A New Paradigm in User Equilibrium-Application in Managed Lane Pricing

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Abstract

Ineffective use of the High-Occupancy-Vehicle (HOV) lanes has the potential to decrease the overall roadway throughput during peak periods. Excess capacity in HOV lanes during peak periods can be made available to other types of vehicles, including single occupancy vehicles (SOV) for a price (toll). Such dual use lanes are known as “Managed Lanes.” The main purpose of this research is to propose a new paradigm in user equilibrium to predict the travel demand for determining the optimal fare policy for managed lane facilities. Depending on their value of time, motorists may choose to travel on Managed Lanes (ML) or General Purpose Lanes (GPL). In this study, the features in the software called Toll Pricing Modeler version 4.3 (TPM-4.3) are described. TPM-4.3 is developed based on this new user equilibrium concept and utilizes it to examine various operating scenarios. The software has two built-in operating objective options: 1) what would the ML operating speed be for a specified SOV toll, or 2) what should the SOV toll be for a desired minimum ML operating speed.

A number of pricing policy scenarios are developed and examined on the proposed managed lane segment on Interstate 30 (I-30) in Grand Prairie, Texas. The software provides quantitative estimates of various factors including toll revenue, emissions and system performance such as person movement and traffic speed on managed and general purpose lanes. Overall, among the scenarios examined, higher toll rates tend to generate higher toll revenues, reduce overall CO and NOx emissions, and shift demand to general purpose lanes. On the other hand, HOV preferential treatments at any given toll level tend to reduce toll revenue, have no impact on or reduce system performance on managed lanes, and increase CO and NOx emissions.

Keywords: Managed Lanes, User Equilibrium, Pricing Policy

1. INTRODUCTION

Raising the capacity on congested corridors can be achieved geometrically by several means such as building a parallel elevated section or a tunnel along the corridors. Such approaches are generally very costly. Building completely new roads through congested urban corridors is also usually not viable due to a lack of right-of-way availability. As such, when new capacity is added, transportation planners use lane management strategies to manage flows on freeway networks such as express lanes, high-occupancy-vehicle (HOV) lanes, high-occupancy-toll (HOT) lanes and managed lanes (ML).

Recently, managed lanes have become the primary option in attempts to reduce traffic congestion by many agencies. During the past few years, an improvement in traffic throughput is indicated when this lane management strategy is implemented [2], [4], [6], [7], [10], [15], [16], [26], [27]. This improvement results in reductions in travel time, fuel consumption and emissions and an increase in revenue [5].

The managed lane concept is suitable for implementing congestion pricing in corridors, for instance, a highway through a downtown area where adding new general purpose lanes (GPL) is not feasible. Instead, part of GPL is converted for a special use, called the managed lane. The TxDOT Research Monitoring Committee has given a definition of managed lane as *"A managed lane facility is one that increases freeway efficiency by packaging various operational and design actions. Lane management operations may be adjusted at any time to better match regional goals."* [18]. Unlike the conventional toll facilities, the managed lane offers the flexibility of adjusting the tolls and policies depending on the traffic demands and regional objectives.

In the past, all motorists were allowed to use toll facilities and were charged a fixed toll rate. Many economists suggested other approaches and constraints for establishing a toll rate [14]. For example, on uncongested roads, Sharp et al. [25] proposed a toll rate to be set equal to operating costs. Ragazzi [24] suggested that the operations-plus-capital-cost toll can subsidize the general lane users and taxpayers. As a result, these average-cost pricing models set a toll at a certain amount. This operating policy, which allows all vehicle classes to enter the toll road and pay a single rate, would simplify the operational requirements such as the toll setting, operating strategy, system complexity, operating cost, and technology deployment. However, allowing all travelers to access the toll lanes would eventually reduce the facility performance [28].

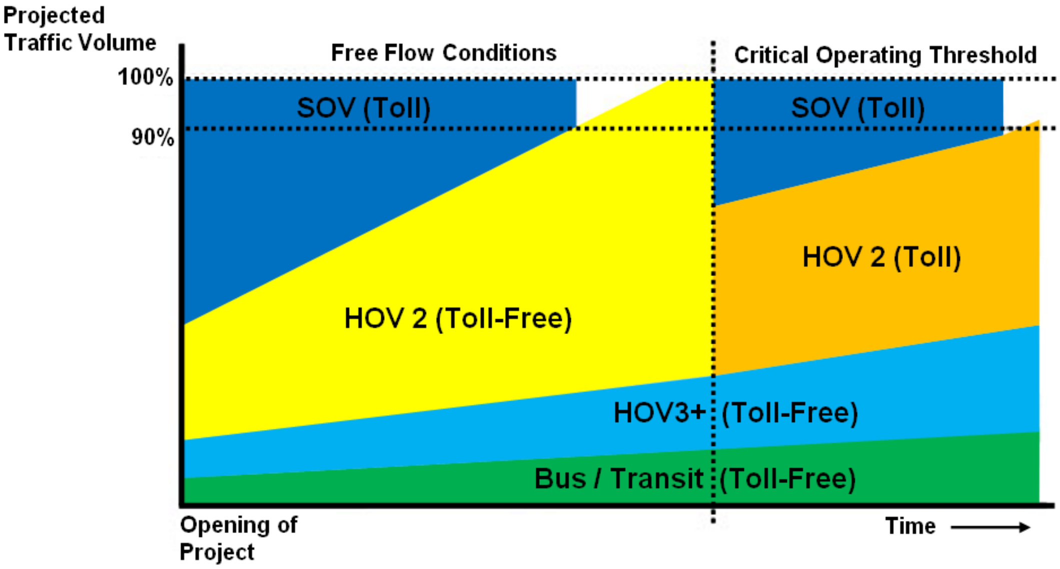


FIGURE 1: Life span of a managed lane.

Figure 1 [9] illustrates the HOV traffic growth over time on managed HOV lanes. The study shows that the projection of managed lanes users increases over time and eventually reaches the road capacity. In other words, a managed lane facility that operates by giving free access to HOV2+ and charging the SOV will eventually become congested due to capacity being exceeded by the HOV2+. As a result, a new policy is needed to solve traffic congestion on managed lanes. In this case, a lack of ability to predict the potential users for each mode in the previous models make planning an optional operating policy difficult. Therefore, a pricing strategy should be capable of analyzing a plan that combines several toll policies among the modes. For examples, as proposed by some transportation agencies, HOV2 could be charged less than SOV; and HOV3+ could get free access [21]. If congestion problems continue on the corridor due to increases in the HOV2 volume, preferential access could only be provided to HOV3+ vehicles.

Due to the underutilization of the HOV facilities, toll pricing strategies have been implemented to utilize the excess capacity on the managed lane facility. However, a number of questions must still be addressed, including how many additional users should be allowed on managed lanes without reaching an unacceptable level of performance, and what should the toll value be corresponding to this level of additional users. These questions pose a challenge for toll pricing studies that attempt to predict the potential users based on toll charges.

Especially, the challenge increases for the facilities that operate using a variety of toll pricing scenarios. Examples may include allowing three classes of vehicles to access the ML and tolling them differently, as well as varying the toll amount by time of day and even day of week. Since flow rates on managed lanes are affected by dynamic toll rates, the pricing strategies become more complex and require a good understanding of changes in demand with respect to toll amounts. Even though previous pricing studies have proposed concepts for pricing the managed lanes to effect a desired level of demand, such concepts are not practical for facilities with various toll rates by class of vehicle and time of day.

Many of the previous studies incorporate an average value of time (VOT) to predict demands and tolls in their respective models. Parsons Brinckerhoff [23] uses the average wage rate to determine the VOT. In their study, the overall network travel time is optimized. Then, one third the average is used as the “low VOT” and one-half the average wage rate is used as the “base VOT” to generate the toll rates for toll roads in Washington State.

Li and Govind et al. [19] developed a tool for the evaluation of pricing strategies using users’ willingness to pay as derived from survey data. Their study has shown that the willingness to pay differs among vehicle classes. Therefore, the assumption that all vehicle classes will have the same response at a certain toll rate seems unreasonable and thus does not allow an accurate prediction of the level of utilization of managed lanes.

He et al. [15] presents a model to assess the impact of the managed lanes on the I-394 corridor in Minnesota. The proposed model is an analytical multiclass stochastic dynamic transportation network model with Monte Carlo simulation and the method of successive averages. They assume a homogenous population of users, so the differences in VOT between the modes are not captured. To achieve an accurate prediction for various classes, the specific VOT distribution of each vehicle class must be used to predict the travel demands.

Wilbur Smith has conducted a toll revenue estimation study for the I-30 Reversible Managed Lanes in the Dallas, TX region [32]. Their estimates are based on the travel demand model databases developed under basic assumptions provided by NCTCOG and micro-simulation using VISSIM. After the model is built, the median VOT is used and several scenarios are examined to measure the impact of different toll rates.

The Toll Pricing Model (TPM-3.1) [1] is developed based on the concepts of price elasticity and the speed-flow-concentration model. TPM-3.1 uses the values for the percentage of users’ willing to pay a certain toll based on data from "stated-preference" surveys. The software can do demand analysis based on one of two objectives. One objective is maintaining a minimum operating speed at a certain level while another is estimating the ML demand and the corresponding operating speed based on a pre-specified toll charge.

More recently, Yin and Lou [34] proposed two toll pricing approaches for managed lane facilities. The first approach applies the concept of a feedback control to determine a toll rate. This concept is easy to implement and requires only one loop-detector. The second concept learns the managed lane users' willingness to pay and determines the pricing strategies to meet the facilities' objectives. This approach requires two sets of loop-detectors to measure the flow rates to be used in calibrating the model parameters.

The objective of this research is to develop a simulation model for volume assignment between managed lanes and general purpose lanes as a function of toll charged for various vehicle classes. As a result, this study proposes a new paradigm in user equilibrium for managed lane networks in order to examine the various operating scenarios to meet operating objectives. A software package known as the Toll Pricing Modeler version 4.3 (TPM-4.3) is developed based on this framework for determining the dynamic toll rates.

This paper has a total of six sections. The next section proposes the concept of a new paradigm in user equilibrium and its components. Section 3 demonstrates a description of the VOT distribution estimates and inputs. Section 4 presents the details of a traffic demand model software package (TPM 4.3) that is developed based on this user equilibrium concept. Section 5 proposes a number of scenarios examined and shows their results. Finally, the conclusions and recommendations are presented in section 6.

2. A NEW PARADIGM IN USER EQUILIBRIUM

In traffic theory, Wardrop's first principle [31] applies to a network where all the used routes between an origin-destination (O-D) pair have the same travel costs under equilibrium conditions. In other words, no one can decrease their travel costs by unilaterally switching to another route. If time spent to drive on each route is the cost, all routes have an equal travel time under equilibrium. In a managed lane network, however, Wardrop's first principle cannot apply directly to determine the equilibrium flows because managed lanes are intended to have a lower travel time when compared to general purpose lanes. Therefore, a new user equilibrium paradigm for managed lanes is needed for incorporation into managed lane demand models.

2.1 Basic Concept and Components

Managed lanes are intended to provide a better level of service in the travel corridor. A typical managed lane travel corridor consists of two types of lanes: general purpose lanes and managed lanes. All travelers can use the general purpose lanes without paying tolls while the managed lanes are tolled with an occupancy restriction. However, the benefit of paying tolls is that the ML travelers are able to experience a higher speed (a lower travel time) relative to GPL travelers in the same travel corridor.

A new paradigm entails two important components: Cost of Time Saving (CTS) and Value of Time (VOT). When commuters travel on managed lane networks, they can choose to travel on either managed lanes or general purpose lanes. CTS is the amount per mile that motorists pay for saving one unit of time (usually measured in minutes) if they choose to take the managed lanes. Mathematically, CTS for the ML can be stated as:

$$CTS = \frac{Toll\ \ per\ \ mile(\$)}{Travel\,Time\,Saving\ \ per\,mile} \tag{1}$$

$$CTS = \frac{T}{\left[(L_{GPL} \times t_{GPL}) - (L_{ML} \times t_{ML})\right] \ / \ L_{ML}} \tag{2}$$

In Equation 1, travel time saving per mile is an average travel time saving per mile that motorists can expect to gain when they travel on managed lanes. In Equation 2, T is a managed lane toll per mile. L_{GPL} and L_{ML} are corridor lengths of general purpose lanes and managed lanes, respectively. Due to this variable (L), this concept can be utilized to examine an impact of toll pricing on alternative toll versus free highway. Both facilities may have the same origin and destination with the different lengths. In this case, GPL inputs are used for the free highway and ML inputs are used for the alternative toll.

In Equation 2, t_{GPL} is the travel time spent for one mile if one chooses to travel on the general purpose lanes and t_{ML} is the travel time spent for one mile if one chooses to travel on managed lanes and pay a toll. The travel times are forecasted based on demand levels using the most common function called the Bureau of Public Roads (BPR) function [11]. If V is the volume per lane and C is the respective capacity per lane on either general purpose or managed lanes, the travel time (t) for each lane can be computed by the following equations:

$$t_{GPL} = 0.8 \times \left[1 + \left(\frac{V_{GPL}}{C_{GPL}} \right)^4 \right] \tag{3}$$

$$t_{ML} = 0.8 \times \left[1 + \left(\frac{V_{ML}}{C_{ML}} \right)^4 \right] \tag{4}$$

The second component is the Value of Time (VOT). VOT is the amount that users are willing to pay for one unit of time saved. In the current study, VOT data derived from previous studies in Texas [12], [20] are utilized. Those studies determine the VOT of the potential users of proposed managed lanes on the I-30 segment in Grand Prairie, Texas, between the cities of Arlington and Dallas. In general, the VOT distribution can be derived by using survey data or other methods to estimate the value of time of the toll users [3], [17].

2.2 Initial and Equilibrium States

The basic concept and components involved in this new paradigm are presented in the previous section. These primary components are the significant factors controlling the volume assignments on the managed lane networks. At an initial state, when a toll is not charged on the managed lanes, the volume is assumed to be equally assigned on both managed lanes and general purpose lanes. In this case, the cost of time savings (CTS) of corridors does not play a role. Later, when a charge is implemented on the tolled lanes, drivers who have a value of time (VOT) higher than the CTS will use the managed lanes in order to save time. On the other hand, drivers who have a VOT lower than CTS will not use the managed lanes and will switch to the general purpose lanes. Due to the change in travel time savings when a motorist switches from ML to GPL or vice versa, CTS is recalculated and compared with the remaining ML users' VOT. The decision rules can be stated as follows:

- Zero toll (CTS = 0) → $V_{ML} = V_{GPL}$, where V_{ML} and V_{GPL} are the volumes of ML and GPL, respectively (Initial loading condition)
- CTS < VOT_i → ML is the choice
- CTS ≥ VOT_i → ML is not chosen

An individual decision (i^{th}) based on their VOT will continually be made on the corridor until the network is stable, i.e., no one else will switch to another lane. At this point, the network's equilibrium is reached and the conditions are satisfied. Under equilibrium conditions, the users' VOT will be equal to the corridor's CTS, i.e., the condition of equilibrium becomes,

$$CTS = VOT \tag{5}$$

The general concept of this new paradigm is that *under user equilibrium conditions, traffic arranges itself in such a way that managed lane users' VOT are equal to or higher than the corridor's CTS and the general purpose lane users' VOT are lower than the corridor's CTS.* If homogeneous travelers (No distinction between vehicle classes such as SOV, HOV2, or HOV3+)

are assumed on the corridor, an average VOT distribution can be used to estimate the volume assignments. In reality, however, various vehicle classes are allowed to travel on the managed lane facility. To approximate the volumes at the equilibrium condition on the managed lane networks, the users' VOT distribution has to be defined for each vehicle class and incorporated into the model.

2.3 Incorporation of Multiple Vehicle Classes

In general, a managed lane facility can operate using different toll policies for multiple vehicle classes. In order to integrate multiple vehicle classes to the new equilibrium concept, additional procedures are developed as follows.

2.3.1 Value of Time Adjustment

Previous researchers [12] have found that the characteristics of the VOT distributions are different among the vehicle classes. Many studies estimate the value of time functions in term of price and travel time saving. These can be converted into a term of VOT and their respective population by applying a travel time saving (see section three). Thus, the proportions of population (*a,b,c,...,z*) based on their VOT can be generated for different vehicle classes (A,B,C,…,Z) and VOT ranges (1,2,3,…,n) as shown schematically in Table 1.

No.	VOT Range ($/hr)	Vehicle Class A	Vehicle Class B	Vehicle Class C	. . .	Vehicle Class Z
1	$0 - VOT_1$	a_1	b_1	c_1	. . .	z_1
2	$VOT_1 - VOT_2$	a_2	b_2	c_2	. . .	z_2
3	$VOT_2 - VOT_3$	a_3	b_3	c_3	. . .	z_3
. . .	. . .	. . .	. . .	. . .	. . . .	. . .
N	$VOT_{n-1} - VOT_n$	a_n	b_n	c_n	. . .	z_n

TABLE 1: Value of Time distributions

Theoretically, in the scenarios where tolls are charged differently for different vehicle classes, CTS must be separately calculated for each class due to unequal tolls (*T)* (Equation 2). However, the VOT distributions can be modified in order to utilize only one equilibrium equation by adjusting the percentages of population in each vehicle class. For example, if R_A is a ratio of toll rate of class A compared to the highest toll rate on the facility, an adjusted VOT percentage (a_{1Adj}) can be calculated as follows:

$$a_{1Adj} = a_1 \times R_A \tag{6}$$

Accordingly, a_{2Adj}, a_{3Adj},…, a_{nAdj} can be computed as follows:

$$a_{nAdj} = \left[\frac{(VOT_n \times R_A) - VOT_{k-1}}{VOT_k - VOT_{k-1}} (a_k) + \sum_{i=1}^{k-1} a_i \right] - a_{n-1Adj} \tag{7}$$

k is the range number where the result of $VOT_n \times R_A$ falls into this range.

After the percentages of population in each vehicle class are adjusted, as shown in Table 2, an equilibrium state can be calculated by using one equation (Equation 5).

No.	VOT Range ($/hr)	Vehicle Class A	Vehicle Class B	Vehicle Class C	. . .	Vehicle Class Z
1	$0 - VOT_1$	a_{1Adj}	b_{1Adj}	c_{1Adj}	. . .	z_{1Adj}
2	$VOT_1 - VOT_2$	a_{2Adj}	b_{2Adj}	c_{2Adj}	. . .	z_{2Adj}
3	$VOT_2 - VOT_3$	a_{3Adj}	b_{3Adj}	c_{3Adj}	. . .	z_{3Adj}
. . .	. . .	. . .	. . .	. . .	. . . .	. . .
n	$VOT_{n-1} - VOT_n$	a_{nAdj}	b_{nAdj}	c_{nAdj}	. . .	z_{nAdj}

TABLE 2: Adjusted Value of Time distributions

2.3.2 Vehicle Conversion

To simulate the behavior of drivers on the managed lane facility, the actual number of vehicles must be known. In this model, the vehicles in all classes are converted into passenger car equivalents. When the passenger-car-equivalency (PCE), the total travel demand, and the percent of vehicles in the mix are given, a number of vehicles in each cell can be computed by the following equation:

$$Z_n = Demand \times Percent\ of\ Class\ Z\ Vehicles\ in\ the\ Mix \times PCE_Z \times z_{nAdj} \qquad (8)$$

where Z_n is the number of class Z vehicles in range n. This actual number of vehicles is computed by multiplying the percentage in each cell by the respective demand, vehicle mix percentage, and PCE. The resulting calculations are summarized in Table 3. For example, A_1 in this table would be the number of class A vehicles with a value of time range of 0 – VOT_1 dollars per hour.

No.	VOT Range ($/hr)	Vehicle Class A	Vehicle Class B	Vehicle Class C	. . .	Vehicle Class Z
1	$0 - VOT_1$	A_1	B_1	C_1	. . .	Z_1
2	$VOT_1 - VOT_2$	A_2	B_2	C_2	. . .	Z_2
3	$VOT_2 - VOT_3$	A_3	B_3	C_3	. . .	Z_3
. . .	. . .	. . .	. . .	. . .	. . . .	. . .
n	$VOT_{n-1} - VOT_n$	A_n	B_n	C_n	. . .	Z_n

TABLE 3: Vehicle conversion

2.3.3 Equilibrium Reaching Concept

The previous sections describe how the VOT percentages of multiple vehicle classes are adjusted and converted into an actual number of passenger car equivalents. This process is key to preparing the data for the model simulation. In this model, when a toll is charged on the managed lanes, a random vehicle from the lowest VOT range among vehicle classes is shifted from the ML to GPL until the equilibrium is reached. This vehicle is randomly selected from a random vehicle class. Internally, CTS and VOT are recalculated, and an equilibrium state is verified every time that a vehicle is shifted from ML to GPL. In conditions where the final volumes fall between the VOT ranges, the model linearly interpolates the VOT between the lower bound and upper bound based on the volumes. However, if all the vehicles in this VOT range are shifted to the general purpose lanes and equilibrium is still not reached, the model will proceed to the next VOT range and continues to shift vehicles from ML to GPL until the equilibrium condition (VOT=CTS) is reached. The equilibrium reaching procedure can be demonstrated as shown in Table 4.

Iteration No.	**Total number of vehicles shifted to GPL**			**ML Volume**	**GPL Volume**	**CTS ($/hr)**		**VOT ($/hr)**
	Vehicle Class A	**Vehicle Class B**	**Vehicle Class C**					
1	0 (0)	1 (1)	0 (0)	Demand (D) - 1	1	CTS_1	>	VOT_1
2	1 (1)	1 (0)	0 (0)	D - 2	2	CTS_2	>	VOT_2
3	1 (0)	2 (1)	0 (0)	D - 3	3	CTS_3	>	VOT_3
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
n	x (0)	y (0)	z (1)	D – (x+y+z)	x+y+z	CTS_n	=	VOT_n

Note: Vehicles shifted to GPL in each iteration are shown in ( )

TABLE 4: Equilibrium reaching procedure

2.4 Application of Flow-Density-Speed (q-k-u) Model

Theoretically, drivers choose to travel on toll lanes when their VOT is higher than the CTS. These decisions directly impact the facility performance. To characterize the performance impact, the flow, density and speed relationship should be derived for the proposed facility. In this study, the result from a traffic flow model study by Nepal [22] is utilized for this purpose. He has found that the Drake [8] model has the best fit on the data collected for freeways in the DFW area. Therefore, the Drake Model is utilized to characterize the relationship between speed, flow, and concentration in the TPM-4.3. The general equation of the Drake Model is shown as Equation 9. However, the model parameters, -0.5 and 2, can also be calibrated through the model calibration process. If a model with new parameters shows a better result (higher R^2), the parameter values can be changed, but is expected to be in the -0.5 and +2 range.

$$u = u_f e^{[-0.5(k/k_c)^2]} \tag{9}$$

Where:

u = speed (mph)
u_f = free flow speed (mph)
k = concentration (pcpmpl)
k_c = concentration at capacity (pcpmpl)

The concentration at capacity (k_c) can be computed by Equation 10 with the given parameters including capacity per lane (q_c) and free-flow speed (u_f). The Drake Model (Equation 9) can be calibrated by obtaining the concentration value from Equation 10 and a given free-flow speed. The Drake Model also yields Equation 11 to estimate the flow (q) as a function of speed and concentration. After a model is calibrated, the TPM-4.3 utilizes Equation 11 to calculate the speed from the flow or the flow from a given speed.

$$k_c = \frac{q_c}{u_f e^{-0.5}} \tag{10}$$

$$q = uk_c \sqrt{-2\ln(u/u_f)} \tag{11}$$

In conditions where demand is higher than capacity but less than twice the capacity, speeds are expected to vacillate between $u = u_f e^{-0.5}$ (at $q = q_c$) and $u = 0$ (at $q = 2q_c$). In those cases, the TPM-4.3 model interpolates the speed between $u_f e^{-0.5}$ and zero for volumes between q_c and $2q_c$. For demands higher than $2q_c$, speed is considered to be zero due to the jam condition.

2.5 Solutions of Analysis Objectives

The operating objectives will vary from one facility to another. In this model, there are two operational objective options. One option is to estimate demands and operating speeds on ML and GPL for a proposed SOV toll charge. A second option is to estimate what the toll charge should be for a desired minimum operating speed on the ML facility.

2.5.1 Toll Objective

In order to measure the impact of toll policies on demand and operating speeds, various SOV toll charges can be examined in the toll objective module. In general, an initial toll rate may be specified based on an existing toll facility in the area. Then, other toll scenarios can be examined to assess the impact on measures of effectiveness such as speeds, emissions and toll revenues. Under this option, the model uses the specified VOT distribution to determine the operational outcomes based on the toll amount specified in the objective option. In conjunction with the facility and user information, the software can then estimate the volumes and speeds on the managed lanes and general purpose lanes. Revenue is accordingly calculated by multiplying the ML volumes by the respective toll rates. Finally, the speed and volume estimates for each respective lane type are used to estimate the expected emissions.

2.5.2 Speed Objective

A second option is to specify a desired average operating speed on managed lanes to determine the corresponding toll charge. For example, in the proposed scenarios, one of the operating objectives could be to maintain the minimum speed on the ML during peak period at 50 mph. This will limit the volume on ML so that the ML will maintain the speed at or above 50 mph. In this case, the model computes toll values, which maintain the desired average speed on the ML. The program output includes the toll amounts to be charged for each vehicle class, the expected volumes and speeds on the both lane types, and the emissions estimates for the travel corridor.

In this option, the model uses the VOT to determine the impact based on the minimum desired speed specified in the objective option. In conjunction with the facility and user information, the software can estimate the corresponding ML volume and GPL volume. The GPL speed can then be computed from the volume. As before, revenue is calculated by multiplying the volumes by the respective tolls. Finally, the speed and volume estimates for each respective lane type are used to estimate expected emissions.

2.6 Emission Estimations

Emission estimates, except for the SO_2 emissions, are based on a number of regression equations which use the average speed as the predictor variable [33]. The SO_2 emission rates are obtained from the information provided by vehicle manufacturers and built into MOBILE6.2 [29]. The regression models for CO, VOC and NOx are developed from the MOBILE6.2 run results. The regression equations for CO_2 are developed based on tailpipe field data from on-board measurements in a passenger car. After the regression equation for passenger cars (SOV&HOVs) is generated, the equations for remaining classes are developed based on the multiplying factors used in MOBILE6.2. To improve emission estimates, future model can incorporate emission modules called Motor Vehicle Emission Simulator (MOVES) [30]. MOVES provides more accurate results and will replace MOBILE6 for all official analyses.

3. VALUE OF TIME DISTRIBUTION

This research was not focused on the accuracy of the value of time (VOT) distribution; however, in order to present a new paradigm for the managed lane networks, a known or assumed distribution must be used. This study used a VOT distribution derived from a stated-preference survey as part of a Texas Department of Transportation (TxDOT) project to study the travel choice behavior of single occupancy vehicle (SOV) travelers between high-occupancy-toll (HOT) lanes and free lanes [20]. This project surveyed a sample of potential HOT lane users in the Dallas-Fort Worth (DFW) area. A total of fifteen mode choice stated-preference questions based on hypothetical travel time savings and toll scenarios were utilized. The scenarios varied tolls at values of one, two, three, four and five dollars per ten miles and travel time savings at values of five, ten and twenty minutes. Each respondent was asked to choose between traveling on HOT lanes or free lanes; and those who chose to use HOT lanes would either pay the toll or convert to high occupancy vehicles (HOV).

Mattingly et al. [20] used logistic regression models to predict the value of a binary dependent variable from a set of independent utility variables. These models estimated the probability that a driver made a decision to travel on a HOT lane under a given price and travel time scenario. The dependent variables in this model were the choice of HOT lane or free lane. The critical variables (travel time savings and toll) for this distribution were derived directly from the stated-preference survey. The SOV binary logit model from the HOT lane study is shown in Table 5. The distribution described by this model is used for generating the VOT input for the SOV class.

Description	Estimated Value
Constant	0.139
Travel Time Saving (mins/10 miles)	0.128
Toll ($/10 miles)	-0.785
-2Log Likelihood	6510.02
Chi-Square	1913.49
ρ^2	0.227
Percentage Correct Estimation	75.7
Percentage Correct Validation	78.8

TABLE 5: SOV binary logit model

The VOT distributions for the HOV class were derived from another TxDOT study [12]. The potential managed lane users in the DFW and Houston areas participated in an Internet survey conducted from May to July, 2006. The survey, tailored to two different cities, was available in both English and Spanish on separate DFW and Houston web sites. The survey asked respondents questions regarding their current travel patterns, reasons for choosing their travel modes, propensity towards managed lanes, as well as socio-demographic characteristics. An adaptive survey ensured that each respondent only received relevant questions. The policy scenarios were also randomized within the context of a previously selected structure for each respondent.

The research also used a stated-preference experiment to assess the decision-making behavior of drivers when choosing between the managed lane (ML) or general purpose lane (GPL). The study presented hypothetical travel time and toll scenarios through four stated-preference questions on mode choice. Each respondent was asked to choose one of six potential travel options: three involved traveling on managed lanes and three on general purpose lanes. The travel time and toll rate would vary in these six alternatives for each of the four scenarios presented to the respondents.

In the stated-preference questions, travel time savings were calculated depending on the input travel distance and randomly assigned speeds for both ML and GPL. A similar technique as for

SOV was used to analyze the VOT distributions for HOV [12]. Table 6 displays the results of the high occupancy vehicle with two occupants (HOV2) and high occupancy vehicle with three or more occupants (HOV3+) binary logit models. In general, except for travel distance, the significant variables included in the HOV2 and HOV3+ models are similar, namely the travel time saving and the toll amount.

Description	HOV2	HOV3+
Constant	-0.553	0.142
Travel Distance (mile)	0.011	-
Travel Time Saving (mins/mile)	1.042	0.868
Toll($/mile)	-7.132	-8.803
Number of Observation -2LL only constant -2LL with variable ρ^2 Percent Correct	860 1182.35 1075.99 0.091 66.2%	212 264.51 247.70 0.064 70.8%

TABLE 6: HOVs binary logit model estimate results

The representative values of time distributions used for the model input are calculated from the binary logit model estimate results. Generally, the VOT distributions for SOV, HOV2 and HOV3+ can be written as Equations 12, 13 and 14, respectively:

$$P_T = \frac{1}{(1+e^{-(0.139+(0.128\times t)-(0.785\times T))})} \tag{12}$$

$$P_T = \frac{1}{(1+e^{-(-0.553+(1.042\times t)-(7.132\times T)+(0.011\times D)})} \tag{13}$$

$$P_T = \frac{1}{(1+e^{-(0.142+(0.868\times t)-(8.803\times T))})} \tag{14}$$

P_T represents a proportion of population who choose to pay a toll T dollars for travel time saving t minutes with travel distance D miles. In order to convert these equations in terms of VOT inputs, the researchers assume a travel time saving of one minute per mile and reformulate the equations in the form of Equations 15, 16 and 17, respectively:

$$P_T = \frac{1}{(1+e^{-1.419+(7.85\, xVOT)})} \tag{15}$$

$$P_T = \frac{1}{(1+e^{-0.5+(7.132\, xVOT)})} \tag{16}$$

$$P_T = \frac{1}{(1+e^{-1.01+(8.803\, xVOT)})} \tag{17}$$

*VOT*s in the above equations are in dollars per minute. The proportion of population who choose to pay a toll *T* dollars for a travel time saving of one minute on a one-mile section can now be defined as the proportion of population *P* who has a value of time greater than *VOT* assumed in the analysis. Equations 15, 16 and 17 specify the VOT distributions, and they are used to generate the VOT inputs in this study. As a result, the percentages of population are calculated for a total of ten intervals with the bandwidth of three dollars per hour, as shown in Table 7.

The absence of previous studies on the VOT distribution for the other vehicle classes is noted through the literature review. This study assumes HOV3+'s VOT distribution for the remaining classes. However, if transportation planners are interested in analyzing impact of the other vehicle classes on the managed lane, a similar survey of SOV and HOVs should be conducted to obtain the VOT distribution for those modes.

VOT ($/hr)	Percentage of Population	HOV2	HOV3+
0.00 - 3.00	26.4%	46.4%	36.1%
3.01 - 6.00	8.3%	8.9%	10.6%
6.01 - 9.00	9.3%	8.6%	10.9%
9.01 - 12.00	9.8%	7.8%	10.2%
12.01 - 15.00	9.5%	6.7%	8.8%
15.01 - 18.00	8.6%	5.5%	6.9%
18.01 - 21.00	7.2%	4.3%	5.2%
21.01 - 24.00	5.8%	3.3%	3.7%
24.01 - 27.00	4.4%	2.4%	2.5%
> 27.00	10.7%	6.2%	5.0%

TABLE 7: VOT inputs

4. THE TOLL PRICING MODEL

A toll pricing model (TPM-4.3) is developed based on the user equilibrium concept for managed lanes described in section two. This section describes the software features to estimate the demands on the managed lane and general purpose lane, among other performance outcomes.

4.1 Facility Information

The facility information includes all the necessary details about the GPL and ML facilities such as number of lanes, corridor length and parameters to utilize the calibrated flow-density-speed models. A number of input parameters must be specified, as follows:

- ***Flow-Density-Speed (q-k-u) model.*** The (model) option is chosen to characterize the performance impact. The specified flow-density-speed relationship should be calibrated for the facility under study or a similar facility.
- ***Number of Lanes.*** The number of lanes is a total number of lanes for each lane type on the corridor. The inputs are separated for managed lanes and general purpose lanes.
- ***Free-Flow Speed.*** Free-flow speed is an average free-flow speed (in mph) in the study corridor. This value should be established when calibrating the flow-density-speed model.
- ***Capacity Per Lane.*** Capacity per lane is a maximum lane flow (in pcphpl) for freeway conditions.
- ***Jam Density.*** Jam density is the concentration at which speeds approach zero (in pcpmpl). This value is required only when the Greenshields model [13] is specified.
- ***Corridor Length.*** The corridor length is a total length (in miles) of the roadway segment. Although the lengths of the ML and the GPL are the same, this is not an absolute requirement. The ability to specify different lengths allows for analysis of two alternative travel corridors unequal in length, one toll and one non-toll.

4.2 User Information

User information requires all the necessary details related to the corridor users such as the vehicle mix, Passenger Car Equivalency (PCE), toll policy, demand, and dead setter percentages. These input variables can be specified as follows:

- ***Vehicle Mix.*** Vehicle mix is the percentage of each vehicle type in the travel corridors. It defines the total number of vehicles for each vehicle type presented in the traffic stream under investigation.
- ***Passenger Car Equivalency (PCE).*** The passenger car equivalency factor (PCE) is a multiplier used to convert a mixed vehicle flow into an equivalent passenger car flow.
- ***Toll Policy.*** Toll policy defines the toll amount for each vehicle class allowed to travel on managed lanes. Toll policies for different classes of vehicles can be specified as a percent of the SOV toll.
- ***Corridor Demand.*** Corridor demand is an expected total directional demand (in vph) including all vehicles in the ML and GPL regardless of vehicle type.
- ***Dead Setters.*** Dead setters are defined as the percent of each vehicle class, except SOV, choosing to use GPL regardless of the amount of toll on ML. This could be due to thier specific origin-destinations or other driver behavioral reasons.

4.3 Value of Time Distributions

VOT distributions reveal the time values for study areas and estimate the potential managed lane users. The value of time distribution is entered separately for each vehicle class. The VOT inputs were presented in section three.

4.4 Analysis Objectives

In the TPM-4.3, the user can select one of two proposed managed lane operational objectives. One option is to set a SOV toll to estimate demands and operating speeds on the ML and GPL. A second option is to set a desired minimum operating speed on the ML facility to estimate the toll amount that should be charged to maintain the desired speed.

4.5 Software Output

After specifying the objective, the results are computed and presented in the output summary. The outputs are road performances, revenues, and emissions, as follows:

- ***Volume.*** Volume is a measure of the demand (in vph). Volumes are shown for each lane type when the equilibrium is reached.
- ***Speed.*** Speed is an average speed (in mph) computed for each lane. Speeds are computed based on the estimated volumes at equilibrium if the toll objective is chosen.
- ***Percentage Share.*** Percentage ML share is the percentage of total users who use the ML. It is calculated for each vehicle class separately.
- ***Toll Charge.*** Toll charges are based on the SOV toll and the toll policies for other vehicle classes. Tolls are calculated according to the percentage of SOV charges specified.
- ***Total Revenue.*** Total revenue is the total toll amount collected from all managed lane users. It is computed based on the toll users estimates.
- ***Emission Summary.*** Emission estimates including CO, HC, NOx, CO_2 and SO_2 are presented for each vehicle class.

5. CASE STUDY AND IMPACT ESTIMATES

The main purpose of the impact analysis is to provide quantitative estimates of how different high occupancy vehicle (HOV) preferential treatments impact toll revenue, air quality, and system performance for the managed lanes and general purpose lanes. The Toll Pricing Model (TPM-4.3) developed under the new user-equilibrium paradigm described in the previous section, is used as a tool to estimate impacts of twenty-four pricing scenarios.

5.1 Case Study

As a case study, a future managed lane segment on I-30 in Grand Prairie, Texas, between the cities of Dallas and Arlington, is modeled to examine a set of proposed operating scenarios. The required inputs, including geometric configuration and the user composition of the facility, are presented below.

- The Drake model is used with free-flow speed of 80 mph and a lane capacity of 2200 pcphpl.
- Corridor demand is assumed to be 11,000 vph and the dead setters are set at 5 percent.
- This study section is five-miles long with two toll lanes and four free lanes.
- The vehicle mix includes 76.4% SOV, 10% HOV2, 5% HOV3+, 1.5% Van-Pool, 0.5% Para-Transit, 0.2% Bus, 0.8% Light Freight truck, 5.2% Single Trailer truck and 0.4% Double Trailer truck [12].
- The PCE for SOV, HOV2, HO3+, Van-Pool, Para-Transit, Bus, Light Freight, Single Trailer and Double Trailer are 1, 1, 1, 1.2, 1.5, 1.2, 1.2, 1.5, 2.0 and 3.0, respectively [12].
- SOV is charged at full toll rates based on the scenarios. HOV2, HOV3+ and Van-Pools are either half-price or free, and Para-Transit and Buses are free.
- The VOTs are based on the values presented in section three.

Scenario	Corridor Length (miles)	Toll Amount ($/mile)				ML Speed (mph)
		SOV	HOV2	HOV3+	Trucks	
1	5	$0.10	SOV	SOV	Not on ML	-
2	5	$0.10	Free	Free	Not on ML	-
3	5	$0.10	0.5xSOV	0.5xSOV	Not on ML	-
4	5	$0.10	0.5xSOV	Free	Not on ML	-
5	5	$0.10	SOV	0.5xSOV	Not on ML	-
6	5	$0.10	SOV	Free	Not on ML	-
7	5	$0.25	SOV	SOV	Not on ML	-
8	5	$0.25	Free	Free	Not on ML	-
9	5	$0.25	0.5xSOV	0.5xSOV	Not on ML	-
10	5	$0.25	0.5xSOV	Free	Not on ML	-
11	5	$0.25	SOV	0.5xSOV	Not on ML	-
12	5	$0.25	SOV	Free	Not on ML	-
13	5	$0.50	SOV	SOV	Not on ML	-
14	5	$0.50	Free	Free	Not on ML	-
15	5	$0.50	0.5xSOV	0.5xSOV	Not on ML	-
16	5	$0.50	0.5xSOV	Free	Not on ML	-
17	5	$0.50	SOV	0.5xSOV	Not on ML	-
18	5	$0.50	SOV	Free	Not on ML	-
19	5	-	SOV	SOV	Not on ML	65
20	5	-	Free	Free	Not on ML	65
21	5	-	0.5xSOV	0.5xSOV	Not on ML	65
22	5	-	0.5xSOV	Free	Not on ML	65
23	5	-	SOV	0.5xSOV	Not on ML	65
24	5	-	SOV	Free	Not on ML	65

TABLE 8: Policy scenarios

A total of 24 policy scenarios are tested on the proposed managed lane section. The policies can be divided into four subsets: 1 to 6, 7 to 12, 13 to 18, and 19 to 24 as shown in Table 8. Each subset includes six different pricing scenarios with various preferential treatments for HOV2 and HOV3+ vehicles. Subsets one to three are analyzed by toll objectives, which cover prices ranging from $0.10/mile to $0.50/mile. The fourth subset is run by maintaining the managed lane speed at 65 mph, with the same preferential treatment scenarios as the first three subsets. These inputs will be entered into TPM-4.3 to estimate outcomes such as traffic volume, speed, revenue and emissions for the ML and GPL.

5.2. Impact Estimates

Table 9 displays the impact estimates of various HOV preferential treatment policies presented in Table 8. The first two scenarios for each subset begin with a scenario of the least preferential treatment (tolled same as SOV) and the most preferential treatment (free) for HOV followed by four more scenario variations for intermediate HOV preferential treatments.

5.2.1 Policy Scenarios 1 to 18

In Table 9, scenarios 1 to 6 have a SOV toll of \$0.10/mile, scenarios 7 to 12 are at \$0.25 /mile and scenarios 13 to 19 specify a SOV toll of \$0.50/mile. CO and NOx emissions show little to no change within each subset regardless of the preferential treatment for HOV2 and HOV3+, but they are significantly reduced when toll amounts increase (Table 5.2). When compared with the first two subsets, subset three, which includes scenarios 13 to 18 results in an increase in CO_2 and VOC. Scenarios 13 and 17, which have ML volumes less than 1800 vehicles per hour, result in the lowest NOx emission, and a decrease in CO emissions when compared to other scenarios.

System performance varies little within scenario subsets, but it differs greatly across the scenarios. The peak-hour average speeds on the ML increase with larger charges. As expected, the GPL becomes more congested under higher toll scenarios due to decreasing use of ML. For ML, volumes vary from 1,723 to 3,472 vph. For GPL, volumes vary from 7,528 to 9,278 vph (Table 5.2). Scenarios 13 to 18, with tolls of \$0.50/mile, show significant differences in the level of performance between ML and GPL. Among scenarios with a full toll price of \$0.50/mile, the charge-all scenario (scenario 13) has the highest impact on speeds, with 77 mph for ML and 30 mph for GPL, and results in the lowest CO (76.9 kilograms/mile) and NOx (4.34 kilograms/mile) emissions, and the highest toll revenue of \$4,115 per hour.

Peak hour revenues range from \$832 to \$4,115. Exempting the HOVs from paying tolls would, as expected, result in the lowest peak revenue. Conversely, charging HOV the same toll as SOV results in the highest revenue. The second greatest peak hour revenue in each subset is attained by charging the HOV2s the same toll as the SOV and charging the HOV3+ half as much. Naturally, as the scenarios become more preferential towards the HOV2 and HOV3+, toll revenues decrease.

5.2.2 Policy Scenarios 19 to 24

Policy scenarios 19 to 24, with tolls as low as \$0.02/mile and as much as \$0.03/mile, are aimed at maintaining the ML speed at 65 mph. These scenarios result in the same GPL speed at 62 mph. They show little difference in VOC emission, and no change is observed for other emissions. Scenario 19 results in the highest ML volume of 3,757 vph. Scenario 20, with the maximum HOV preferential treatment, yields the lowest peak hour toll revenue of \$289. Scenario 24 which charges SOV and HOV2 at \$0.03/mile and HOV3+ at half price yields the maximum peak hour revenue of \$445.

TABLE 9: Impact estimates using the TPM-4.3

Scenario	Toll Amount ($/mile)			Peak Hr. Volume (vph)		Peak Hr. Avg. Speed (mph)		Peak Hr. Emissions (Kilograms/mile)					Peak Hr. Corridor Revenue ($/peak hr)
	SOV	HOV2	HOV3+	ML	GPL	ML	GPL	CO	VOC	NOx	CO$_2$	SO$_2$	
1	$0.10	SOV	SOV	3344	7656	69	58	114.4	0.983	4.77	1,987	0.084	$1,634
2	$0.10	Free	Free	3472	7528	67	60	117.2	0.983	4.80	1,977	0.084	$832
3	$0.10	0.5xSOV	0.5xSOV	3381	7619	68	59	115.7	0.983	4.79	1,982	0.084	$1,478
4	$0.10	0.5xSOV	Free	3404	7596	68	59	115.8	0.985	4.79	1,982	0.084	$1,224
5	$0.10	SOV	0.5xSOV	3357	7642	69	58	114.4	0.984	4.77	1,987	0.084	$1,562
6	$0.10	SOV	Free	3380	7620	68	59	115.7	0.984	4.79	1,982	0.084	$1,308
7	$0.25	SOV	SOV	2622	8378	73	40	88.0	0.972	4.44	2,199	0.084	$3,182
8	$0.25	Free	Free	2959	8041	71	52	104.6	0.970	4.64	2,034	0.084	$1,438
9	$0.25	0.5xSOV	0.5xSOV	2714	8286	73	41	89.5	0.972	4.46	2,178	0.084	$2,925
10	$0.25	0.5xSOV	Free	2791	8209	72	43	91.8	0.968	4.48	2,144	0.084	$2,327
11	$0.25	SOV	0.5xSOV	2660	8340	73	40	88.1	0.973	4.44	2,198	0.084	$3,062
12	$0.25	SOV	Free	2739	8261	73	42	90.8	0.970	4.48	2,160	0.084	$2,469
13	$0.50	SOV	SOV	1723	9278	77	30	76.9	1.016	4.34	2,503	0.084	$4,115
14	$0.50	Free	Free	2179	8821	75	35	82.1	0.986	4.38	2,322	0.084	$925
15	$0.50	0.5xSOV	0.5xSOV	1853	9147	77	31	78.1	1.012	4.35	2,459	0.084	$3,772
16	$0.50	0.5xSOV	Free	2014	8986	76	33	80.1	0.997	4.36	2,385	0.084	$2,770
17	$0.50	SOV	0.5xSOV	1779	9221	77	31	77.9	1.010	4.34	2,463	0.084	$3,959
18	$0.50	SOV	Free	1936	9064	76	32	78.9	1.004	4.35	2,420	0.084	$2,930
19	**$0.02**	SOV	SOV	3757	7243	**65**	62	120.0	0.982	4.83	1,970	0.084	$368
20	**$0.03**	Free	Free	3733	7267	**65**	62	120.0	0.981	4.83	1,970	0.084	$289
21	**$0.02**	0.5xSOV	0.5xSOV	3751	7249	**65**	62	120.0	0.983	4.83	1,970	0.084	$330
22	**$0.03**	0.5xSOV	Free	3733	7267	**65**	62	120.0	0.982	4.83	1,970	0.084	$406
23	**$0.02**	SOV	0.5xSOV	3750	7250	**65**	62	120.0	0.983	4.83	1,970	0.084	$350
24	**$0.03**	SOV	Free	3733	7267	**65**	62	120.0	0.982	4.83	1,970	0.084	$445

5.3 Sensitivity Analysis

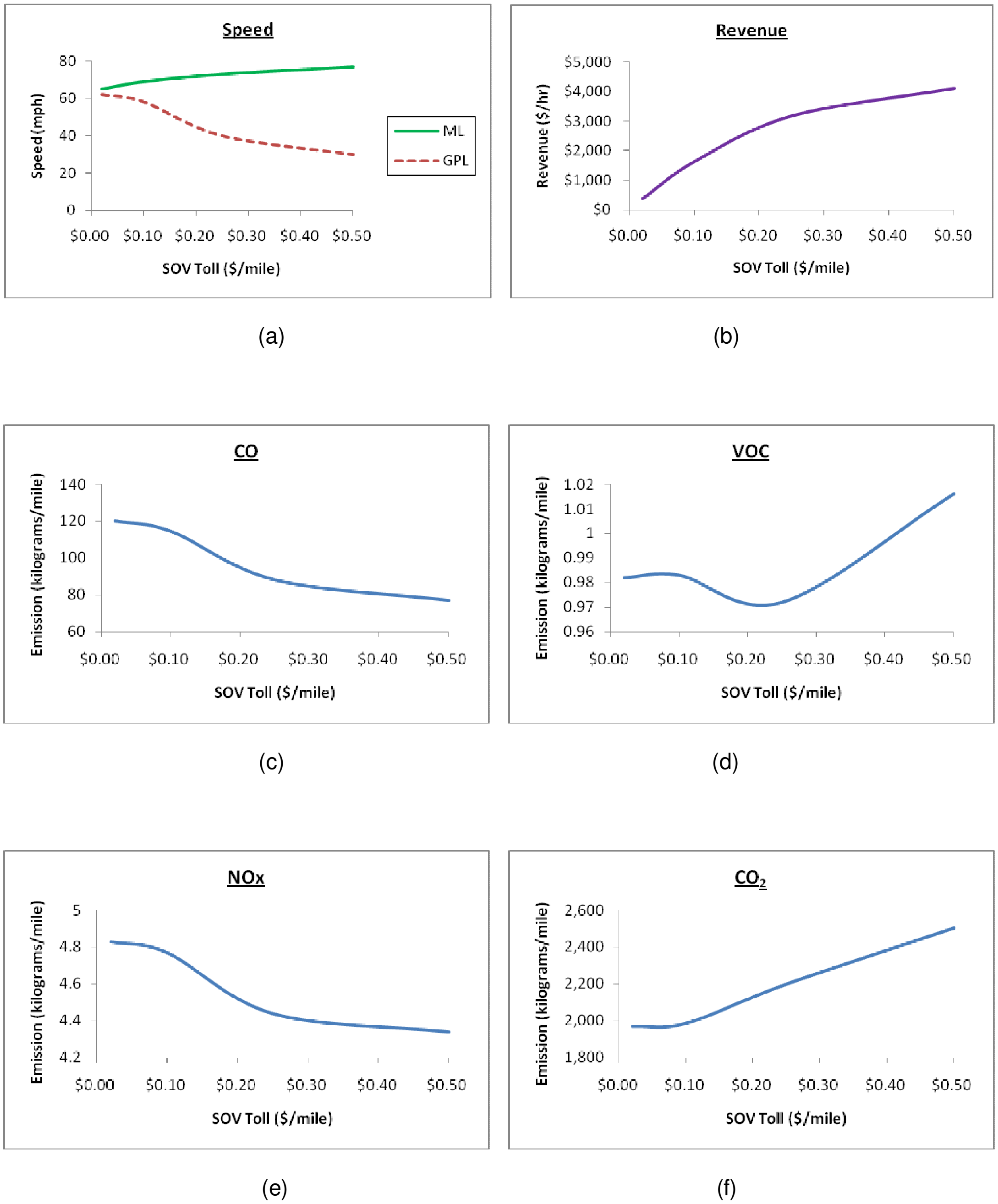
In this section, sensitivity analysis is performed and the results are graphically presented to better explain the relationship between various operational outcomes and toll rates as well as demand levels.

5.3.1 Toll Rate Sensitivity

Figures 2 through 7 illustrate the toll sensitivity curves under various toll policies. The figures show the effects that toll rates have on average speed on both managed lanes (ML) and general purpose lanes (GPL), revenue and emissions. Graph (a) in each figure presents the average operating speeds on ML and GPL. As seen, the speeds between ML and GPL slightly differ at low toll rate (< $0.10) and the difference increases when toll is increased. This also shows that increasing the average operating speed on the ML can be achieved by implementing a higher toll rate.

Graph (b) in each figure shows the estimated revenue collected from the proposed managed lane facility. As toll increases, revenue also increases to a point where the maximum revenue is reached (Figure 3) or the curve slope starts decreasing.

Graphs (c) through (f) in each figure show the relationship between toll rate and emissions. As seen, CO (graphs (c)) and NOx (graph (e)) decrease when toll increases. In contrast, CO_2 (graphs (f)) increases as toll increases. An increase in CO_2 is associated with a reduction in CO and NOx. Interestingly, as toll increases, VOC (graphs (d)) drops to the minimum level at toll rate between $0.20 and $0.25.

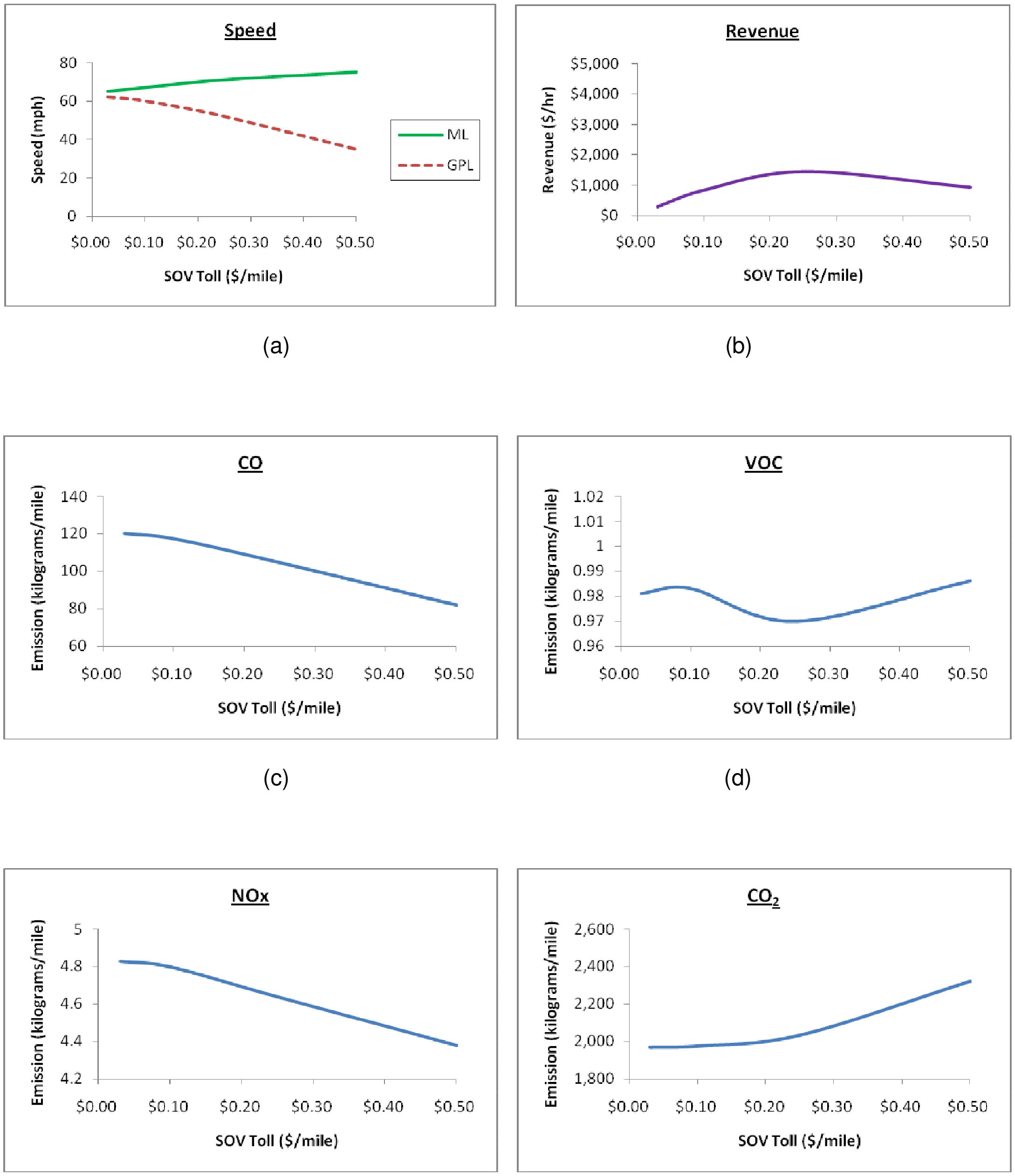


(a) (b)

(c) (d)

(e) (f)

FIGURE 2: Operational outcomes for policy: HOV2 toll = SOV and HOV3+ = SOV;
(a) Speed, (b) Revenue, (c) CO, (d) VOC, (e) NOx, (f) CO_2.

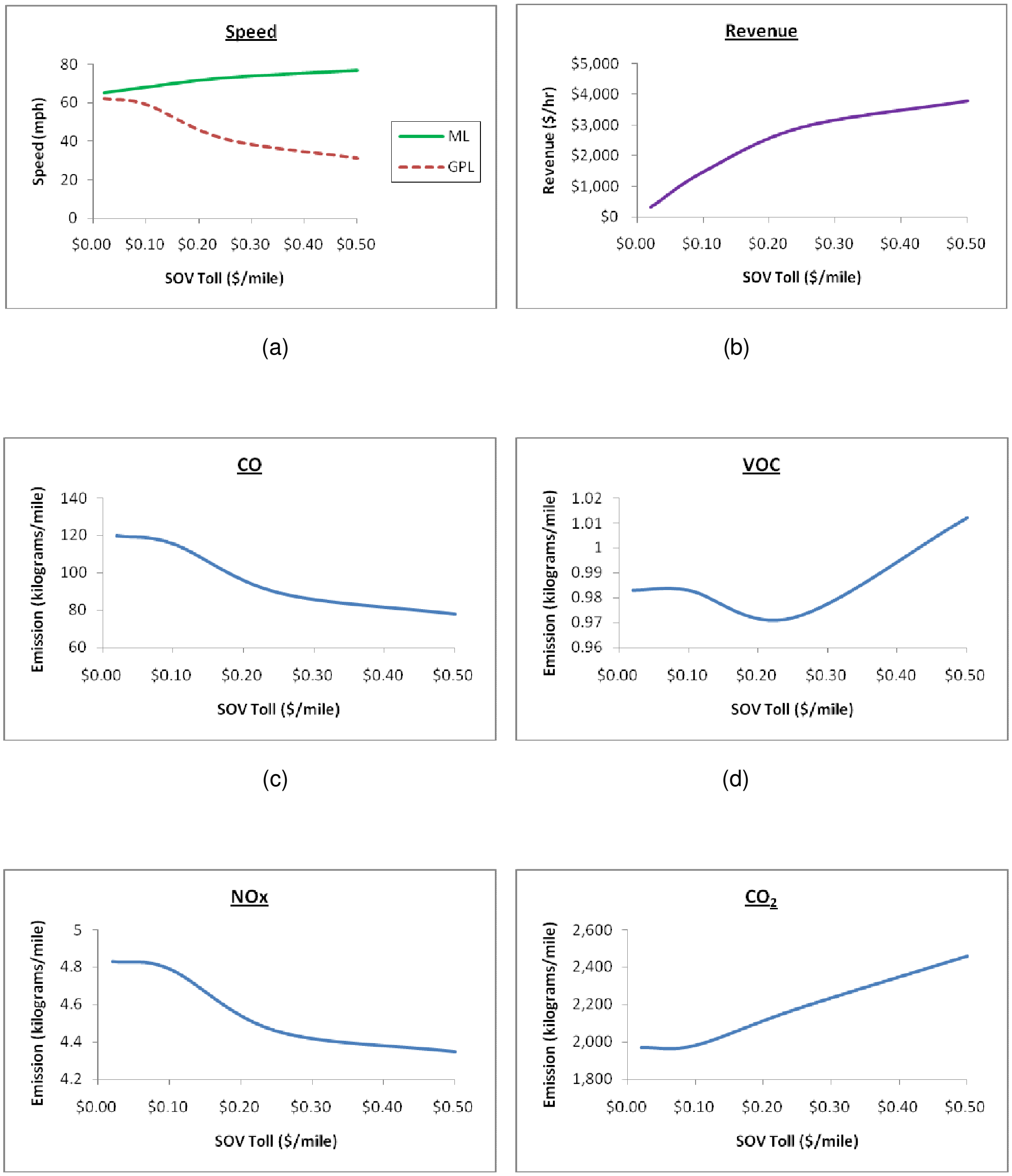


(a) (b)

(c) (d)

(e) (f)

FIGURE 3: Operational outcomes for policy: HOV2 toll = Free and HOV3+ = Free; (a) Speed, (b) Revenue, (c) CO, (d) VOC, (e) NOx, (f) CO_2.

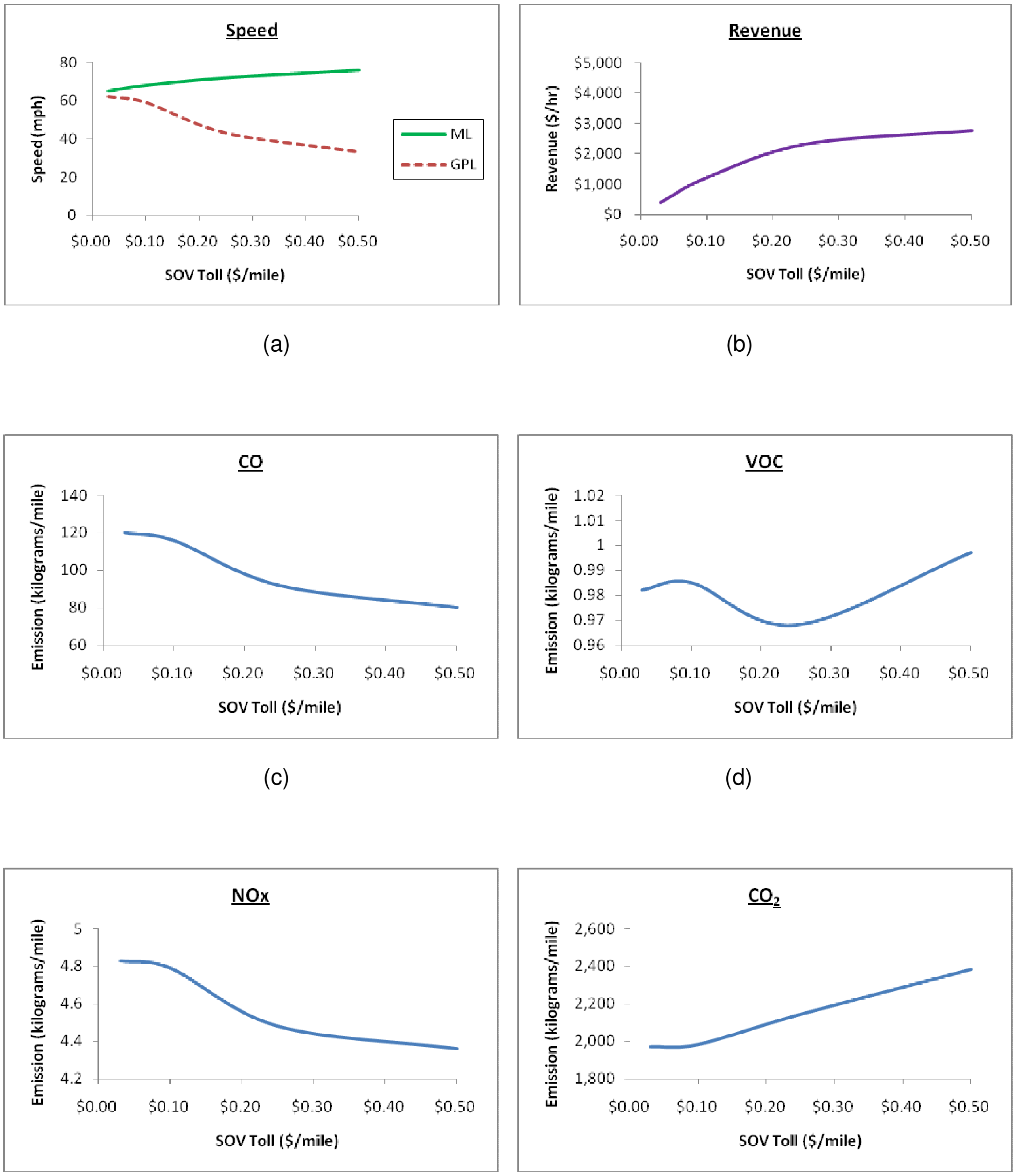


(a) (b)

(c) (d)

(e) (f)

FIGURE 4: Operational outcomes for policy: HOV2 toll = 50%SOV and HOV3+ = 50%SOV; (a) Speed, (b) Revenue, (c) CO, (d) VOC, (e) NOx, (f) CO_2.

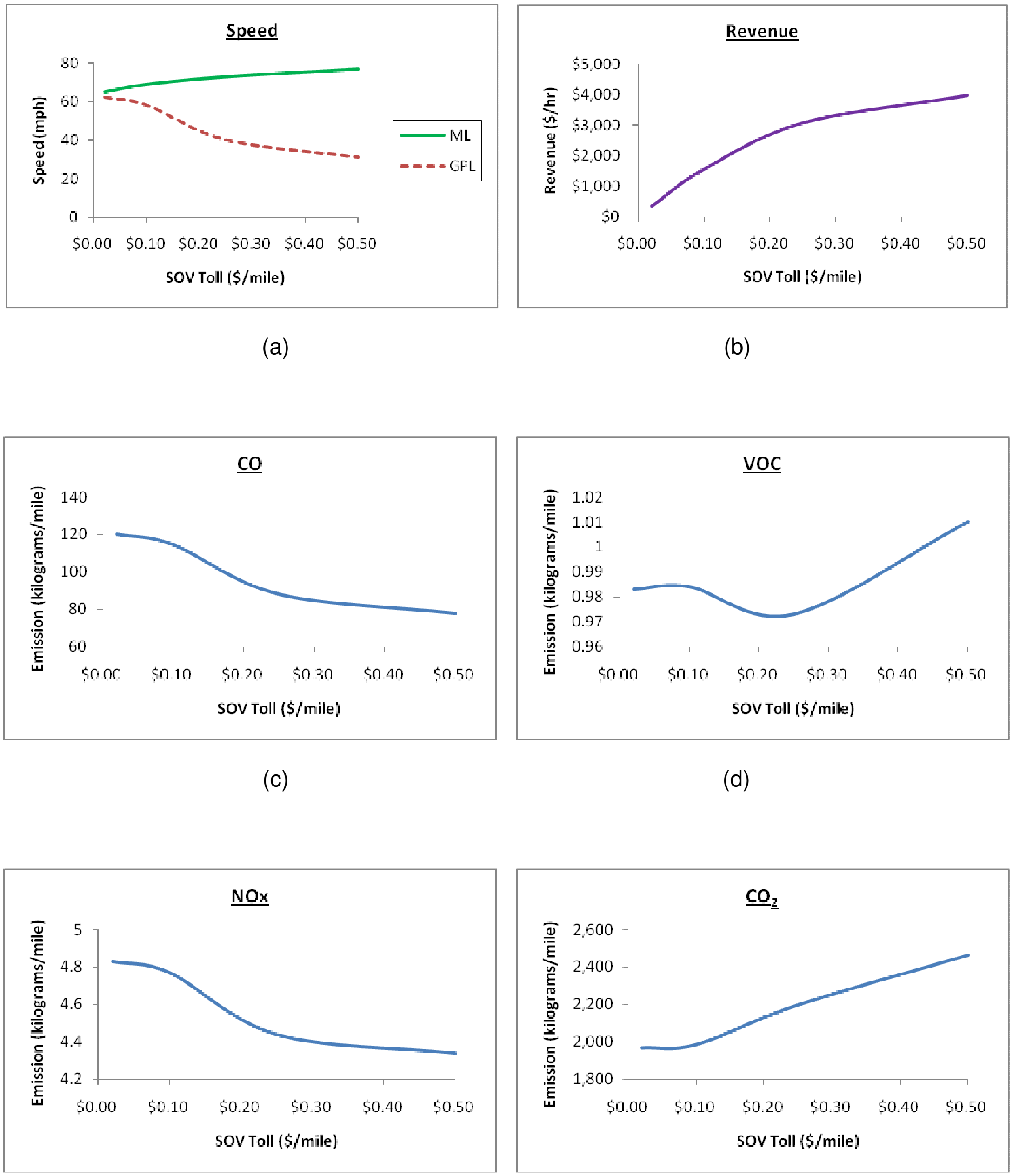


(a) (b)

(c) (d)

(e) (f)

FIGURE 5: Operational outcomes for policy: HOV2 toll = 50%SOV and HOV3+ = Free; (a) Speed, (b) Revenue, (c) CO, (d) VOC, (e) NOx, (f) CO_2.

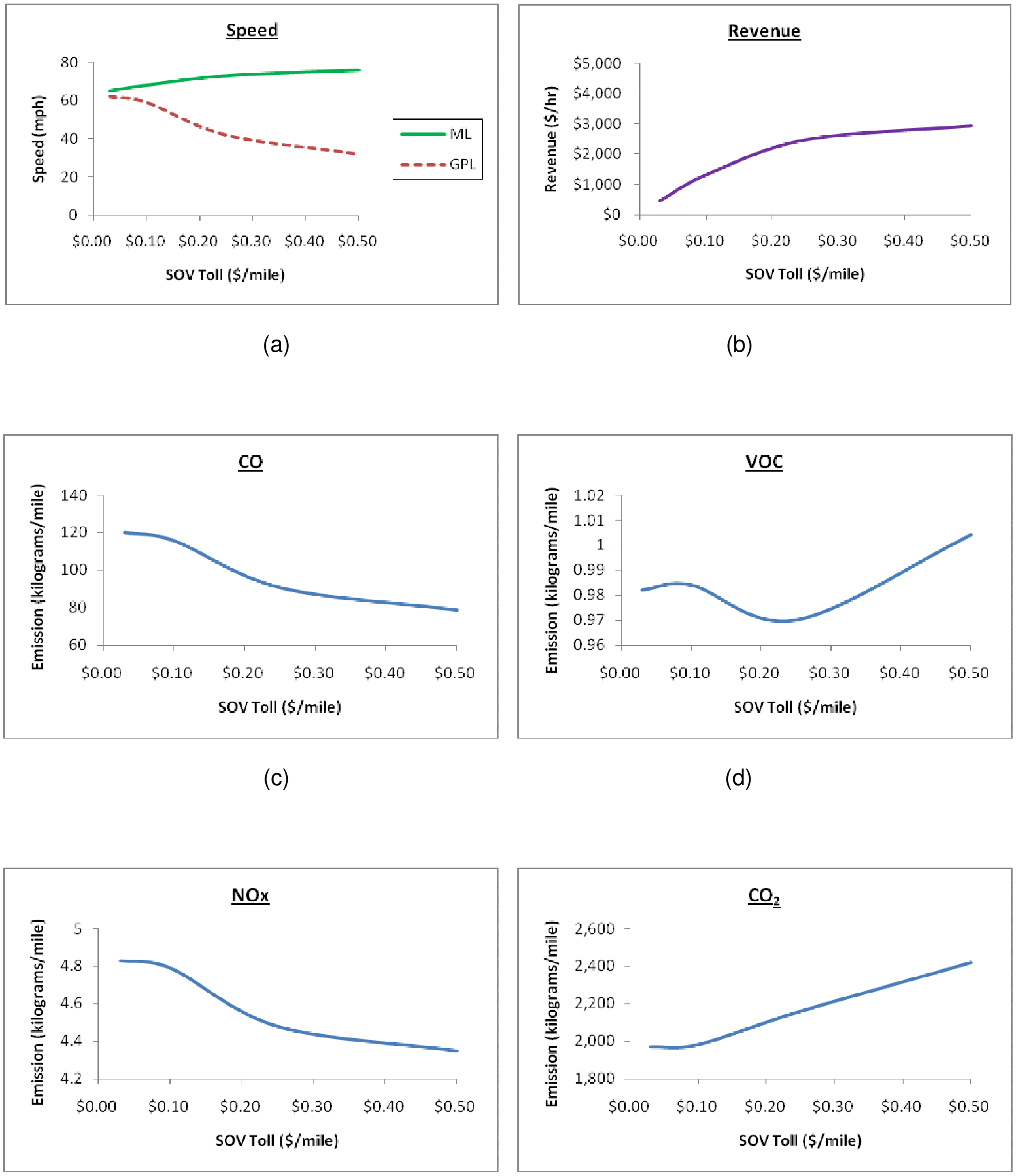


(a) (b)

(c) (d)

(e) (f)

FIGURE 6: Operational outcomes for policy: HOV2 toll = SOV and HOV3+ = 50%SOV;
(a) Speed, (b) Revenue, (c) CO, (d) VOC, (e) NOx, (f) CO_2.



(a) (b)

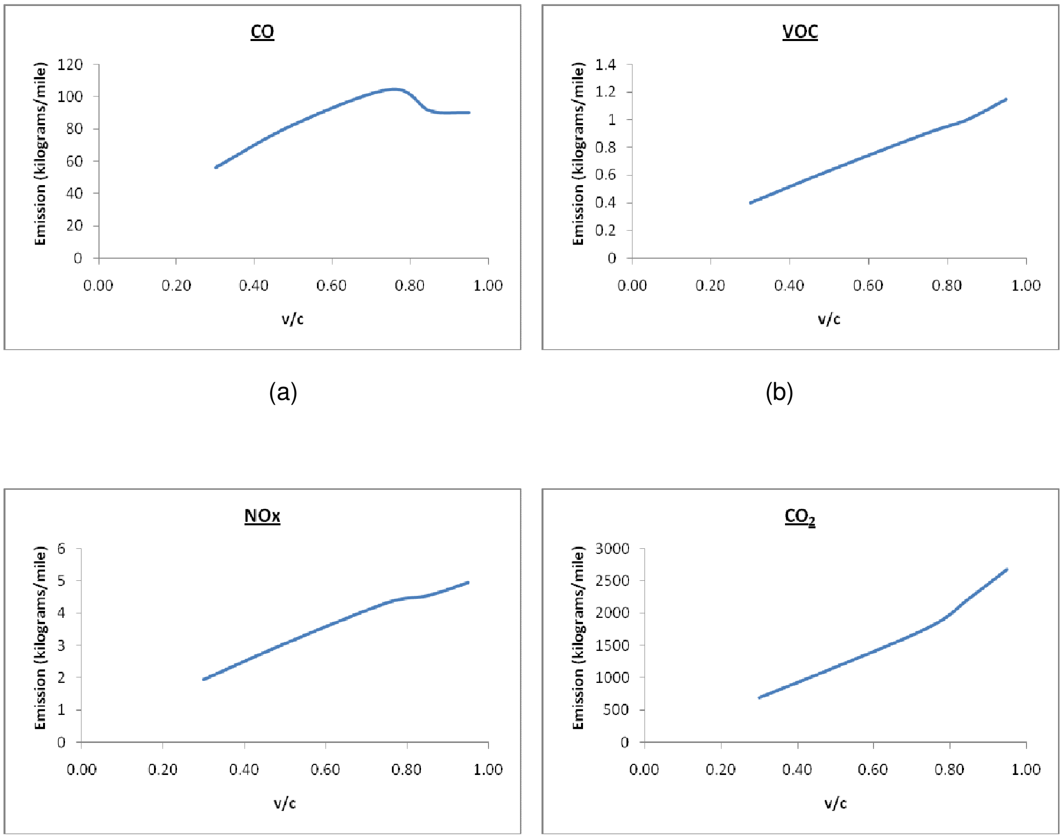
(c) (d)

(e) (f)

FIGURE 7: Operational outcomes for policy: HOV2 toll = SOV and HOV3+ = Free; (a) Speed, (b) Revenue, (c) CO, (d) VOC, (e) NOx, (f) CO_2.

5.3.2 Demand Sensitivity

Figure 8 shows the demand sensitivity curves based on the per mile policy of SOV toll = $0.25, HOV2 toll = $0.125 and HOV3+ = Free. Graphs (a), (b), (c) and (d) illustrate the relationship between demand level (v/c) and the amounts of CO, VOC, NOx and CO_2, respectively. As seen, the amounts of all emissions increase as demand increases, except for CO. In general, lesser speed emits lower CO. When demand is greater than 75% of the capacity, speeds on both GPL and ML drop. This results in reduction in CO.



(a) (b)

(c) (d)

FIGURE 8: Emissions emitted at different demand levels (v/c) based on the policy of SOV toll = $0.25, HOV2 toll = $0.125 and HOV3+ = Free;
(a) CO, (d) VOC, (e) NOx, (f) CO_2.

5.4 Impact Summary

Based on the results, impacts on system performance, emissions and revenue can be summarized as follows:

5.4.1 System Performance Impacts

Based on the stated-preference price sensitivities derived from previous studies for Texas drivers, tolls below $0.10/mile tend to equally spread out vehicles in both the GPL and ML. As a result, there would be no significant difference in speeds between the GPL and ML. Charging a toll of $0.25/mile or higher would increase system performance on the ML and reduce system performance on the GPL. In each subset, HOV preferential treatments have little impact on the overall system performance. However, lower HOV preferential treatment (higher tolls) would increase system performance on the ML.

Maintaining a speed of 65 mph on the ML requires a tradeoff between toll rate and HOV preferential treatment, namely, either a SOV toll rate of $0.02/mile with no HOV preferential treatment, or a toll rate of $0.03/mile with free HOV access, or some combination of these pricing policies.

5.4.2 Emissions Impacts

As seen, the most preferential treatment scenario generates the most CO and NOx emissions. Regardless of the toll policy, no change in the amount of peak hour SO_2 emissions is observed. Trucks are by policy not allowed on the ML. Scenarios 13 to 18 have the greatest CO_2 emissions followed by scenarios 7 to 12. The greatest reduction in CO and NOx emissions occurs in scenarios at the toll level of $0.50/mile. Among all scenarios, the policy with a toll rate of $0.50/mile and no HOV preferential treatment results in the least CO and NOx emissions. It is observed that a reduction in NOx is generally associated with an increase in VOC.

5.4.3 Revenue Impacts

Although HOV preferential treatments do not significantly affect peak hour system performance, they do negatively impact the peak hour revenue. In general, a lower HOV preferential treatment (higher tolls) results in an increase in overall toll revenues. In scenarios where HOV has free access to ML, revenue is observed to be the smallest for every subset. The maximum revenue of $4,115 per peak hour is obtained in scenario 13 at a toll of $0.50 with the least preferential treatment for HOV, followed by $3,959 and $3,772 for scenarios 17 and 15, respectively.

Overall, except for the highest preferential treatment scenarios for HOV, higher toll rates tend to generate higher toll revenues, reduce overall CO and NOx emissions, and shift travel demand to GPL. HOV preferential treatments at any given toll level tend to reduce toll revenue, either have no impact or reduce system performance on ML, and increase CO and NOx emissions.

6. CONCLUSIONS AND RECOMMENDATIONS

This research developed and implemented the Toll Pricing Modeler version 4.3 (TPM-4.3) for a dynamic toll pricing study for multiple vehicle classes based on a new paradigm in user equilibrium. The TPM-4.3 was utilized to estimate impacts of toll pricing scenarios on system performance, toll revenue and emissions on the proposed I-30 managed lane facility in Texas by using value of time (VOT) distributions derived in the Dallas-Fort Worth area. For each vehicle class, different VOT distributions were used to estimate the impact on user equilibrium assignment.

6.1 Conclusions

The impact analysis results indicate that various toll pricing policies could have substantial impacts on the volume assignment, system performance, total revenue and emissions. A number of key conclusions can be drawn from this analysis, as follows:

1. In the low volume conditions, the managed lanes (ML) become less-attractive to single occupancy vehicles (SOV) if the ML travel times do not differ or are only slightly lower than the

general purpose lane (GPL) travel times and SOVs are likely to continue using the GPLs. As the volume increases to the point where volumes can greatly increase the travel time on the GPLs, the probability of using MLs will also increase.

2. Based on the stated-preference price sensitivities for Dallas-Fort Worth drivers, tolls above \$0.10/mile tend to spread vehicles across the GPLs and MLs in such a way to generate significant ML travel time improvements. At this toll rate (\$0.10/mile), more than 30% of travelers on the corridor would pay a toll to use managed lanes.

3. In the scenarios where SOVs and high occupancy vehicles (HOV) are charged the same price, the predicted ML shares are different because characteristics of the VOT distribution of the SOVs differ from those of the HOVs.

4. HOV preferential treatments (lower HOV tolls) have little impact on system performance. However, lower HOV preferential treatment (higher HOV tolls) would increase system performance on the ML.

5. A tradeoff between SOV toll rate and HOV preferential treatment can be used to maintain a speed on the ML at or above a threshold value.

6. The HOV preferential treatment (lower HOV tolls) on the managed lanes increases the level of CO and NOx emissions.

7. There is no difference in the amount of peak hour SO_2 emissions across the various policies since SO_2 does not depend on the speed. In general, SO_2 is emitted by trucks using diesel fuel and trucks are not allowed on ML under any of the policies examined.

8. The greatest reduction in CO and NOx emissions occurs at a high toll rate. A policy with a high toll rate and no HOV preferential treatment results in the least CO and NOx emissions. Also, a reduction in NOx is generally associated with an increase in VOC and CO_2.

9. HOV preferential treatments do not significantly affect peak hour system performance but they do negatively impact the peak hour revenue. In general, lower HOV preferential treatment and higher toll rate result in an increase in toll revenues.

6.2 Future Directions

In this version, the TPM-4.3 software does not include a conversion between modes. If HOV preferential treatments (lower HOV tolls or free) are implemented on the ML to encourage carpooling, a SOV may become a HOV. In this case, mode change can occur but it cannot be captured in the software. Also, when the managed lane concept is implemented on the corridor, travelers may change their commute route. A possibility of route change (increase or decrease in demand) is also not accommodated in the TPM-4.3 model. A future version should include modules to capture potential mode and route changes.

As mentioned previously, the TPM-4.3 has potential application in analysis of alternative toll versus free highway that has a same origin-destination pair with different lengths. However, further validation of this analysis type should be performed to ensure the model applicability. Additionally, the model validation using I-30 or Katy freeway data is needed when it is available because various components in the TPM-4.3 are based on the results from previous studies using Texas data.

Finally, in the TPM-4.3, the last VOT range for the VOT input is assumed to have a same interval as the previous range. This assumption may lead to prediction errors. This group of motorists (high VOT) has an important role on the ML utilization since they will influence the toll charge when available capacity for SOV is low. In order to improve the results, actual characteristic of

VOT distributions at upper limits must be better known. Thus, a future study should be conducted to capture this characteristic for inclusion in the model.

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