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ABSTRACT

Congestion pricing has been advocated as an efficient way to mitigate traffic congestion since 1920s. A prevalent form of congestion pricing in the U.S. is high occupancy/toll (HOT) lanes. The operating objective of HOT lanes is to improve the throughput of the whole freeway segment while ensuring a superior level of service on HOT lanes. To achieve this, ideally tolls should vary in response to real-time traffic conditions. Microscopic simulation has been used to evaluate pricing schemes or operation strategies of managed lanes. As a trustworthy traffic simulation tool, CORSIM has a very limited capability of simulating dynamic tolling strategies and drivers' lane choice behaviors in the presence of tolls. This research enhanced CORSIM and developed a CORSIM-based simulation platform to evaluate the impacts of a variety of pricing strategies on managed-lane operations.

EXECUTIVE SUMMARY

High-occupancy/toll (HOT) lanes are facilities that combine pricing and vehicle eligibility to maintain free-flow conditions on those lanes while maximizing the freeway's throughput. High-occupancy vehicles (HOVs) are allowed to use HOT lanes for free while single- or low-occupancy vehicles must pay a toll to gain access. Other types of managed lanes, such as HOV lanes, have been used for decades while HOT lanes are a much newer innovation. The first HOT lanes opened at SR91 in California in December 1995 and currently there are about twelve HOT lane facilities in operation nationwide. Some of them are single-segment facilities while others consist of multiple segments. A single-segment HOT facility has essentially one entrance and one exit. In some situations, 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 regardless of where they enter or exit. In contrast, a multi-segment HOT lane facility has multiple well-separated ingress or egress points and there is more than one tolling point in the facility. Depending on where they enter or exit, motorists may pay different amounts of toll.

To efficiently operate HOT lanes, ideally tolls should vary real-time in response to traffic conditions. Currently, there are at least four authorities pricing their toll lanes dynamically, such as California Department of Transportation on Interstate 15, Florida Department of Transportation on Interstate 95, Minnesota Department of Transportation on Interstate 394, and Washington Department of Transportation on SR167. Microscopic simulation has been used to evaluate dynamic pricing schemes of HOT lanes. However, as a trustworthy traffic simulation tool, CORSIM has a very limited capability of simulating dynamic tolling strategies and the drivers' lane choice behaviors in the presence of tolls. This research aimed to enhance CORSIM and develop a CORSIM-based simulation platform to evaluate the impacts of a variety of pricing strategies on freeway traffic operations.

Three sets of modules were developed. The first one implements three pricing strategies including responsive pricing, closed-loop-control-based algorithm and time-of-day pricing schemes. The second module mimics drivers' lane choice behaviors in the presence of toll and the third includes different toll structures or charging approaches for multi-segment HOT lanes. Simulation experiments were conducted using the network of 95 Express in southeast Florida to demonstrate the enhanced CORSIM.

CHAPTER 1 BACKGROUND

Transportation economists have been advocating road pricing as an efficient way to internalize congestion externality since the seminal work by Pigou (1920) and Knight (1924). For a recent review, see Lindsey and Verhoef (2001) among others. However, only recently this idea has become practical. Singapore implemented its area licensing scheme to restrict vehicular traffic into the city's central area in 1975. In Norway, the first toll ring was operational in Bergen in 1986 and, subsequently two additional toll rings were established in Oslo and Trondheim. More recently, the city of London introduced in February 2003 a £5 (later increased to £8) fee on cars entering the city center.

A more prevalent form of congestion pricing in the U.S. is managed lanes or express toll lanes, which can be viewed as a first step toward more widespread pricing of congested roads. In a typical setting, lanes on a given freeway are designated either as regular or managed toll lanes. The former has no toll while the latter can only be accessed by paying toll. If high-occupancy vehicles (HOVs) need not pay, the lane is widely known as high-occupancy/toll (HOT) lane. Since the first HOT lane was implemented in 1995 on State Route 91 in Orange County, California, the concept is becoming 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 additional option it offers to motorists and the low utilization of HOV lanes. Many have expressed concern about the wasted capacity resulting from a low utilization of many 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 in order to avoid congestion. The managed-lane operator must ensure a superior level of service in order to attract motorists to pay to use the lanes.

To achieve the above objective, 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, such as California Department of Transportation (Caltrans) on Interstate 15, Florida Department of Transportation (FDOT) on Interstate 95, Minnesota Department of Transportation (MnDOT) on Interstate 394, and Washington Department of Transportation (WSDOT) on SR167. In Florida, the toll rate for 95 Express is adjusted every 15 minutes, varying from $0.25 to $7.25. The rate is determined based on the current traffic density and the change in traffic density of the HOT lanes. When an increase or decrease in the detected density occurs, the rate is adjusted upward or downward accordingly. The magnitude of the adjustment is determined from a “look-up” table (FDOT, 2008).

Microscopic simulation is very useful in evaluating pricing schemes or operation strategies of managed lanes (e.g., Zhang et al., 2009). Unfortunately, as a trustworthy traffic simulation tool, CORSIM has a very limited capability of simulating dynamic tolling strategies and the drivers’ lane choice behaviors in the presence of tolls. CORSIM is a widely-used and comprehensive microscopic traffic simulation program. It was initially developed by FHWA and is now being maintained and further developed by McTrans at the University of Florida. It is applicable to simulation of surface streets, freeways, and integrated networks with a complete selection of control devices. It adopts commonly-accepted vehicle and driver behavior models to simulate traffic operations and control. During recent years, CORSIM has been expanded to simulate HOV lanes, two-lane highways, freeway ramp metering and new vehicle technologies, and have enabled large-scale network simulation.

This project focuses on enhancing CORSIM for simulating HOT lane operations. For this purpose, three sets of additional modules were developed. The first set is to simulate a variety of pricing strategies, including the one being implemented for 95 Express in south Florida, the closed-loop-control-based algorithm developed by Yin and Lou (2009) and time-of-day pricing. The second is to mimic drivers’ choices between general purpose (GP) and HOT lanes in the presence of toll based on a specific lane-choice model selected. The third is to allow for different toll structures or charging approaches for multi-segment HOT lane facilities.

The remainder of this report is organized as follows. Chapter 2 discusses pricing strategies for HOT lanes and provides a detailed description of those implemented in CORSIM. Chapter 3 presents a brief literature review on lane choice models and introduces the one implemented in CORSIM. Chapter 4 reviews the current practice of different toll structures for multi-segment HOT-lane facilities and describes the ones implemented in CORSIM. Chapter 5 presents a case study of using the enhanced CORSIM to simulate the current and future 95 Express and chapter 6 summarizes the report. Lastly, a user guide on how to simulate HOT lanes in CORSIM is provided in the appendix.

CHAPTER 2 TOLLING ALGORITHMS

2.1 INTRODUCTION

In the literature, many studies have been conducted to develop pricing algorithms that can be potentially used for HOT lane operations. However, many of these studies (see, e.g., Morrison, 1986; Palma and Lindsey, 1997; Arnott et al., 1998; Liu and McDonald, 1999) consider hypothetical and idealized situations to derive analytical solutions. For example, the travel demand function or travel demand is usually assumed to be known. For CORSIM enhancement, we selected practical and easy-to-implement pricing algorithms, including the one implemented for 95 Express in south Florida and the approach proposed by Yin and Lou (2009) that determines time-varying tolls based on the concept of feedback control. In addition, time-of-day pricing was implemented since it is being implemented at a few HOT lane facilities. Below we describe in detail those three pricing algorithms.

2.2 RESPONSIVE PRICING ALGORITHM

Responsive pricing is an approach of determining toll values based on the current HOT lane conditions to manage traffic demand and maintain free-flow conditions on HOT lanes. One of responsive pricing schemes was implemented on 95 Express, a facility with two HOT lanes on I-95 in south Florida. The toll is determined by the traffic density currently detected on 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 procedure of calculating toll is the following:

1) Calculate average traffic density of the HOT lane segment, denoted as $TD(t)$. Adjust $TD(t)$ for specific geometric conditions if necessary, such as weaving areas, by multiplying it with a parameter α.
2) Calculate the change in density $\Delta TD = TD(t) - TD\ (t-1)$, where $TD(t)$ and $TD(t-1)$ are traffic densities at time interval t and $t-1$, respectively.

3) Determine toll amount adjustment, ΔR, from the Delta Setting Table (DST), i.e., Table 2-1, based on ΔTD 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.

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

Table 2-1. Delta Setting Table of Responsive Pricing

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. Delta 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

2.3 CLOSED-LOOP-CONTROL-BASED PRICING ALGORITHM

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

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

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

where, $R(t)$ is the current toll amount; K is a regulator parameter defined by a 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 by a 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.

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

2.4 TIME-OF-DAY PRICING SCHEME

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

In CORSIM implementation, multiple tolling periods with different toll amounts and durations can be simulated. The number of tolling periods is up to 24, and the duration of each tolling period varies from 3 to 60 minutes, with a toll amount ranging from $0.00 to $12.00.

CHAPTER 3 LANE CHOICE

In the enhanced CORSIM, both the HOT and GP lanes are integrated as a single facility and the lane-choice behaviors are simulated endogenously. 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 lane-choice model developed in those empirical studies (e.g., Small and Yan, 2001; Yan et al., 2002; Small et al., 2005a, 2005b) in CORSIM is technically feasible. However, 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, a CORSIM 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. The model is essentially a simple decision rule that motorists will pay to use the HOT lanes if the benefit they perceive from travel time saving (TTS) is greater than the toll amount they are charged. The perceived benefit is the value of time (VOT) of the traveler multiplying the perceived TTS, which is assumed to follow a truncated normal distribution whose mean is the real or actual TTS (RTTS) and a standard deviation specified by a CORSIM user. The RTTS is the difference between the travel times on GP and HOT lanes, averaged across a user-specified time interval. The lane choice procedure for a particular vehicle, say j, that is approaching a warning sign upstream to a HOT lane entrance is illustrated in Figure 3-1.

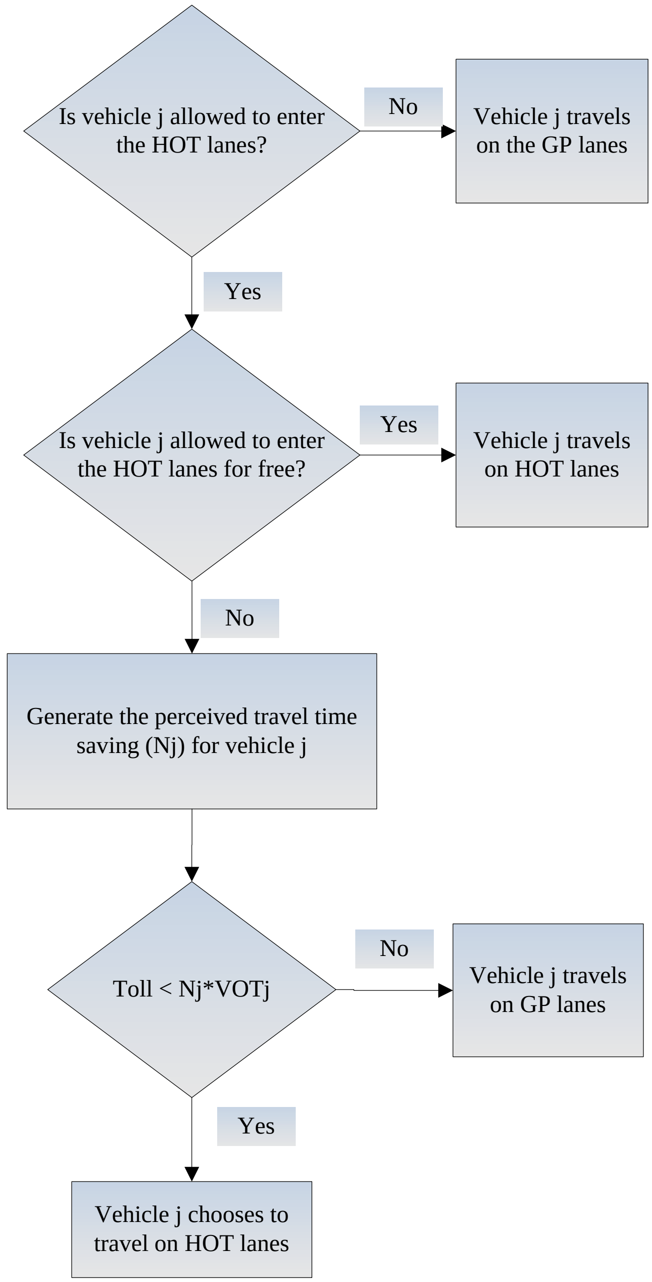

Figure 3-1. Drivers' Lane Choice in CORSIM

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 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%.

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

CHAPTER 4 TOLL STRUCTURES

4.1 INTRODUCTION

Some 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 chapter reviews the toll structures implemented in practice for the multi-segment HOT facilities in the U.S., compares their advantages and disadvantages and describes the ones implemented in CORSIM.

4.2 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.
- SR167 between Renton and Auburn, Washington.
- I-10 (Katy Freeway), Houston, Texas.

4.3 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.

4.3.1 Zone-based Tolling

In this approach, a HOT facility is divided into multiple 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. 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 MnPass I-394 HOT lanes in Minneapolis. Below we review these facilities one by one.

4.3.1.1 Salt Lake City, Utah

I-15 express lanes in Salt Lake City, Utah, is a multi-segment facility, 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 (UDOT, 2010a). The map of the facility is shown in Figure 4-. 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. 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).

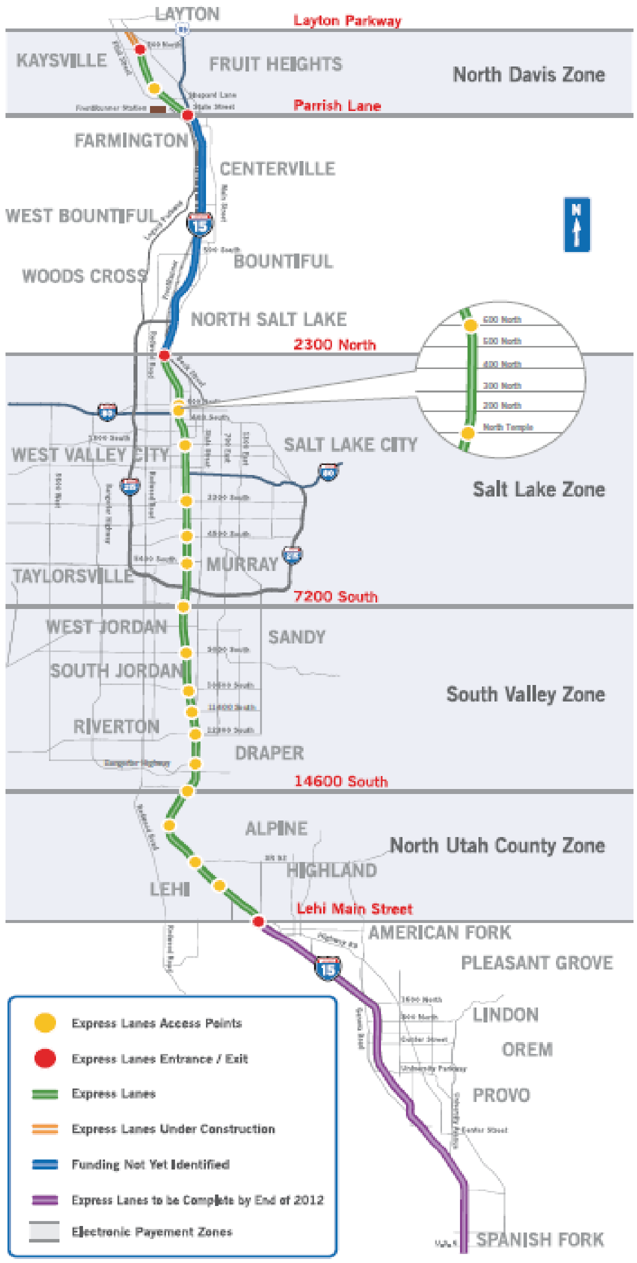

Figure 4-1. Map of I-15 HOT Lanes at Salt Lake City, Utah (Source: http://www.udot.utah.gov/expresslanes/dld/Express%20Lanes%20Zone%20map.pdf)

4.3.1.2 I-10 (Katy Freeway), Houston, Texas

The Katy managed lanes at I-10 corridor in Texas 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-. 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- 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).

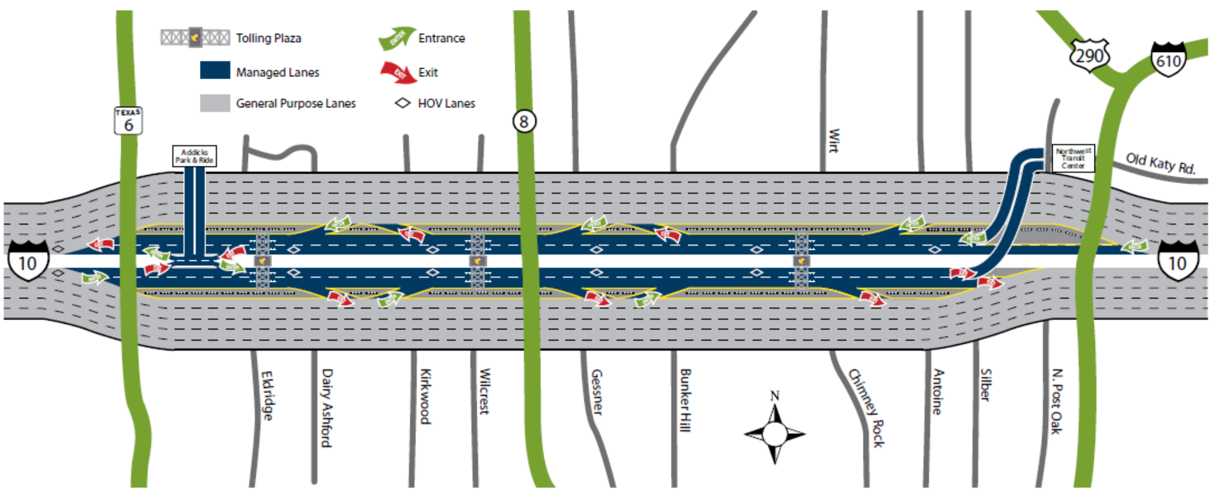

Figure 4-2. Map of Katy Managed Lanes at Houston, Texas (Source: https://www.hctra.org/katymanagedlanes/media/katy_managed_lanes_map.pdf)

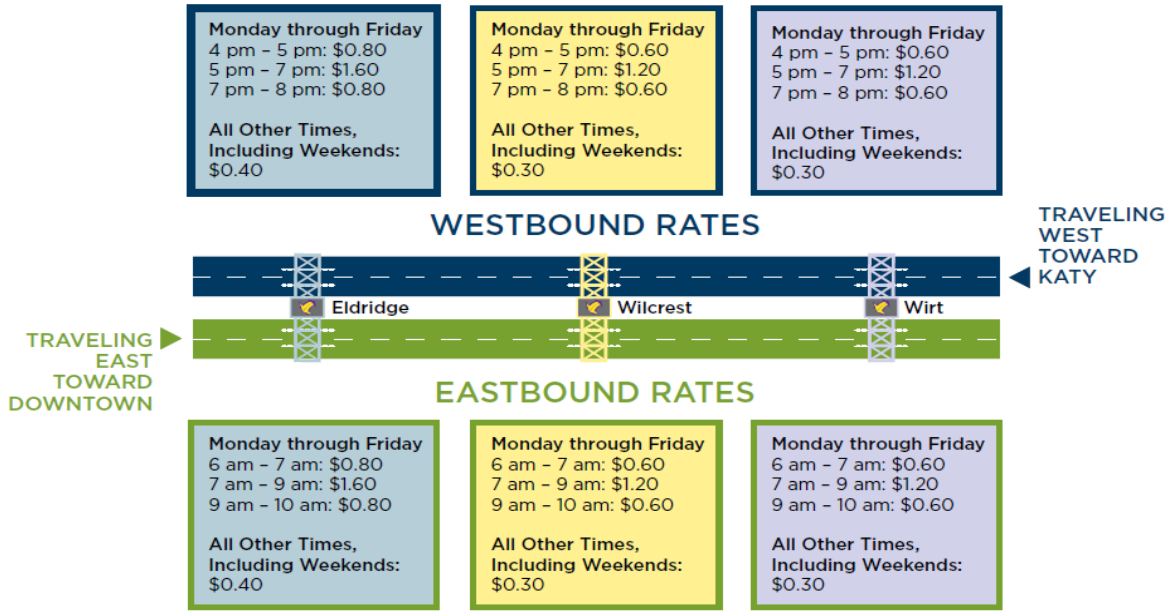

Figure 4-3. Toll Schedule of Katy Managed Lanes at Houston, Texas (Source: https://www.hctra.org/katymanagedlanes/media/road_rate_chart.pdf)

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.

4.3.1.3 I-394, Minneapolis, Minnesota

The MnPass HOT lanes at I-394 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-. 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 (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.

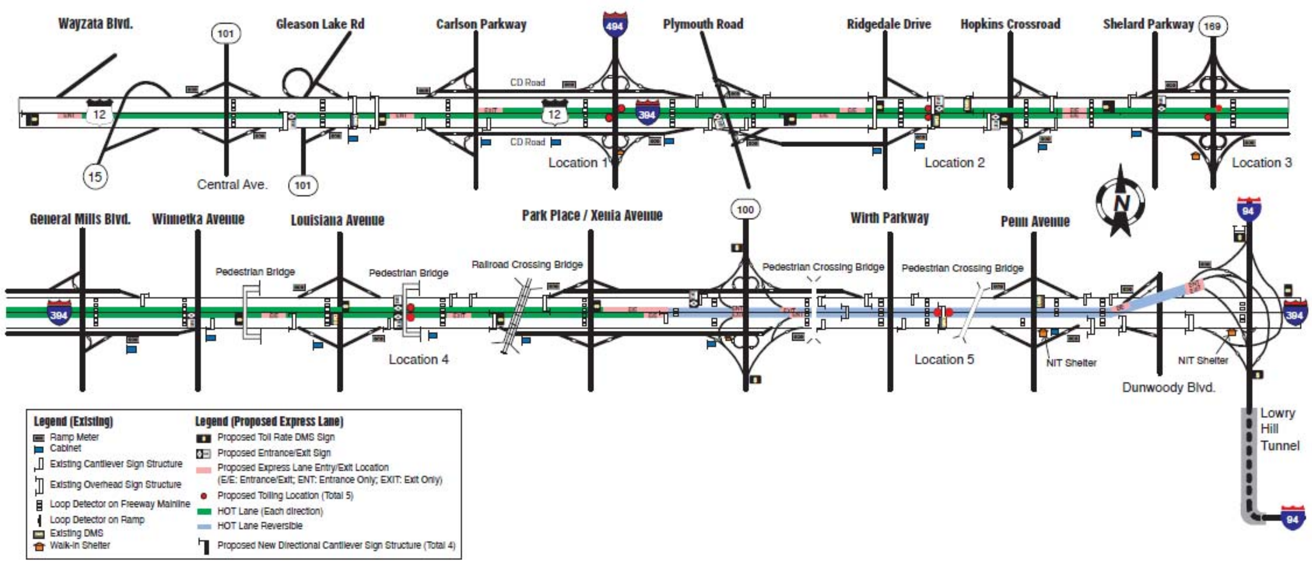

Figure 4-4. Map of I-394 HOT Lanes, Minnesota (Source: http://www.mnpass.org/pdfs/394mnpass-schematic.pdf)

4.3.2 Origin-specific Tolling

In origin-specific 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. The origin-specific tolling is implemented on SR 167 HOT lanes in Washington.

4.3.2.1 SR 167, Washington

The SR 167 HOT lanes are 10 miles long and have six access points northbound and four access points southbound where drivers can either enter or exit (WSDOT, 2008). Figure 4- 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.

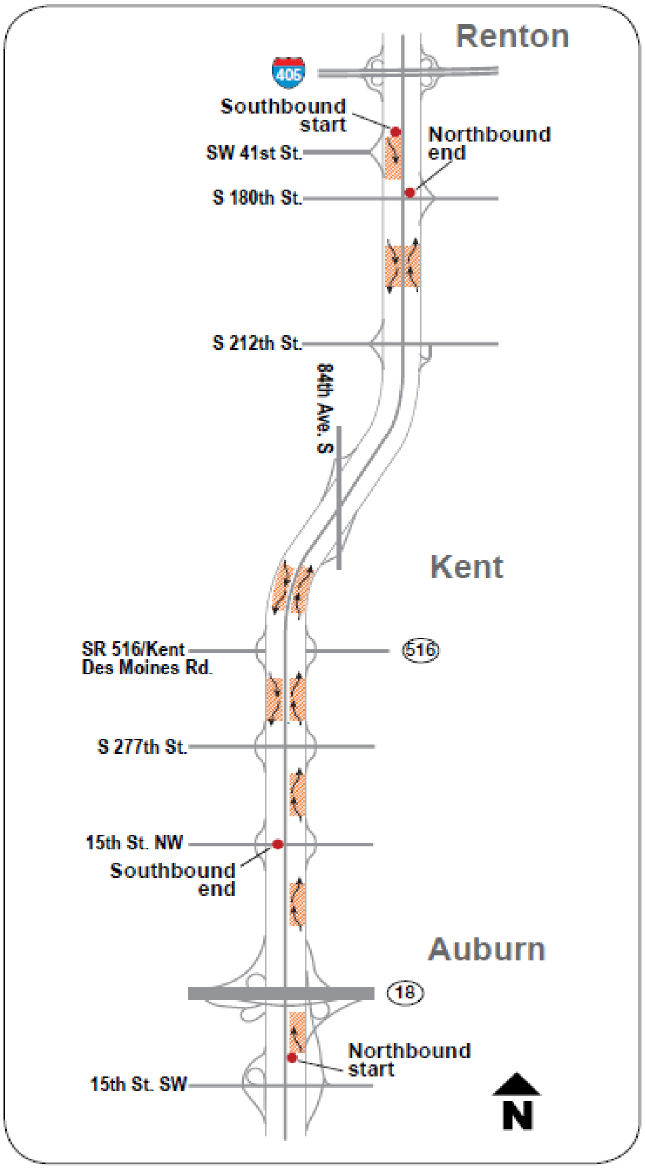

Figure 4-5. Map of SR-167 HOT Lanes, Washington (Source: http://www.wsdot.wa.gov/NR/rdonlyres/31FB3D24-79CC-4332-82F7-EBECEBE1CA71/0/HOTLanesAnnualReport2009.pdf)

4.3.3 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. This toll structure is implemented on I-15 in San Diego.

4.3.3.1 I-15, San Diego, California

I-15 HOT lanes in San Diego 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 but in March 2009, dynamic pricing was implemented. 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 4-6. Map of I-15 HOT Lanes at San Diego (Source: http://fastrak.511sd.com/documents/I-15ExpressLanesMAP.pdf)

4.3.4 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. Such a toll structure has been recently implemented on I-85 HOT lanes in Georgia.

4.3.4.1 I-85, Atlanta, Georgia

I-85 HOV lanes in the northeast Atlanta area, Georgia, were converted to HOT lanes in October 2011. They are about sixteen miles long and have one lane per direction. The toll changes dynamically every about fifteen minutes to ensure uncongested traffic conditions on the HOT lanes. Transit vehicles, carpools with three or more occupants, motorcycles, emergency vehicles and alternative fuel vehicles can access the lanes for free. All vehicles willing to use the HOT lanes should register with State Road and Tollway Authority (SRTA). There are five entries and six exits in the NB direction and four entries and four exits in the SB direction. The sign at each entry location displays the toll amount to the first downstream exit, which is the minimum toll one has to pay when he or she enters the facility, and the toll amount to the last exit, i.e., the maximum someone can be charged. If a traveler exits between the first and last exit, he/ she pays depending on the miles traveled on the HOT lanes.

4.4 SUMMARY

Table 4-1 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 4-1. Summary of Multi-segment HOT Facilities in the U.S.

Facility	Length	Access Points	Tolling Points	GP/HOT Separation	Toll Structure
I-15 Salt Lake City, Utah	38 miles	18 access points[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
I-85 Atlanta, Georgia	16 miles	5 entrances and 6 exits NB and 4 entrances and 4 exits SB	6 NB and 4 SB	Double White line	Distance-based: Dynamic Pricing

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

4.5 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 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 4-2 summarizes the advantages and disadvantages of the different toll structures presented above.

Table 4-2. Pros and Cons of Toll Structures

Toll Structure	Pros	Cons
Zone-based	Easy to implement, particularly when expanded from a single-segment HOT facility	Additional lane changes at the beginning of each zone may cause disruptions; difficulty of balancing utilization of capacity and the disruptions caused by lane changes
Origin-specific	Easy to implement and convenient for users	Inefficient utilization of capacity and cause 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

4.6 TOLL STRUCTURES IN CORSIM

Capturing different toll structures is very important in simulating multi-segment HOT-lane facilities. Currently, three toll structures; i.e., zone-based, origin-based and distance-based, are fully implemented in CORSIM.

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

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

In the distance-based tolling, the toll amount a motorist is charged depends on the distance that he or she travels on the HOT lanes. The toll rate, i.e., toll per mile, is the same for all HOT lane 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. In CORSIM, the toll calculation in distance-based tolling is similar to that in zone-based tolling. More specifically, a CORSIM user also needs to specify zones and toll calculation also takes place at the first HOT entry link to each zone. To find the toll rate, the toll amount is then divided with the length of the zone. The toll per mile is the same at all the entrances to the same zone, but can be different from zone to zone.

CHAPTER 5 CASE STUDY

To test and demonstrate the enhanced CORSIM, we coded and calibrated the current and future 95 Express for the northbound direction. The current 95 Express is used for demonstrating a single-segment HOT facility simulation while the future 95 Express is to illustrate a multi-segment facility simulation.

95 Express is a HOT lane facility implemented by FDOT on I-95 in the Miami and Fort Lauderdale regional area. The system consists of two HOT lanes and 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 (FDOT, 2010b).

Figure 5-2 shows the map of the current 95 Express and Figure 5-3 illustrates the complete or future 95 Express. It can be seen that the current 95 Express is essentially a single-segment facility while the future 95 Express is slated to be a multi-segment facility. 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 currently changes every 15 minutes, varying from \$0.25 to \$7.25.

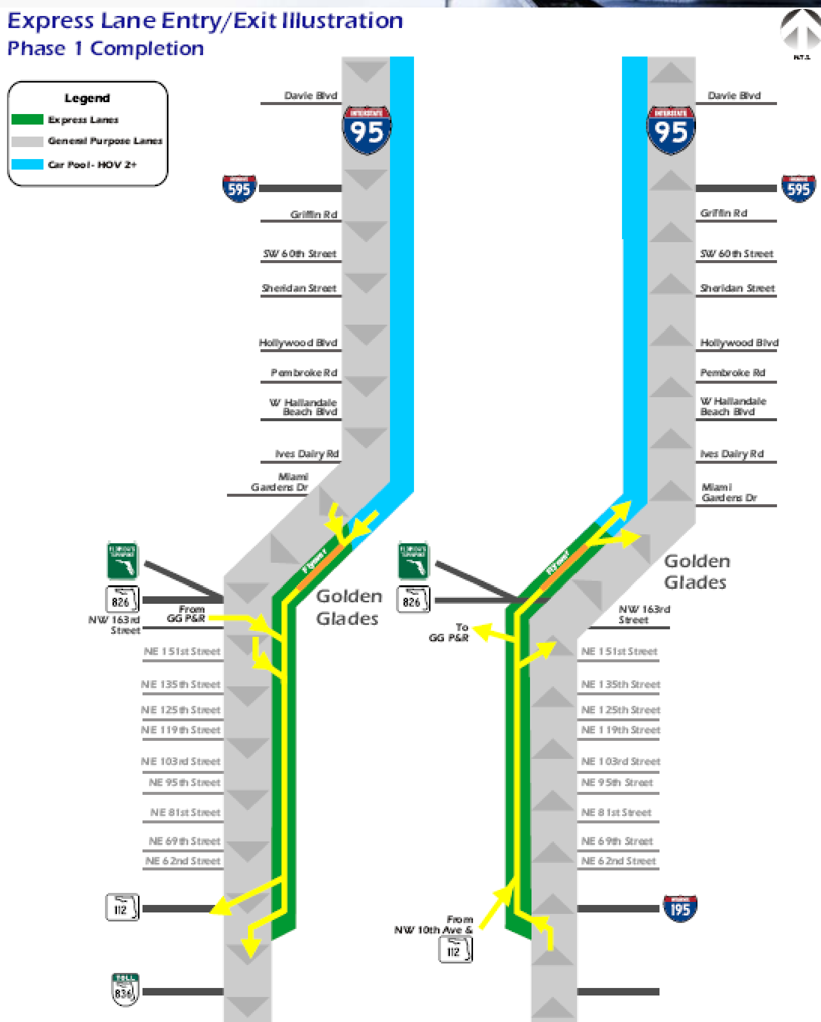

Figure 5-2. Map of 95 Express after Phase 1 Completion

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

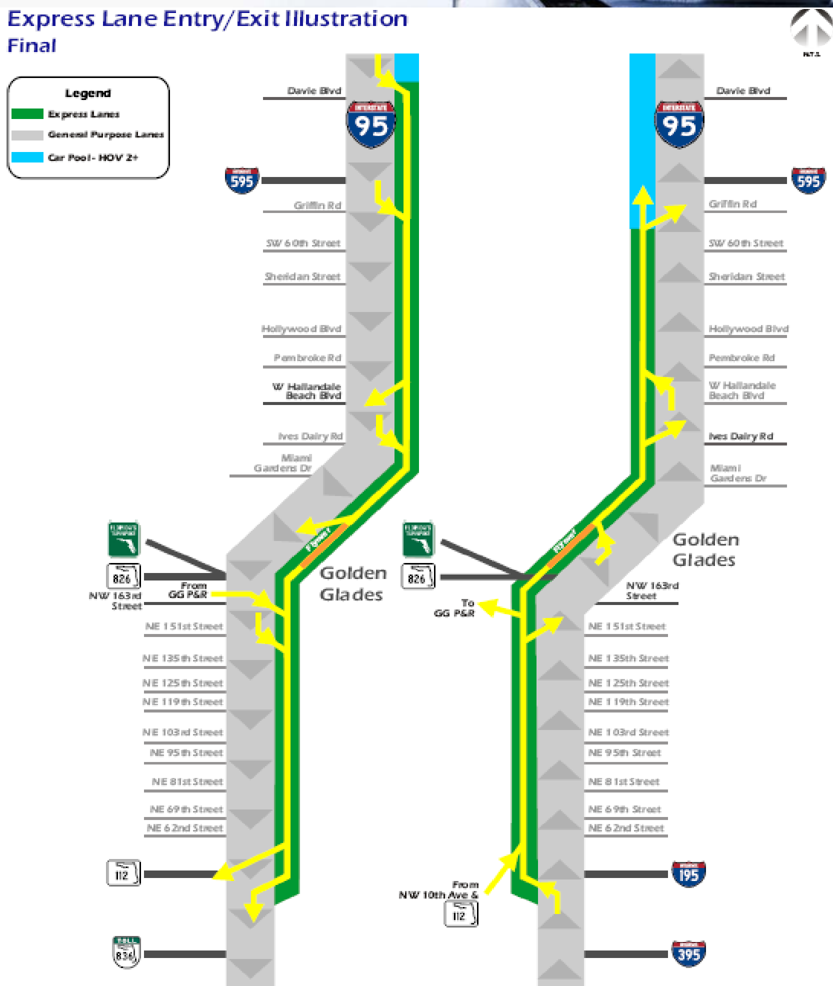

Figure 5-3. Completed 95 Express

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

5.1 SIMULATING THE CURRENT 95 EXPRESS

To demonstrate the capability of the enhanced CORSIM to simulate single-segment facilities, we simulated the current 95 Express (Figure 5-2). The data used in the simulation 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 5-3 compares the reported performance statistics of the northbound direction of 95 Express and the simulated ones.

Table 5-3. 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 pretty well. In the simulation, the actual TTS was calculated every minute and was then used for the lane-choice decision during the next minute. Also, the standard deviation of the perceived TTS distribution was assumed to be a half of the actual TTS. To achieve the lane distribution between the HOT and GP lanes on the 95 Express network , drivers' VOT had to be calibrated. The calibrated VOT for the 95 Express network is shown in Table 5-4.

Table 5-4. 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 was 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.

5.2 SIMULATING THE FUTURE 95 EXPRESS

The future 95 Express will have five entrances and four exits in the SB direction and four entrances and five exits in the NB direction (Figure 5-3). Some of these entrances and exits will be located very close while others will be at a distance of approximately 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 to operate a multi-segment HOT lane facility. 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. Below we use the enhanced CORSIM to simulate two zoning scenarios with zone-based tolling.

5.2.1 Zone-based Tolling for 95 Express

Based on the design and location of the HOT lane entrances and exits (Figure 5-3), one possible zoning scenario is to treat Phase 1, i.e., the current 95 Express, as one zone and the extended portion as another two zones, as shown in Figure 5-4. More specifically, the potential zone 3 for the SB direction and zone 1 for the NB direction are the current 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.

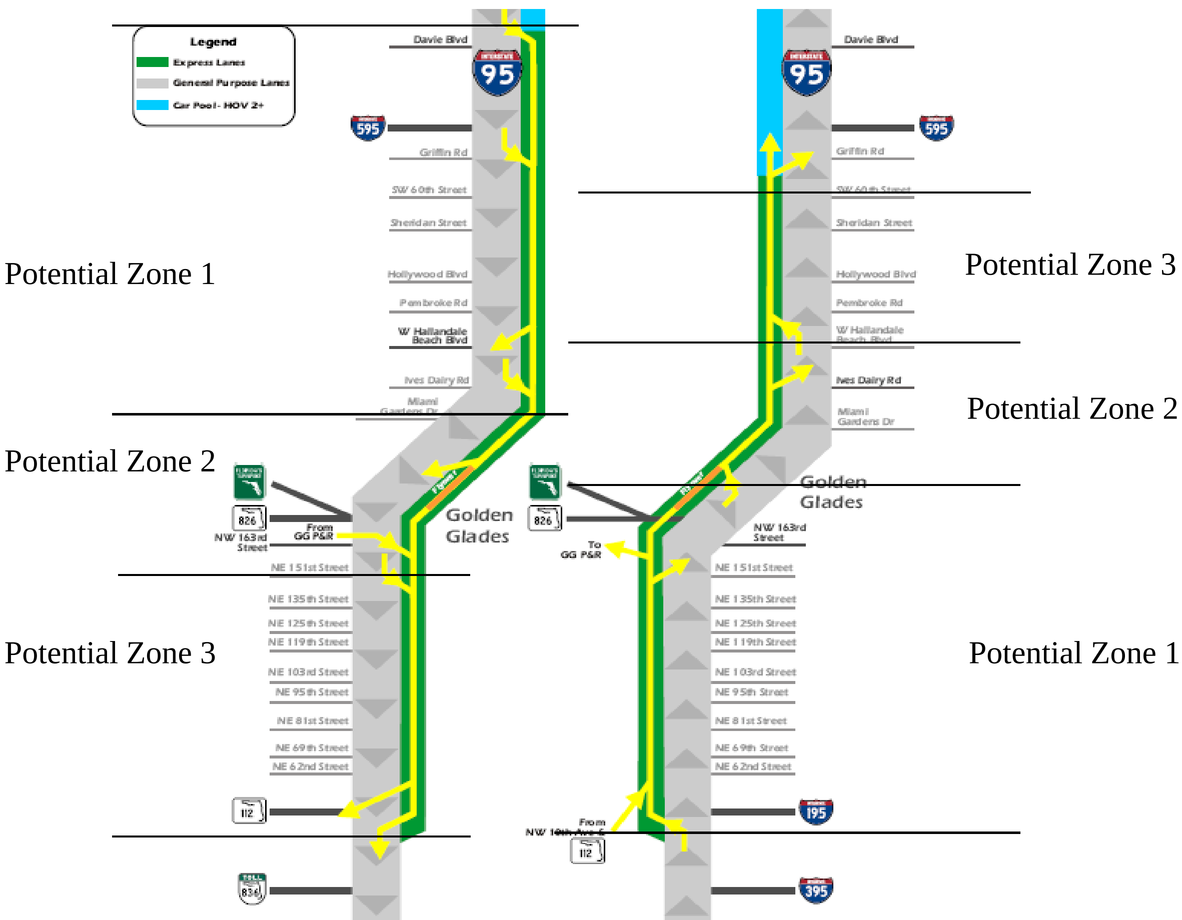

Figure 5-4. Potential Zoning for 95 Express

The evaluation of the zone-based tolling approach with two different zoning designs for the northbound direction is shown in Figure 5-4. 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 or responsive pricing 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 5-5. The simulated performance measures of the two zoning designs are summarized in Table 5-6.

Table 5-5: Toll Ranges for the 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 5-6: Future 95 Express 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 5-6 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. However, the CORSIM simulation may need further validation and verification.

CHAPTER 6 CONCLUSIONS

This report summarized a project that aimed to enhance CORSIM to simulate HOT lane operations. Three main components were developed, including three pricing strategies, a lane-choice module and three toll structures for multi-segment HOT facilities. The enhanced CORSIM was demonstrated in simulation experiments for the current and future 95 Express in south Florida. The experiments showed that the enhanced CORSIM appears adequately capturing the primary characteristics of HOT lane operations and management.

In the future, additional experiments will be conducted to further test the models implemented. For example, we plan to implement all the toll structures available in CORSIM to the future 95 Express to evaluate and compare their performances. Some other model components, such as OD-specific tolling and the perceived TTS calculation, will be added or modified to further enhance CORSIM’s capability of simulating HOT lane operations and management.

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APPENDIX

SIMULATING HOT LANES IN CORSIM

This appendix provides a guide on how to use CORSIM to simulate a HOT lane network. It describes all the steps in coding a network, selecting a pricing algorithm, inputting drivers' lane-choice parameters and specifying the toll structure for multi-segment HOT lane facilities. When drafting this appendix, we assumed that readers are already familiar with using CORSIM to simulate a regular freeway network. The HOT lane characteristics for HOT lane simulation in CORSIM are specified in Record Types 101 through 105. Details about the Record Types can be found in CORSIM Reference Manual.

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

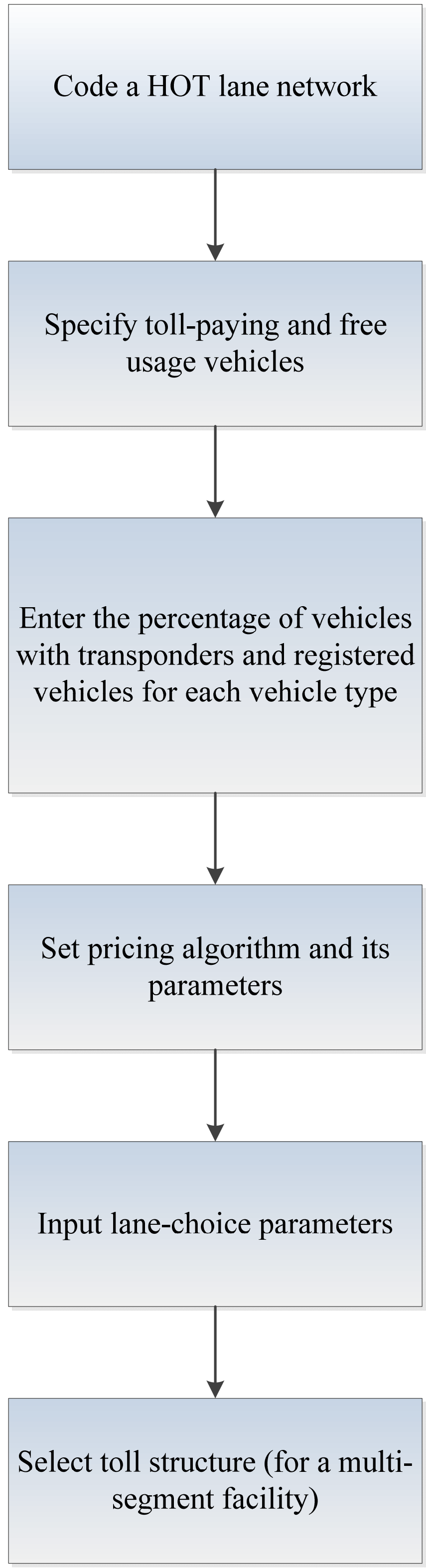


Figure A-1. Simulating HOT Lanes in CORSIM

CODING HOT LANE NETWORK

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

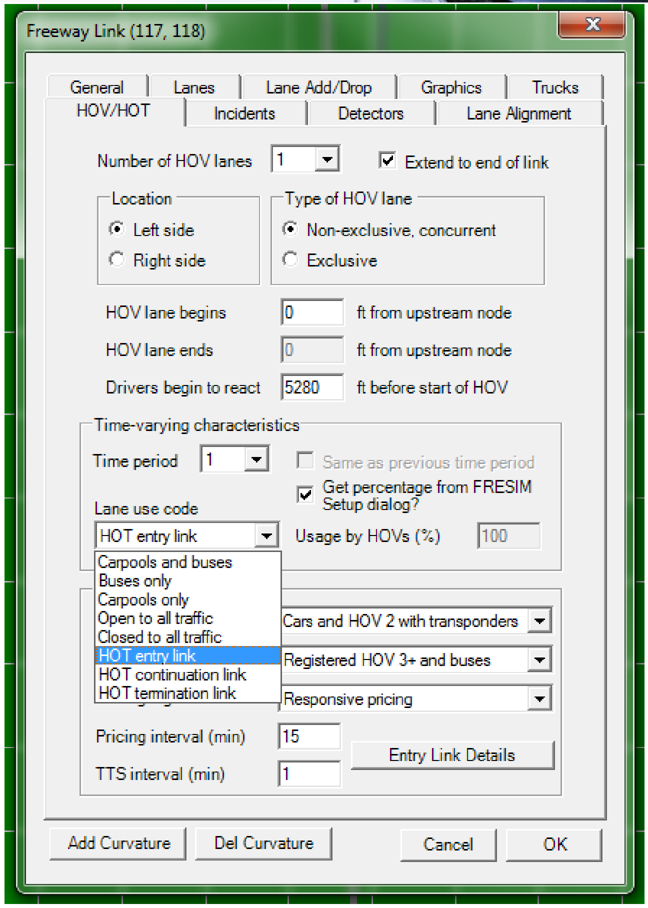


Figure A-2. HOT/HOV Lane Use Codes

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

First, the vehicles that are either allowed to access the HOT lanes by paying or for free should be specified. CORSIM has the following options for these vehicle groups (See Figure A-3 and Figure A-4):

1) Toll-paying vehicles
   a) Cars with transponders
   b) Cars and HOV 2 with transponders

c) All vehicles with transponders

d) All traffic

e) Closed to all traffic

2) Free usage vehicles

a) Registered HOV 2, Registered HOV 3+ and Buses

b) Registered HOV 3+ and Buses

c) All HOV 2, all HOV 3+ and Buses

d) All HOV 3+ and Buses

e) Only registered HOV 3+

f) Only Buses

g) All traffic except trucks

h) All traffic

i) Closed to all traffic

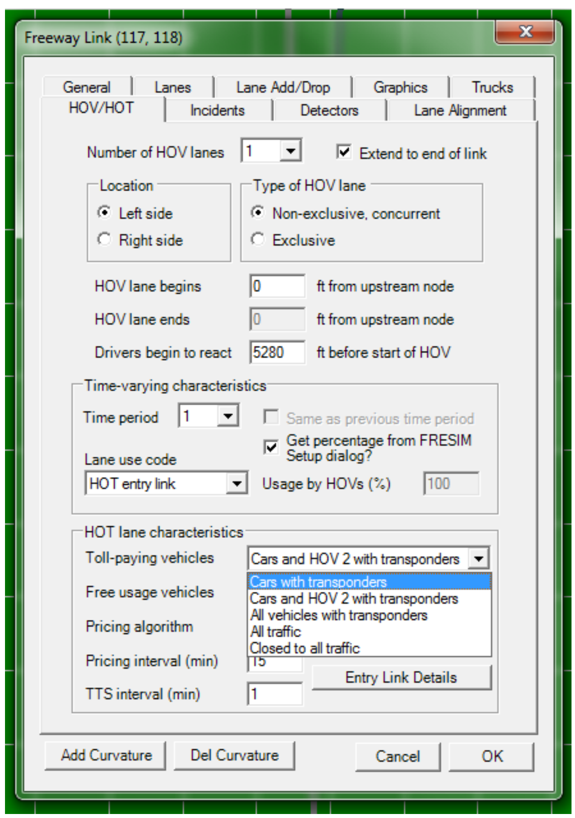


Figure A-3. Toll-paying Vehicles

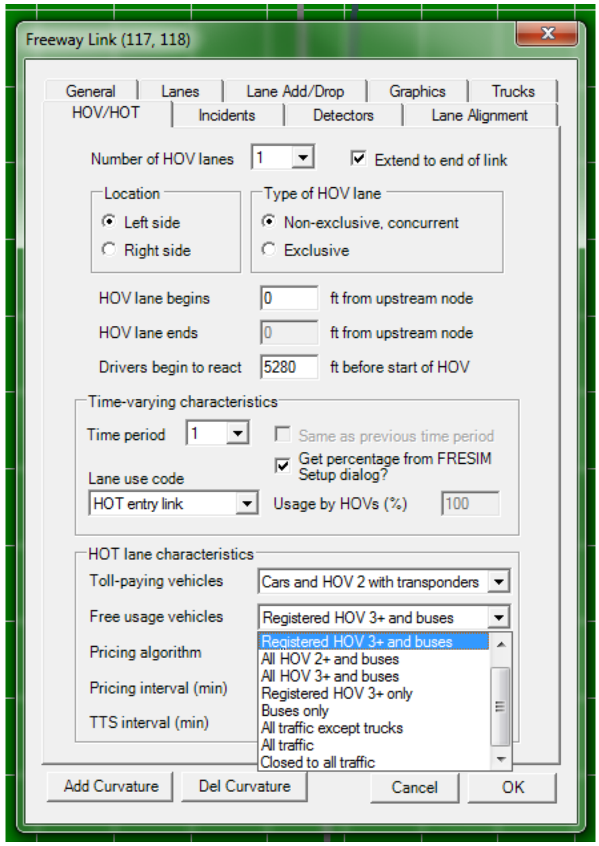


Figure A-4. Free Usage Vehicles

Since toll collection on the HOT lanes is conducted electronically, among the toll-paying vehicles only those that are equipped a transponder can legally enter the HOT lanes. The percentage of such vehicles for each vehicle type can be entered in CORSIM. The free usage vehicles are not required to have a transponder to use the HOT lanes but they may need to register. Registered vehicles are those that are registered to the HOT-lane operator to use facility without paying a toll. The HOT lane operator specifies which vehicles are eligible for registration and also the registration process and requirements. Eligible vehicles for registration can be cars with two or more occupants, buses and others. Not every HOT lane operator requires vehicles to register in order to be toll-exempt. However, if operators have such requirement, all non-registered vehicles are expected to pay to enter the HOT lanes.

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

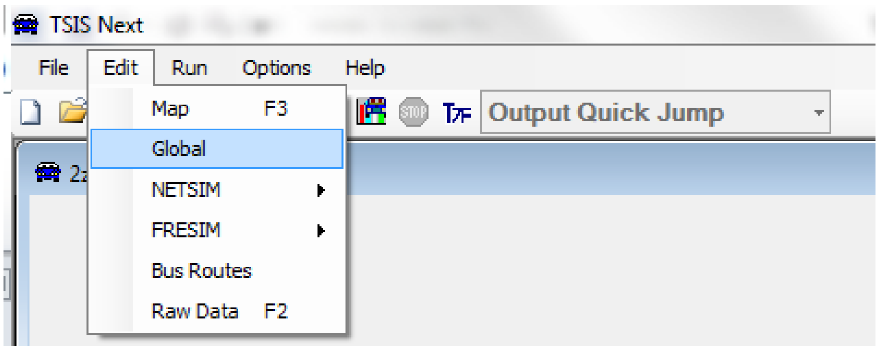


Figure A-5. Specifying Network Properties in TSIS Next

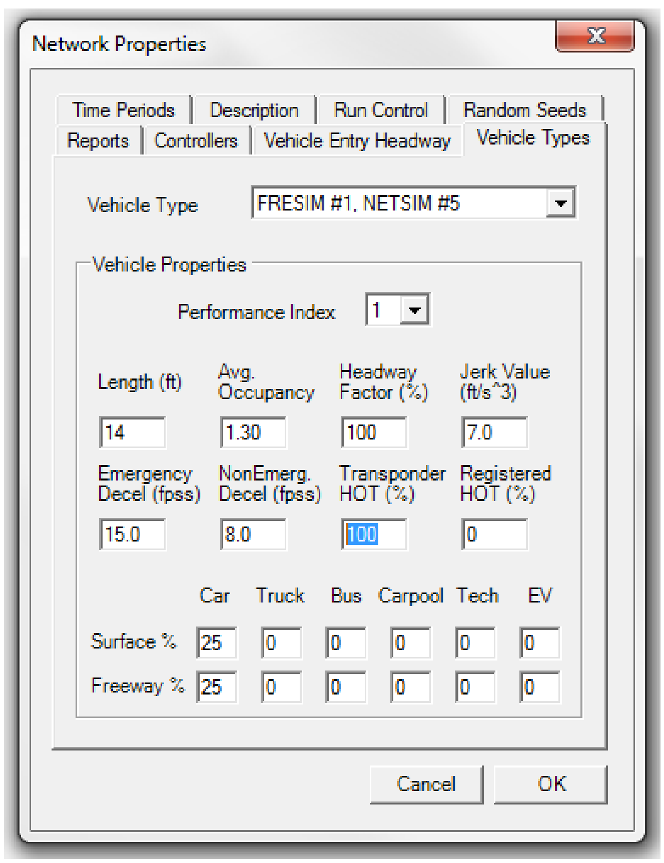


Figure A-6. Transponder and Registered Percentage Input

SETTING THE PRICING ALGORITHM

After all the parameters mentioned above are set, the pricing algorithm and the corresponding pricing interval (in minutes) for toll calculation should be selected. The former specifies how a toll amount is computed while the latter indicates how often the toll amount will be calculated and updated. In CORSIM, three different pricing algorithms are implemented as shown in Figure A-7.

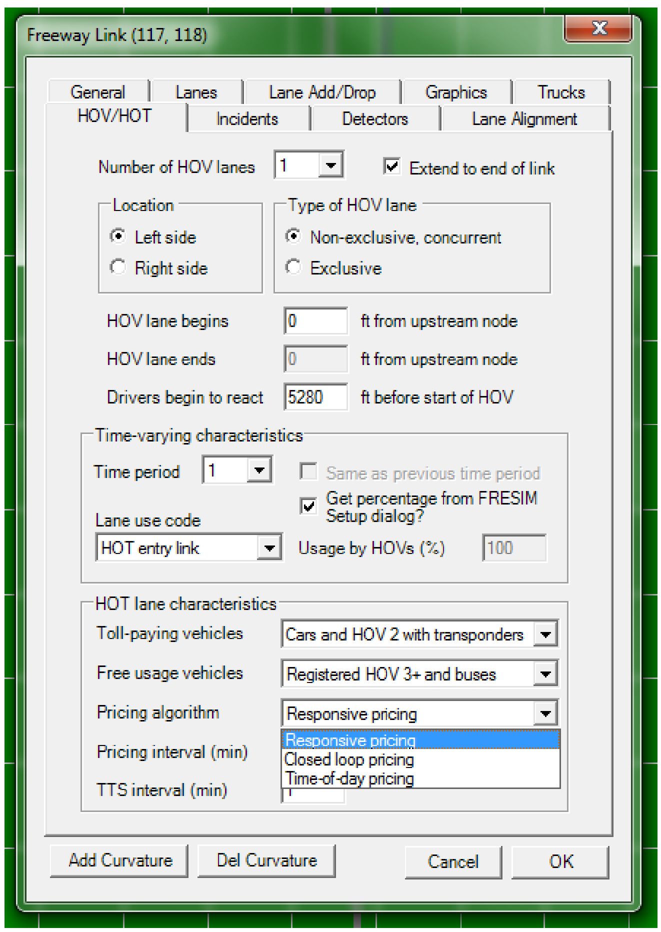
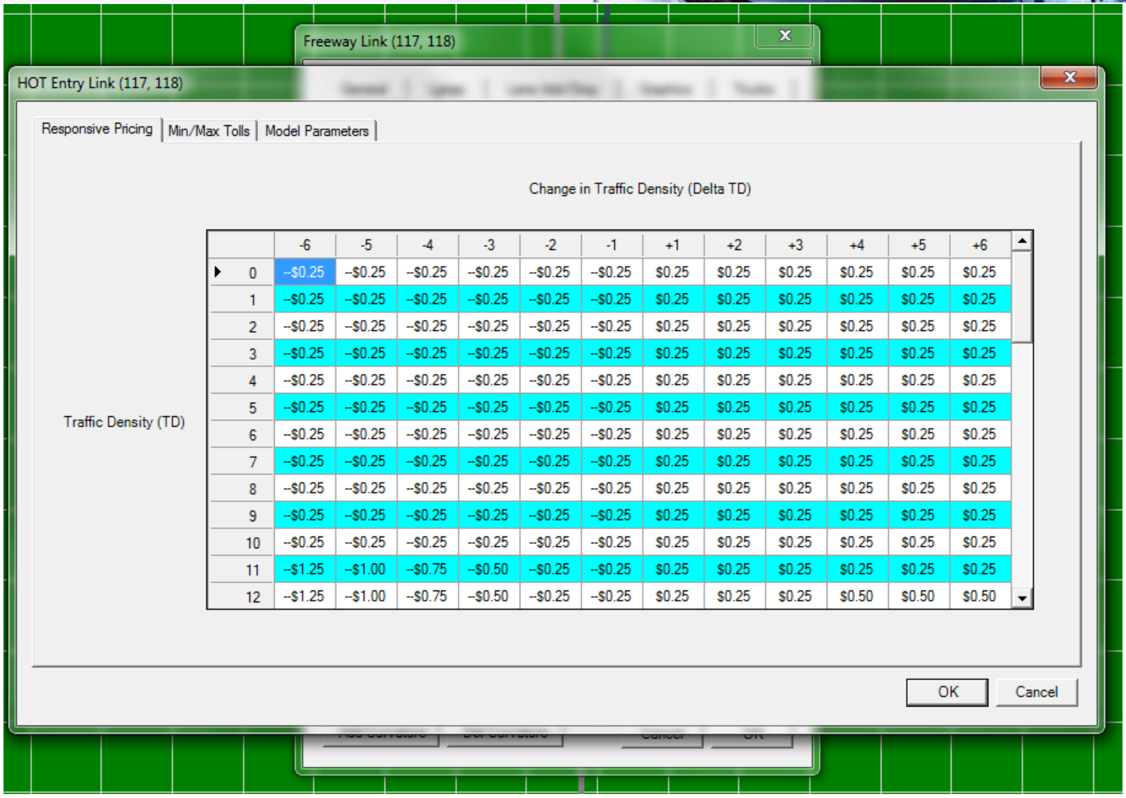


Figure A-7. Pricing Algorithms Available in CORSIM

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

1) TD is calculated for each HOT lane link and further averaged for each HOT lane segment for every toll interval. TD is then rounded to an integer and multiplied by an alpha parameter, which adjusts the calculated TD to reflect segment-specific conditions, such as weaving areas and geometric conditions. The default alpha parameter is set to one, implying no impact on the TD calculation. The alpha value can be specified under the model parameters tab (Figure A-10);
2) TD calculated for the previous time interval is subtracted from TD of the current interval to determine the change in TD (ΔTD);
3) Using the Delta Settings Table (Figure A-8), a toll change is determined. The toll change is either added or subtracted to the toll of the previous interval to calculate the current toll. All the parameters in the Delta Settings Table are user modifiable;
4) The toll is compared with the minimum and maximum toll values in the LOS setting table (first table in Figure A-9). If the toll is outside the acceptable toll range for the corresponding TD, the maximum or minimum toll is applied correspondingly. Again, the toll intervals for each LOS are user modifiable.



Freeway Link (117, 118)

HOT Entry Link (117, 118)

Responsive Pricing | Min/Max Tolls | Model Parameters

Change in Traffic Density (Delta TD)

Traffic Density (TD)

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

OK Cancel

Figure A-8. Delta Settings Table for Responsive Pricing

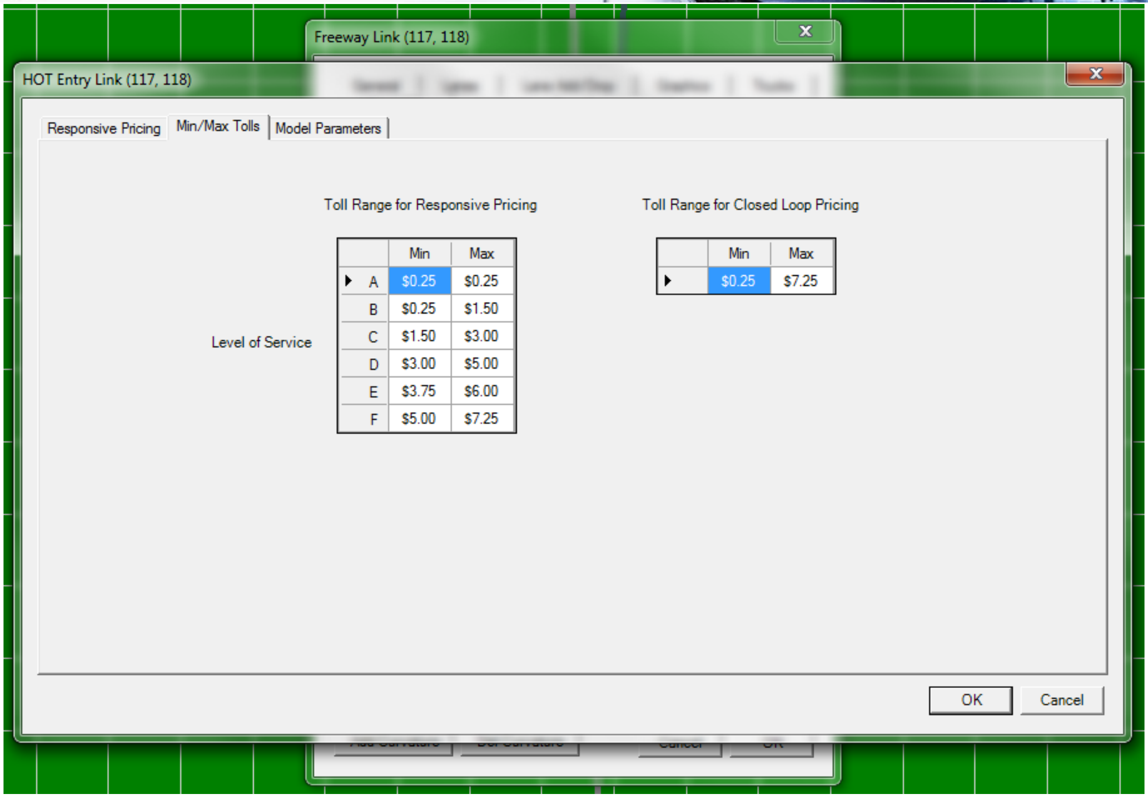


Figure A-9. Minimum and Maximum Toll Values for Responsive and Closed-loop-control-based Pricing Algorithms

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

1) Calculate TD as in the above responsive pricing;
2) The toll for the next time interval is calculated as follows:

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

where, $R(t)$ is the current toll amount; K is a regulator parameter defined by the user under the model parameters tab (Figure A-10). 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 under the model parameters tab (Figure A-10).

3) The $R(t+1)$ is rounded to the closest quarter;
4) Compare $R(t+1)$ with the minimum and maximum toll values defined by the user (second table in Figure A-9). If $R(t+1)$ is less than the minimum value or greater than the maximum value, then it takes the minimum or maximum value respectively.

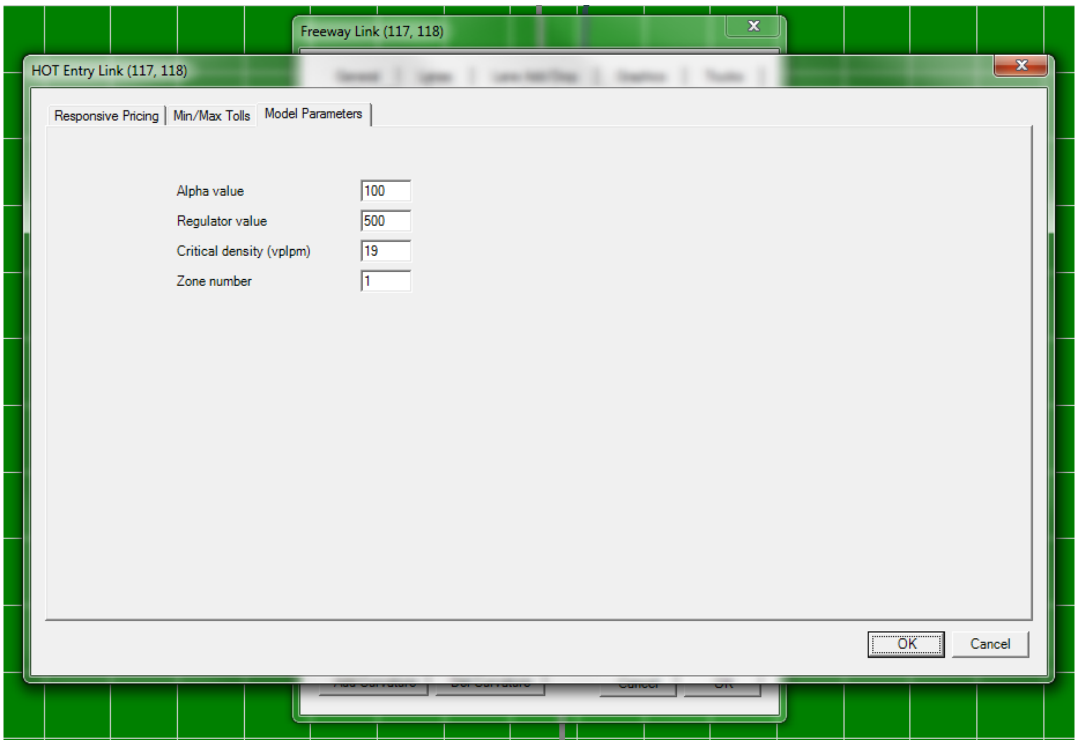


Figure A-10. Model Parameters for Pricing Algorithms

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

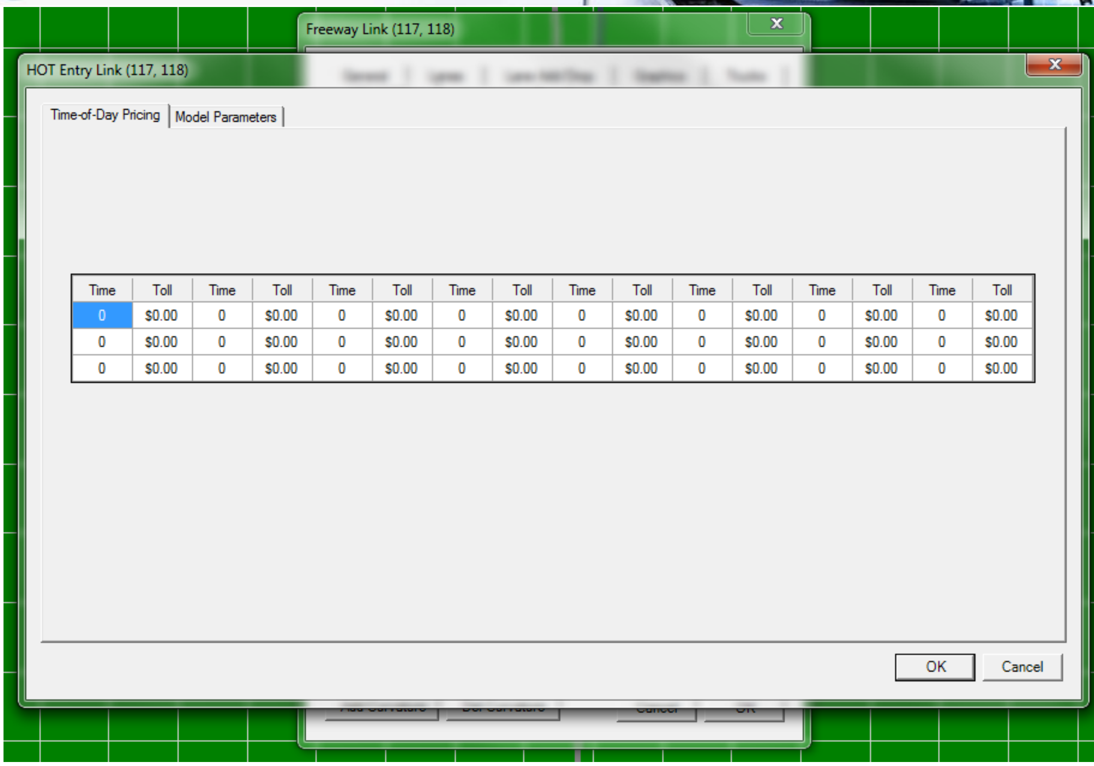


Figure A-11. Time-of-day Pricing

LANE CHOICE PARAMETERS

After toll amount is calculated using one of the pricing algorithms, drivers' reaction to the toll in the choice between the HOT and the GP lanes is simulated in CORSIM. The lane-choice model implemented is based on a decision rule that motorists will pay to use the HOT lanes if the benefit they perceive from the travel time savings (TTS) is greater than the toll they are charged. The perceived benefit is the value of time (VOT) of the traveler multiplying by the perceived TTS, which is assumed to follow a truncated normal distribution whose mean is the real or actual TTS (RTTS) and standard deviation specified by a user. The RTTS is the difference between travel times on GP and HOT lanes, averaged across a user-specified time interval. The RTTS interval in minutes can be input in the HOV/HOT lane tab (see Figure A-7), which determines how often RTTS will be evaluated. For example, if it is 10 minutes, RTTS will be evaluated every 10 minutes, and all decisions made during the next 10 minutes will be based on the average of the previous 10 minutes. Decisions made during the first 10 minutes are based on the value of average RTTS at time 0. Decisions made during minutes 11 to 20 will be based on the average RTTS calculated at time 10. The lane choice decisions are made whenever the vehicle encounters the warning sign for the HOT lane. The location of the warning sign is specified by the user (Figure A-7).

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

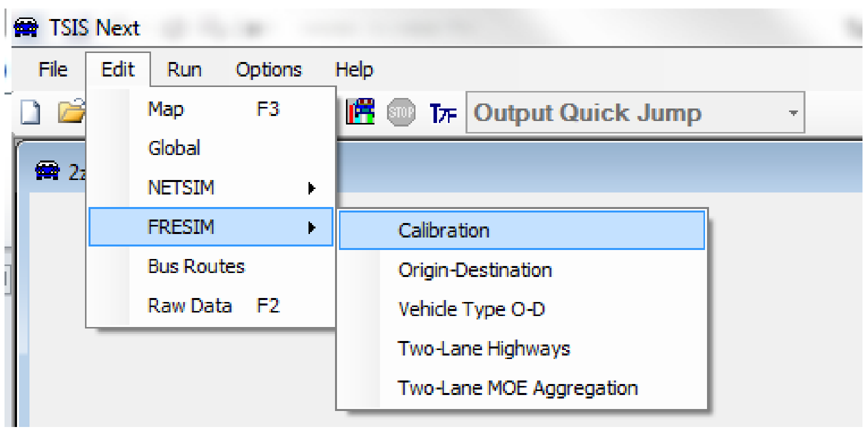


Figure A-12. FRESIM Calibration

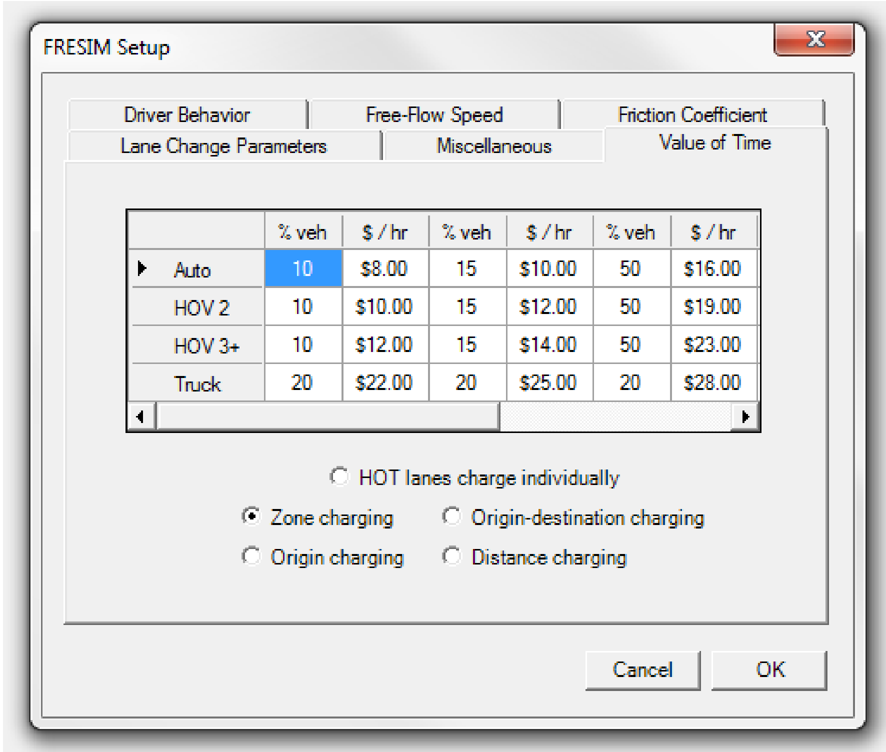


Figure A-13. Value of Time Tab under FRESIM Setup

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, distance-based and origin-destination (OD)-based. The toll structure can be selected in the Value of Time tab under FRESIM Setup, see Figure A-13. Also the option 'HOT lanes charge individually' is provided, which means that each HOT segment functions as a stand-alone single-segment HOT lane facility.

Zone-based Tolling

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

Origin-based Tolling

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

Distance-based Tolling

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

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.

Note that only the former three are fully implemented in CORSIM. OD-based tolling will be implemented in the future.

EXAMPLE

Below we provide an example for coding a multi-segment facility in CORSIM. Assuming that a HOT lane network consists of the following links:

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

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

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

1) HOT lanes charge individually

When the 'HOT lanes charge individually' option is selected, there will be three different toll calculations. These calculations can be done using any of the three pricing schemes available in CORSIM, i.e., responsive, closed-loop-control-based, time-of-day. If the former two, i.e., dynamic pricing, are used:

i) The toll amount at entrance 5a will be calculated based on the average density of segments 5a-7a;

ii) The toll amount at entrance 5b will be calculated based on the average density of segments 5b-7a;

iii) The toll amount at entrance 5c will be calculated based on the average density of segments 5c-7b.

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

2) Zone-based tolling

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

If dynamic pricing is implemented, we have the following:

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

3) Origin-based tolling

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

4) Distance-based tolling

As aforementioned, the distance-based tolling is similar to the zone-based tolling in the sense that zones should be specified for both structures. If we assume that there are two zones, i.e., 5a-7a and 5c-7b, the toll rate displayed on 5a and 5b will be the same. The toll calculation is the same as in the zone-based tolling. However, in distance-based tolling, a driver who exits before the end of a zone will be charged less than in zone-based tolling.

5) OD-based tolling

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

i) 5a-6b
ii) 5a-7a
iii) 5a-6e
iv) 5a-7b
v) 5b-7a
vi) 5b-6e
vii) 5b-7b
viii) 5c-6e
ix) 5c-7b

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

HOT-LANE SIMULATION OUTPUTS

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

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

(a)

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

(b)

Figure A-14. HOT Lane Output

All these columns are further explained in Table A-1

Table A-1. HOT Output Explanation

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