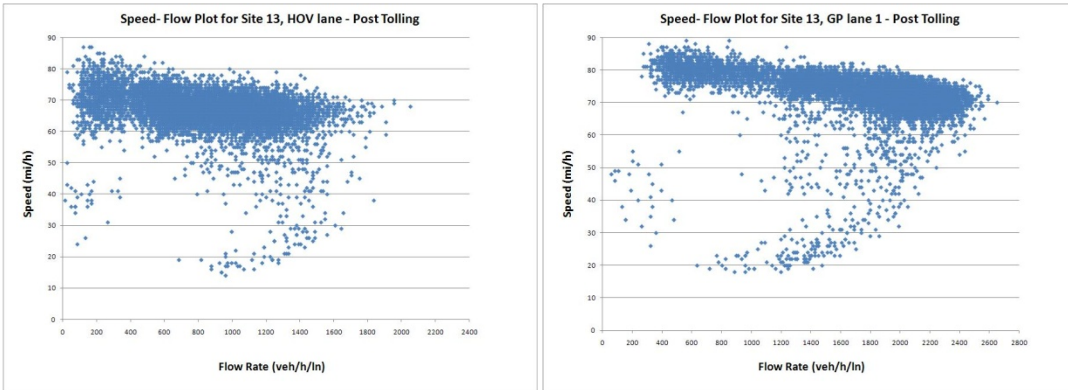
B) Speed-flow plots of GP lane 2 and GP lane 3 for Site 12



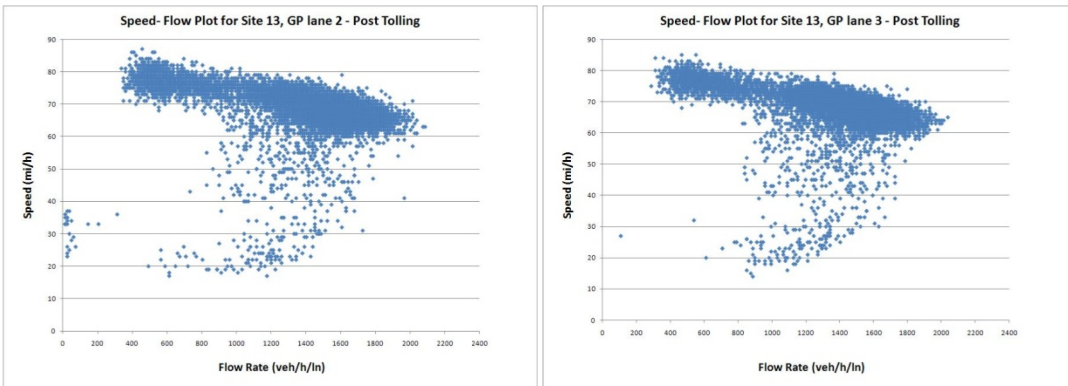


C) Speed-flow plots of GP lane 4 and GP lane 5 for Site 12

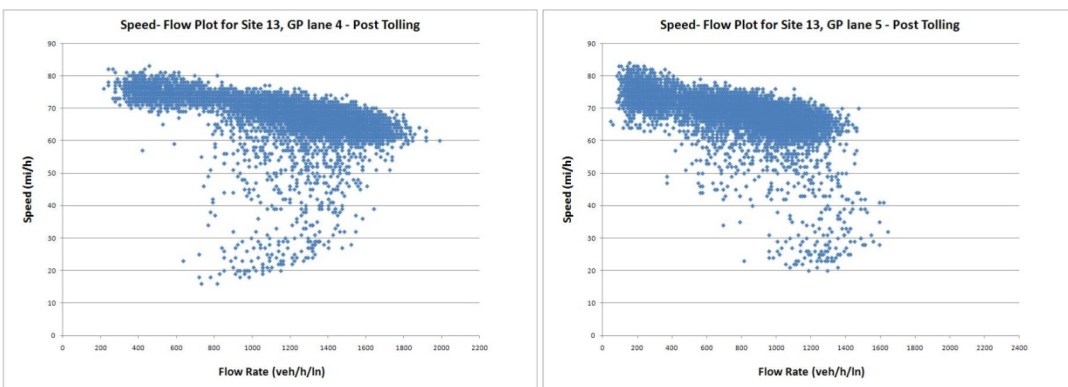
FIGURE 3.15 Speed-Flow Plots of GP Lanes for Site 12 on I-95 Other in SB Direction



A) Speed-flow plots of HOV and GP lane 1 for Site 13

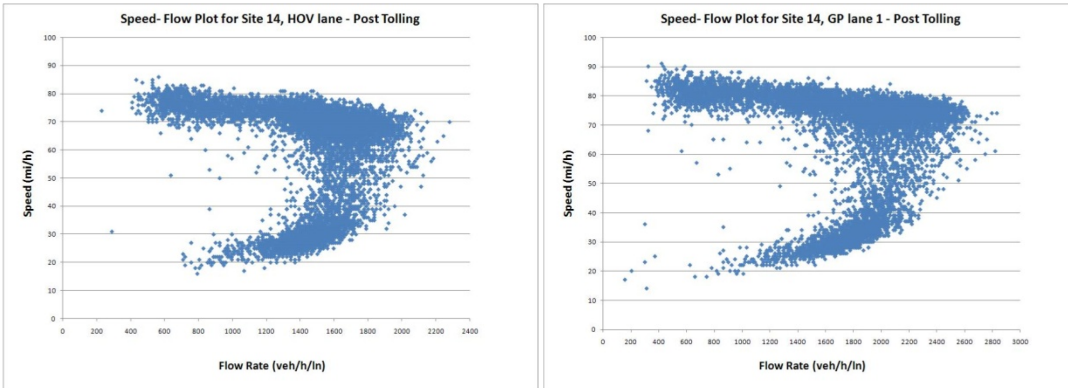


B) Speed-flow plots of GP lane 2 and GP lane 3 for Site 13

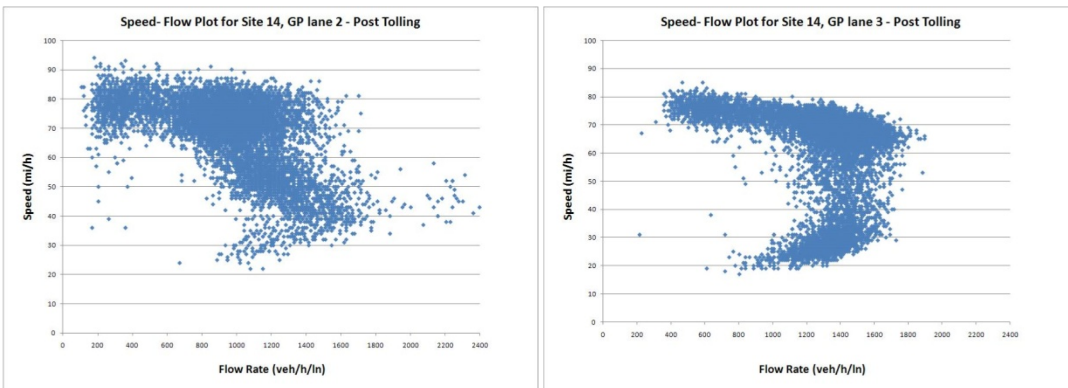


C) Speed-flow plots of GP lane 4 and GP lane 5 for Site 13

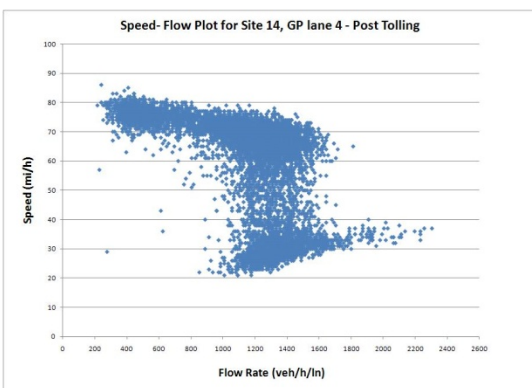
FIGURE 3.16 Speed-Flow Plots of GP Lanes for Site 13 on I-95 Other in SB Direction



A) Speed-flow plots of HOV and GP lane 1 for Site 14

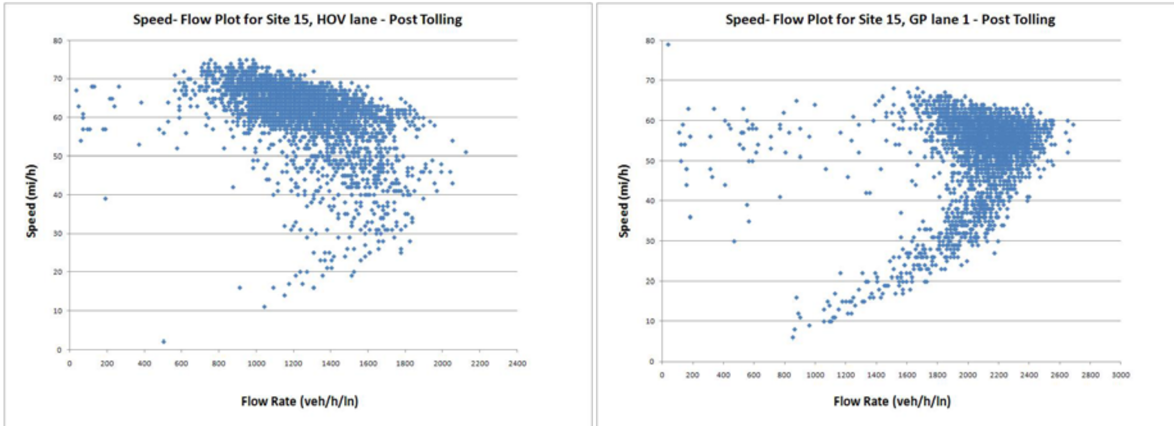


B) Speed-flow plots of GP Lane 2 and GP Lane 3 for Site 14

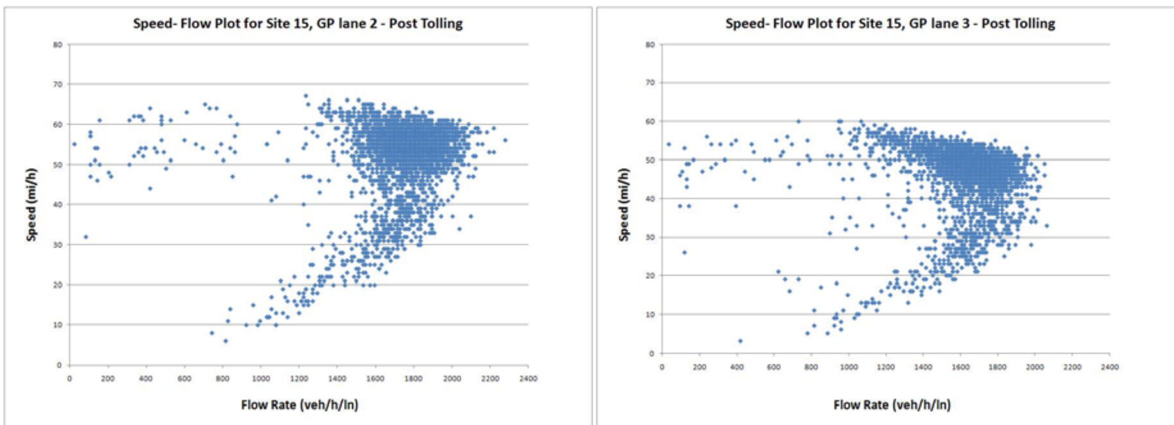


C) Speed-flow plots of GP lane 4 for Site 14

FIGURE 3.17 Speed-Flow Plots of GP Lanes for Site 14 on I-95 Other in SB Direction



A) Speed-flow plots of HOV lane and GP lane 1 for Site 15



B) Speed-flow plots of GP lane 2 and GP lane 3 for Site 15

FIGURE 3.18 Speed-Flow Plots of GP Lanes for Site 15 on I-95 Other in SB Direction

3.3 Conclusions

Capacity analysis was performed for the 95 Express lanes in Miami to study the effects of the delineator installation/tolling and the reduced lane/shoulder widths on the newly constructed HOT lanes. Several sites were selected for these analyses along the 95 Express (from Phase 1A and 1B), SR-826 (Palmetto Expressway), and sites from I-95 Other (that are not a part of the current 95 Express lanes). The data for these analyses were obtained from Florida's Central Data Warehouse (aka STEWARD). For all the selected sites, the aggregated 5-minute volume and speed data were obtained. At first, the Van Aerde model capacity estimation method as suggested by Rakha (2007) was used to calculate the capacities of the selected freeway segments across the sites mentioned above. It was observed that the capacities from this estimation method appeared to be considerably lower than the generally accepted capacity values for a basic freeway segment. Therefore, another capacity estimation method as suggested by Washburn et al. (2010) was used, which calculates the capacity of a freeway segment on the basis of averaging the highest flow-rates observed at a site.

Three time, or data, periods were identified during the course of this task. They are defined as the pre-delineator installation period, the post-delineator installation but pre-tolling period, and the post-tolling time period. To study the effects of the delineator installation on the operations of 95 Express lanes, the capacity values of the GP and HOT lanes at a station level were obtained and compared for all three time periods. Also, the changes in the average vehicular speeds on the selected sites were studied for all three time periods. The capacity and speed analyses were also performed on a lane-by-lane basis, focusing primarily on the GP lane next to the delineators. Similar analyses were performed to study the effect of tolling on the operations of the GP lanes and HOT lanes. For studying the impact of the reduced lane widths, sites from SR-826 and I-95 Other were selected as comparison sites since data corresponding to before the narrowing of the mainline freeway segments were not available. All the detailed observations on the findings from the analyses are provided in the respective sections of this report.

The following conclusions are made from the capacity analysis of the 95 Express lanes:

Delineator/Tolling effect on GP lanes

- In general, the capacities or the throughput of the GP lanes (except GP lane 1) have increased after the delineators were installed and tolling had started. The reduced demand on the HOT lanes because of tolls implementation could have increased the demand on the adjacent four GP lanes.
- The capacity or the utilization of the GP lane 1 on 95 Express, particularly in the vicinity of the entry point of HOT lanes, has reduced from the pre-delineator installation period to the post-tolling period because of the presence of delineators. It is possible that the

delineators have made the drivers less comfortable in driving next to a physical barrier-separated lane.

- The average vehicle speeds on the GP lanes are found to be higher during the post-tolling period at sites 1 and 3 as compared to the pre-delineator installation period. However, the average vehicle speeds on the two adjacent lanes next to the delineators are found to be higher as compared to the two lanes next to the shoulders.

Delineator/Tolling effects on HOT lanes

- The capacities or the throughput of the HOT lanes, in general, decreased after the tolling started. Also, the average vehicle speeds are found to be higher during the post-tolling period on the HOT lanes than the pre-delineator installation period. The implementation of tolling is likely responsible for the capacity reduction and speed increase, as it has reduced demand on these lanes.
- The capacities or the throughput of the HOT lanes (not in close vicinity of ingress point) are lower for the lanes next to the delineator. It is possible that the delineators make drivers less comfortable in driving next to a physical barrier-separated lane as compared to the lane next to the median.
- The HOT lane 2 near to the ingress point is found to be congested and have lower average vehicle speeds because of the merging/incoming traffic from the adjacent GP lanes.
- The average vehicle speeds on the HOT lanes are higher at the locations downstream of the ingress point during the post-delineator installation. This is probably due to the decreased lane-changing maneuvers with the adjacent GP lanes.

Effect of reduced lane/shoulder widths

- The capacities for the sites with the 11-ft wide GP lanes are generally higher than the sites with the 12-ft wide GP lanes. However, it cannot be generalized that the capacities for 11-ft wide lanes are higher than the capacities for 12-ft lanes. There are many site-specific characteristics (e.g., horizontal/vertical curvature, percentage of heavy vehicles, etc.) that could have a much larger impact on maximum throughput than the lane widths. Ideally, comparisons would have been made for the 95 Express sites both before and after the lane narrowing, but unfortunately, data were not available for these sites before the lanes were narrowed. On the other hand, it does not appear that the 11-ft lanes have had a negative impact on the capacity of the 95 Express GP lanes.

Ingress/Egress points

- As the capacity and speed analyses were performed, the designs of the ingress and egress points of the 95 Express lanes were briefly studied. It is observed that the southbound ingress point is in close vicinity to the on-ramp from the arterial NW 151st St. It may be possible that the vehicles from this on-ramp enter the HOT lanes and make five lane-changing maneuvers in less than 500 feet. Also it appears that the vehicles coming from the on-ramps connected with the Florida Turnpike and SR-826 may possibly cause congestion in the vicinity of the HOT lanes entrance. However, at this point, there is no data evidence that the congestion in the vicinity of the ingress point is due to the on-ramp from NW 151st St./SR-826/Florida Turnpike. These observations were made after reviewing some video recordings taken by the researchers while traveling along the southbound direction.
- The site near the entry point of the HOT lanes from the GP lanes as it is more congested with low average vehicle speeds during the post-tolling period.

3.4 Recommended Future Study

With the implementation of tolling and ramp metering on the 95 Express lanes zone, the operations on the GP lanes have improved as compared to the pre-tolling time period. However, there are still some analyses that could be conducted in the future that might shed additional light on the effects of delineator installation/tolling/reduced lane widths. These analyses, briefly, are:

- Similar analyses could be performed if the lane widths in the 95 Express Phase-II are reduced since the traffic data would be available before and after the re-striping of 95 Express lanes.
- To estimate the capacity values using the reasonably well accepted stochastic capacity estimation method due to its sound theoretical concepts.
- Detailed analysis of ingress/egress point operations through video recording.

4 DYNAMIC TOLLING ALGORITHMS FOR MANAGED TOLL LANES

4.1 Background

The operating objectives of managed-lane facilities are to maximize the throughput of the whole freeway segment while maintaining a superior level of service at the managed lanes. To achieve these objectives effectively, ideally tolls should vary real time in response to changes in traffic conditions. Currently, there are at least four authorities pricing their toll lanes dynamically, including Caltrans on I-15, FDOT on I-95, MnDOT on I-394, and Utah Department of Transportation (UDOT) on I-15. Other HOT lane facilities, such as the I-10 in Houston, Texas, implement TOD 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. Chapter 2 of this report compared dynamic and time-of-day pricing and concluded that, when the demand pattern is predictable, time-of-day tolling could perform as well as dynamic tolling, provided that the toll profiles are optimized against the demand level. However, since dynamic tolling is adaptive to variations in traffic demand and condition, its performance is more robust and stable.

This chapter discusses dynamic tolling algorithms for single- and multi-segment HOT lane facilities. The former 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 of toll to use the facility no matter where they enter or exit. In contrast, the latter has multiple ingress or egress points that are located distantly from each other. Depending on where they enter or exit, motorists may pay different amounts of toll. This task focuses on enhancement and evaluation of the tolling algorithms for the current and future 95 Express. The former is a single-segment facility while the latter will consist of multiple segments.

The remainder of this chapter is organized as follows. Section 4.2 introduces the pricing algorithm currently implemented on 95 Express and then presents an optimization procedure to fine-tune some parameters of the algorithm. Section 4.3 describes a new version of CORSIM enhanced to simulate HOT lane operations. The enhanced CORSIM is used to evaluate the fine-tuned tolling algorithms. Section 4.4 reviews the current practice of the multi-segment HOT lane facilities and discusses the pros and cons of different toll structures for this type of facilities.

Section 4.5 recommends a tolling approach for the future 95 Express and evaluates it with different configurations. Lastly, Section 4.6 presents concluding remarks.

4.2 Enhancement of Dynamic Tolling Algorithm of the Current 95 Express

4.2.1 Dynamic tolling algorithm of 95 Express

The primary goal of 95 Express is to safely and efficiently maximize the throughput of the facility while providing free-flow services, more specifically, 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, as reported in Table 2.1(FDOT, 2008). Below is a description of the tolling algorithm of 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 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 the toll amount adjustment, ΔR, from the Delta Setting Table (DST), i.e., , Table 2.1based on $\Delta TD$and $TD(t)$.
4) Calculate the 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 the resulting toll amount with the minimum and maximum toll values in the LOS setting table (Table 2.2). If the toll amount is not within the toll range corresponding to $TD(t)$, either the maximum or minimum toll will be applied.

It can be seen that the toll amount at each time interval highly depends on ΔR drawn from the DST. In other words, DTS plays a major role in determining the adjustment in toll amount. Therefore, extra attention should be paid to designing the table and fine-tuning its parameters.

4.2.2 Optimizing parameters of the 95 Express pricing algorithm

The current pricing algorithm implemented on 95 Express is very effective in managing the traffic demand on the HOT lanes. The parameters of DST have been updated to adapt to the current traffic condition. As the traffic condition of the I-95 corridor is expected to change in the future, the parameters will need to be updated again. In this section, we present an optimization approach to fine-tune the DST parameters without trials and errors. The approach is a genetic-algorithm (GA) procedure that incorporates the macroscopic simulation tool developed in Matlab (refer to Section 2.2).

We first identify the parameters in DST that are most influential in determining the toll amount. For example, the parameters corresponding to the level of service (LOS) A, i.e., traffic density lower than 11vpmpl, do not play any role in determining the toll amount because they are always equal to $0.25 in accordance to Table 2.2. Also, when the traffic density change is small, i.e., -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, we only consider fine-tuning 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. In Table 4.1, the cells in gray represent the values that remain intact.

TABLE 4.1 DST Parameters Subject to Fine Tuning

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
	11	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
B	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 4.1. DST Parameters Subject to Fine Tuning (cont'd)

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
	11	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25
B	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

4.2.2.1 Optimization Objective

To be consistent with the operating objective of 95 Express, the objective of the DST parameter optimization is to maximize the average speed on the general-purpose (GP) lanes while ensuring the speed at the express lanes higher than 45 mph. Mathematically, the objective function can be written as:

$$\max\ S = \sum_{i} [GP\_speed\ (i) + M \cdot \min(EL\_speed(i) - 45, 0)]$$

where$i$ is the tolling interval indicator; $GP_speed\ (i)$is the speed on the GP lanes at the tolling interval i; $EL_speed\ (i)$is the speed on the express lanes at the tolling interval i, and M is a penalty parameter. If the speed at 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 amount, which is not beneficial to the overall performance of the system. In this task, M is set to be equal to100.

4.2.2.2 GA Procedure

GA is a procedure that mimics natural selection, and is often used to generate optimal solutions for large-scale problems. The evolution of the procedure maintains a population of individuals, each of which 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 4.1.

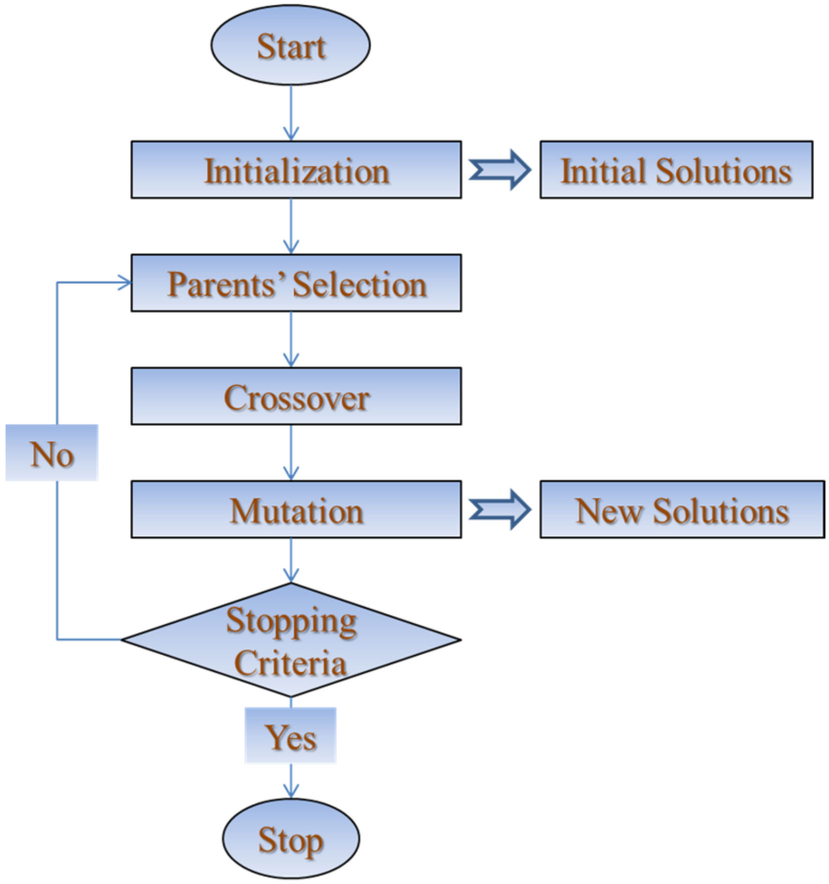


FIGURE 4.1 GA Procedure Flowchart

Below we describe each major step in detail:

Initialization. A population of 10 different DSTs is randomly generated, each of which represents an 'individual' in the GA procedure. These 10 individuals are then evaluated using the macroscopic simulation toll in Matlab and the corresponding fitness values, i.e., 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, we only capture the points where the price changes or, in other words, jumps. From Table 4.1, 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 columns of -2 and +2, only one price jump point exists, which yields two prices. In total, there are 18 jump points. Optimizing DST is equivalent to optimizing the locations of these 18 jump points. 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. For the columns with one jump point, the location may be at any row from 14 to 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 five-digit binary a substring (gene). For each DST, the corresponding binary string contains 18 genes and is 90 bits long. The coding process is illustrated as in Figure 4.2, where the column "+3" contains two price jump points X1 and X2. The first jumping point is at density 17 where the toll increases from \$0.50 to \$0.75 (the toll value is only allowed to change in an increment 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.

	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 4.2 Representation of Price Jump Points

Selection of parents. After generating the initial population of 10 individuals, we perform 100 iterations of GA operations to obtain the optimal solution. At each iteration, a new set of 10 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 there are six parents 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.

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.

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 that helps the optimization problem to avoid local optimum. However, the mutation rate of the GA should not be very large. Otherwise, the GA would generate too many random genes, slowing convergence. A 10% mutation probability (flip the digit to the opposite value, for example, from 0 to 1) is set in this model.

Stopping Criteria. The procedure stops after 100 iterations and the best solution will be treated as optimal solution. The specific number of iterations was selected based on the change in the objective function value. We did experiments and found that the objective function value stabilized in less than 100 iterations in all scenarios tested.

4.2.2.3 Optimized DST

We applied and configured the above GA procedure to optimize the DST parameters under different traffic demand scenarios. Since the macroscopic traffic simulation tool developed in Matlab was calibrated against the traffic conditions in April 2010, we used the travel demand of April 2010 as the base demand scenario. We then increased the demand by 5% to create an increased demand scenario.

Base Demand Scenario. Table 4.2 compares the performances of the original and optimized DSTs. The performance measures include the average speed of express lanes (AvgSpeedEL), the average speed of GP lanes (AvgSpeedGP), and the percent time that the express lanes are operated above 45 mph (reliability). The reported values in Table 4.2 are taken from the 95 Express performance report for April 2010 (FDOT, 2010a) while the other values are obtained from the macroscopic simulation tool. It can be observed that both the original and optimized DSTs provide satisfactory performances and the latter slightly outperforms the former. The optimized DST improves the speed reliability by 4.65%. The *t*-test was conducted to confirm that the improvements are statistically significant.

TABLE 4.2 Performance Measures for Base Demand Scenario

Performance Measures	Reported	Original	Optimized	% Improvement
AvgSpeedEL(mph)	55.80	53.46	53.64	0.34%
AvgSpeedGP(mph)	41.90	43.16	44.65	3.44%
Reliability	94.40%	95.56%	100.00%	4.65%

The optimized DST for the based demand scenario is shown in Table 4.3.

TABLE 4.3 Optimized DST for Base Demand Scenario

Traffic Density	Change in Traffic Density									
	-6	-5	-4	-3	-2	+2	+3	+4	+5	+6
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
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
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
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

Increased Demand Scenario. The performance measures for the increased demand scenario are presented in Table 4.4, and the optimized DST is illustrated in Table 4.5.

TABLE 4.4 Performance Measures for Increased Demand Scenario

Performance Measures	Reported	Original	Optimized	% Improvement
AvgSpeedEL(mph)	/	45.67	47.56	4.14%
AvgSpeedGP(mph)	/	40.01	41.08	2.67%
Reliability	/	65.28%	76.11%	16.60%

TABLE 4.5 Optimized DST for Increased Demand Scenario

Traffic	Change in Traffic Density									
Density	-6	-5	-4	-3	-2	+2	+3	+4	+5	+6
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
19	-\$1.25	-\$1.00	-\$0.50	-\$0.50	-\$0.25	\$0.25	\$0.25	\$0.75	\$0.75	\$1.00
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
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
36	-\$1.25	-\$1.25	-\$0.75	-\$0.50	-\$0.50	\$0.50	\$0.75	\$0.75	\$1.25	\$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

Table 4.4 shows that the current DST does not yield satisfactory results when there is 5% demand increase. On the other hand, 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 developed in Matlab, due to its computational efficiency. However, the tool may not adequately capture the flow dynamics and thus the optimized DSTs do not necessarily yield the performance as predicted by the macroscopic tool.

To verify their effectiveness, we further evaluate the optimized DSTs using CORSIM, a microscopic traffic simulation tool.

4.3 Evaluation of Optimized DST using CORSIM

4.3.1 Enhanced CORSIM

The current version of CORSIM has a very limited capability of simulating dynamic tolling strategies and drivers' lane choice behaviors in the presence of tolls. A project sponsored by the Center of Multimodal Solutions for Congestion Mitigation at University of Florida recently enhanced CORSIM's functionality of simulating HOT lane operations. Three sets of modules have been developed for the CORSIM enhancement. The first one implements a variety of pricing strategies including the 95 Express tolling algorithm, a closed-loop-control-based algorithm and a time-of-day pricing scheme. The second module mimics drivers' lane choice behaviors in the presence of tolls and the third includes different toll structures or charging approaches for multi-segment HOT facilities. Below we briefly explain these three components.

4.3.1.1 Pricing Strategies

Three different pricing algorithms are implemented in the enhanced CORSIM. The first one is the 95 Express pricing algorithm as described in Section 4.2.1. The second one is closed-loop-control-based algorithm, which adjusts the toll amount based on real-time traffic measurement. The toll amount for the next 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 toll is described as follows:

1) Calculate the average traffic density of the HOT lane segment, denoted as $TD(t)$.
2) The toll amount for the next time interval ($R(t+1)$) is calculated based on the following equation:

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

   where,$R(t)$is the current toll amount; K is a regulator parameter defined by the user. It is used to adjust the disturbance of the closed-loop control, i.e., 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.

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

The third pricing algorithm implemented in CORSIM is the time-of-day pricing scheme. In this scheme, the toll amount varies by time of day according to a pre-determined toll schedule determined by the user. This scheme is useful for freeway facilities that have stable traffic demand pattern during, e.g., the weekdays. Multiple tolling periods with different toll prices and durations can be simulated in the enhanced CORSIM. The number of tolling periods is up to 24, and the duration of tolling periods varies from 3 minutes to 60 minutes, with a toll amount varying from $0.00 to $ 12.00.

4.3.1.2 Lane Choice

After the toll is set using one of the pricing algorithms, drivers' reaction to the toll on the choice between the HOT and the GP lanes is simulated in CORSIM. Empirical studies (e.g., Li, 2001; Burris 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 model developed in empirical studies (e.g., Small and Yan, 2001; Yan et al., 2002; Small et al., 2005c, 2005a,) in CORSIM is technically feasible. However, such a model calibrated for one facility may not be transferable to another one without calibration, which is often too costly to do for the new site. Even if the model is transferable, the user needs to provide site-specific input data for many explanatory variables in the model. Those data are often not readily available. For these reasons, a simple lane-choice model was selected for implementation in CORSIM, which 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 multiplying the perceived TTS, which is assumed to follow a truncated normal distribution whose mean is the actual TTS and a standard deviation specified by the user. The actual TTS is the difference between the travel times on GP and HOT lanes, averaged across a user-specified time interval.

Some studies (e.g., Small, 1982; Waters, 1982 and Miller, 1996) suggested that the average VOT of an individual is about 50 percent 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 percent of the wage rate, depending on the length and type of travel. Moreover, Outwater and Kitchen (2008) suggested that the VOT increases as the vehicle occupancy increases. The increase of VOT between HOV 2 and HOV 3+ can range from 3.8% to 39.7%. In order to consider the variation of travelers' VOT, up to five different VOTs for each toll-paying vehicle type (cars, HOV2, HOV3+, trucks) can be specified by the user in the enhanced CORSIM as well as the percentage of each vehicle type.

4.3.1.3 Toll Structures

When a HOT lane facility has multiple segments, motorists can be charged in different ways based on the toll structure implemented. There are four basic toll structures for multi-segment facilities, including zone-based, origin-specific and origin-destination (OD)-based and distance-based. All the toll structures are briefly described below and in more detail in Section 4.4.

Zone-based tolling. The HOT lane facility is divided into zones. Each zone can have multiple entrances and multiple exits. The toll is the same for all the entrances to the same zone. The total amount of toll a motorist pays depends on the numbers of zones traversed.

Origin-based tolling. In origin-based tolling, 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 how far they are going to travel on the HOT lanes.

OD-based tolling. In OD-based tolling, the toll amount 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 decide if they want to use the HOT lanes or not.

Distance-based tolling. In this toll structure, the toll charged depends on the distance that motorists travel on the HOT lanes. The toll rate, i.e., 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 (the toll to the first exit), a toll rate and the toll amount for traveling to the end of the facility.

Currently, only the first two toll structures are fully implemented in CORSIM.

4.3.2 Calibration of 95 Express network in enhanced CORSIM

We coded and calibrated the current 95 Express for the northbound direction in the enhanced CORSIM, which models both the HOT and GP lanes as one facility and simulates the lane-choice behaviors endogenously.

The data used for calibration were obtained from the STEWARD database for every 15 minutes between May 10 and 12, 2011 (Tuesday, Wednesday and Thursday). On those days, the data from most detectors were available and there was no special event. Based on the 95 Express Monthly Operations Report of May 2011 (FDOT, 2011), the peak period was 4:00-7:00pm for northbound. We thus calibrated our model against this time period and one extra half hour was used for initialization.

Table 4.6 compares the reported performance statistics of the northbound direction of 95 Express and the simulated ones.

TABLE 4.6 Comparison of Performance Statistics for PM Peak Northbound

	Simulation Model		Reported (May 2011)	
Tolls				
Range	$0.25 - $5.75		$0.00 - $5.50	
Avg. Peak Period	$2.17		$2.12	
Performance Measures	EL	GP	EL	GP
Avg Speed (mph)	57	49	58	46
EL Operated above 45 mph	99.6%		99.7%	

It can be seen that the simulation model replicates those major performance measures very well. In the simulation, the actual TTS is calculated every minute and is then used for the lane-choice decision during the next minute. Also, the standard deviation of the perceived TTS distribution is assumed to be a half of the actual TTS. The calibrated VOT for the 95 Express network is shown in Table 4.7. The % vehicles columns represent the percentage of vehicles that have VOT equal to the value shown in the next column. For example, 10% of cars have a VOT of $8 per hour and 15% of them have a VOT equal to $10 per hour.

TABLE 4.7 Value of Time ($/hr)

	% vehicles	VOT	% vehicles	VOT	% vehicles	VOT	% vehicles	VOT	% 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

The above calibrated VOT values appear consistent with the 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 HOV3+ appears reasonable too. It should be noted that another set of VOT values may also yield a good match.

The lance choice model in CORSIM is applied to toll-paying vehicles. However, there are some toll-exempt vehicles on 95 Express, including transit, hybrid vehicles and registered HOV 3+. The types and percentages of the toll-exempt vehicles can be specified in CORSIM. We estimated from the 95 Express Monthly Operations Report of May 2011 that approximately 11% of the HOT traffic is toll exempted.

4.3.3 Evaluation of optimized DST for 95 Express tolling algorithm

Using the calibrated CORSIM model, we evaluated the optimized DSTs described in Section 4.2.2and compared their performances with those of the original DST. The simulation results are summarized in Table 4.8.

TABLE 4.8 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	
Performance Measures	EL	GP	EL	GP
Avg Speed (mph)	57.20	49.10	58.61	46.23
EL 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	
Performance Measures	EL	GP	EL	GP
Avg Speed (mph)	56.55	47.62	56.83	46.00
EL Operated above 45 mph	95.3%		97.7%	

The following observations can be made from the CORSIM simulation studies:

- The original and optimized DSTs present comparable performances in both demand scenarios. They both effectively achieve the operating objectives of 95 Express. In the increased demand scenario, the optimized DTS slightly increases the speed reliability, but charges higher average toll. However, the highest toll value does not go beyond $5.00, while the original DST charges up to $7.00.

- The proposed GA procedure provides a sensible approach to fine-tune the DST parameters, avoiding trial and errors. However, the optimized DSTs do not produce much noticeable improvement, as predicted in the optimization procedure, in the CORSIM simulation. This is due to the discrepancy between the Matlab macroscopic simulation tool and CORSIM. If the latter is incorporated into the GA procedure, more substantial improvement can be expected. However, a CORSIM-based GA optimization will be very time consuming, although it remains feasible to utilize a parallel-computing framework to expedite the optimization process.

4.4 Pricing of Multi-Segment HOT Lane Facilities

Similar to 95 Express, quite a few HOT lanes in operation in the U.S. are single-segment facilities while others consist of multiple segments. A single-segment HOT facility means that there are essentially one entrance and one exit. Sometimes, more than one entrances or exits exist, but they are very close to each other and motorists still pay the same amount of toll to use the facility no matter where they enter or exit. In contrast, a multi-segment HOT lane has multiple ingress or egress points that are located distantly from each other and there are more than one tolling points in the facility. Depending on where they enter or exit, motorists may pay different amounts of toll.

Similar to 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 among motorists. For example, if not priced properly, those who access the HOT lanes via a downstream entry point could end up with paying much higher tolls for smaller time savings.

This section reviews the tolling practice for the multi-segment HOT facilities in the U.S. The review focuses on the implemented toll structures and compares their advantages and disadvantages.

4.4.1 Multi-segment HOT lanes in the U.S.

There are five multi-segment HOT lanes currently in operations nationwide, including:

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

4.4.2 Toll structures

Although a multi-segment facility often has multiple tolling points along the facility, a motorist may or may not pay at each tolling point, depending 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. The former three have been implemented in practice.

4.4.2.1 Zone-Based Tolling

In this approach, a HOT 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. Such a 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 MnPassI-394 HOT lanes in Minneapolis. Below we review these facilities one by one.

Salt Lake City, Utah. I-15 express lanes in Salt Lake City, Utah, opened in September 2006 (via converting HOV to HOT). The facility is 40 miles long. There are two entrances and one exit at each direction, and in between 18 access points where drivers can enter, leave or overpass a slow-moving vehicle. Those access points, separated by dashed white line from the GP lanes, are 3,000 to 9,000 feet long and located at each I-15 interchange (UDOT, 2010a). The map of the facility is shown in Figure 4.3. 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 nor the adjacent passing lane to the express lanes. When this system first opened, the single occupancy vehicles had to buy a monthly decal of $50 to use it unlimitedly. 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).

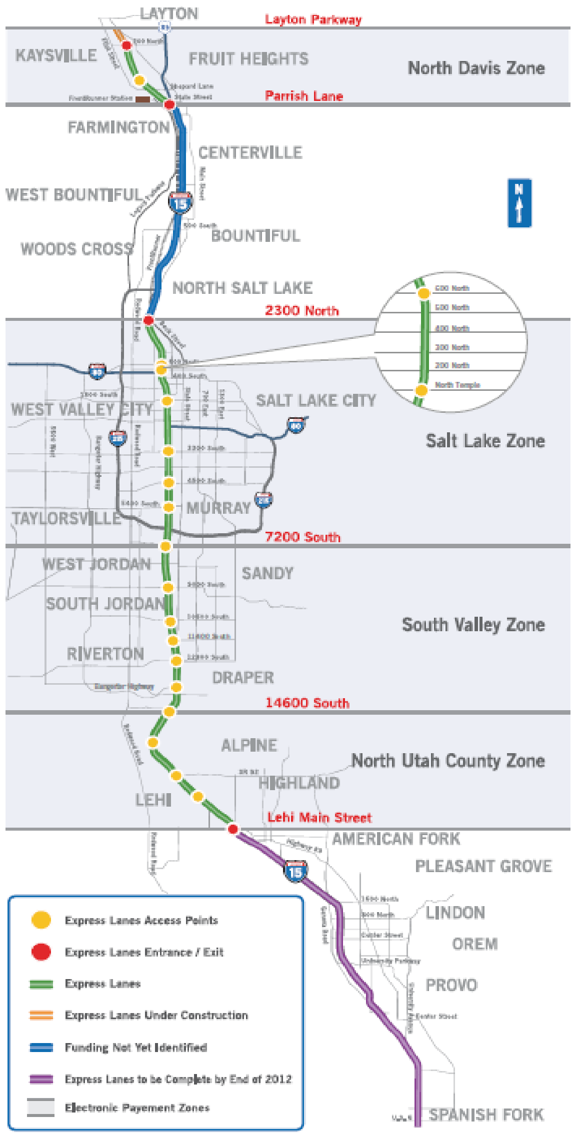


FIGURE 4.3 Map of I-15 HOT Lanes at Salt Lake City, Utah (Source: http://www.udot.utah.gov/expresslanes/dld/Express%20Lanes%20Zone%20map.pdf)

I-10 (Katy Freeway), Houston, Texas. The Katy managed lanes at I-10 corridor in Texas opened in 1998 and became fully operational in 1999. They are 13 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 & ride lot in each direction where buses can enter and exit the managed lanes (HCTRA, 2010). The map of the facility is given in Figure 4.4. Vehicles with two or more persons and motorcycles can enter the lanes for free during 5:00–11:00 and 14:00–20:00. For other times, all vehicles must pay a toll to access the managed lanes. The tolls are determined as per a toll schedule and vary by time of day and tolling zone. Figure 4.5 presents the toll schedule. There are three tolling points. Therefore, a driver that traverses the entire HOT facility needs to pay three different tolls. Commercial vehicles with 3+ axles and vehicles towing trailers are allowed to use the HOT lanes by paying $7.00 for each zone regardless the time of day and the traffic condition (HCTRA, 2010).

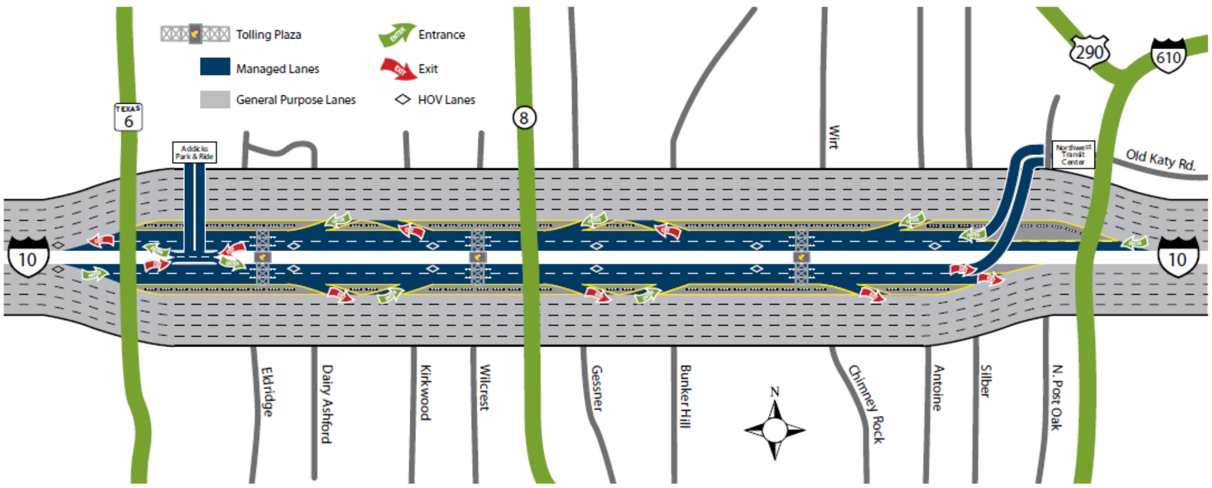


FIGURE 4.4 Map of Katy Managed Lanes at Houston, Texas(Source: https://www.hctra.org/katymanagedlanes/media/katy_managed_lanes_map.pdf)

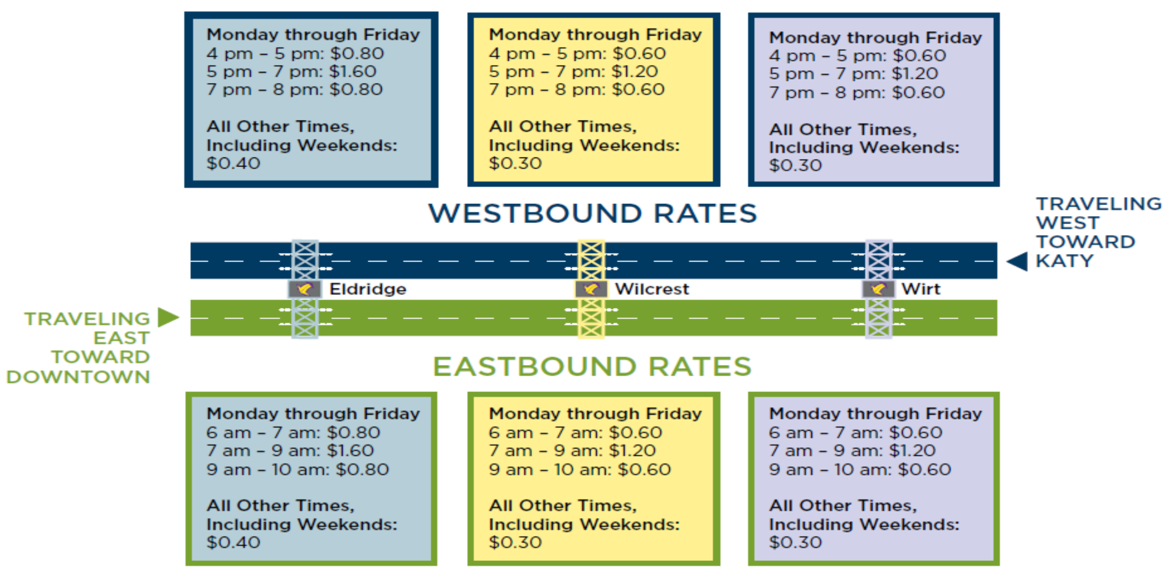


FIGURE 4.5 Toll Schedule of Katy Managed Lanes at Houston, Texas(Source: https://www.hctra.org/katymanagedlanes/media/road_rate_chart.pdf)

Obviously the toll structure of the Katy managed lanes is zone-based, and the toll amounts vary by time of day according to a pre-determined schedule. Such a time-of-day tolling is easier to implement. However, it may not be able to manage the traffic demand well when there are substantial demand fluctuations, such as those during holidays or large sport events.

I-394, Minneapolis, Minnesota. The MnPass HOT lanes at I-394 opened in May 2000. They 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 map of the MnPass HOT lanes is presented in Figure 4.6. 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 reversible lanes are always tolled, running east between 6 AM and 1 PM and west between 2 PM and 5 AM. The tolls at the HOT lanes are in effect between 6 AM to 10 AM and 2 PM to 7 PM, Monday through Friday. For the other hours, HOT lanes are open to all traffic (MnDOT, 2010).The I-394 corridor is divided into two tolling zones. The price of each zone is determined independently to manage the demand in that particular zone. The sign at an entry point lists the tolls by destination, i.e., 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 to pass that point, he or she will pay the second price posted on the sign at the entrance.

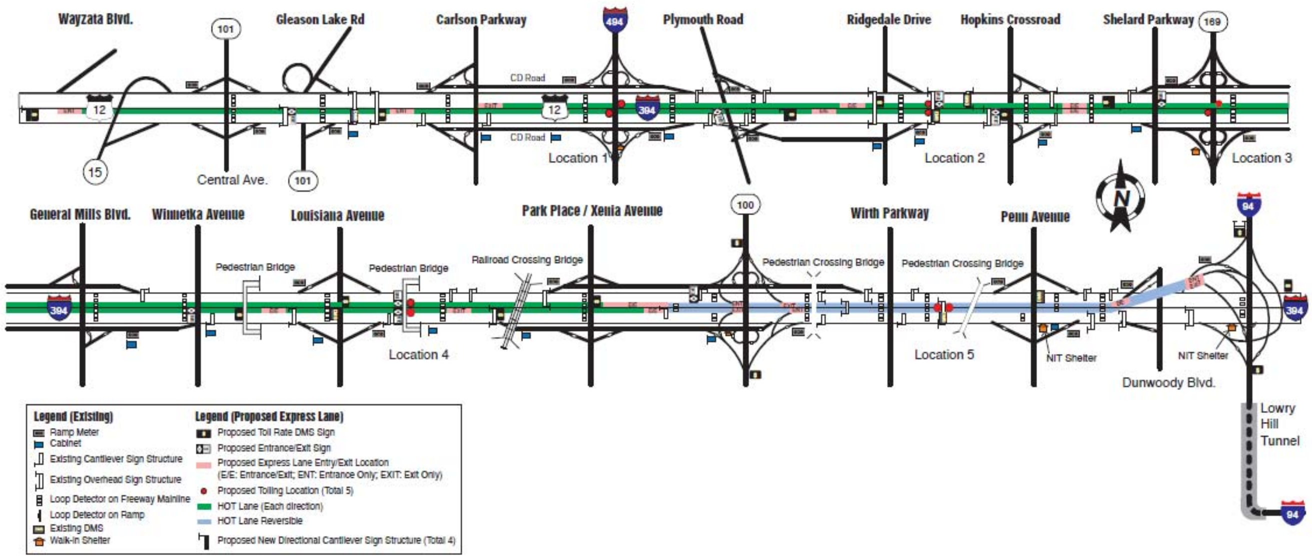


FIGURE 4.6 Map of I-394 HOT Lanes, Minnesota(Source: http://www.mnpass.org/pdfs/394mnpass-schematic.pdf)

4.4.2.2 Origin-Specific Tolling

In origin-specific tolling, the toll amount a motorist will pay depends only where he or she enters the facility. Regardless how far the motorist travels along the facility, he or she pays the toll displayed at the entry point. The origin-specific tolling is implemented on SR-167 HOT lanes in Washington.

SR-167, Washington. The Washington State Department of Transportation (WSDOT) opened the SR-167 HOT lanes in May 2008. The HOT lanes are 10 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). Figure 4.7 presents the map of the facility. 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. At SR-167, the tolls are adjusted every five minutes based on real-time traffic condition to ensure that the traffic in the HOT lanes always flows smoothly and the speed does not drop below 45 mph. The toll rate ranges from $0.50 to $9.00. Users of the HOT lanes pay the toll displayed at their entrances even if they traverse the entire facility. If the traffic on the HOT lanes increases significantly, the signs at the entrances of the HOT lanes will display 'HOV only', restricting the access of all solo drivers.

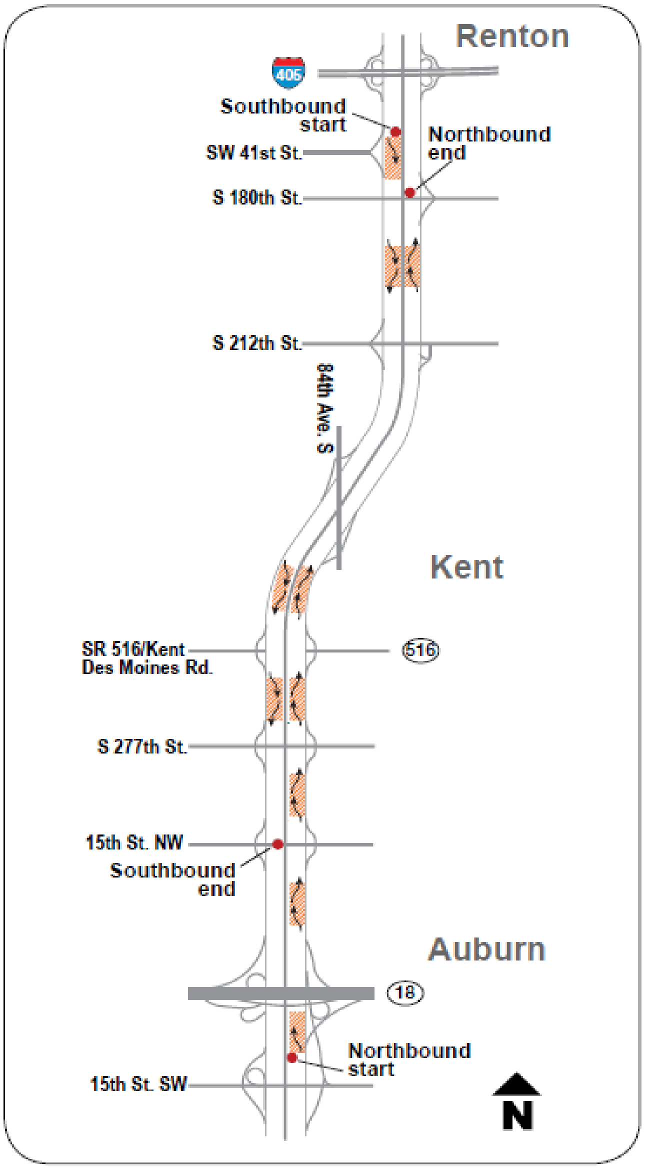


FIGURE 4.7 Map of SR-167 HOT Lanes, Washington(Source: http://www.wsdot.wa.gov/NR/rdonlyres/31FB3D24-79CC-4332-82F7-EBECEBE1CA71/0/HOTLanesAnnualReport2009.pdf)

4.4.2.3 OD-Based Tolling

The OD-based tolling implies that the toll rate a motorist will pay depends on where he or she enters and leaves the facility. This toll structure is implemented on I-15 in San Diego.

I-15, San Diego, California.I-15 HOT lanes in San Diego opened in December 1996. They are 16 miles long and have nine entrances and eight exits at the northbound direction and nine entrances and nine exits at the southbound direction. The facility was initially barrier-separated HOV lanes but then solo drivers were allowed to gain unlimited access via purchasing a monthly permit ($50 and then $70). In March 1998, time of day pricing was implemented. The toll schedule is presented in Figure 4.8, and the facility map is shown in Figure 4.9.

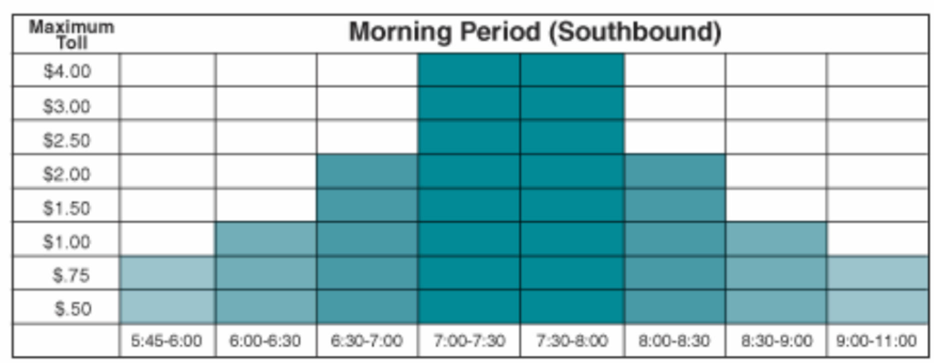


FIGURE 4.8 Toll Rates on I-15 San Diego Prior to March 2009(Source: http://tti.tamu.edu/documents/0-4898-1.pdf)

In March 2009, dynamic pricing was implemented on I-15 Express Lanes. The sign at the entrance displays the minimum toll for entering the facility, a toll rate per mile and a toll amount for traveling to the end of the facility. 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 a rate per mile at their entry locations. Every a few minutes, the system will recalculate the per-mile 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 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 between the first possible interchange, the expected toll can fall between the minimum and the toll for traveling all the way to the interchange (SANDAG, 2010).

FIGURE 4.9 Map of I-15 HOT Lanes at San Diego(Source: http://fastrak.511sd.com/documents/I-15ExpressLanesMAP.pdf)

4.4.2.4 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, i.e., toll per mile, is the same for all entry locations at a specific time interval. Such a toll structure has not been implemented in practice yet.

4.4.3 Summary

Table 4.9 summarizes the characteristics and toll structures of the multi-segment HOT facilities in U.S. The detailed description of each tolling algorithm is not available in the open literature.

TABLE 4.9 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[1], 2 entrances and 1exits 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[2]	8 NB and 9 SB	Concrete Barriers	OD-based: Dynamic Pricing

Note: [1]Access points are the points where drivers can either enter or exit the HOT lanes.
[2]Information provided by the I-15 Express Lanes Customer Service Center

4.4.4 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 condition of 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. In this approach, motorists will make their decisions on whether to pay to access the HOT lanes multiple times. However, they are fully aware of the toll charges whenever they make those lane-choice decisions. One of the critical issues in implementing the zone-based toll structure is to determine the number and locations of zones. If a zone is too long, pricing becomes less effective in managing demand. On the other hand, many short zones will create additional lane changes, possibly yielding moving bottlenecks and disrupting the managed-lane operations.

The origin-specific toll structure is also relatively easier to implement. Moreover, it 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. More specifically, 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 to be 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 recent opposition to ramp metering in the Twin Cities, Minnesota area where the state legislature passed a bill in Spring 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 the inequality among users who access the facility via different entrances. However, it is more sophisticated and thus more difficult to implement than the previous two. It may require a relatively high implementation cost as 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), when a motorist enters the facility, he or she needs to pay the minimum toll, regardless of his or her destination. The sign at each entrance advises one or more possible fares for longer trips to upcoming exits. If the destination is somewhere before the first possible exit, the expected toll can fall between the minimum and the toll for traveling all the way to the exit.

Comparatively, the distance-based toll structure seems easier to implement than the OD-based tolling. However, from a software point of view, the implementation difficulty for both schemes is approximately the same. The distance-based tolling is more flexible than the origin-based structure in managing the traffic demand. 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 4.10 summarizes the advantages and disadvantages of the different toll structures presented above.

TABLE 4.10 Pros and Cons of Toll Structure

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 and inequality concerns
OD-based	Effectively manage demand and utilize capacity	More costly to implement
Distance-based	No equity concern	More costly to implement and inefficient utilization of capacity

4.5 Recommendations for Pricing of Future 95 Express

4.5.1 95 Express future implementation

95 Express is deployed in two phases. Phase 1 has been completed, which includes express lanes between SR-836/I-395 and Miami Gardens Drive/NW 186th Street in Miami-Dade County. Phase 2 will expand the express lanes northward to Broward Boulevard in Broward County

(FDOT, 2010b). Figure 4.10 shows the map of I-95 with the express lanes after the completion of Phase 1 and Figure 4.11 illustrates I-95 with the completed 95 Express. Currently, 95 Express operates as a single-segment facility. After the completion of Phase 2, the express lanes will be extended for more than 10 miles, and the facility should be separated into multiple segments for operation efficiency.

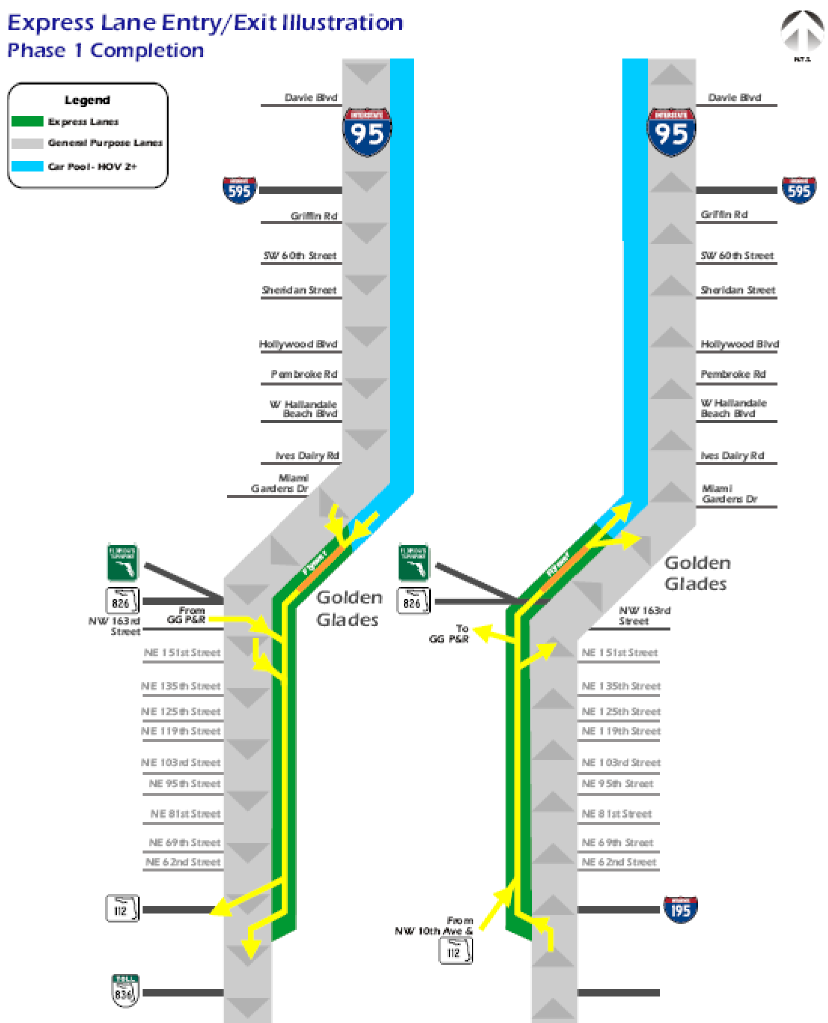


FIGURE 4.10 Map of 95 Express After Phase 1 Completion(Source: http://www.95express.com/PDF/2008-05-19_Entry-Exit%20Phase%201.pdf)

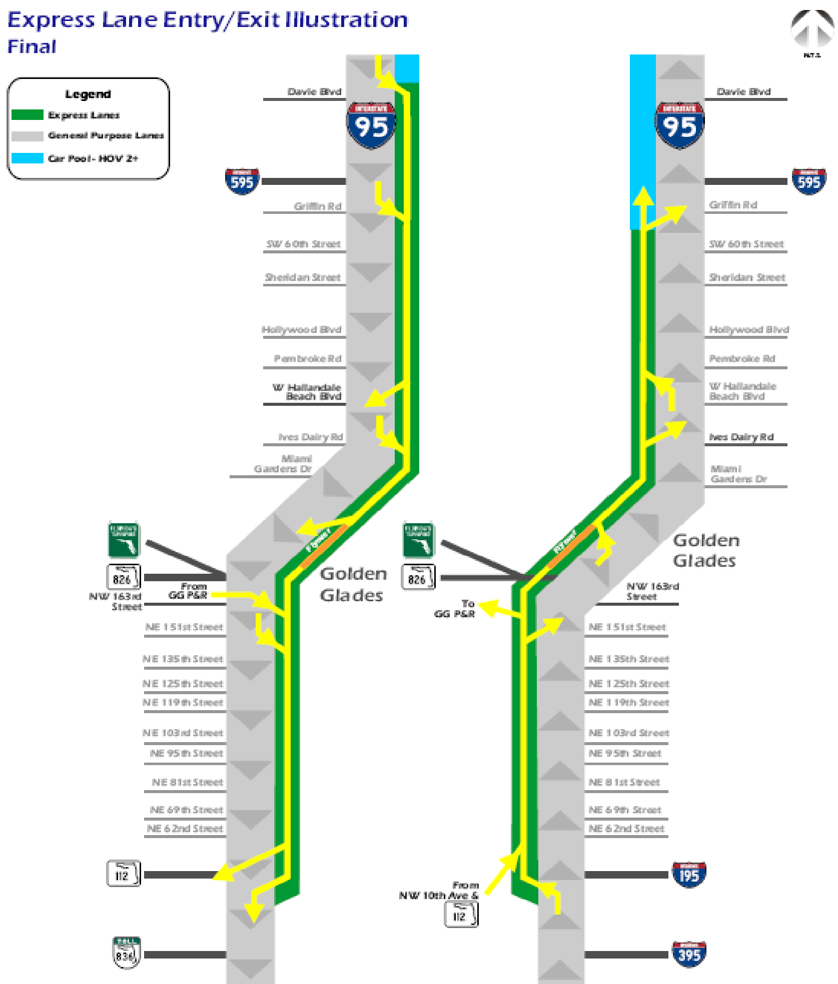


FIGURE 4.11 Completed 95 Express (Source: http://www.95express.com/PDF/2008-05-19_Entry-Exit%20Phase%201.pdf)

4.5.2 Recommendations of toll structure for future 95 Express

The completed 95 Express will have five entrances and four exits in the SB direction and four entrances and five exits in the NB direction (Figure 4.11). Some of these entrances and exits will be located very close while others will be at a distance of about 10 miles. This implies that setting one toll amount may not be effective in managing traffic demand or fair for all users. Therefore, the future 95 Express may better be managed as a multi-segment facility. As mentioned previously, there are four different toll structures that can be applied, but not all would be appropriate for 95 Express. Taking into account the advantages and disadvantages of these toll structures, the zone-based and OD-based tolling seem more appropriate for 95 Express.

4.5.2.1 Zone-Based Tolling for 95 Express

Given the fact that dynamic pricing is being implemented on the current facility, it will be easier and more cost-effective to implement the zone-based dynamic tolling for the future 95 Express. The critical issue is still to determine the zoning. One approach we recommend is to open the facility for free access for a certain period of time, once it is completed. An empirical study may then be conducted to identify the recurring bottlenecks of the facility. The zoning can then be determined to ensure that each zone contains exactly one bottleneck.

If the above approach is not practically feasible, we can rely on simulation studies to evaluate and compare multiple zoning designs. One possible design is to treat Phase 1 as one zone and the extended portion as another two zones, as shown in Figure 4.12. The potential zone 3 for the SB direction and zone 1 for the NB direction are the existing 95 Express while zones 1 and 2 for SB, and zones 2 and 3 for NB 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 to be fine-tuned.

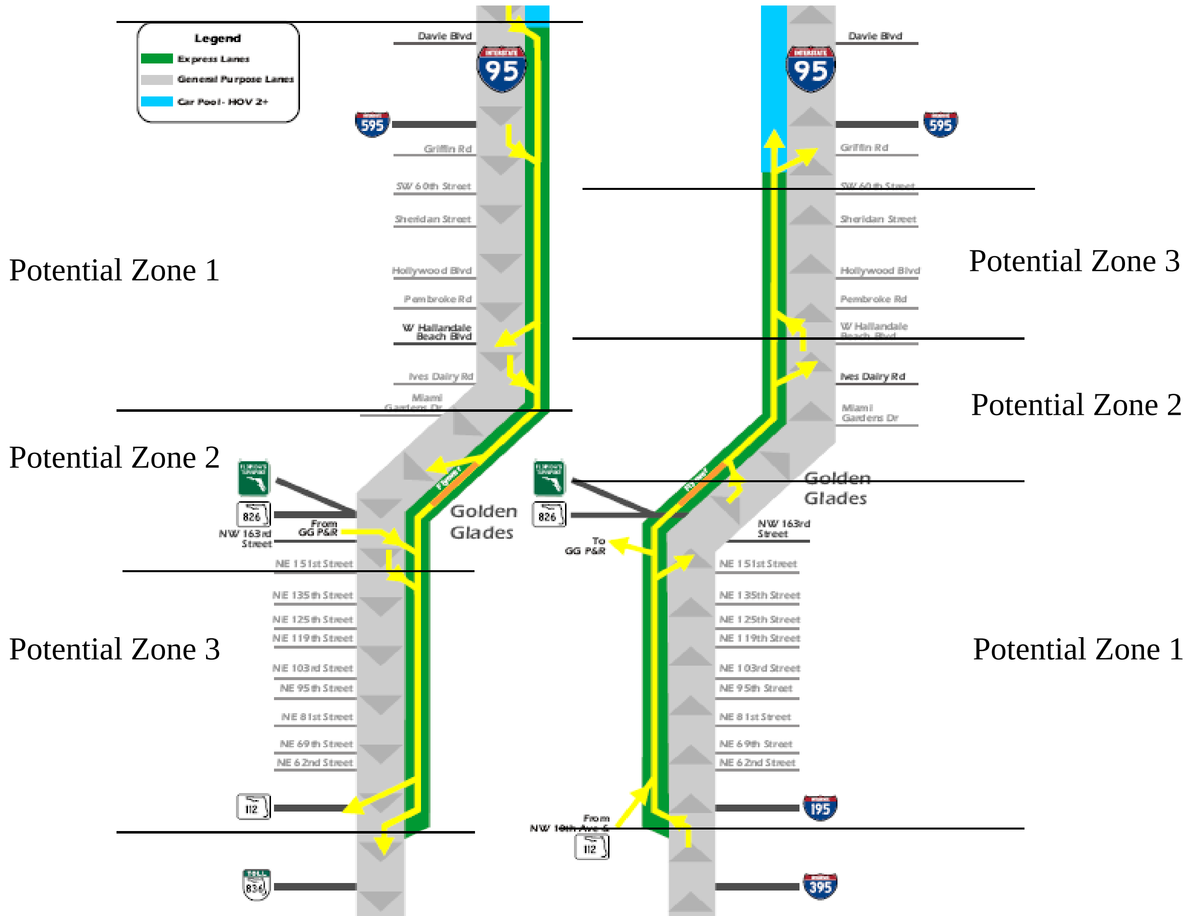


FIGURE 4.12 Potential Zoning for 95 Express

4.5.2.2 OD-Based Tolling for 95 Express

OD-based tolling is another potential approach for 95 Express. However, it is more costly and difficult to implement. A more sophisticated tolling algorithm should be developed to charge users based on their origins and destinations to maintain the desired traffic condition on the express lanes and fully utilize the available capacity of express lanes without creating much inequality among users of different O-D pairs. A simulation study is needed to examine whether the OD-based toll structure outperforms the zone-based one and whether the additional benefit justifies its additional implementation cost.

4.5.3 Evaluation of the recommended toll structures for 95 Express

Currently, the enhanced CORSIM is not capable of simulating the OD-based tolling structure for multi-segment HOT lane facilities. We thus evaluated only the zone-based tolling approach with two different zoning designs for the northbound direction, as shown in Figure 4.12. The data used for the calibration were obtained from the STEWARD database for every 15 minutes for three weekdays, May 10-12, 2011,for all the detectors along the future 95 Express corridor.

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

For determining the price of each zone, the 95 Express dynamic pricing algorithm was used with the same DST parameters. However, the minimum and maximum toll values in the LOS setting table (Table 2.2) for LOS D, E and F were increased to match the increased zone length, as shown in Table 4.11. The simulated performance measures of the two zoning designs are summarized in Table 4.12.

TABLE 4.11 Toll Ranges for the NB Zones of Future 95 Express

Scenario 1, Zone 3			
Level of Service	Traffic Density (vpmpl)	Toll Rate Min	Toll Rate 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	**$5.75**
E	> 35 - 45	**$4.75**	**$7.00**
F	> 45	**$6.25**	**$8.50**

Scenario 2, Zone 2			
Level of Service	Traffic Density (vpmpl)	Toll Rate Min	Toll Rate 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	**$9.25**
E	> 35 - 45	**$8.75**	**$11.00**
F	> 45	**$11.25**	**$13.50**

TABLE 4.12 Future 95 Express NB Zoning Performance Measures

Three Zone Design								
Tolls	Zone 1		Zone 2		Zone 3		Facility	
Range	$1.25 - $2.75		$0.25 - $0.75		$0.25 - $1.00		$2.25 - $3.75	
Avg. Peak Period	$2.23		$0.38		$0.45		$3.05	
Performance Measures	EL	GP	EL	GP	EL	GP	EL	GP
Avg Speed (mph)	56	44	64	55	63	59	61	57
EL Operated above 45mph	98.6%		99.8%		100%		99.4%	

Two Zone Design						
Tolls	Zone 1		Zone 2		Facility	
Range	$1.50 - $2.75		$0.25 - $0.75		$2.00 - $3.00	
Avg. Peak Period	$2.20		$0.38		$2.55	
Performance Measures	EL	GP	EL	GP	EL	GP
Avg Speed (mph)	56	41	65	55	60	56
EL Operated above 45mph	98.7%		99.6%		99.3%	

As Table 4.12 indicates, the three-zone design produces similar performance as the two-zone design. The primary reason is that the freeway segment of Phase 2 is not very congested in the CORSIM simulation. It is thus sufficient to treat Phase 2 as a single zone and use dynamic pricing to effectively manage the segment. Given the above simulation results, it seems more cost effective to implement the two-zone design. However, we caution that the above observation is based on the CORSIM simulation, which needs to be further validated and verified.

4.6 Conclusions and Recommendations

This task focused on enhancing and evaluating dynamic pricing algorithms for the current and future 95 Express. A GA-based optimization framework was developed to fine-tune the parameters, more specifically, the toll adjustments in the Delta Setting Table, of the 95 Express tolling algorithm. The optimized tables were evaluated using the enhanced CORSIM, which explicitly implements the 95 Express tolling algorithm and simulates the lane-choice behaviors endogenously. The chapter also provided a detailed review of current practices of operating multi-segment HOT lane facilities, and compared the pros and cons of four toll structures for this type of facility. We further made recommendations of the toll structure for the future 95 Express and used the enhanced CORSIM to evaluate the recommended zone-based toll structure with different zoning designs.

The proposed GA procedure provides a sensible approach to fine-tune the parameters of the 95 Express tolling algorithm to adapt to future increases in traffic demand. The simulation experiments demonstrated that the procedure produces good results and yield some improvement. To achieve much more noticeable improvement, it is necessary to incorporate CORSIM into the GA procedure. Further research is needed to improve the computational efficiency of the CORSIM-based GA optimization procedure.

For the future 95 Express, the zone-based tolling approach is a good candidate to consider for implementation. The simulation results suggested the two-zone design. Future research is needed to verify and validate the simulation. Future research is also needed to develop an OD-based tolling algorithm for 95 Express and further enhance CORSIM to compare the OD-based toll structure with the zone-based one.

As Phase 1 of 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' decision to use the HOT lanes and estimate their values of travel time 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.

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