

# **FSUTMS-Cube Framework**

## *A Framework for Modeling High Occupancy Toll Lanes in Florida*

### Draft Final Report

*prepared for*

**Florida Department of Transportation Systems Planning Office**



*February 2010*

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*Final report*

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**Draft Final Report**

*prepared for*

Florida Department of Transportation Systems Planning Office

*prepared by*

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# Table of Contents

<b>1.0</b>	<b>Subtask-1: Literature Review and Survey of Current Practice .....</b>	<b>1-1</b>
1.1	Overview .....	1-1
1.2	Road Pricing Definitions .....	1-2
1.3	Types of Road Pricing.....	1-2
1.3.1	Toll Roads.....	1-2
1.3.2	Congestion Pricing.....	1-3
1.3.3	Hot Lanes .....	1-3
1.3.4	Area Charges .....	1-3
1.3.5	Cordon Charges .....	1-3
1.3.6	Vehicle Use Fees .....	1-3
1.3.7	Parking Congestion Fees.....	1-4
1.4	Setting Road Pricing .....	1-4
1.4.1	Static.....	1-4
1.4.2	Variable.....	1-4
1.4.3	Dynamic .....	1-4
1.5	Implementation Types.....	1-4
1.6	Travel Impacts .....	1-5
1.7	Characteristics of HOT Lanes.....	1-6
1.8	Current HOT Managed Lane Modeling Practice in the United States.....	1-8
1.8.1	Florida Turnpike Enterprise .....	1-8
1.8.2	I-394 MnPASS Model.....	1-8
1.8.3	SANDAG Model .....	1-9
1.8.4	DRCOG Model .....	1-9
1.8.5	NC RTPB Model.....	1-9
1.8.6	Portland Model.....	1-10
1.8.7	SACMET Model .....	1-10
1.8.8	Other Managed Lane Models.....	1-10
1.9	Discussion of Approach to HOT Lanes Modeling .....	1-11
1.9.1	Toll Versus Free at Mode Choice .....	1-11
1.9.2	Toll Versus Free at Highway Assignment.....	1-11
1.9.3	Preliminary Recommendations.....	1-12
<b>2.0</b>	<b>Sub-Task 2: Develop Prototype Model .....</b>	<b>2-1</b>
2.1	Overview .....	2-1
2.2	Model Structure.....	2-1
2.2.1	Trip Generation Sub-model .....	2-1
2.2.2	Network.....	2-1
2.2.3	Mode Choice .....	2-2
2.2.4	Time-of-Day .....	2-2
2.2.5	Toll Modeling .....	2-3

# Table of Contents

(continued)

2.2.6	High Occupancy Requirements .....	2-7
2.2.7	General Software Approach .....	2-11
<b>3.0</b>	<b>Sub-Task 3: Sensitivity Analysis .....</b>	<b>3-1</b>
3.1	Lane Configuration Alternatives .....	3-1
3.2	Demand Alternatives.....	3-1
3.3	Model Structure.....	3-2
3.4	Results of Model Runs.....	3-3
3.5	Conclusion.....	3-4

## Appendix A - List of HOT Lanes Projects

## Appendix B - Iterations of Estimate Toll

## List of References

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# List of Tables

1-1	Comparing Road Pricing Objectives .....	1-2
1-2	Appropriate Scale of Pricing Strategies .....	1-5
1-3	Summary of Fee Collection Options .....	1-6
2-1	Toll Values for a Basic Freeway Segment .....	2-7
2-2	Travel Time Values for Person Trips, Southeast Florida Travel Time Values for Core Markets .....	2-8
2-3	Travel Time Values for Person Trips, Southeast Florida Travel Time Values by Travel Demand Model Trip Purpose .....	2-9
2-4	Travel Time Values for Person Trips, Southeast Florida Travel Time Values by Time of Day .....	2-9
2-5	Toll Value for Saved Time .....	2-10
2-6	Iterations Required for Convergence .....	2-12
3-1	Lane Configuration Alternatives for the Olympus Model.....	3-2
3-2	Alternatives, Demand Levels and Toll Values .....	3-4

# List of Figures

2-1	A Supply-Demand Diagram for Congestion Pricing.....	2-4
2-2	Toll and V/C Relationship for a BPR Function .....	2-6
2-3	MnPass Diversion Curve .....	2-11
2-4	Relation between Relative Gap and Number of Iterations .....	2-12
2-5	Volume Changes vs. Toll Iteration .....	2-13
3-1	General Model Structure for All Periods .....	3-3

# 1.0 Subtask-1: Literature Review and Survey of Current Practice

## ■ 1.1 Overview

The Corradino Group has been charged with studying how High Occupancy Toll (HOT) lanes are being modeled throughout the US, and developing a framework for modeling them in the context of the Florida Standard Transportation Urban Model Structure (FSUTMS). The study will develop a prototype model using the Olympus training model. It will define data requirements, and will suggest methods and parameters. Sensitivity tests will be conducted with the prototype model so the reasonableness of the model results can be judged.

In the past several years HOT lanes have garnered an increasing amount of attention in the US as congestion on freeways increases and funding becomes scarce. The 95 Express project in Miami-Dade and Broward Counties, which opened partially in summer 2008, is evidence that HOT lanes are important for Florida. Most large urbanized areas with congestion want to evaluate whether HOT lanes would be beneficial for their roadway system.

While perhaps an oversimplification, the idea behind HOT lanes is to encourage higher occupancies with carpool lanes, and to sell any excess carpool lane capacity to lower occupancy drivers who are willing to pay to use the lanes. The incentive to pay to use the lanes is the promise of a faster ride. To achieve faster speeds, the price to use the lanes is determined dynamically, so that the congestion level in the HOT lanes is kept low and the speed is kept high. As more low occupancy vehicles choose the HOT lanes, the toll is raised. Conversely, the price to use the lanes is low when the demand is low. Overall congestion on the freeway is reduced as carpools are formed and drivers shift their travel times to less congested hours. Most HOT lanes are set to allow vehicles with three or more occupants, including buses, to use the lanes without charge, but to charge a toll for others. Tolls are collected electronically. Issues related to toll collection and enforcement will not be addressed in this paper or in the modeling approach.

An extensive list of references has been provided at the end of this paper. While many of these references were used in the preparation of the paper, some were not and are provided as a convenience to allow the reader to locate more information on the subject of HOT lanes and road pricing.

HOT lanes are a strategy in a general class called road pricing projects. The discussion of road pricing in subsequent chapters provide context to the discussion of HOT lanes.

## ■ 1.2 Road Pricing Definitions

Road pricing means that drivers pay directly for using a particular highway or driving in a particular area or particular time. Value pricing is a marketing term, which emphasizes that road pricing, can directly benefit drivers through reduced congestion or improved highways.

Road pricing may be an efficient and equitable way to fund highways and encourage more efficient transportation. Road pricing has two general objectives:

- Revenue generation; and,,
- Congestion management.

They differ in several ways, as shown in Table 1-1 below.

**Table 1-1 Comparing Road Pricing Objectives**

Revenue Generation	Congestion Management
<ol style="list-style-type: none"> <li>1. Generates funds.</li> <li>2. Rates set to maximize revenues or recover specific costs.</li> <li>3. Revenue often dedicated to roadway projects.</li> <li>4. Shifts to other routes and modes not desired (because this reduces revenues).</li> </ol>	<ol style="list-style-type: none"> <li>1. Reduces peak-period vehicle traffic.</li> <li>2. Is a TDM strategy.</li> <li>3. Revenue not dedicated to roadway projects.</li> <li>4. Requires variable rates (higher during congested periods).</li> <li>5. Traveling shifts to other modes and times considered desirable.</li> </ol>

Source: Victoria Transport Policy Institute

## ■ 1.3 Types of Road Pricing

### 1.3.1 Toll Roads

Tolls are a common way to fund highway and bridge improvements. Tolls are a fee-for-service. Usually, revenues are dedicated to highway project costs. Tolling may be proposed in conjunction with road privatization. Tolls are often structured to maximize revenues and success is measured in terms of project cost recovery. Tolling may discourage development of alternative routes or modes.

### **1.3.2 Congestion Pricing**

Congestion pricing refers to road pricing used as a demand management strategy to reduce peak-period vehicle trips. It is a type of responsive pricing, meaning that it is intended to change consumption patterns. Congestion pricing requires time-variable tolls, with higher tolls during peak periods and lower or non-existent tolls when roads are uncongested. Time-variable tolls can be based on a fixed schedule daily and weekly schedule or they can be dynamic, meaning that rates change depending on the level of congestion that exists at a particular time. They can be implemented on existing highways to avoid the need to add capacity. Some highways have a combination of unpriced lanes and value priced lanes, allowing drivers to choose between driving in congestion and paying a toll for an uncongested trip.

### **1.3.3 Hot Lanes**

High Occupancy Toll (HOT) lanes are High Occupancy Vehicle (HOV) lanes that also allow access to low occupancy vehicles if drivers pay a toll. It is a type of managed lane. This allows more vehicles to use HOV lanes while maintaining an incentive for mode shifting, and raises revenue. HOT lanes are often proposed as a compromise between HOV lanes and road pricing.

### **1.3.4 Area Charges**

Typically, an area charge is applied to all vehicles traveling within a congestion charge area. For such a system, monitoring is required not only on the periphery of the zone, but in the interior of the congestion charge area. An area charge is expected to reduce the total volume of traffic within the congestion charge area and the immediate surrounding area.

### **1.3.5 Cordon Charges**

Under a cordon charge system, a cordon line is established, typically around the central area of a city. Vehicles are charged to pass through the cordon line regardless of the functional class of the roadway. Some cordon tolls only apply during peak periods of weekdays. This can be done by simply requiring vehicles driven within the area to display a pass, or by tolling at each entrance to the area. Cordon charges reduce traffic in and around the cordoned area. Though substantially simpler to administer than an area charge, a cordon charge may not be quite as effective.

### **1.3.6 Vehicle Use Fees**

Distance-based charges, such as mileage fees, can be used to fund highways or reduce congestion. The existing vehicle registration fees and fuel taxes can be replaced by a

variable road user charge using GPS-based pricing methods as a way to reduce traffic congestion and more equitably reflect the roadway costs imposed by each vehicle.

### **1.3.7 Parking Congestion Fees**

Instead of charging road use directly, parking fees can be managed to reduce congestion. Such a system has been proposed for the City of Chicago.

## ■ **1.4 Setting Road Pricing**

Road pricing is set in variety of ways.

### **1.4.1 Static**

Flat fees can be established to reduce congestion. For example, Florida Turnpike tolls are a constant fixed value regardless of the congestion level and are not regularly adjusted to reflect travel conditions. Flat fees are not well suited to performance-based pricing.

### **1.4.2 Variable**

Variable charges are set to vary by time of day, reflecting average demand. Such charges are typically reviewed quarterly and reset to meet highway performance standards. Variable charges enable stable travel mode choices, since the charges are known in advance.

### **1.4.3 Dynamic**

Dynamic prices employ real-time data to vary prices throughout the day as needed to meet highway performance standards. Dynamic prices permit lower average prices than variable prices, but users may not know the prices until they are en-route. Therefore, dynamic prices are more likely to affect route choice than mode choice. Most HOT lanes projects use dynamic pricing.

## ■ **1.5 Implementation Types**

Road pricing is usually implemented by public or private highway agencies or local authorities as part of transportation project funding packages or transportation demand management programs. Implementation may require approval of other levels of government (for example, U.S. federal law restricts tolling on the Interstate Highway System).

Road pricing can be implemented at various scales:

- **Point:** Pricing a particular point in the road network, such as a bridge or a tunnel.
- **Facility:** Pricing a roadway section.
- **Corridor:** Pricing all roadways in a corridor.
- **Cordon:** Pricing all roads in an area, such as a central business district.
- **Regional:** Pricing roadways at regional centers or throughout a region.

Table 1-2 illustrates the appropriate scale of various pricing strategies.

**Table 1-2 Appropriate Scale of Pricing Strategies**

Strategy	Spot	Facility	Corridor	Cordon	Regional
Toll Roads (fixed rates)	X	X	X		
Congestion Pricing (time-variable)	X	X	X	X	
HOT Lanes	X	X			
Cordon Fees			X	X	
Distance-Based Fees					X

Source: Victoria Transport Policy Institute

A variety of pricing methods can be used to collect fees, as summarized in Table 1-3. Newer electronic pricing systems tend to have lower costs, greater user convenience, and more price adjustability, making Road pricing more feasible.

Road pricing should be implemented in conjunction with improved transportation options, so consumers have viable alternatives. For example, congestion pricing can be implemented with transit and rideshare and flextime improvements so motorists have more ways to avoid driving on the priced road. This increases its effectiveness at reducing traffic congestion problems.

## ■ 1.6 Travel Impacts

The travel impacts of road pricing depend on the type and magnitude of fees, where they are applied, what alternative routes and modes are available, and what is assumed to be the alternative or base case.

- Pricing roads that would otherwise be free can shift vehicle travel to free routes, alternative modes and closer destinations, and reduce vehicle trip frequency.

- Congestion pricing (i.e., higher rates during peak periods) can cause vehicle trips to shift from peak to off-peak periods.
- If road pricing is used to fund roadway capacity expansion that would not otherwise occur, it may increase total vehicle travel.
- Road pricing reduces total vehicle travel if used to fund roadway capacity expansion that would otherwise be free.
- The better the travel alternatives (transit, ridesharing and non-motorized), the more road pricing will cause mode shifts.

**Table 1-3 Summary of Fee Collection Options**

Type	Description	Equipment Costs	Operating Costs	User Inconvenience	Price Adjustability
Pass	Motorists must purchase a pass to enter a cordoned area.	Low	Low	Medium	Poor to medium
Toll Booths	Motorists stop and pay at a booth.	High	High	High	Medium to high
Electronic Tolling	An electronic system bills users as they pass a point in the road system.	High	Medium	Low	High
Optical Vehicle Recognition	An optical system bills users as they pass a point in the road system.	High	Medium	Low	High
GPS	GPS is used to track vehicle location. Data are automatically transmitted to a central computer that bills users.	High	Medium	Low	High

Source: Victoria Transport Policy Institute

## ■ 1.7 Characteristics of HOT Lanes

The HOT lane definition provided by Federal Highway Administration in “A Guide for HOT Lane Development” states that:

“HOT lanes are limited-access; normally barrier-separated highway lanes that provide free or reduced cost access to qualifying HOVs, and also provide access to other paying vehicles not meeting passenger occupancy requirements.”

This definition underlines several physical and operational characteristics of HOT lanes. They are also described in “Managed Lanes: A Cross-Cutting Study” provided by FHWA. Themes among HOT lane facilities and other similar facilities are as follows:

- The managed lane concept is typically a “freeway-within-a-freeway” facility, where a set of lanes within the freeway cross-section is physically separated from general purpose lanes;
- The facility incorporates a high degree of operational flexibility, so that over time operations can be actively managed to respond to growth and changing needs;
- The operation of the facility is managed using a combination of tools and techniques in order to continuously achieve an optimal condition, such as free-flow speeds; and,
- The principal management strategies can be categorized into three groups: pricing, vehicle eligibility, and access control.

HOT lane facilities combine the pricing and eligibility features of highways, with the eligibility and access control features of exclusive busways. The category of managed lanes could include other features, such as allowing hybrid vehicles to use the lanes without charge even if there is only one occupant. While the HOT lanes projects noted thus far are typical, there is a wide range of ways to implement them. Thus, the modeling strategy should be flexible. For example, HOT lanes could be operational only for certain hours, and could involve reversible lanes.

A study for the Atlanta Regional Commission found HOT lanes to be feasible in several corridors. It also developed a policy framework for HOT lane development and emphasized the importance of flexibility in applying various pricing and eligibility strategies according to the travel demand. Since the idea behind HOT lanes is to improve the HOV lanes’ utilization and sell the underused capacity to those who are willing to pay, the operational features of HOT lane facility may vary by time and locations.

The Santa Clara County HOT Lane Feasibility Study recommended two demonstration projects in the region and concluded with a list of next steps for implementation. It also noted that the potential success of those two projects would be increased because of the availability of existing HOV lanes and direct connector ramps, and few geometric constraints. Conclusions were that these amenities would lead to greater potential financial return.

In the Managed Lane Manual developed by the Texas Department of Transportation, a managed lane is defined as “a facility that increases freeway efficiency by packaging various operational and design actions, which includes high-occupancy vehicle (HOV) lanes, value-priced lanes or high-occupancy toll (HOT) lanes, exclusive-use lanes such as bus or truck lanes, separation and bypass lanes, dual-use lanes, and lane restrictions.” It also states that “variations of HOT lanes are value-priced, value-expressed, and fast and intertwined regular (FAIR) lanes, which may or may not be occupancy driven depending on the region or state.”

HOT lane facilities can be implemented and operated in many different ways. Thus, it is important to develop a flexible way of modeling them.

## ■ 1.8 Current HOT Managed Lane Modeling Practice in the United States

The first HOT lane project was on State Route 91 in Orange County, California in 1995. After that, other states including Texas, Minnesota, Virginia, Colorado, and Florida have implemented HOT lane projects. Although many proposed projects are under evaluation and models have been developed, there is little consensus on a systematic framework for modeling HOT lanes and integrating them into regional travel demand models.

The initial objective in reviewing the HOT lanes projects around the United States is to identify good practices and provide background information on how they could be modeled successfully in FSUTMS. Because the concept of implementing a HOT lane project sometimes combines other road pricing projects such as Express Toll Lanes (ETL), Truck Only Toll Lanes (TOT), Bus Rapid Transit Lanes (BRT), FAIR Lanes, and other variations, the review covered other innovations as might provide guidance on the development of a comprehensive framework for future Florida's HOT lanes projects. An updated list of completed and ongoing HOT lane and managed lane projects appears in Appendix A.

### 1.8.1 Florida Turnpike Enterprise

The Florida Turnpike has developed a toll mode choice model, which could be used as part of a model of HOT lanes. It was statistically estimated from a stated preference survey. Models were developed for a combination of four periods and four trip purposes, including visitor trips. The Turnpike's modeling system includes a pre-mode-choice time-of-day process; a generalized cost-assignment procedure that uses travel time and costs by time of day (rather than travel time alone); production of zone-to-zone travel time and costs consistent with travel paths; and a feedback loop process that uses an iterative successive averaging procedure to estimate travel times.

### 1.8.2 I-394 MnPASS Model

In the MnPASS system study, toll modeling components were added into the Metropolitan Council's Twin Cities Regional Model. Toll facilities were added to the network as new links with one of two new assignment groups: SOV toll facilities and HOV toll facilities. The network was skimmed to obtain highway time, distance and toll costs. Toll and highway travel time coefficients for different market segments, determined by age, gender, income, education, and trip purpose, were applied to calculate an equivalent travel time. The equivalent travel time was used in the mode choice model to

allocate trips to free vs. toll paths. The model is applied by time-of-day using 24 unequal time periods.

### 1.8.3 SANDAG Model

The San Diego region (SANDAG) has a four-step travel demand model implemented in TransCAD. The SANDAG model uses eight auto trip modes, which are:

- Drive-alone, Non-Toll,
- Drive-alone, Toll
- Shared ride 2, Non-Toll, Non-HOV
- Shared Ride 2, Non-Toll, HOV
- Shared Ride 2, Toll
- Shared Ride 3+, Non-Toll, Non-HOV
- Shared Ride 3+, Non-Toll, HOV
- Shared Ride 3+, Toll

In the model, managed lanes, including HOT lanes, are assigned a speed 5 mph faster than regular mixed lanes. HOT lane tolls are \$0.10/mile for off-peak travel, and \$0.26/mile for peak travel. The model also assigns the trips by mode and uses three time-of-day periods. Since the Interstate 15 HOT lane project has been in operation for several years, the choice constants were based on observed data. The model did not fully address the dynamic toll structure currently used, and actual tolls, determined from congestion in adjacent lanes, may be considerably higher than those used in the model.

### 1.8.4 DRCOG Model

The Denver Region Council of Governments (DRCOG) developed a TransCAD four-step travel model called Compass. The toll structure is included in the trip distribution step and is different for SOV and HOV vehicle classes. The toll cost is converted into a travel time skim cross-classifying by three income groups and purpose of trips. In this model, the User Equilibrium highway assignment is used; in which path algorithms contain toll information. However, the HOT lane concept didn't get specific procedures in the mode choice part and the existing 8 miles HOT lanes on US 36 doesn't apply any dynamic toll rates.

### 1.8.5 NC RTPB Model

The National Capital Region Transportation Planning Board (NC RTPB) has developed a four-step TP+ model for evaluating proposed HOT lanes projects in Northern Virginia. The HOT lanes toll is converted to travel time and is added to the highway travel time

skim file. The TPB mode choice model allocates trips to modes, and is applied by trip purpose. Highway modes are drive alone, group ride 2 occupants, group ride 3 occupants, and group ride 4 or more occupants. The model is not set up to directly model HOT lanes, and employs an iterative process, and manually adjusts HOT tolls, to arrive at an optimum highway assignment.

### **1.8.6 Portland Model**

Portland Metro developed a tour-based activity model to estimate the impact of value pricing projects on the choices of modes, routes, and time of day, by income class and vehicle type. It is highly disaggregate and uses nested logit discrete choice models and destination choice models. A time-equivalent toll is added to the skimmed travel time. Travel time is computed from a generalized multi-class user equilibrium assignment and a volume delay function. In the assignment vehicles of each income class are assigned a separate toll weight to represent the willingness to pay.

### **1.8.7 SACMET Model**

Sacramento's 2001 four-step model uses a joint destination and mode choice logit model. The mode choice portion of the joint model estimates the number of drive-alone, shared ride 2, shared ride 3+, walk-to-transit, drive-to-transit, walk, and bike trips. The highway assignment model assigns trips by auto mode and time-of-day. This model does not deal with HOT lanes. The earlier 1996 version of the model allocated HBW trips between toll and free modes in mode choice, but this procedure was not part of the subsequent 2001 model.

### **1.8.8 Other Managed Lane Models**

Atlanta has conducted several studies of managed lanes in the region. Its model makes the toll/non-toll choice in the highway assignment step and applies a variable toll structure according to the V/C ratio in the HOT lane.

The Pennsylvania Department of Transportation utilizes a customized assignment process to permit fixed tolls as well as variable tolls by time-of-day and traffic conditions. Managed lanes are modeled with the goal of maintaining a high LOS in the HOT lanes. The choice of toll versus non-toll is made in the highway assignment step.

San Francisco uses feedback from the MTC demand model to account for shifts in routes, trip times, and mode choice in response to tolls and restricted access locations. The MTC model is a disaggregated activity-based model, which can deal with HOT lanes.

## ■ 1.9 Discussion of Approach to HOT Lanes Modeling

Generally, there are two fundamental approaches to modeling HOT lanes. They are:

- Modeling toll versus free as modes in the mode choice model; and,
- Determining the toll versus free choice during the highway assignment process.

Both approaches require the highway vehicle trip tables that are provided to the highway assignment process to be stratified by auto occupancy level – generally drive-alone, 2-person carpools, and 3 or more person carpools.

There are pros and cons for each approach.

### 1.9.1 Toll Versus Free at Mode Choice

This is the option that the Florida Turnpike is using in their new models. This option allows a wide range of travel characteristics to be evaluated in the choice, and provides a relatively simple set of options for the highway assignment model, as the choice as to whether the driver is willing to pay is known before the assignment begins.

This procedure, however, may be less able to respond to the effects of congestion and dynamic pricing, as the effects of congestion, which in turn affect the toll that should be charged to maintain the promised level of service in the HOT lanes, are not known until after the assignment. Thus, the mode choice and assignment process must be included in an iterative feedback loop, thereby allowing the mode choice model to consider new travel times and to revise toll rates.

### 1.9.2 Toll Versus Free at Highway Assignment

The Cube Voyager highway assignment program (HIGHWAY) has features that allow multiple paths (e.g., toll and free) to be skimmed for each trip interchange during the highway assignment process, applying a split based on a function or look-up table, and then loading the path. A multiple-class assignment is used for each level of auto occupancy and toll choice (pay versus free). With these features, between each assignment iteration travel times can be adjusted using a volume-delay function and tolls can be adjusted to approach a target volume to capacity ratio in the HOT lanes. The toll versus free split can be based on a diversion curve or some logit or other function. Please note that in this method, as with the toll mode choice method, the toll choice is really “willing to pay” versus “not willing to pay.” Travelers not willing to pay are prohibited from using the toll lanes, while those willing to pay are allowed to use the minimum impedance path, which may or may not involve a toll.

There are several disadvantages here also. First, in order for the equilibrium assignment routine to behave well, the toll adjustment must be performed in a loop outside of assignment. That is, multiple assignments must be made, adjusting the toll in between the

assignments. The disadvantage here is the large amount of computer time required in this method, although new Cube Voyager assignment routines hold great promise. Second, in general, a lot less household and trip purpose data are available at the assignment stage than in mode choice. This could be overcome by specifying multiple classes, at the expense of computer running time. For example, separate classes could be assigned for each auto occupancy level and trip purpose.

### **1.9.3 Preliminary Recommendations**

The preliminary recommendation is to implement the second option, toll versus free at the time of highway assignment. Corradino will develop a prototype model of this type in the Olympus training model and will evaluate its performance.

## 2.0 Sub-Task 2: Develop Prototype Model

### ■ 2.1 Overview

This memorandum describes a framework for modeling High Occupancy Toll (HOT) lanes in the context of the Florida Standard Transportation Urban Model Structure (FSUTMS). This memo will serve as a guide to developing a prototype model and will also be foundation for the guidelines that will be developed later after the prototype model.

### ■ 2.2 Model Structure

The proposed prototype travel demand model will be a four-step FSUTMS model. The following sections describe the requirements and issues of its sub-models.

#### 2.2.1 Trip Generation Sub-model

While the FSUTMS trip generation model is segmented by trip purpose, usually internal-external (IE) and external-external (EE) trips have their own trips purposes and are not further segmented by the internal trip purposes. In the time-of-day sub-model for the peak periods, trip purpose segmentation is needed for all trips, including EE and IE. Thus, IE and EE trips must also be segmented by trip purpose. A reasonable assumption would be to distribute IE and EE trips cross trip purpose types using the same method used for internal trips. Therefore the total trip production distribution for each purpose should be calculated in the trip generation step to use later to segment the IE and EE trips. Obviously, if better data on the actually purpose of external trips is available, it should be used.

#### 2.2.2 Network

In the usual configuration, High Occupancy Toll (HOT) lane links operate inside the existing general-purpose highway facilities - they are the inside lanes, or even a separate roadway. A network link should be specified for each segment of the HOT lane facility. The number of lanes on the HOT lanes could vary by travel demand and available space, but as an example, 95 Express in Miami-Dade County HOT lanes provide two travel lanes in each direction. A link attribute with a binary value also should be defined to identify

the HOT lane links. The value of this link attribute is normally nonzero (e.g., 1) for the HOT lane links and zero for all other network links.

### 2.2.3 Mode Choice

The mode choice step determines the amount of travel that will take place on each available mode of transport. Normally the mode choice sub-model has a nested structure. The "Auto" trips should be split into "Drive Alone", "2-Person Shared Ride", and "3+Person Shared Ride." Also separate models should be used for the main trip purposes namely, HBW, HBO, and NHB. The following steps will require that the outputs of the mode choice model to be segmented as:

- HBW Drive Alone person trips
- HBO Drive Alone person trips
- NHB Drive Alone person trips
- HBW 2-Person Shared Ride trips
- HBO 2-Person Shared Ride person trips
- NHB 2-Person Shared Ride person trips
- HBW 3+ Person Shared Ride person trips
- HBO 3+ Person Shared Ride person trips
- NHB 3+ Person Shared Ride person trips

### 2.2.4 Time-of-Day

For the each time period a combination of trip-purpose and vehicle occupancy segmentation is suggested. The same HOT lanes assignment process would be applied for each time period. The purpose/occupancy segments are:

- HBW Drive Alone vehicle trips
- HBO Drive Alone vehicle trips
- NHB Drive Alone vehicle trips
- HBW 2-Person Shared Ride vehicle trips
- HBO 2-Person Shared Ride vehicle trips
- NHB 2-Person Shared Ride vehicle trips
- HBW 3+ Person Shared Ride vehicle trips
- HBO 3+ Person Shared Ride vehicle trips
- NHB 3+ Person Shared Ride vehicle trips

## 2.2.5 Toll Modeling

One of the most commonly used conditions in the traffic assignment modeling is called “User Equilibrium” (UE). This condition reasonably assumes that every motorist will try to minimize his or her own travel time when traveling from origin to destination. A stable condition is reached only when no driver can improve his travel time by unilaterally changing routes.

The user-equilibrium condition, however, is not only possible principle to use. The other common principle that is oriented towards transportation planners and traffic engineers trying to manage traffic is to minimize the total travel costs and therefore achieve an optimum social equilibrium. The solutions to the two conditions do not coincide; in other words, the user equilibrium solution generates higher total costs than the social equilibrium solution. The difference lies in the external effects due to congestion. Users perceive only their own personal costs and do not discern the additional delay incurred by other drivers due to each extra vehicle on the road. In economic theory, the discrepancy between these solutions is called the congestion charge. One can envision electronic road pricing, implemented as variable tolls, as a possible method to make drivers perceive marginal rather than average costs.

Basic price theory says that whenever the average variable cost rises, it means the marginal cost curve lies above it. The vertical difference of the two cost curves is the marginal (external) congestion cost- the additional delay that one driver imposes on all other drivers.

The basic principles of congestion pricing can be illustrated in the following simple setting. Most studies consider a standard case of a homogenous traffic stream moving along a given uniform stretch of road. Traffic flows, speeds and densities are uniform along the road and independent of time. As shown in Figure 2-1, the AC curve represents the average (private) cost of congestion at each level of demand, and the MC curve represents the marginal cost which is the additional cost of adding one extra vehicle or trip to the traffic stream. At low volumes vehicles can travel at the free-flow speed, and the trip cost curve, AC (q), is constant at the free flow cost. At higher volumes congestion develops, speed falls, and AC (q) slopes upwards.

If flow is interpreted to be the quantity of trips “demanded” per unit of time, then a demand curve  $P(q)$  can be added to Figure 2-1 to form a supply-demand diagram. The demand curve is assumed to slope downwards to reflect the fact that, as for most commodities, the number of trips people want to make decreases with increasing price. Any individual user entering the road will consider only the costs to the society (AC) he or she personally bears. Most drivers will be either unaware of or unwilling to consider the external congestion costs that he or she imposes on the other road users. Therefore, the MC curve relates to the marginal social cost for the new trip-maker and the existing road users of an addition to the traffic flow, while AC curve is equivalent to the marginal private costs or the additional cost borne and perceived by the new trip-maker alone. The difference between the AC and MC curves at any level of travel demand reflects the economic costs of congestion at that demand.

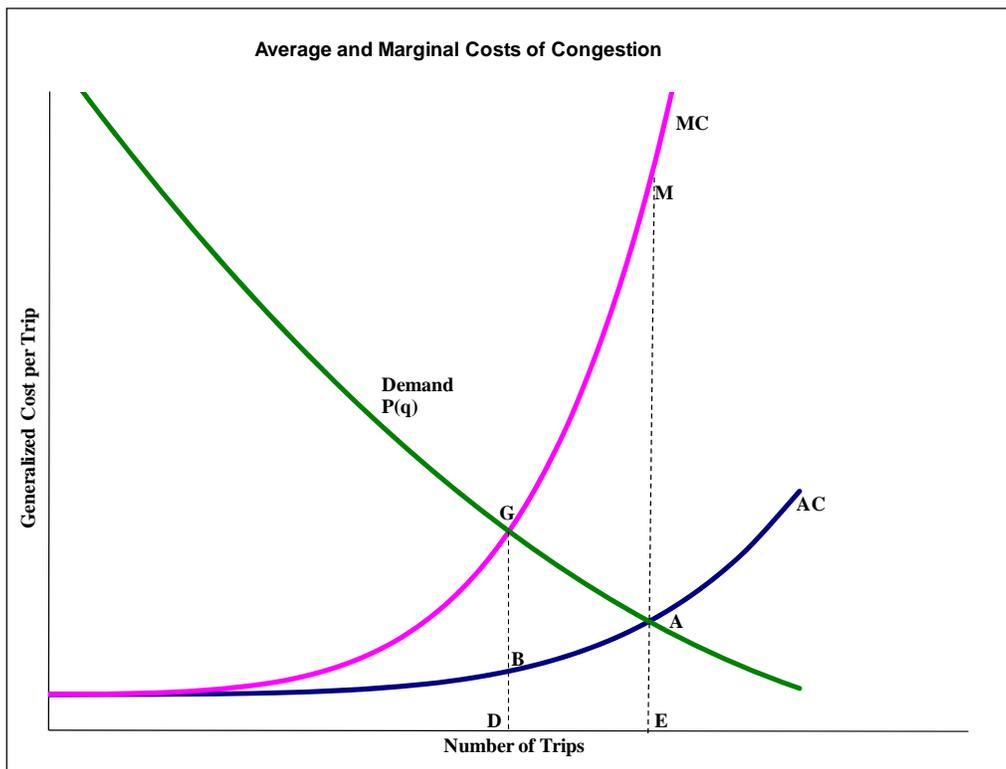
The unregulated 'no-toll' equilibrium occurs at the intersection of AC and demand curves, resulting in an equilibrium flow equal to E (see Figure 2-1), because road users ignore the congestion imposed on others. AC (q) measures the cost to the traveler of taking a trip. If external travel costs other than congestion, such as accidents and air pollution, are ignored, then the total social cost of q trips is:

$$TC(q) = AC(q) \times q$$

And the marginal social cost of an additional trip is:

$$MC(q) = \partial TC(q) / \partial q = AC(q) + q \times (\partial AC(q) / \partial q)$$

**Figure 2-1 A Supply-Demand Diagram for Congestion Pricing**



The social optimal is found in Figure 2-1 at the intersection of MC (q) and demand curves, where the marginal willingness to pay for trips is MC (q\*) for the optimal number of q\* trips at D is less than in the unregulated equilibrium. The optimum can be supported as equilibrium if travelers are forced to pay the price of their trips and the toll, the requisite toll is:

$$T^* = q^* \times (\partial AC(q^*) / \partial q^*)$$

Where  $T^*$  is the marginal congestion cost imposed by a traveler on others. This toll is known as a “Pigouvian” tax, after Pigou.<sup>1</sup>

From a social point of view, the actual demand,  $E$ , is excessive because the  $E$ th user is only enjoying a benefit of  $EA$ , but imposing costs of  $EM$ . The additional traffic beyond the optimal level  $D$  can be seen to be generating costs equal to the area  $EMGD$ , but enjoying a benefit equal to the area  $EAGD$ , a deadweight welfare loss of the area  $AMG$  is apparent and the optimal toll to be charged is equal to  $BG$ .

In most traffic assignment models, the effect of road capacity and travel times is specified by means of volume-delay functions  $T(V)$  which used to express the travel time (or cost) on a road link as a function of volume  $V$ , such as the BPR function. Following is the derivation of the estimate of marginal cost (MC) used in the model.

The total social cost of  $V$  trips is:

$$TC(V) = V \times AC(V)$$

Where  $AC(V)$  is the average cost. The marginal social cost of an additional trip is:

$$MC(V) = \partial TC(V) / \partial V = AC(V) \times \partial V / \partial V + V \times (\partial AC(V) / \partial V)$$

The BPR equation is:

$$AC(V) = T_0 [1 + \alpha (V/C)^\beta]$$

Therefore;

$$\partial AC(V) / \partial V = T_0 \alpha \beta (1/C) \times (V/C)^{\beta-1}$$

$$V \times (\partial AC(V) / \partial V) = T_0 \alpha \beta (V/C)^\beta$$

$$MC(V) = T_0 [1 + \alpha (V/C)^\beta] + T_0 \alpha \beta (V/C)^\beta$$

The optimal toll is:

$$T^* = T_0 \alpha \beta (V/C)^\beta$$

Using the BPR volume-delay function, Figure 2-2 shows the optimal toll values ( $T^*$ ) in minutes for different Volume/Capacity values. The curve in Figure 2-2 was derived from the following assumptions and table (Table 2-1):

$T_0 = 1$  minute (Free flow speed is assumed 60 mph)

$\alpha = 0.15$

$\beta = 6.5$

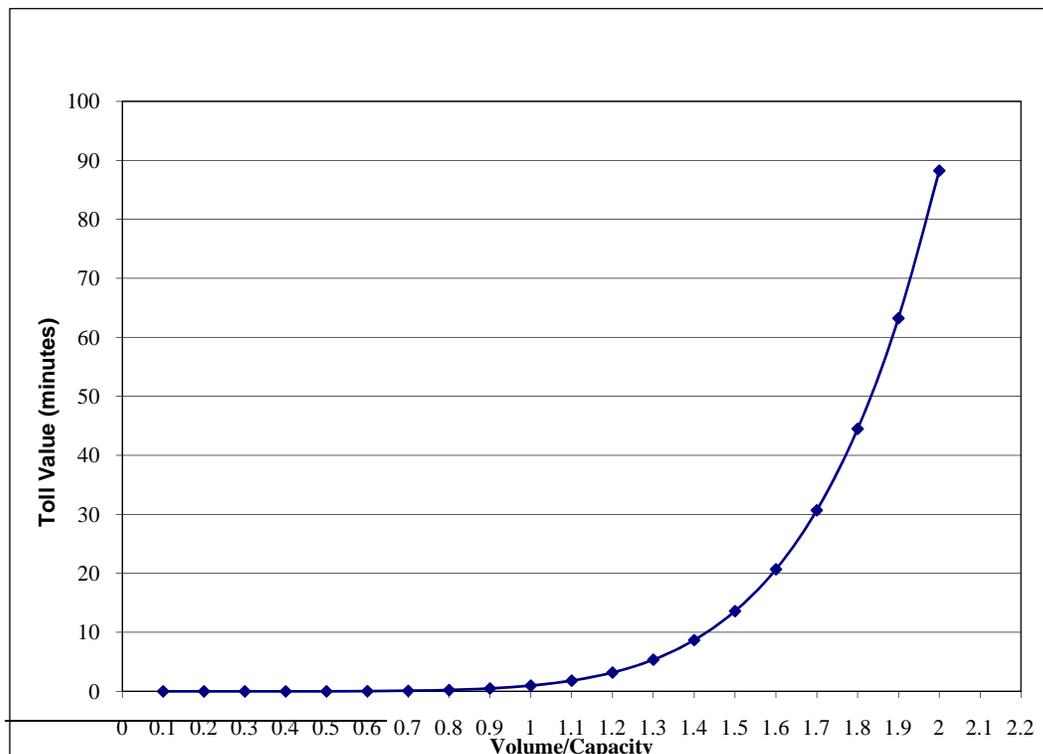
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<sup>1</sup> Pigou, A.C. (1920) *Wealth and Welfare*, Macmillan.

As shown in Figure 2-2, the optimal toll is almost zero when Volume/Capacity is about 0.85. According to HCM 2000,<sup>2</sup> Exhibit 23-2, page 23-4, for a basic freeway segment with free-flow speed of 60 mph, speeds begin to decline with increasing volumes at level of service D and maximum V/C value of 0.88. This property is consistent with the positive and vertical difference between marginal and average costs in Figure 2-1 which is introduced as the congestion toll. Prior to this level of service and speeds, neither the curve in Figure 2-1 and nor the curve in Figure 2-2 justify applying any tolls. As the freeway segment become more congested or even hyper congested, the toll value increases sharply to make the toll road much more expensive to use.

Finally, the toll value calculated in this way, does not depend on the length of the freeway, and in fact depends on congestion and the operation conditions on freeway segments. The flow on a freeway may be interrupted by vehicles entering from an on-ramp facility or exiting the freeway using an off-ramp. From a practical point of view, these locations may be used for resetting toll charges and in fact, as indicated, volumes and operation conditions may also change before or after these ramp-freeway junctions. If a toll value were depended on the length of road, then it would not be impacted by the congestion and traffic volumes and as a Transportation Demand Management strategy would not probably achieve the true goal of relieving road congestion.

**Figure 2-2 Toll and V/C Relationship for a BPR Function**



<sup>2</sup> Highway Capacity Manual (HCM 2000), Transportation Research Board, National Research Council, Washington, D.C., 2000

**Table 2-1 Toll Values for a Basic Freeway Segment**

To (free-flow time in minutes)	ALPHA	BETA	V/C	TOLL VALUE (minutes)
1	0.15	6.5	0.1	3.08E-07
1	0.15	6.5	0.2	2.79E-05
1	0.15	6.5	0.3	0.000389
1	0.15	6.5	0.4	0.002526
1	0.15	6.5	0.5	0.010772
1	0.15	6.5	0.6	0.035236
1	0.15	6.5	0.7	0.095971
1	0.15	6.5	0.8	0.228607
1	0.15	6.5	0.9	0.491565
1	0.15	6.5	1	0.975
1	0.15	6.5	1.1	1.811578
1	0.15	6.5	1.2	3.189207
1	0.15	6.5	1.3	5.365824
1	0.15	6.5	1.4	8.68634
1	0.15	6.5	1.5	13.60184
1	0.15	6.5	1.6	20.69114
1	0.15	6.5	1.7	30.68475
1	0.15	6.5	1.8	44.49138
1	0.15	6.5	1.9	63.22706
1	0.15	6.5	2	88.24693

### 2.2.6 High Occupancy Requirements

High Occupancy Vehicles (HOV) should be grouped into 2-Person vehicles and 3+Person vehicles. This grouping is due to fact that the HOT lane facilities often provide free or reduced cost access to qualifying 3+Person vehicles, and also provide access to other paying lower occupancy vehicles not meeting passenger occupancy requirements. The test case used the operating plan for the 95 Express project now operating in Miami-Dade County, which allows 3+ carpools to use the lanes without a toll, but assess a toll for drive-alone and 2-person carpools. In this regard, the assignment procedure makes the following assumptions:

- Vehicles with three or more occupants can use any HOT or other lanes without paying a toll.
- Vehicles with two or fewer occupants must pay a toll to use HOT lanes. Each occupant of a 2-Person carpool shares the toll equally.
- Tolls are collected electronically using transponders - there are no toll booths or plazas, so there are no time delays associated with toll collection.

- Drivers who perceive a higher value of travel time values are willing to pay more than drivers who perceive a lower value of travel time for the same amount of travel time saved. In this model, the trip purpose is the main factor for determining the value of travel time in relation to willingness to pay on the basis of toll/time saved.

The above last assumption is the diversion curve between the toll value and saved travel time. While information on HOT lanes is plentiful, there is not much information on toll diversion curves. In order to establish this type of diversion curve, travel time values should be developed for trip purposes based on localized wage and salary data, paired with information derived from national sources on the percentage of annual wages that can be applied to a particular trip purpose. These values should be validated and extended to other trip purposes through a traffic counts and household survey.

A stated-preference survey of 200 households was conducted in January 2005 for the Southeast Florida region.<sup>3</sup> The following tables (Tables 2-2 through 2-4) present various travel time values stratified by various trip purposes.

**Table 2-2 Travel Time Values for Person Trips**  
**Southeast Florida Travel Time Values for Core Markets**

Market	Value (2004 Dollars)
Commuter	\$12.69 per hour
Personal (Local)	\$10.58 per hour
Personal (Visitor)	\$10.83 per hour
On-the-Clock	\$25.80 per hour
<b>All</b>	<b>\$12.70 per hour</b>

<sup>3</sup> *Assessment of Southeast Florida Road User Costs, Final Report*, Florida Department of Transportation District 4, February 2006.

**Table 2-3: Travel Time Values for Person Trips  
Southeast Florida Travel Time Values by Travel Demand  
Model Trip Purpose**

<b>Market</b>	<b>Value (2004 Dollars)</b>
Home-Based Work	\$12.69 per hour
Home-Based Shopping	\$10.59 per hour
Home-Based School	\$10.58 per hour
Home-Based Social/Recreational	\$10.59 per hour
Home-Based Other	\$12.10 per hour
Home-Based Unknown	\$11.34 per hour
Non-Home-Based	\$12.10 per hour

**Note: Does not include on-the-clock trips.**

**Table 2-4 Travel Time Values for Person Trips  
Southeast Florida Travel Time Values by Time of Day**

<b>Market</b>	<b>Value (2004 Dollars)</b>
6:30 a.m.-9:00 a.m.	\$11.76 per hour
9:00 a.m.-11:30 a.m.	\$11.79 per hour
11:30 a.m.-1:30 p.m.	\$11.82 per hour
1:30 a.m.-4:30 p.m.	\$11.92 per hour
4:30 p.m.-6:30 p.m.	\$11.92 per hour
Other	\$11.64 per hour

**Note: Does not include on-the-clock trips.**

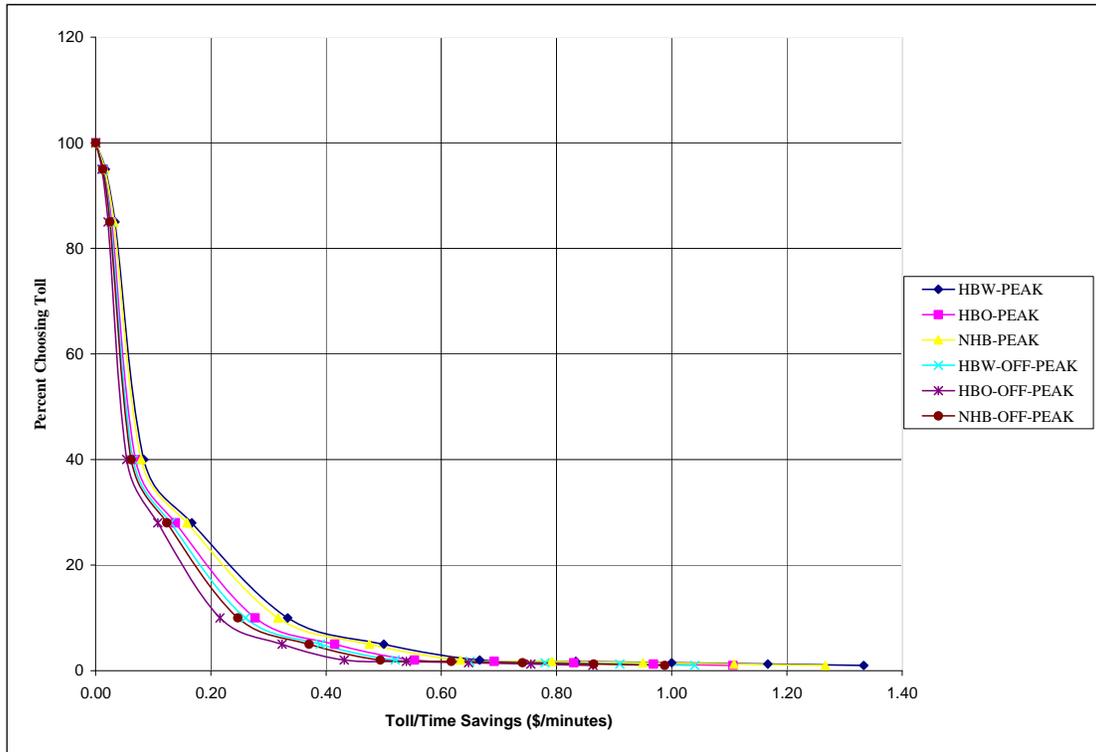
Also, a diversion curve was adapted from the results of a stated preference survey conducted in 2004-2005 for the I-394 MnPASS Express Lane project in Minneapolis, Minnesota. A 2005 publication on the Atlanta HOT lanes stated preference survey<sup>4</sup> shows that the results from Atlanta and Minnesota are very similar. This suggests that the I-394 curve is transferable and suitable for the prototype model. The following table (Table 2-5) and curves (Figure 2-3) display the diversions between the toll/time saved used in this study. Based on Tables 2-2 and 2-3, travel time values for HBO and NHB trips are 83 percent and 95 percent of travel time values for HBW trips respectively.

<sup>4</sup> Interstate 75 Stated Preference Survey, Final Report, NuStats, November 2005.

**Table 2-5 Toll Value for Saved Time**

PEAK PERIODS						
TRIP PURPOSE						
Percent Choosing Toll	HBW		HBO		NHB	
	Toll in Dollars/Hour Saved	Toll in Dollars/Minute Saved	Toll in Dollars/Hour Saved	Toll in Dollars/Minute Saved	Toll in Dollars/Hour Saved	Toll in Dollars/Minute Saved
100	0	0.00	0.00	0.00	0.00	0.00
95	1	0.02	0.83	0.01	0.95	0.02
85	2	0.03	1.66	0.03	1.90	0.03
40	5	0.08	4.15	0.07	4.75	0.08
28	10	0.17	8.30	0.14	9.50	0.16
10	20	0.33	16.60	0.28	19.00	0.32
5	30	0.50	24.90	0.42	28.50	0.48
2	40	0.67	33.20	0.55	38.00	0.63
1.75	50	0.83	41.50	0.69	47.50	0.79
1.5	60	1.00	49.80	0.83	57.00	0.95
1.25	70	1.17	58.10	0.97	66.50	1.11
1	80	1.33	66.40	1.11	76.00	1.27

Figure 2-3 MnPass Diversion Curve



### 2.2.7 General Software Approach

The Florida Model Task Force has adopted Cube Voyager as the main modeling engine for FSUTMS. The prototype model requires Cube Voyager software and is contained in a CUBE/Voyager catalog file that includes a series of applications.

#### *Initial Approach*

The consultant developed an initial approach to implementing the managed lane model that simultaneously estimated the toll value and the allocation between general purpose and managed lanes. The problem with this approach is described below, and a revised approach is described in the next section of this report.

In the assignment sub-model, there is an issue with the Cube HIGHWAY user equilibrium keyword:

“PARAMETERS COMBINE = EQUI.”

The issue with “EQUI” is related to the “LAMBDA” estimation process and volume-weighted average costs in the “COST” function at present. Specifically, the current version of the Voyager code is written such that during the “LAMBDA” estimation process, only total volume is updated with each revision of “LAMBDA”, but not the individual volume

sets. The individual volumes of V1, V2, V3, etc. are not available in “TC” or “COST” functions and therefore the “LAMBDA” estimation is not based upon volume-weighted average cost. According to Citilabs supporting staff, this capability will probably be added in a future release of Cube Voyager.

In the meantime a practical alternative is to use “COMBINE=AVE”, which, behaves correctly because “LAMBDA” is fixed at “1/ITERATION” and no “LAMBDA” estimation process is invoked. Using the “AVE” process may require a high number of iterations for occurrence of convergence. Tests that used “COMBINE=WTD” instead did not speed up the convergence process.

The Figure 2-4 shows the relationship between convergence values and number of required iterations.

**Table 2-6 Iterations Required for Convergence**

Relative Gap	Number of Iteration
0.1	15
0.01	35
0.001	55
0.0001	69
0.00001	75

**Figure 2-4: Relation between Relative Gap and Number of Iterations**

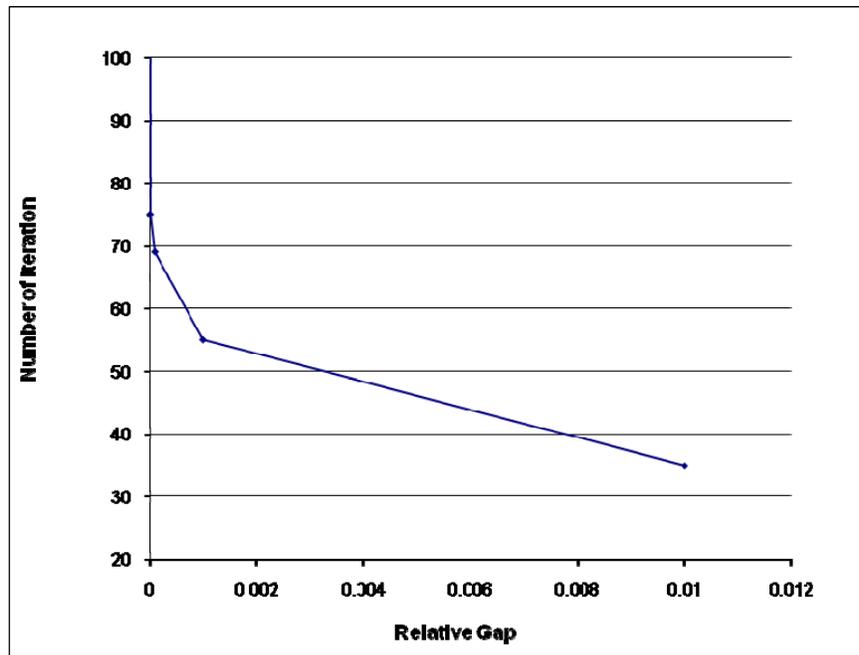
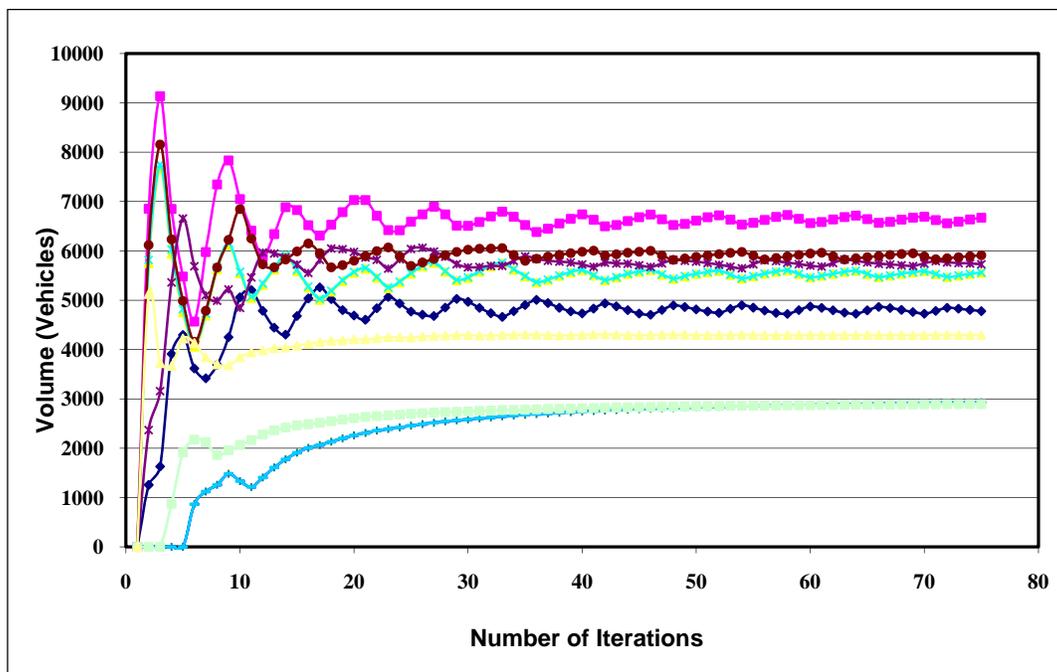


Figure 2-5 displays volumes on selected links using “AVE” process. The volumes on links are stabilized after initial fluctuations when the number of iterations is high enough. This leads to the conclusion that the equilibrium volumes are achieved.

Even though this process apparently leads to a stable solution, the consultant believed that additional investigation should be conducted to find a true user equilibrium solution. The averaging process was not very satisfying from the standpoint of developing an assignment that conformed to the equilibrium process used throughout Florida. Thus, additional research was conducted, and a method that finds an optimal toll and also results in convergence under user equilibrium was found. This method is described in the next section.

**Figure 2-5: Volume Changes vs. Toll Iteration**



**Revised Approach**

The initial approach similar to other assignment techniques follows an iterative pattern and the link toll values depend on the traffic volumes for each iteration. The toll values were changed after each assignment iteration, and consequently the link cost functions, i.e. the rule of assignment. Those rules were changed for the subsequent iteration and in fact, for a set of cost function values, traffic loading occurs only once and the assignment never had a chance to change the flow for a better route and the toll value was not actually established.

In the revised approach the toll value calculation process is separate from the assignment process. For a set of toll values, the assignment process is implemented until the convergence. Then the resultant link volume and capacity ratios are input to a subsequent

toll value calculation. This iterative pattern is applied until the changes in subsequent toll values are no longer significant, that is, the toll calculation and assignment model both independently converge. In other words, for each set of toll values, the link traffic volumes are results of a convergence assignment (Figures 2-4 and 2-5).

## 3.0 Sub-Task 3: Sensitivity Analysis

This memorandum describes alternatives for sensitivity analyses and results of the test runs. Since HOT and General Purpose (GP) lanes are almost always implemented as part of a freeway with a limited right-of-way, alternatives were defined in terms of the number of HOT and GP lanes, noting that HOT and GP lanes are competitive lanes in terms of attracting freeway traffic on a freeway. Congestion on one type will make the other more attractive.

### ■ 3.1 Lane Configuration Alternatives

A simple alternative is to provide two lanes of each type, HOT and GP, in each direction. This design provides passing lanes for faster traffic and requires four total lanes in each direction. Many freeways have three lanes in each direction and may not have enough right-of-way for the fourth lane. Therefore, in order to test the impact of implementing a HOT lane facility with minimum resources, two other less costly alternatives were considered. The suggested alternatives would have three lanes in each direction, combining one HOT lane and two GP lanes or vice versa. These alternatives would be interesting in terms of congestion, achieving the target speeds, toll revenue and road length for HOT and GP lanes.

In response to the growth of traffic demand, additional lanes will be needed. Thus, another alternative is to analyze first the future traffic demand with two HOT lanes and two GP lanes in each direction and then add another HOT lane in each direction. Clearly, the last alternative will analyze the upper bound of the demand for the HOT lanes.

The following table (Table 3-1) summarizes the aforementioned alternative configurations. It should be mentioned that the configuration of access ramps to and from HOT and GP lanes may have several different geometric designs within each alternative, but these geometric details are not modeled and thus are not discussed here.

### ■ 3.2 Demand Alternatives

Impacts of the HOT lane tolls would clearly be plausible in a congested network. Two trip table levels are assumed to apply to the above alternative networks for the sensitivity analysis. The current Olympus trip table is multiplied by two and three for creating medium and highly congested networks. The medium trip table was applied to the alternatives 1-2, 2-1, and 2-2 and the high trip table was applied to alternatives 2-2 and 3-2.

**Table 3-1: Lane Configuration Alternatives for the Olympus Model**

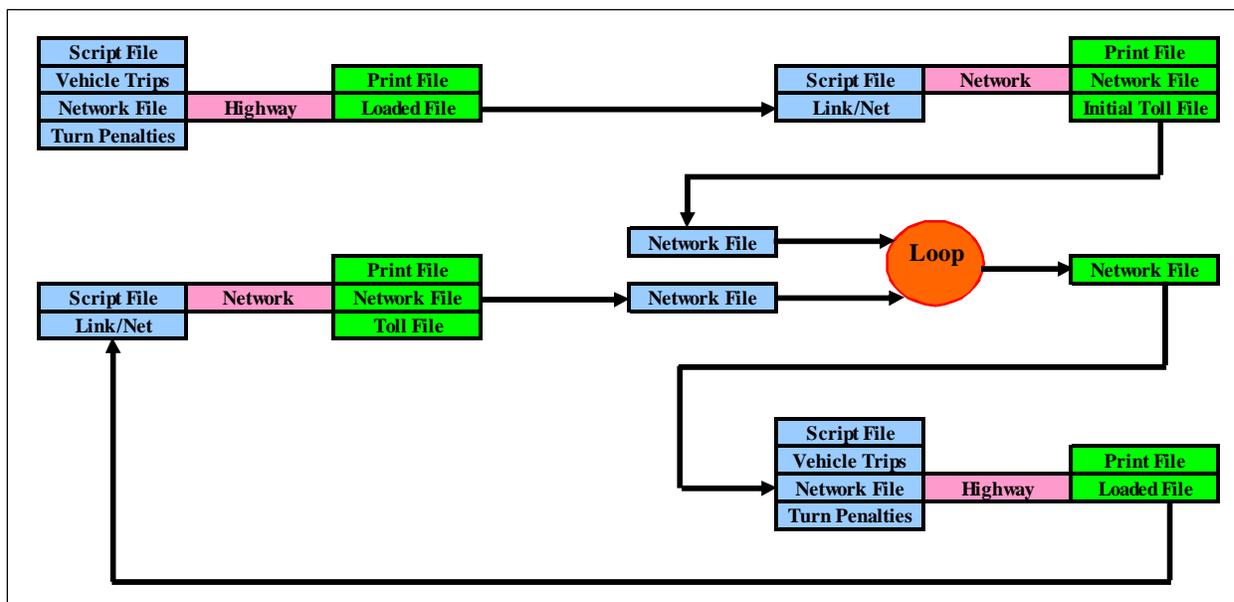
Alternative Name	Year	Lane Type	
		HOT	General Purpose
		Number of Lanes	Number of Lanes
Alternative 1-2	Base	1	2
Alternative 2-1	Base	2	1
Alternative 2-2	Base/Future	2	2
Alternative 3-2	Future	3	2

### ■ 3.3 Model Structure

There are two main factors in modeling the HOT lane tolls. First is the toll value and second is the diversion curve between the toll/time saved used in this study. Route selection in terms of the travel cost is explained by the user-equilibrium model. But when the HOT lane toll is introduced as an external factor, then the diversion curve may be defined as a behavioral factor in route selection which is not explicitly explained by the equilibrium assignment procedure. Thus, the determination of the optimum toll should be done outside the equilibrium assignment. The proposed model structure suggests calculating a HOT lane toll after each complete equilibrium assignment procedure. This toll value would be fixed for all the assignment iterations. However, since travel times in each type of lane will depend on the traffic volumes in the capacity constrained assignment, traffic volumes would change after each iteration. Therefore the changing travel times would affect the total cost and the drivers may change their routes. The diversion curve of the toll/time saved procedure is applied prior to each assignment iteration, attempting to explain driver route selection behavior in terms of time and cost.

The assignment process begins with a warm-up UE assignment step where there is no toll on the HOT lanes. Then a toll value is computed for the initial condition and the calculated toll will be an input for a subsequent assignment. A loop was designed comprised of toll calculation and UE assignment. In this loop, tolls are calculated and trips are assigned until the changes in subsequent toll values are no longer significant, that is, the toll model converges.

Figure 3-1 General Model Structure for All Periods



### ■ 3.4 Results of Model Runs

A series of figures is presented in Appendix B. Each figure shows the time value of the toll calculated at each iteration of the model. Each curve in the figures represents a toll link in the test network.

The figures in Appendix B show the toll values for HOT links in loop iterations for all the alternatives. As shown in all figures, after about four loop iterations all the link toll values do not change and that indicates the toll model convergences. Also, when the network is more congested the toll values increase sharply (Table 2-1). The number of total HOT and GP lanes in a direction is a major factor for determining the toll values. The other factor is existence of passing lane for GP and HOT lane types.

The following table (3-2) summarizes the subsequent figures. This table shows the total link toll values for all the alternatives. The table rows highlighted in blue are those most likely to be encountered in actual operation. Since the highway network topology is the same in all the alternatives, and only the number of freeway lanes (i.e. capacity) and demand (i.e. Traffic volume) are variables, therefore all the link toll values follow similar trends in all the figures in Appendix B. Please note that in the Olympus model, the flow on the freeway is not very directional. However, the time-of-day factors are set so that the PM Peak is more congested than the AM Peak - not an unusual situation. Thus, the PM toll values are higher than the AM in both directions.

The table displays the fact that as the demand grows the toll value increases, and as the number of freeway lanes increases the toll value decreases. Therefore, the toll value

depends on the number of lanes and traffic volumes. In fact, for a certain toll value it is possible to estimate the number of required HOT and GP freeway lanes in a highway network setting. As the table indicates the reasonable toll values belong to the alternative with two HOT and GP lanes.

As with the aforementioned alternatives, this study suggests that the HOT and GP lanes should have similar attributes as much as possible and the HOT lanes should have similar entry and exit ramps as the GP lanes. Similar conditions are efforts to level the playing field and achieve greater equality between the HOT and GP lanes.

**Table 3-2 Alternatives, Demand Levels and Toll Values**

Number of HOT Lanes	Number of GP Lanes	Period	Demand Level	Toll Value for the Entire of Southbound		Toll Value for the Entire of Northbound	
				(Minutes)	(\$)	(Minutes)	(\$)
3	2	AM	High	47.45	13.48	13.74	3.90
2	2	AM	High	148.76	42.26	44.49	12.64
2	2	AM	Medium	11.18	3.18	4.17	1.18
2	1	AM	Medium	57.25	16.26	18.22	5.18
1	2	AM	Medium	47.28	13.43	18.93	5.38
3	2	PM	High	63.44	18.02	134.56	38.23
2	2	PM	High	196.65	55.87	377.90	107.36
2	2	PM	Medium	17.6	5.00	33.63	9.55
2	1	PM	Medium	87.32	24.81	139.20	39.55
1	2	PM	Medium	72.46	20.59	114.82	32.62
3	2	MD	High	6.69	1.90	7.17	2.04
2	2	MD	High	22.91	6.51	24.04	6.83
2	2	MD	Medium	1.78	0.51	1.82	0.52
2	1	MD	Medium	13.67	3.88	12.1	3.44
1	2	MD	Medium	9.21	2.62	9.43	2.68

### ■ 3.5 Conclusion

The tests show that the HOT lanes model, implemented as a loop encompassing toll estimation and equilibrium assignment produces reasonable assignments for HOT and GP lanes. The assignments show proper sensitivity to supply and demand, determine HOT lane tolls in a reasonable manner, and achieve user equilibrium in a reasonable number of iterations. This method, however, requires the model to be repeated several times to determine a stable toll value. Thus, the consultant recommends that in practice the new Cube Voyager “path-based,” bi-conjugate FW, and warm start assignment options be

investigated and used in the model to reduce computer running time. These routines, as explained by Citilabs staff, hold great promise. But at the time of writing this paper, they were not available for testing other than in an “alpha” release that was suitable for inclusion in the prototype model delivered to FDOT with this paper. Note that the computer running time for the HOT lanes assignment step, which includes four time periods and the estimate of the HOT lanes toll for each period, was 1:19 hours on a Core2 Duo quad-core computer running Windows XP at 2.4 GHZ.

# **Appendix A**

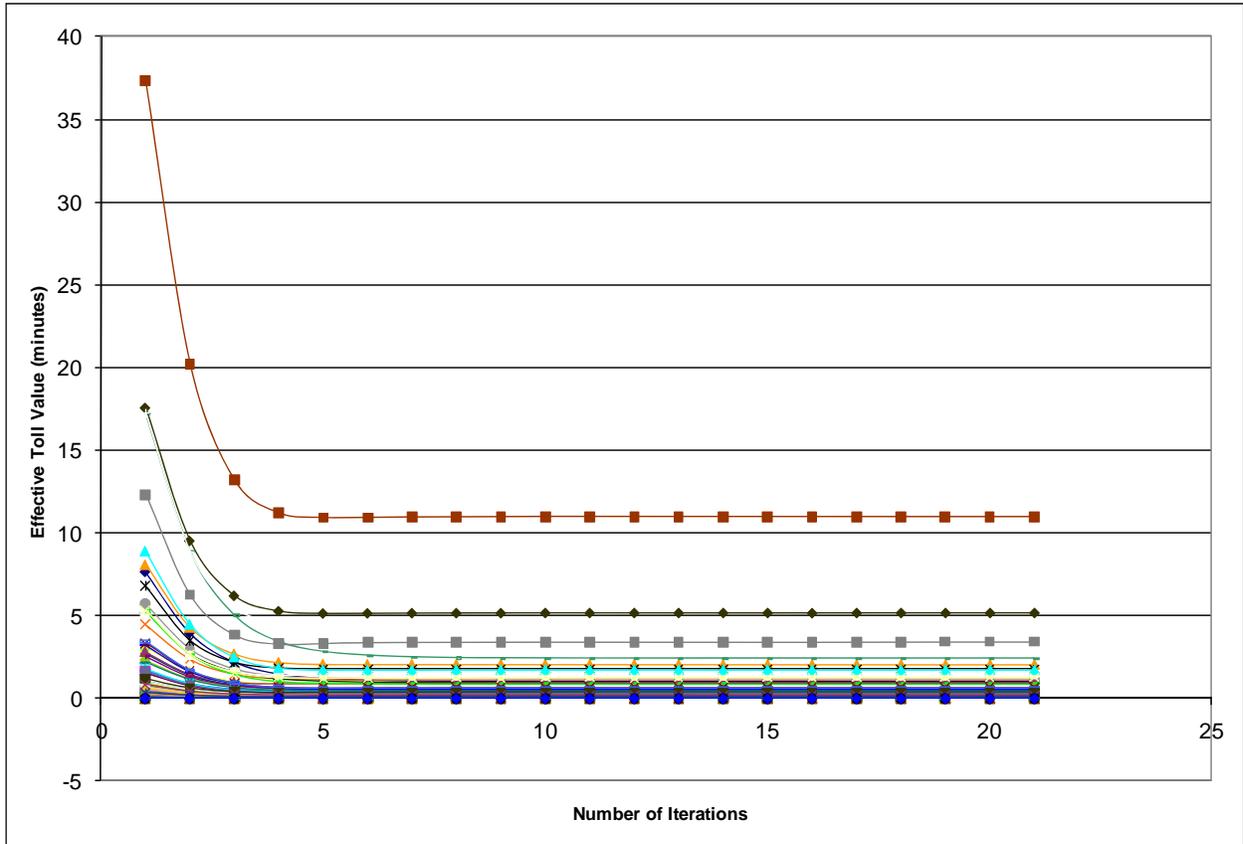
# List of HOT Lanes Projects

Location	Name	Status
CA	I-15 FasTrak	Operating
CA	SR-91 Express Lanes	Operating
CA	I-15 FasTrak Expansion	Planning & Developing
CA	I-5 HOT Lanes	Planning & Developing
CA	I-805 Managed Lanes	Planning & Developing
CA	I-680 HOT Lane	Planning & Developing
CO	I-25 HOT Lanes	Operating
CO	US 36 Express Toll Lanes	Planning & Developing
CO	I-70 Express Toll Lanes	Planning & Developing
CO	C-470 Express Toll Lanes	Planning & Developing
CO	I-25 North Express Toll Lanes	Planning & Developing
CO	I-70 Mountain Corridor	Planning & Developing
FL	I-95 HOT to HOT Express Toll Lanes	Under Construction
FL	I-595 Express Lane	Planning & Developing
GA	I-285 HOT Lanes	Planning & Developing
GA	I-75/I-575 HOT Lanes	Planning & Developing
GA	GA 400 HOT Lanes	Planning & Developing
MD	I-95 Kennedy Expressway Express Lanes	Under Construction
MD	Intercounty Connector (ICC)	Planning & Developing
MD	I-270 Express Toll Lanes	Planning & Developing
MD	I-495 Capital Beltway Express Toll	Planning & Developing
MN	I-394 MnPASS	Operating
NC	I-40 HOT Lanes	Planning & Developing
OR	Highway 217 Express Toll Lanes	Planning & Developing
TX	Katy I-10 QuickRide	Operating
TX	US-290 QuickRide	Operating
TX	Katy Freeway I-10	Under Construction
TX	Loop 1 (MoPac)	Planning & Developing
TX	I-635 LBJ Managed Lanes	Planning & Developing
TX	I-30 Managed Lanes	Planning & Developing
TX	I-820/SH183 Managed Lanes	Planning & Developing
TX	I-35W Managed Lanes	Planning & Developing
TX	SH 288 Managed Lanes	Planning & Developing
UT	I-15 Express Lanes	Operating
UT	I-15 Express Lane Extension	Planning & Developing
VA	I-495 Capital Beltway HOT Lanes	Under Construction
VA	I-95/I-395 HOT Lanes	Planning & Developing
WA	I-405 Managed Lanes	Planning & Developing
WA	SR 167 HOT Lanes	Operating

Source: The Corradino Group, Inc.

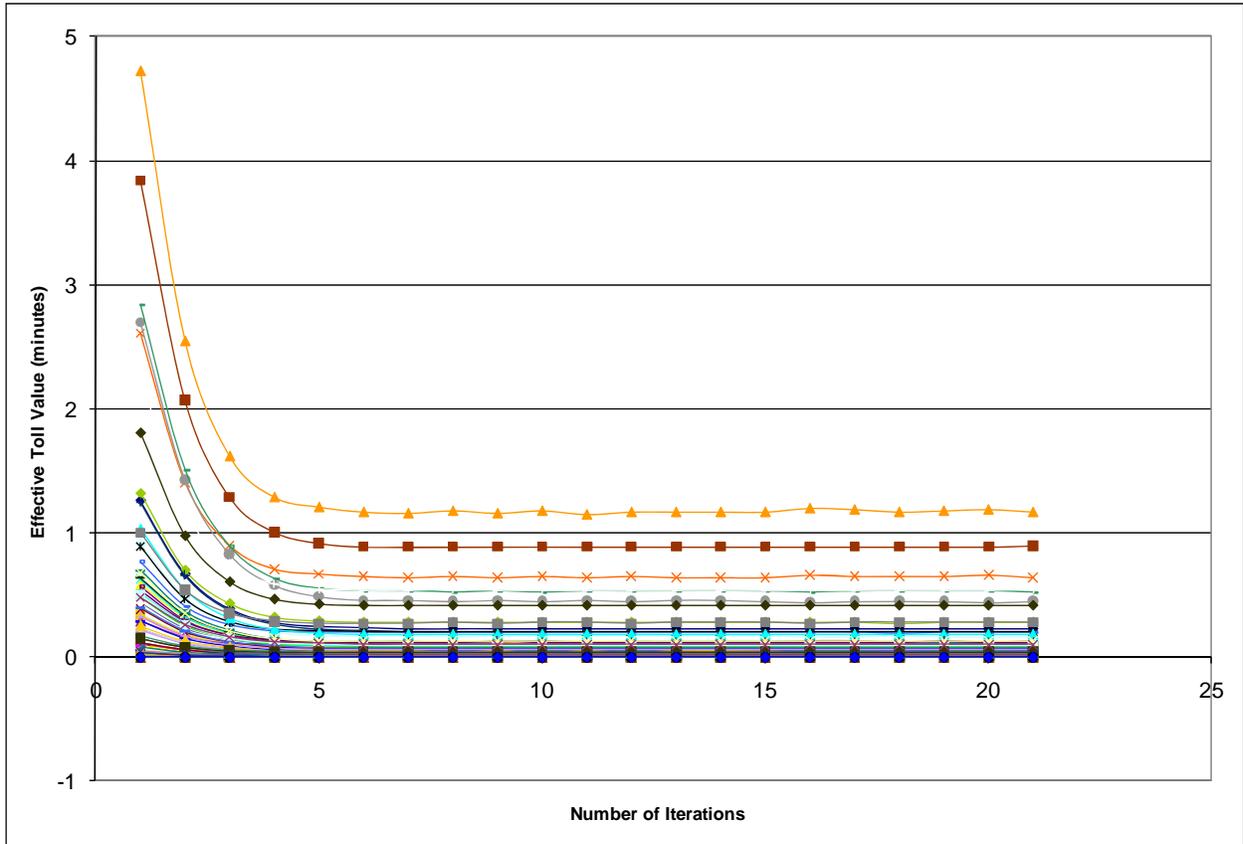
# **Appendix B**

Number of HOT Lanes: 3  
Number of GP Lanes: 2  
Period: AM  
Demand: High



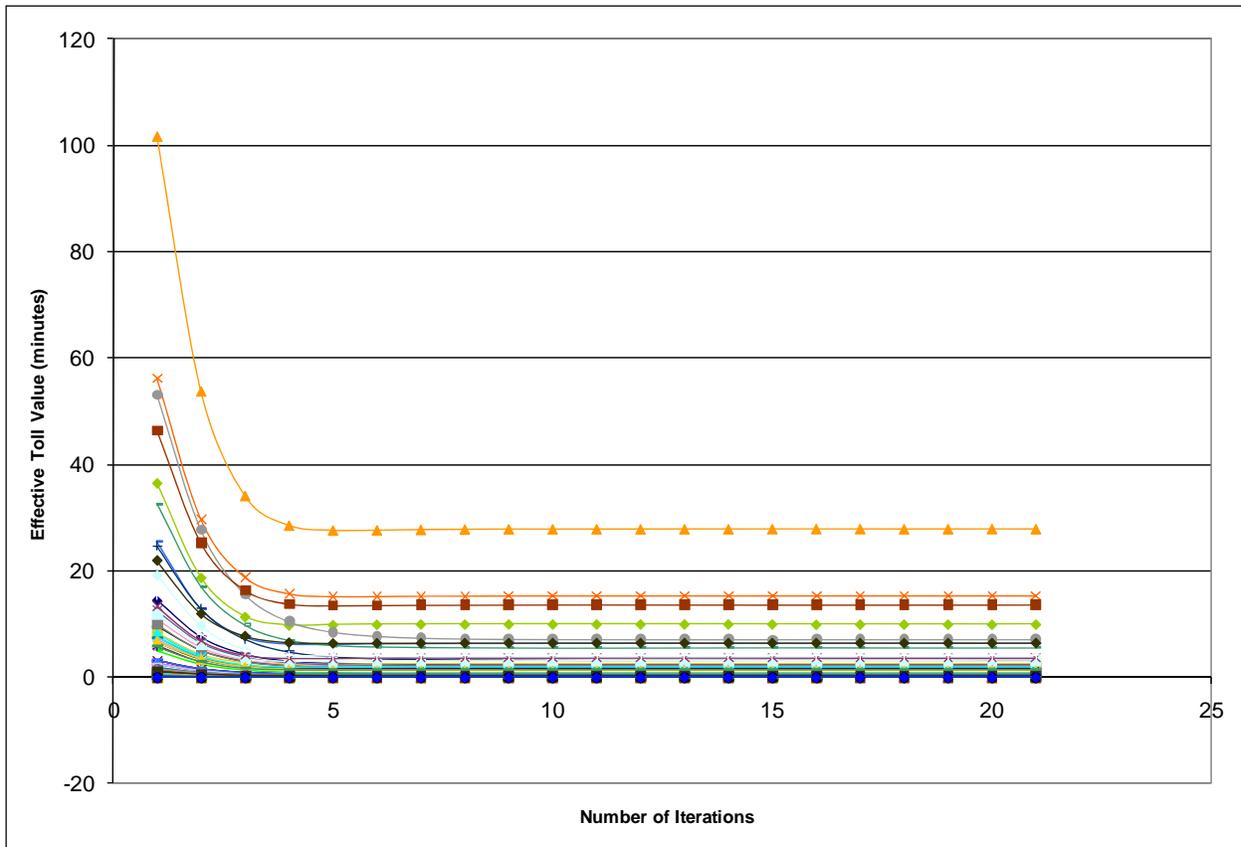
Note: Each curve represents one toll link.

Number of HOT Lanes: 3  
Number of GP Lanes: 2  
Period: MD  
Demand: High



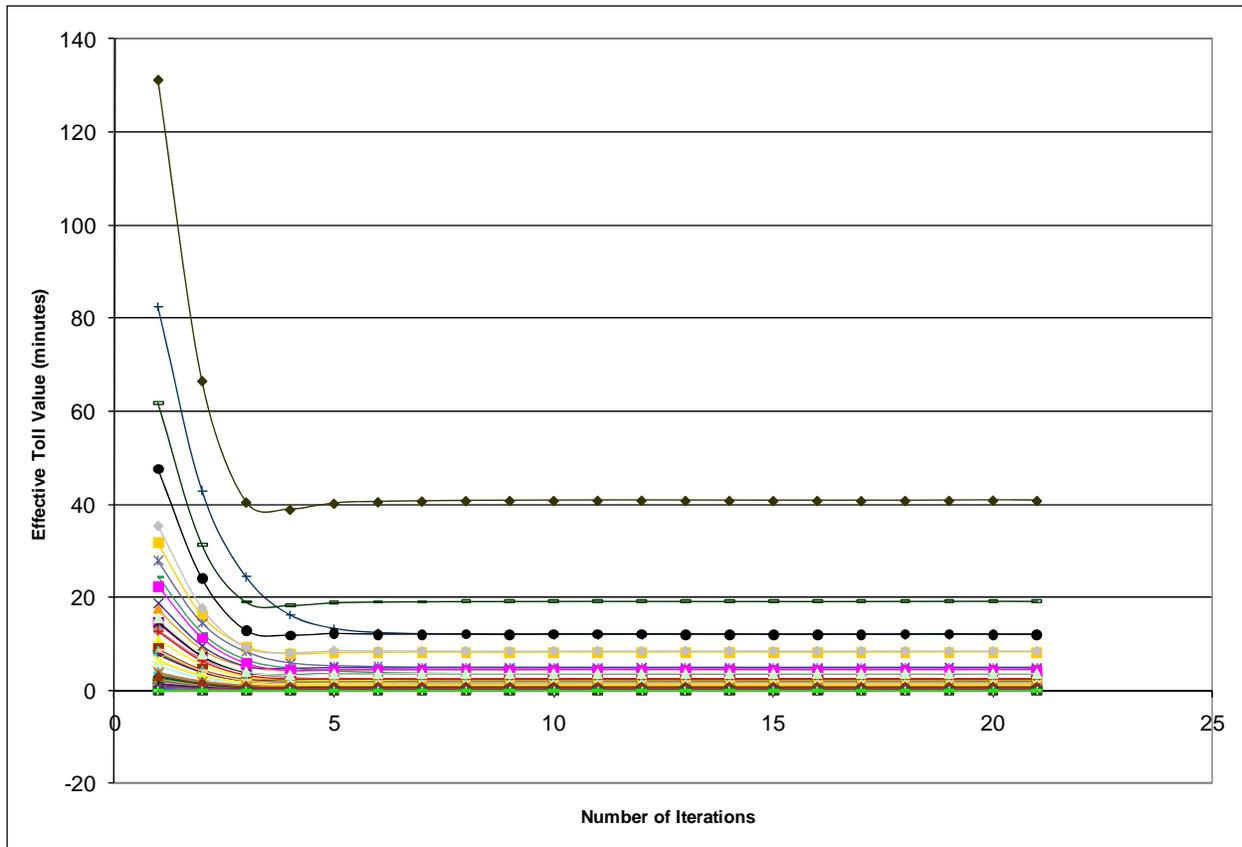
Note: Each curve represents one toll link.

Number of HOT Lanes: 3  
Number of GP Lanes: 2  
Period: PM  
Demand: High



Note: Each curve represents one toll link.

Number of HOT Lanes: 2  
Number of GP Lanes: 2  
Period: AM  
Demand: High



Note: Each curve represents one toll link.

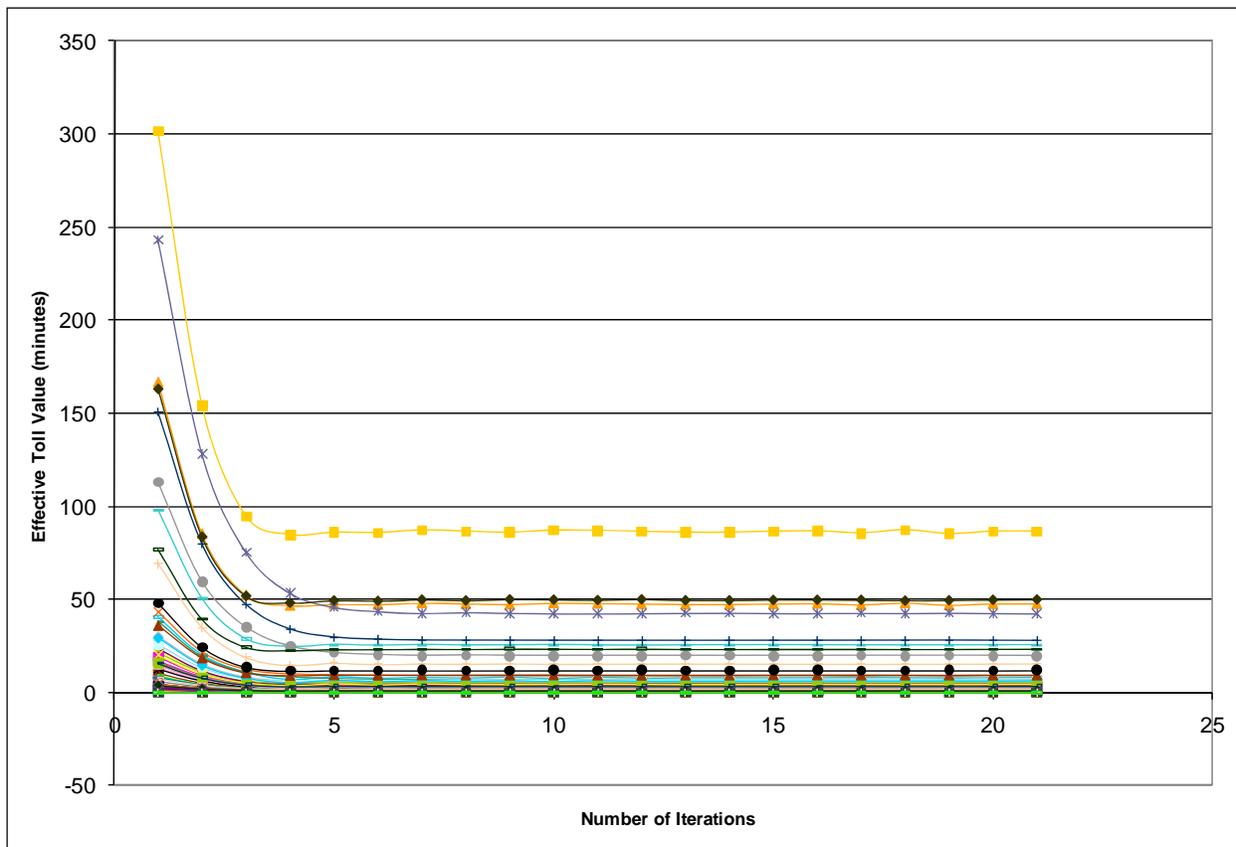


Number of HOT Lanes: 2

Number of GP Lanes: 2

Period: PM

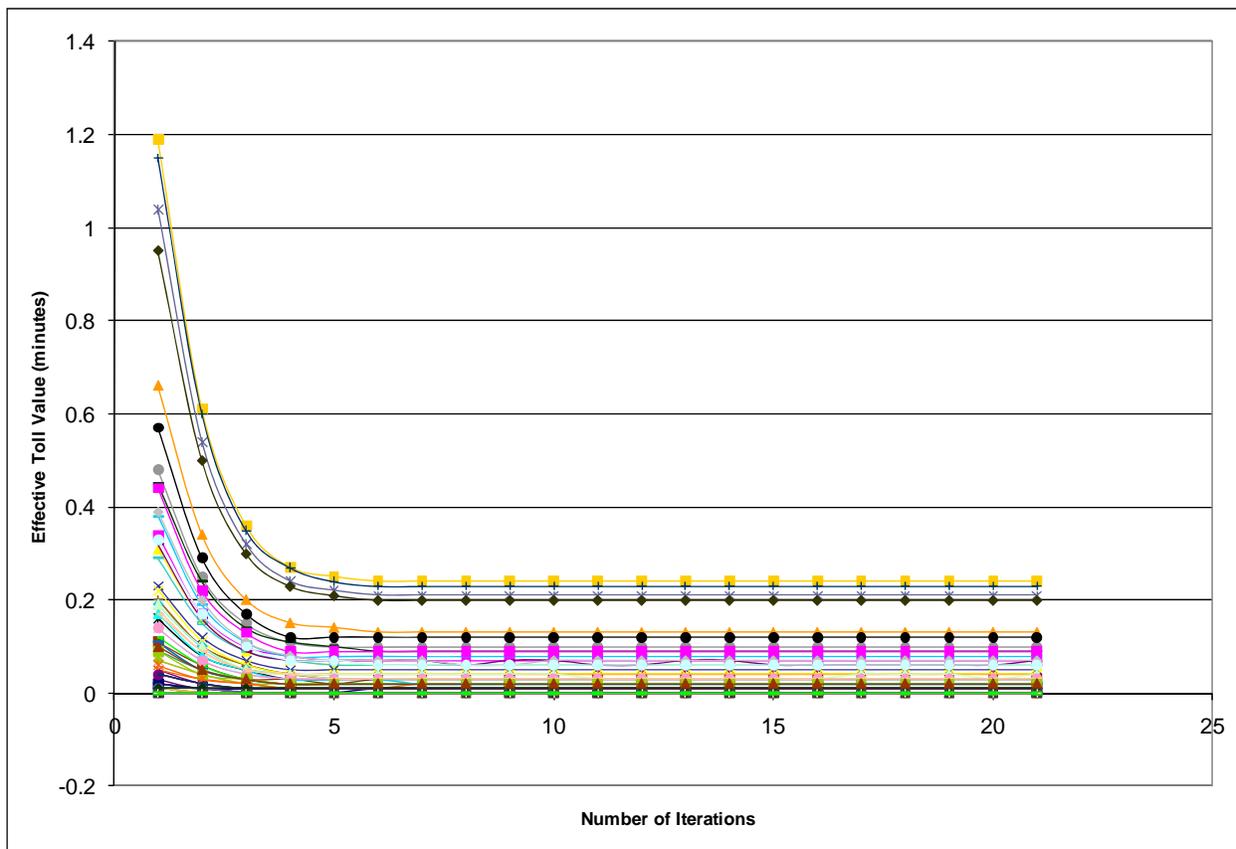
Demand: High



Note: Each curve represents one toll link.

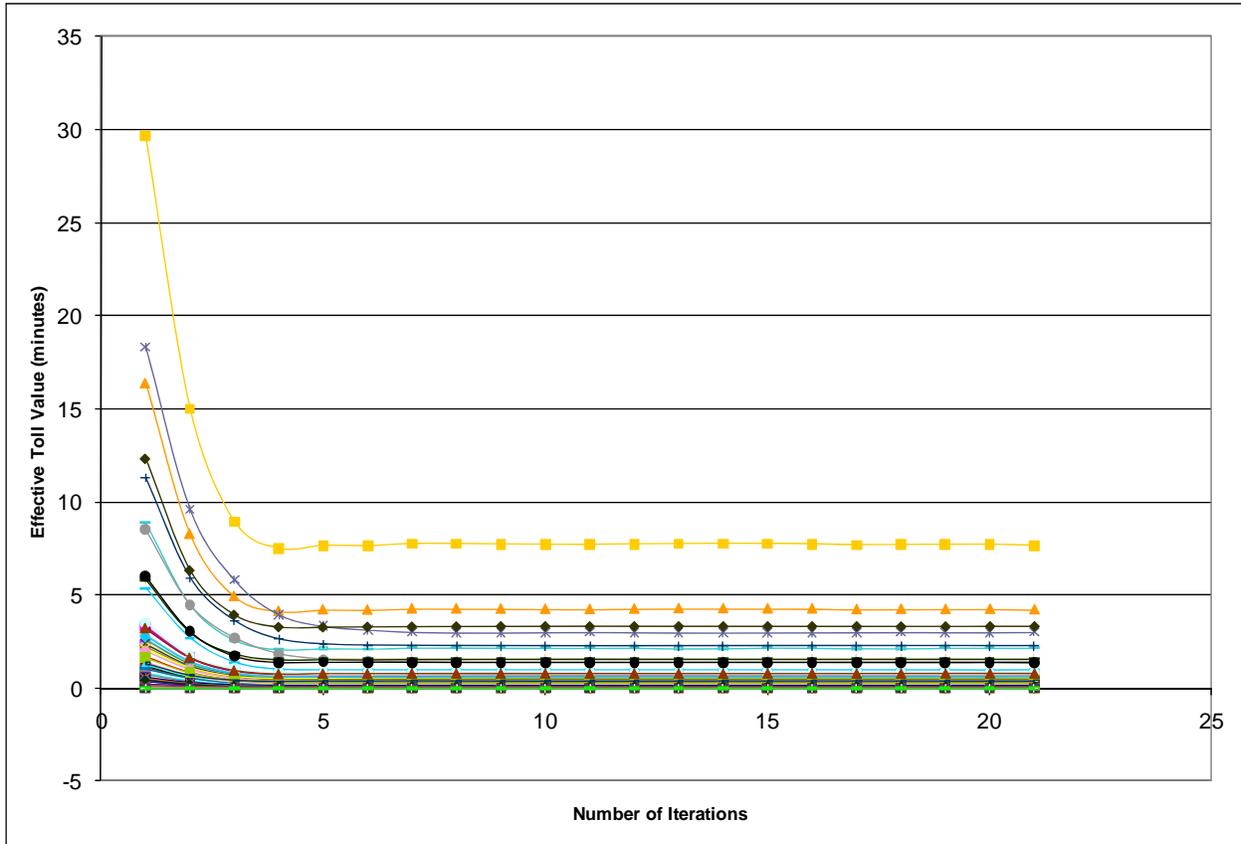


Number of HOT Lanes: 2  
Number of GP Lanes: 2  
Period: MD  
Demand: Medium



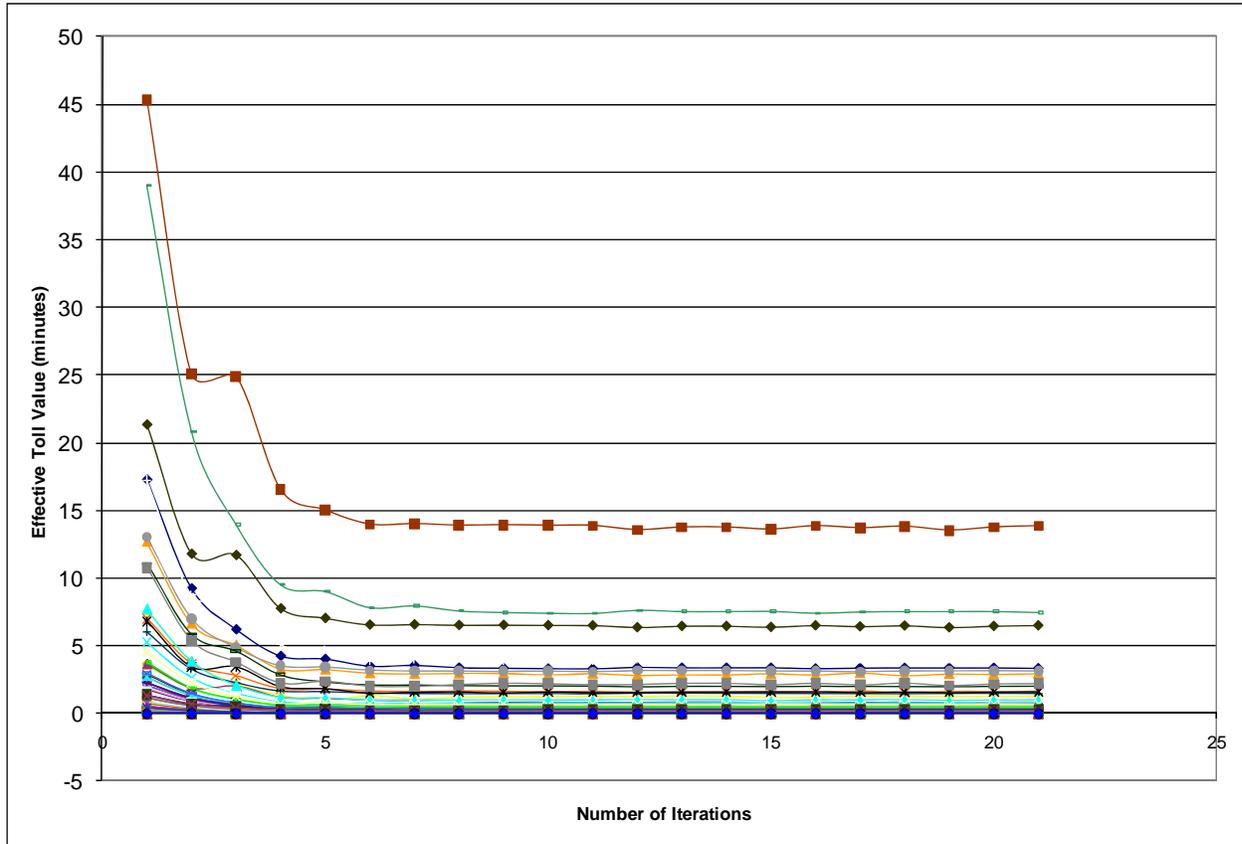
Note: Each curve represents one toll link.

Number of HOT Lanes: 2  
Number of GP Lanes: 2  
Period: PM  
Demand: Medium



Note: Each curve represents one toll link.

Number of HOT Lanes: 2  
Number of GP Lanes: 1  
Period: AM  
Demand: Medium

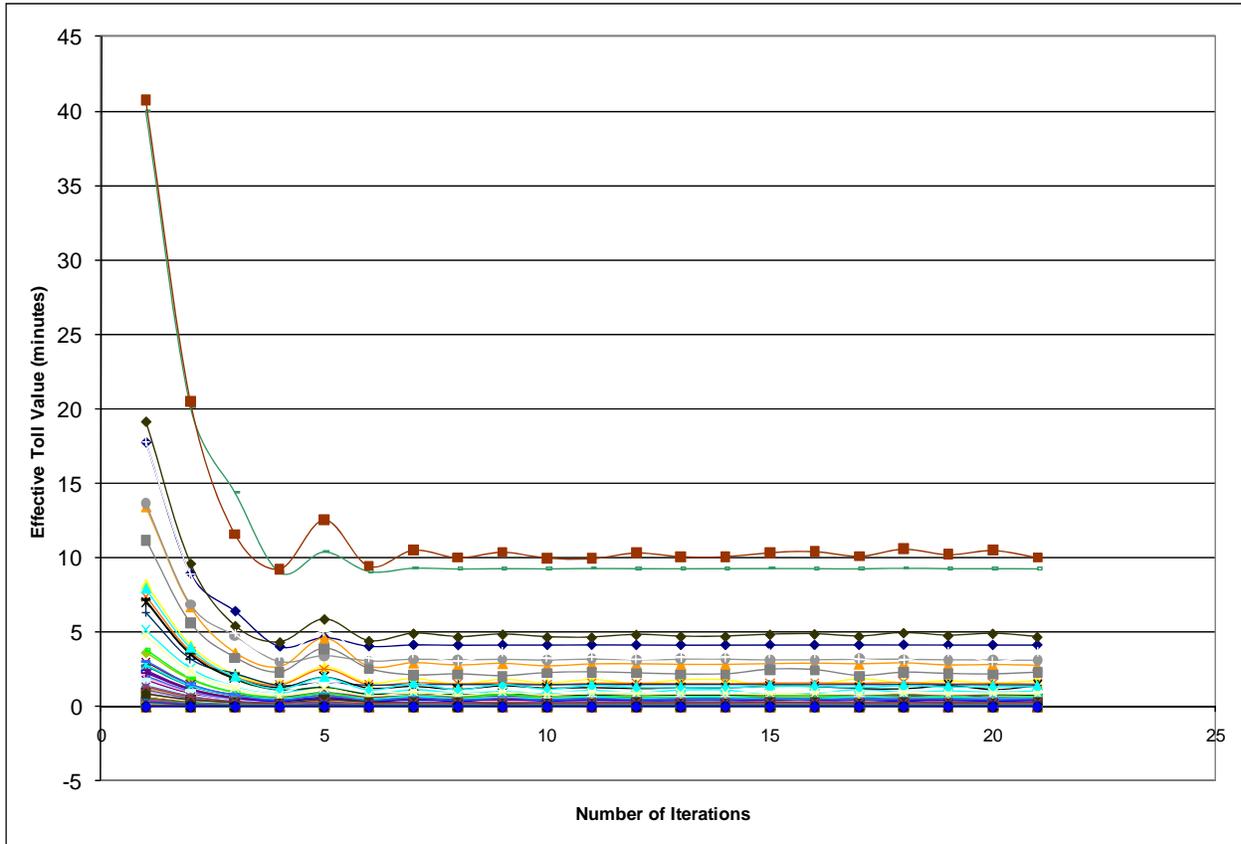


Note: Each curve represents one toll link.



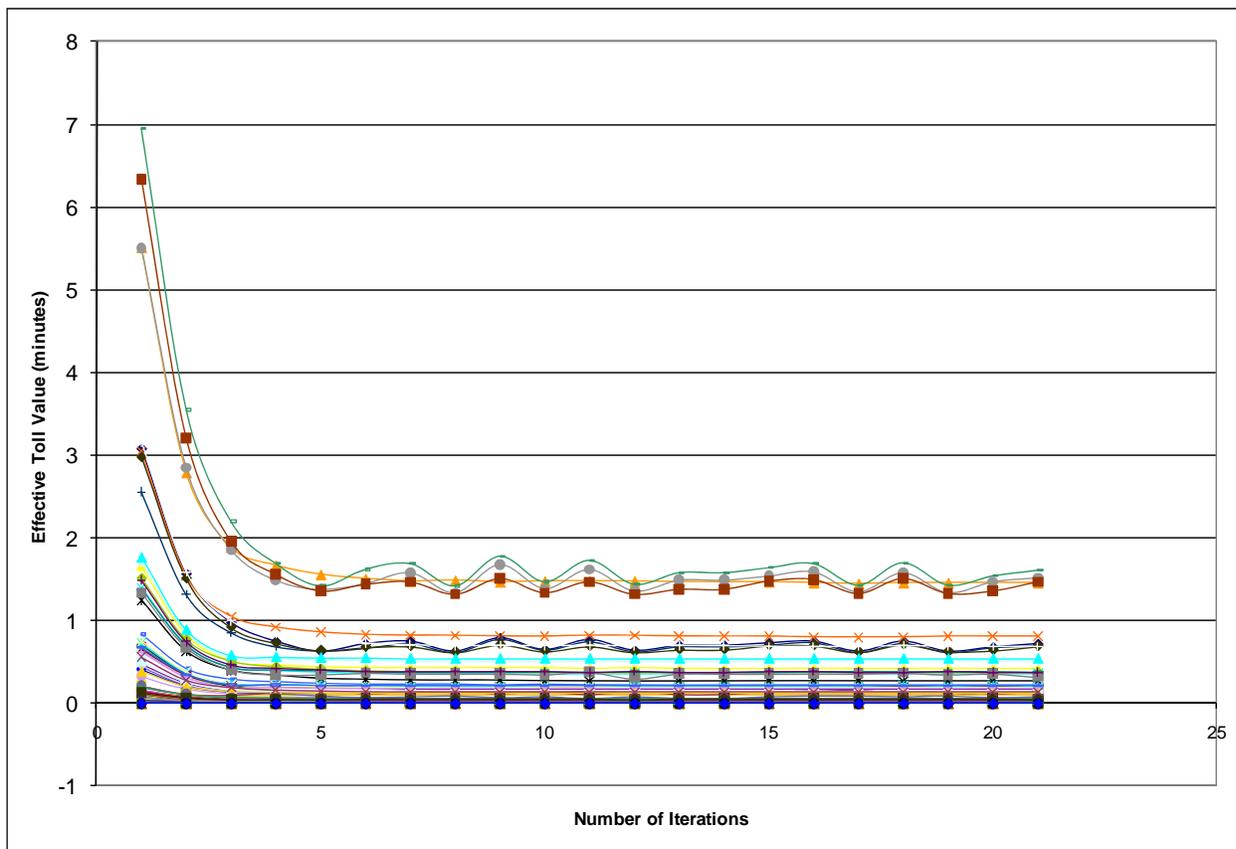


Number of HOT Lanes: 1  
Number of GP Lanes: 2  
Period: AM  
Demand: Medium



Note: Each curve represents one toll link.

Number of HOT Lanes: 1  
Number of GP Lanes: 2  
Period: MD  
Demand: Medium



Note: Each curve represents one toll link.



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