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A Self-Adaptive Toll Rate Algorithm for High Occupancy Toll (HOT) Lane Operations

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16. ABSTRACT

Dramatically increasing travel demands and insufficient traffic facility supplies have resulted in severe traffic congestion. High Occupancy Toll (HOT) lane operations have been proposed as one of the most applicable and cost-effective countermeasures against freeway congestion. By allowing Single Occupancy Vehicles (SOVs) to use High Occupancy Vehicle (HOV) lanes with a toll, excess capacities of HOV lanes can be utilized. Through balancing pricing and vehicle occupancy constraints, an HOT lane system can optimize traffic allocations between HOT and General Purpose (GP) lanes and hence enhance the overall infrastructure efficiency if a proper tolling strategy is employed. Although there exist several tolling strategies, two major problems with these tolling strategies may significantly degrade the HOT lane system performance. First, the under-sensitive tolling algorithm is incapable of handling the hysteresis properties of traffic systems and may cause severe response delays. Secondly, unfavorable flow fluctuation on both HOT and GP lanes may result from over-sensitive tolling strategies and generate agitating traffic operations.

To address these problems, a new self-adaptive dynamic tolling algorithm is developed in this study to optimize HOT lane operations. To reduce the computational complexity, a second-order control scheme is exploited in this algorithm. Based on traffic speed conditions and toll changing patterns, the optimum flow ratio for HOT lane utilization is calculated using feedback control theory. Then the appropriate toll rate is estimated backward using the discrete route choice model. To examine the effectiveness of the proposed tolling algorithm, simulation experiments were conducted. A microscopic traffic simulation software tool, VISSIM, is utilized. The proposed algorithm is implemented and integrated with the VISSIM package through an external module specifically developed for this study. Data from the Washington State Route (SR) 167 HOT lane system is used to build and calibrate the simulation model. The simulation experiment results show that the proposed tolling algorithm is capable of responding to traffic changes promptly and effectively. It performed reasonably well in optimizing overall traffic operations of the HOT lane system under various traffic conditions. This algorithm is logically straightforward and not difficult to implement.

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EXECUTIVE SUMMARY

Over the past decades, dramatically increasing travel demands and insufficient traffic facility supplies have resulted in severe traffic congestion problems, which cost billions of dollars every year due to lost time, wasted energy, excess air pollution, and lost productivity. Because constructing new transportation infrastructure becomes more difficult in metropolitan areas, it is of utmost importance to manage the existing transportation facilities more efficiently with advanced traffic control and management technologies in addition to travel demand control. High Occupancy Toll (HOT) lane operations have been proposed as one of the most applicable and cost-effective countermeasures against freeway congestion. By allowing Single Occupancy Vehicles (SOVs) to use High Occupancy Vehicle (HOV) lanes with a toll, excess capacities of HOV lanes can be utilized. Consequently, through balancing pricing and vehicle occupancy constraints, HOT lane operations can optimize traffic allocations between HOT and General Purpose (GP) lanes and hence enhance the overall infrastructure efficiency.

Tolling is a key component that distinguishes HOT from HOV operations. An appropriate tolling mechanism is crucial for the success of HOT lane operations because traffic allocation between HOT and GP lanes ties directly to toll rate. Although there exist several tolling strategies, they are likely under-sensitive or over-sensitive due to the lack of feedback mechanism. On the one hand, an under-sensitive tolling algorithm is incapable of handling the hysteresis properties of traffic systems and may cause severe response delays. On the other hand, unfavorable flow fluctuations on both HOT and GP lanes may be caused by an over-sensitive tolling strategies and result in agitating traffic operations. To address these problems, a new self-adaptive dynamic tolling algorithm is developed in this study to optimize HOT lane operations. To reduce the computational complexity, a second-order control scheme is used in this algorithm. Based on traffic speed conditions and toll changing patterns, the optimum flow ratio for HOT lane utilization is calculated using feedback

control theory. Then the appropriate toll rate is estimated backward using the discrete route choice model. By dynamically adjusting toll rate based on traffic conditions, traffic allocations between GP and HOT lanes can be controlled and the overall system efficiency can be maximized. To examine the effectiveness of the proposed tolling algorithm, simulation experiments were conducted. A microscopic traffic simulation software tool, VISSIM, is utilized. The proposed algorithm is implemented and integrated with the VISSIM package through an external module specifically developed for this study. The Component Object Model (COM) is used to overcome functional constraints with the VISSIM built-in modules. This HOT lane module also provides additional flexibility that can be used by researchers and/or practitioners to satisfy any specific demands.

Data from the Washington State Route (SR) 167 HOT lane system is used to build and calibrate the simulation model. Five HOT lane sections on the northbound SR-167 are included in the simulation model. Various experimental test scenarios are designed to identify potential problems with existing traffic infrastructure and evaluate the overall system performance under different traffic demands. The simulation experiment results show that the proposed tolling algorithm is capable of responding to traffic changes promptly and effectively. It can avoid being under-sensitive or over-sensitive due to its feedback-based self-adaptive nature. This algorithm is proven effective in dynamically optimizing overall traffic operations of the HOT lane system under various traffic conditions and has a great potential to be used to improve HOT lane performance. In addition to this self-adaptive dynamic tolling algorithm, the simulation platform used in this study may be used as a cost-effective evaluation tool for HOT lane operations.

Due to the differences in geometric design, lane configuration, and driver composition, each HOT lane system may have its unique feature to be considered in the tolling mechanism. Therefore, the proposed algorithm needs to be tested using data from other HOT lane systems before being finalized for field implementations.

CHAPTER 1 INTRODUCTION

1.1 Research Background

Over the past decades, dramatically increasing travel demands and insufficient traffic facility supplies have resulted in severe traffic congestion. From 1980 to 2007, yearly vehicle miles traveled increased by 98%, while road mileage increased by less than 7% nationally (Bureau of Transportation Statistics 2009). The enlarging gap between travel demand and infrastructure supply has increased the level of congestion nationwide. Traffic congestion costs billions of dollars every year due to lost time, wasted energy, excess air pollution, and lost productivity. The 2009 Urban Mobility Report indicates the annual average delay per person in the 439 urban areas surveyed was 36 hours in 2007, a 162% increase compared to that in 1982. Congestion costs an average of $757 per traveler in the surveyed urban areas in 2007 (Schrank and Lomax 2009). The greater Seattle area has been consistently ranked as one of the most congested areas in the U.S. Traffic congestion resulted in a total of 73.64 million hours of travel delays and 50.54 million gallons of excess fuel consumption in Seattle in 2007, which corresponded to a congestion cost of 1.59 billion dollars, the 15th highest in the U.S. (Shrunk and Lomax 2009).

Adding more roadways has been a traditional solution to solving traffic congestion problems. Due to the high construction cost, long project cycle, and complicated procedure for new construction, however, the increase of roadway supply has lagged far behind the increase of demand over the past several decades. A commonly accepted solution to address the gap between roadway supply and travel demand is to manage the existing infrastructure more efficiently with advanced traffic control and management technologies, specially for locations where expanding highway capacity becomes very difficult or impossible. High-Occupancy

Vehicle (HOV) lane has been a solution for several decades. The concept was originally proposed as dedicated bus lanes. Gradually, HOV lane allowed vanpools and carpools. The initial goal of HOV lane was to motivate people to shift from Single Occupancy Vehicles (SOV) to carpools or buses in order to reduce SOV trips and traffic congestion. It has been widely recognized that HOV lanes can carry more people than General Purpose (GP) lanes during peak hours. Kim (2002) conducted a study using micro-simulation models and found HOV lanes improved HOV user travel time significantly.

On the other hand, research on the usage of HOV lane conducted by Dahlgren (1998) indicated that under some circumstances, HOV lanes are less effective in reducing traffic delay. Kwon and Varaiya (2005) found that HOV lanes increased congestion in the Bay area by underutilizing the HOV lane capacity by about 20% or 400 vph. Many HOV facilities are underutilized when other GP lanes are congested. A partial explanation may be that about 43% of carpoolers are members of the same household and exploitation of HOV lanes is restricted to some extent (Fielding and Klein 1993). Under such a condition, converting HOV lanes to High Occupancy Toll (HOT) lanes creates a win-win solution to reduce traffic delays and enhance total traffic throughputs. SOVs are allowed to pay a toll for using HOV lanes to better utilize the excess capacities of HOV lanes. Currently, there are about 1285.3 miles of HOV lanes in the US (Chu, Nesamani, and Hamed, 2007). Successful operations of HOT lanes by fully exploiting their excess capacities can potentially generate huge time savings and significantly mitigate traffic congestion. Therefore, the HOT lane concept has been increasingly recognized and accepted as a potential measure to improve traffic mobility.

1.2 Problem Statement

HOT lane operation has been accepted as one of the most effective countermeasures against freeway congestion. Under a HOT lane system, SOVs are allowed to access HOV lanes by paying a toll when excess capacities of HOV lanes are available. By balancing pricing and vehicle occupancy constraints, HOT lane systems can optimize traffic allocation between HOT and GP lanes and enhance the overall infrastructure efficiency. HOT lane operation is still in its early stage and few existing studies focused on developing tolling strategies. Inferior tolling strategies for HOT lanes can severely degrade system performance by lengthening vehicle delay, increasing accident risk, and introducing disruptions to traffic progression.

Due to theoretical deficiency in modeling toll schemes, most existing tolling strategies are not clearly set for optimal HOT lane operations. Two major problems associated with these inferior tolling strategies degrade HOT lane system performance. First, an under-sensitive tolling algorithm is incapable of handling the hysteresis properties of traffic systems and may cause severe response delays. Second, operation-agitating flow fluctuations on HOT and GP lanes may result from an over-sensitive tolling algorithm. To visualize the weakness of these tolling algorithms, an illustrative example is shown in Figure 1-1. This example shows three tolling strategies employed to improve HOT lane traffic speed from 35 MPH to 45 MPH. Response processes associated with these tolling strategies are illustrated. The underdamped tolling strategy may generate unfavorable flow fluctuation because of over-sensitive reaction, although it can quickly respond to traffic condition changes. The under-sensitive tolling strategy may control traffic stably, but at the cost of severe response delays due to overdamped characteristics.

In such tolling systems, hysteresis properties of traffic systems cannot be sufficiently handled and will severely degrade overall system performance.

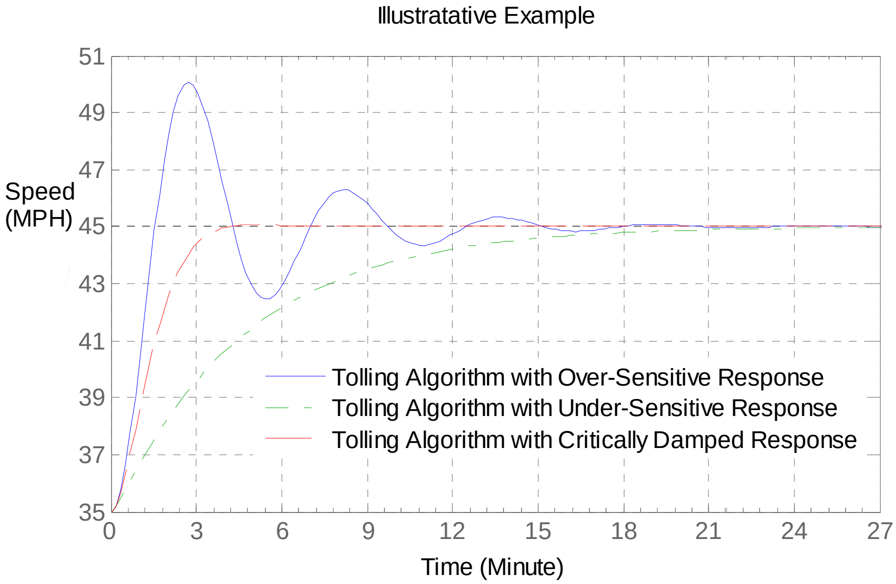

Figure 1-1 Comparisons of speed response on HOT lanes for different tolling algorithms

This study thus proposes a new self-adaptive tolling algorithm to dynamically optimize HOT lane operations based on feedback control theory. The operational goal is to enable the tolling algorithm to adaptively accommodate traffic variations in a fast and stable way as illustrated by the critically damped curve in Figure 1-1. Note that in this study, the HOT lane operation optimization is characterized by two operational criteria: 1) preserving high-quality travel conditions on HOT lanes; and 2) maximizing the total throughputs. Through dynamic toll adjustment, traffic allocation can be regulated to fully utilize the extra capacity of an HOT lane without degrading its operational conditions.

1.3 Research Objective

The objectives of this study include:

- To explore the feasibility of applying control theories for optimal HOT operations;
- To develop a self-adaptive tolling algorithm based on the feedback control theory for real-time toll rate calculations using real-time traffic sensor measurements, such as lane occupancy, speed, and flow rate; and
- To develop an independent simulation module to enable the VISSIM package to simulate the HOT lane system and analyze simulation results for performance evaluation.

1.4 Report Organization

The remainder of this report structured as follows. Chapter 2 reviews previous work related to HOT system operations and pricing strategies. Chapter 3 presents the optimal feedback-based tolling algorithm development. A second-order control scheme is exploited to reduce the computational complexity. The optimal toll rate is backward estimated based on feedback control. Details of VISSIM-based simulation model development and experiment design are discussed in Chapter 4. To realize HOT lane operation simulation, one external control module is developed and integrated with the VISSIM package. Also simulation model calibration efforts are described and emphasized in this chapter to enhance models' credibility. Representative test scenarios are established and various Measures of Effectiveness (MOEs) are selected to quantify system performance. Then, simulation experiments are conducted in Chapter 5 to verify the effectiveness and practicality of the proposed tolling algorithms. Test results are analyzed and discussed. Finally, Chapter 6 provides conclusions of this research effort and recommendations for future research.

CHAPTER 2 STATE OF THE ART

The first HOT lane project was implemented on SR 91 in Orange County, California in 1995. After that, HOT lane systems have been implemented in California (I-15), Texas (I-10 and US-290), Minnesota (I-394), Utah (I-15), Colorado (I-25), and Washington (SR-167). Other states, such as Virginia, are currently in the process of implementing HOT lanes (Tilahun and Levinson, 2008). Two representative HOT lane systems, including the I-394 MnPass lane system and the SR-167 HOT lane system, are presented as following:

1) The I-394 MnPass lane system has been in operation in Minnesota since 2005. Before implementing the MnPass lane system, the original HOV lane system consists of two different sections: one is the three-mile long, barrier-separated reversible section located to the west of downtown Minneapolis. The other is an eight-mile section of concurrent flow HOV lanes located to the west of the first section (Turnbull, 2008). The total length is about 11 miles. To implement the I-394 MnPass lanes, several actions were taken, including restriping the concurrent flow HOV lanes to change from unlimited to limited access, installing the electronic toll collection and enforcement systems, and so on. A simple pricing mechanism was employed based on the performance indictor, traffic density. The tolls are adjusted to accommodate traffic condition changes ensuring that the HOT lane flows in the range of about 50-55 MPH. The tolling update interval is specified as three minutes. The toll rate is set in the range of 25 cents to $8 based on the HOT lane traffic conditions (Zmud et al, 2007).

2) The SR-167 HOT lane system has been open to the public since May 2008. This freeway corridor connects south King and north Pierce counties to the Seattle/Bellevue metropolitan area.

It contains one HOT lane and two GP lanes in each direction. The HOT lane and GP lanes are not separated by physical barriers. Instead, a double-white line is employed to separate them. Crossing this double-white line is illegal. This HOT lane system contains nine miles of southbound and 12 miles of northbound HOT lanes. Vehicles are allowed to enter and exit the HOT lanes at access points. There are three several access points on the southbound HOT lane and five for the northbound HOT lane (WSDOT, 2007). The operation of this HOT lane system is based on a flexible pricing technology and the toll will be automatically adjusted to optimize the HOT lane volume and maintain its speed of 45 MPH or faster. The toll varies from $0.50 to $9.00 based on the level of services on HOT and GP lanes (WSDOT, 2007). This SR-167 HOT lane system has archived various sorts of data for performance measurement and cost-benefit analysis. These data are excellent resources for this project.

Although many studies have been conducted to evaluate the system performance of these projects *(*Appiah and Burris 2005, Halvorson et al. 2006*,* Yin and Lou 2007, Zmud et al. 2007, and Mowday 2006*)*, few focused on the development of optimized tolling strategies. In practice, rough and empirical dynamic tolling strategies have been employed for HOT lane operations. For example, for the I-15 HOT lanes in San Diego, the basic price varies from $0.50 to $4.00 according to the time of day. The tolls may be manually adjusted in response to real-time traffic conditions. The maximum value of $8.00 is employed for heavily congested situations (Yin and Lou 2007). Although these tolling approaches approximately realize traffic response-based toll adjustment, due to insufficient theoretical basis, it is hard to quantitatively achieve the goal of optimal system performance.

Review of previous literature did not find a systematic approach that is ready to apply for dynamically determining toll for HOT lane operations. Chu, Nesamani, and Benouar (2007) proposed a priority-based operation framework for HOV lane usages based on vehicle occupancy, type, and toll rate. But no further investigations were conducted on dynamic tolling strategies. Yin and Lou (2007) proposed two approaches for dynamic toll determination. The first one employs the control logic of the ramp metering control algorithm, ALINEA (Papageorgiou et al, 1997), for dynamically changing toll rates. This control logic is expressed as follows:

$$r(t+1) = r(t) + K \cdot (o(t) - o^{*}) \tag{2-1}$$

where, $r(t)$ and $r(t+1)$ are the toll rates at interval t and $t+1$, respectively; $o(t)$ is the measured occupancy; K is the regulator parameter; o^{*} is the desired occupancy of the HOT lane.

The other approach utilizes the discrete choice model, the Logit model, for tolling determination. Their major research efforts focused on parameter estimation and model calibration using real-time traffic counts collected from both HOT and GP lanes. Although there are certain similarities among ramp metering control, discrete choice models, and HOT lane tolling strategies, the unique characteristics of HOT lane operations cannot be sufficiently accommodated by simply transplanting other control or modeling methods. Hence, a more efficient tolling algorithm aims at optimizing the overall performance of a HOT lane facility is needed.

CHAPTER 3 RESEARCH METHODOLOGY

3.1 Algorithm Scheme

Practical experience on HOT lane operations and in-depth investigations of existing tolling approaches provide valuable insights into intrinsic problems in tolling optimization. From a macroscopic perspective, the toll can function as an adjustment lever to direct the traffic inflow to the HOT lane. As shown in Figure 3-1, based on the traffic conditions on HOT and GP lanes, the tolling algorithm is executed and the toll is determined for the next interval. Then motorists make decisions on whether to use the HOT lane according to the toll and traffic situations in the network. Finally, the desired number of vehicles access the HOT lane and optimum system operation can be achieved.

However, due to the complicated nonlinear relationship between the toll rate and the traffic flow entering the HOT lane, a simple tolling algorithm may not offer the flexibility required to control traffic assignment. Although complex tolling algorithms are capable of adjusting traffic allocation competently, they are not easily implemented to meet practical needs. To address these problems, we propose an effective yet easy-to-implement tolling algorithm in this study. A second-order control scheme is exploited in this algorithm. First, using feedback control logic the ideal traffic flow ratio for optimal HOT lane utilization is calculated. Then, the optimal toll rate is estimated backward using the Logit model, one of the most widely recognized route choice models. By decomposing the calculation complexity, this new algorithm can satisfy the implementation and effectiveness requirements of the HOT lane system.

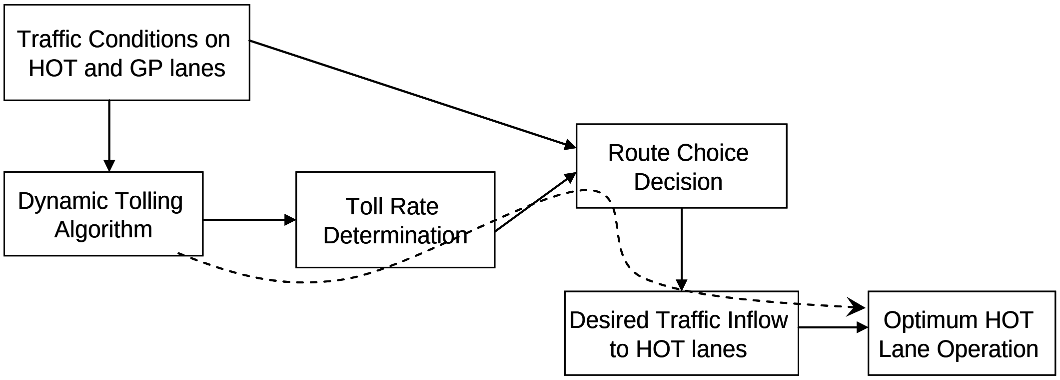

Figure 3-1 A schematic flow chart of the typical HOT lane operation

3.2 Modeling HOT Lane Utilization

In reality, motorists will make decisions on whether to pay for accessing the HOT lane based on the toll rate and traffic conditions on the HOT and GP lanes. Such a decision-making process can be formulated by the commonly used Logit model.

To quantify the attractiveness of different lanes, the total cost, TC_i, for choosing lane type i is computed as

$$TC_i = \alpha * TT_i + TR_i \tag{3-1}$$

where, TT_i is the average travel time and TR_i is the toll rate for lane type i; α is the coefficient (value of time) to convert TT_i into cash value. For the type of GP lane, the toll rate $TR_{GP}=0$. The travel distance is excluded in this equation due to its static attributes. Then, utility function U for each lane choice is calculated as

$$\begin{aligned} U_{HOT} &= \frac{1}{TC_{HOT}} = \frac{1}{\alpha * TT_{HOT} + TR_{HOT}} \\ U_{GP} &= \frac{1}{TC_{GP}} = \frac{1}{\alpha * TT_{GP}} \end{aligned} \tag{3-2}$$

where, U_{HOT} is the utility function of the HOT lane and U_{GP} is the utility function of the GP lane. Then the traffic assignment is modeled by the Logit model. The SOV flow, F_{HOT} , entering the HOT lane can be obtained as

$$F_{HOT} = F_{total} * P_{HOT} = F_{total} * \frac{\exp(U_{HOT})}{\exp(U_{HOT}) + \exp(U_{GP})} = F_{total} * f(TR_{HOT}, TT_{HOT}, TT_{GP}) \tag{3-3}$$

where, F_{total} is the total approaching SOV flow; P_{HOT} is the probability of choosing the HOT lane for each individual vehicle; also, from a macroscopic perspective, P_{HOT} denotes the flow ratio of the HOT lane volume to the total volume, termed as the flow ratio of HOT lane utilization. $f()$ is an abstract function that associates the independent variables, TR_{HOT}, TT_{HOT}, and TT_{GP} with dependent variable P_{HOT}. Due to the one-to-one transformation between TR_{HOT} and P_{HOT}, the toll rate can be calculated inversely as follows,

$$TR_{HOT} = f^{-1}(F_{HOT} / F_{total}, TT_{HOT}, TT_{GP}) = f^{-1}(P_{HOT}, TT_{HOT}, TT_{GP}) \tag{3-4}$$

where, $f^{-1}()$ indicates the corresponding inverse function. In this equation, the variables, TT_{HOT}, TT_{GP}, and F_{total} are measurable from the traffic detectors typically deployed for an HOT lane system. Therefore, if F_{HOT} is determined, the optimal toll rate TR_{HOT} can be backward computed.

In reality, the approaching traffic flow F_{total} can be approximately regarded to be consistent between two consecutive update intervals. So the calculation of F_{HOT} can be simplified by computing P_{HOT}. In the following sections, a feedback-based piecewise control algorithm is exploited to calculate P_{HOT}, and then, after the related coefficients are calibrated, the toll rate can be estimated.

3.3 Feedback Control Mechanism

Feedback control is one simple yet effective control approach that has been widely applied in engineering and mathematic fields, such as automobile speed control, satellites, robots, and industrial processes (Lewis 1992). Enlightened by feedback control mechanisms applied in other fields, a feedback-based piecewise linear function is developed and utilized to calculate P_{HOT}, the optimum flow ratio for HOT lane utilization.

In many HOT lane projects the HOT lane speed is employed as one of critical MOEs to indicate the system operation status. For instance, in the Washington SR 167 HOT lane pilot project, the HOT lane speed is required to be higher than 45 MPH (WSDOT 2007). Therefore, in this study, the speeds of HOT and GP lanes are employed as feedback variables and the operation criterion is to maintain the HOT lane speed higher than 45 MPH to ensure the HOVs' travel reliability. The control principle of the algorithm is to divide the HOT lane operation status into three manipulation zones based on HOT lane speed, and then to develop the specific control strategy for each zone to achieve the optimal performance for the entire system. Let S_{HOT} and S_{GP} denote the average speeds of HOT and GP lanes, respectively. Three manipulation zones are partitioned according to their robustness: the first zone is $S_{HOT} > 50$ MPH, which indicates sufficient HOT lane capacities are available, and the toll needs to be decreased if there is a need to carry more traffic; the second zone is $50 \geq S_{HOT} > 45$ MPH, which shows the traffic density on the HOT lane is close to its critical level, and the toll should be maintained at the same level; the third zone is $S_{HOT} \leq 45$ MPH, indicating the overflowing traffic has degraded the HOT lane performance and the toll must be increased to reduce the HOT lane volume.

Different feedback control mechanisms are adopted for these three zones. These control mechanisms can be formulated as:

$$P_{HOT}(t+1) = P_{HOT}(t) + \Delta P_{HOT}(t) = P_{HOT}(t) + \begin{cases} b_1 + k_1(S_{HOT}(t) - S_{GP}(t)) & S_{HOT}(t) > 50 \\ sign^*[b_2 + k_2(S_{HOT}(t) - S_{GP}(t))] & 50 \geq S_{HOT}(t) > 45 \\ k_3(S_{HOT}(t) - 45) & S_{HOT}(t) \leq 45 \end{cases} \quad (3\text{-}5)$$

where, $P_{HOT}(t+1)$ and $P_{HOT}(t)$ are the flow ratios for HOT lane usage at time interval t and $t+1$, respectively; $\Delta P_{HOT}(t)$ is the feedback increment; b_1, b_2, k_1, k_2, and k_3 are the parameters indicating control intensities of feedback quantities; $S_{HOT}(t)$ and $S_{GP}(t)$ are the average traffic speeds on HOT and GP lanes at time interval t, respectively; *sign* is a variable describing the changing pattern of P_{HOT}, and is defined as:

$$sign = \begin{cases} 1 & P_{HOT}(t-1) > P_{HOT}(t) \\ 0 & P_{HOT}(t-1) = P_{HOT}(t) \\ -1 & P_{HOT}(t-1) > P_{HOT}(t) \end{cases} \quad (3\text{-}6)$$

In Equation (3-5), when $S_{HOT} > 50$ MPH, the speed difference between the HOT and GP lanes is employed as the feedback variable. The feedback increment, $\Delta P_{HOT}(t)$, is represented by a linear function, $b_1 + k_1(S_{HOT}(t) - S_{GP}(t))$. Such a feedback layout can effectively reflect traffic conditions on HOT and GP lanes and provide sufficient flexibilities to ameliorate feedback mechanism. When $50 \geq S_{HOT} > 45$ MPH, besides an analogous feedback function, the indication variable, *sign,* is used to reflect the changing tendency of $P_{HOT}(t)$. Consequently, the feedback increment, $\Delta P_{HOT}(t)$, presents an alternative scheme to preserve HOT lane operation stability. When $S_{HOT} \leq 45$ MPH, $P_{HOT}(t)$ decreases directly by adding a negative item, $k_3(S_{HOT}(t) - 45)$.

According to this feedback-based piecewise control algorithm, the optimum traffic flow ratio for HOT lane utilization can be calculated iteratively for each time interval. Then the appropriate toll rate can be backward estimated. The details of parameter calibration and toll estimation are presented in the next section.

3.4 Toll Rate Estimation

Real-time traffic speed can be measured by the detection system in both the HOT and GP lanes. Then the travel times are calculable for both types of lanes. Based on Equations (3-5) and (3-4), toll rate can be estimated after the related parameters are determined.

In Equation (3-5), five parameters, b_1, b_2, k_1, k_2, and k_3, need to be determined. These parameters denote the weighting factors of feedback quantities and have to be calibrated separately according to different control strategies. For instance, when the HOT lane speed is higher than 50 MPH, then redundant capacity on the HOT lane is available. To optimize the overall traffic operation, traffic allocation needs to be adjusted rapidly. Based on the range of traffic speed and the efforts of trial and error, the parameters b_1 and k_1 are set as b_1=0.075 and k_1 = 0.005. Similarly, the other parameters can be calculated as b_2=0.024, k_2=0.0012, and k_3 =0.03. The reasonableness of these values can be demonstrated by the following example:

$$\begin{cases} S_{HOT}=53; & S_{GP}=48; \quad then \quad \Delta P_{HOT}=0.075+0.005*(53-48)=10\% \\ S_{HOT}=53; & S_{GP}=28; \quad then \quad \Delta P_{HOT}=0.075+0.005*(53-28)=20\% \\ S_{HOT}=48; & S_{GP}=35; \quad then \quad \Delta P_{HOT}=0.024+0.0012*(48-35)=3.9\% \\ S_{HOT}=40; & \quad then \quad \Delta P_{HOT}=0.03*(40-45)=-15\% \end{cases} \tag{3-7}$$

Assume $S_{HOT}=53$ MPH and the traffic on the HOT lane operates in a robust status. Then the feedback increment, ΔP_{HOT}, is updated at a larger changing pace, such as 10% to 20% depending on the GP lane speed; when $S_{HOT}=48$ MPH, traffic speed of the HOT lane is close to the critical speed, 45 MPH, and thus should be maintained at a consistent level, and the flow ratio for HOT lane utilization changes slightly. For example, when $S_{GP}=35$ MPH, ΔP_{HOT} is only 3.9% (increase or decrease is associated with the variable, *sign*, in Equation (3-6)); when $S_{HOT}=40$ MPH, the HOT lane speed is lower than the critical speed, so the flow ratio for HOT lane utilization needs to decrease sharply without considering the GP lane speed. Note that these values are not unique solutions for these parameters. Different sets of values may achieve analogous control results. Following the control principle proposed in this study, parameter calibration can be strengthened to meet the specific requirements of other applications.

After P_{HOT} is calculated for the next interval using Equation (3-5), the toll rate TR_{HOT} can be estimated by the inverse function in Equation (3-4). Further calculation is conducted to embody this process. The toll rate TR_{HOT} can be obtained as:

$$TR_{HOT} = f^{-1}(P_{HOT}, TT_{HOT}, TT_{GP}) = \frac{1}{\frac{1}{\alpha \cdot TT_{GP}} - \ln(\frac{1-P_{HOT}}{P_{HOT}})} - \alpha \cdot TT_{HOT} \qquad (3\text{-}8)$$

where, the coefficient α needs to be determined. In our study, the capital-to-travel time ratio of \$11.70 per hour is applied to compute α, e.g. α = 11.70 dollar / hour = 0.325 cent / second. This ratio value was obtained from the traffic survey in the greater Seattle area. Actually, this coefficient indicates motorists' willingness to pay for using HOT lanes and is closely associated with many particular factors, such as local economic conditions, traffic patterns, geographic characteristics, population distribution, and so on. Some studies were conducted to quantify the impact of these factors on HOT lane usage (Zmud and Peterson 2007, Li 2007, and Zmud et al. 2007). Findings show these factors are location-specific variables, and no uniform settings are applicable for manifold practical applications. More detailed discussions are beyond this study's scope. When this tolling algorithm is used in other applications, the coefficient α should be recalibrated to adapt to different situations. Based on Equations (3-5) and (3-8), it is straightforward to estimate the toll rate for next interval.

3.5 Tolling Algorithm Development Summary

Evolved from a HOV lane system, a HOT lane system is increasingly recognized and accepted as a viable measure to mitigate freeway congestion and improve travel time reliability. Optimized

HOT lane management can yield significant economic returns and social benefits. However, it is difficult to quantitatively accomplish optimal HOT lane exploitation due to theoretical deficiency in their tolling schemes, although rough traffic-response-based tolling algorithms are applied to HOT lane operations based on practical experience. In this project, therefore, a new self-adaptive tolling algorithm will be developed to dynamically optimize HOT lane operations. A second-order control scheme is exploited in this algorithm. Based on traffic speed conditions and toll changing patterns, the optimum flow ratio for HOT lane utilization is calculated based on feedback control theory. The proper toll rate, then, is backward estimated using the Logit model. By decomposing the calculation complexity, this optimal tolling algorithm can satisfy the practicality and effectiveness required by the HOT lane system operations in practice.

The effectiveness of the proposed tolling algorithms has been proven by the traffic simulation experiments using the model calibrated using the traffic sensor data collected from Seattle area freeways. Details of simulation model development and experimental tests are described in following chapters. The in-depth research and investigation conducted in this study can significantly improve our understanding of the control schemes for HOT lane system operations and provide a solid platform for optimizing HOT lane facility utilization.

CHAPTER 4 SIMULATION MODEL DEVELOPMENT AND EXPERIMENTAL DESIGN

To verify the effectiveness and applicability of the proposed algorithms for HOT lane system operations, simulation-based experiments are conducted. Due to its cost-effective and risk-free features, VISSIM is widely employed by transportation researchers for exploring optimal traffic control strategies, identifying potential problems, and evaluating various alternatives. In this study, a VISSIM-based simulation model is developed to simulate HOT lane system operations. Before presenting model configuration and external module development, the operating principle of VISSIM and its underlying driver behavior model are introduced. Then the details of simulation model configuration and calibration are described for freeway networks. To fully examine the effectiveness of the proposed tolling algorithm, various representative experimental test scenarios are designed. Finally a brief summary is provided to summarize this effort on simulation model development and experimental design.

4.1 VISSIM traffic simulator

VISSIM is a microscopic, time step and behavior-based simulation tool developed to model urban traffic and public transit operations. This software can simulate and analyze traffic operations under various scenarios. It is also very useful for evaluating various alternatives using the MOEs in transportation engineering and planning. In VISSIM, the traffic movement model is based on the work of R. Wiedemann (1974 and 1991), which combines a perceptual model of the driver with a vehicle model. The behavioral model for the driver involves a classification of reactions in response to the perceived relative speed and distance with respect to the preceding vehicle. Four driving modes are defined: free driving, approaching, following, and braking. In each mode a driver behaves differently, reacting either to its following distance, or trying to match a prescribed target speed. Details of each mode are described as follows:

- Free driving: In this model, there are no impacts from the preceding vehicle on the following vehicle. Drivers seek to travel at a desired speed. Due to the randomness of simulation operations, the observed individual vehicle speed may oscillate around this desired value.

- Approaching: In this mode, the following driver adapts to the preceding vehicle's lower speed. When the distance between two consecutive vehicles reaches the desired safety distance, the approaching vehicle applies a deceleration or acceleration so that the relative speed can maintain zero.

- Following: In this mode, the relative distance between two adjacent vehicles maintain a safety distance, and their relative speed fluctuates around zero. The following vehicle follows the preceding vehicle without continuously accelerating or decelerating

- Braking: In this model, the relative distance between vehicles falls below a safety distance, which can result from an abrupt deceleration of the preceding vehicle, or lane changing of another vehicle. A continuous deceleration is required.

Also, drivers can decide to change lanes. This decision can be forced by a routing requirement, for example, when approaching an intersection, or made by the driver to access a faster-moving lane. In addition, traffic signals can be simulated, and are controlled in VISSIM by the Signal State Generator (SSG), which is a separate module from the traffic simulation module. Through the virtual signal controller, the user can access loop detector measurements and use such information to perform control strategies. Based on VISSIM, many modeling studies have been conducted. Gomes, May, and Horowitz (2004) developed and calibrated a VISSIM model for a congested freeway. Moen et al. (2000), Bloomberg and Dale (2000), and Tian et al. (2002) investigated the performance of VISSIM by comparing it to CORSIM, a popular traffic simulator developed by Federal Highway Administration (FHWA), and to which VISSIM compared favorably. More details can be found in (PTV 2007).

4.2 External tolling control module development

Although VISSIM is widely used for modeling freeway traffic operations based on its competent capabilities of simulating common transportation operations, because of functional constraints with its built-in modules, VISSIM cannot provide sufficient flexibility to enable the dynamic tolling strategies. Dynamic tolling strategies are required for most HOT lane systems in practical applications. For example, for the I-15 HOT lane system in San Diego, the basic price varies from $0.50 to $4.00 according to the time of day. The tolls may be adjusted in response to real-time traffic conditions. For the I-394 MnPass Express lane in Minnesota, a similar pricing mechanism is implemented. The tolls are adjusted upward or downward to ensure the HOT lane flow rates at about 50-55 MPH. Therefore, simulation models must be able to handle dynamic toll changes to fully investigate HOT lane system operations and examine alternative tolling strategies.

However, VISSIM cannot accept dynamically changeable tolls with its built-in modules. In VISSIM, a static toll rate can be set up as the financial cost for each roadway segment, but it is not dynamically changeable to reflect changing traffic conditions under the flexible tolling strategies required by HOT lane operations. Review of previous literature does not find any VISSIM-based simulation research for HOT lane operations. In the latest version, one extra module has been developed to support HOT lane operations in VISSIM. However, only limited control criteria, such as time savings and revenues, can be specified by users, considering the particular requirements of customized tolling algorithms, such as traffic information acquisition and toll determination, the standard VISSIM HOT lane module may not provide adequate flexibility to satisfy the unique demands for a specific researcher and practitioner. Therefore, an independent functional module of VISSIM enabling HOT lane simulations is desired.

In this project, an external HOT lane operation controller module was developed. This module uses standard VISSIM Component Object Model (COM) interfaces for general applications and supports complex tolling algorithms for dynamic toll rate determination on the basis of real-time traffic measurements. Also it can be easily incorporated in VISSIM simulation models to test HOT lane operations under various traffic scenarios and tolling strategies. Besides its standard built-in modules, VISSIM offers COM interfaces for executing COM commands from external programs (PTV 2007). Such customer-based COM applications provide extensive simulation capacities needed for satisfying various requirements from users. After the VISSIM COM server is registered in the computer operation system, communications between the external program and the VISSIM model are set up. The COM objects, such as individual vehicles, and roadway segments, can be utilized and controlled by external programs. Through a COM interface, an external program can access the VISSIM simulation model to retrieve traffic data and logic decisions. In this study, Microsoft Visual Basic is used as the computer language to implement the HOT lane operation module. The communications between this external module and the built-in modules of VISSIM are shown in Figure 4-1, the overall system architecture of the HOT lane simulation.

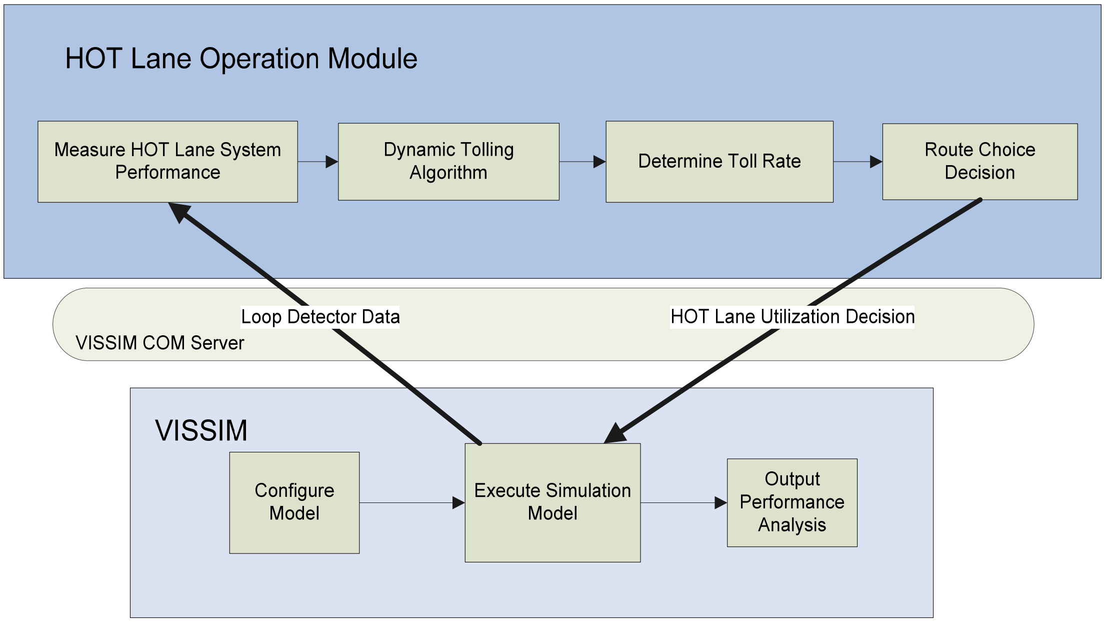

Figure 4-1 System architecture of the HOT lane simulation model

After the VISSIM simulation model is correctly configured, including accurate geographic characteristics of the HOT lane system, proper traffic demand matrices, and traffic compositions, etc., the model is executed in the single-step mode (default frequency: 1 step per second). When the traffic is allocated into the network by the dynamic assignment module, the flow rates, lane occupancies, and speeds are measured by loop detectors on both HOT and GP lanes. At each single step, these traffic detection data are exported and transferred to the external HOT lane module via the VISSIM COM server. To synchronize with toll updating intervals, these data are aggregated in a 5-minute interval in this study. Based on these measurements from the simulation model, the utilization of HOT and GP lanes are assessed. Then, the dynamic tolling algorithm is performed and the optimal toll rate is determined.

In reality, individual motorists will make decisions on whether to pay for accessing the HOT lane based on the real-time toll rate and traffic conditions on the HOT lane and GP lanes. In our simulation experiments, we employ a Logit model to imitate this decision-making process. To quantify the attractiveness of different lanes, the total cost (TC) for choosing lane type i is computed following Equation (3-1). Then, the utility function U for each lane choice is calculated using Equation (3-2). The desired proportion of vehicles that should enter the HOT lane can be estimated by Equations (3-3) and (3-4).

Via the COM interface, the roadway segment of a merging area can be instantiated, and each vehicle on this segment can be controlled by the external module. Then, a sequence of random numbers, $\{ N_j \}$, uniformly distributed in the range of 0 to 1, is generated and used to simulate the probabilistic route decisions for each individual vehicle. The logic of decision for choosing the HOT lane is conducted as follows:

$$\begin{cases} N_j \le P_{HOT} \Rightarrow True \\ N_j > P_{HOT} \Rightarrow False \end{cases} \tag{4-1}$$

where j denotes the jth vehicle; the decision *True* indicates when N_j is less than or equal to P_{HOT}, vehicle j will choose the HOT lane, and vice versa. After assigning an individual vehicle to a

HOT lane or a GP lane, this route decision is imported to the VISSIM model to replace its original route decision. Consequently, dynamic HOT lane utilization is realized.

By following the procedure above, the external HOT lane tolling controller module can be developed to implement the proposed tolling algorithm. Then the simulation model can be used to evaluate the performance of the HOT lane system after proper configuration and calibration. Details of the simulation model configuration and calibration are described in following sections.

4.3 Simulation model configuration and calibration

The simulation model is specifically developed for performance evaluation of the proposed tolling algorithm for HOT lane system operations. Freeway simulation model configuration and calibration requires significant efforts due to its complexity. The simulation test site chosen for this study is Washington SR 167. The simulation model is configured based on the SR-167 HOT lane system's roadway geometric features, traffic demands, and operational patterns. Simulation model calibration is critical for ensuring realistic representations of simulated scenarios and achieving reliable simulation results. In this project, the simulation model is calibrated based on the observed ground-truth data. A standardized simulation calibration approach for freeway traffic operations is employed.

4.3.1 SR-167 HOT lane systems

SR-167 is a primary highway routes through south King County, the Seattle/Bellevue metropolitan area, and north Piece County. It is also an important alternative route to Interstate 5 for moving both people and goods in the Puget Sound Region. Currently, a four-year pilot project converts nine miles of HOV lanes to HOT lanes on SR-167 from Southwest 15th Street in Auburn to Interstate 405 in Renton (WSDOT 2007). There is one HOT lane and two GP lanes on each direction of the corridor. The HOT lanes opened in May 2008. The SR-167 HOT lanes provide toll-free, express trips for transit and carpools. SOVs are allowed to use HOT lanes if they pay the toll and their usage does not compromise speed and travel time reliabilities for HOVs. Tolls are collected electronically by the over-roadway detectors and vehicle-mounted sensors. This pilot project will use flexible pricing technology to maintain the optimum number of vehicles in the HOT lane. The toll price will automatically adjust up or down to optimize the HOT lane volume and maintain its speed at 45 MPH (72 KM/H) or faster.

4.3.2 Modeling scope and data source

Simulation models must be built on the exact roadway geometry to realistically simulate traffic operations. In this SR-167 HOT lane system, the simulation model is configured to exactly represent the roadway geometric features, including the location of on-ramps and off-ramps, horizontal and vertical curves, weaving sections, the number of lanes and so on. Several major network editors, such as Link and Connector, are utilized to appropriately construct the traffic network in VISSIM. Three morning-peak hours, from 6:00 am to 9:00 am, are chosen as the simulation time period. This study concentrates on the HOT lane operations on Northbound SR-167. The arterial map of SR-167 is illustrated in Figure 4-2, and a sketch map for the overall simulation network is shown in Figure 4-3. Following the design from the Urban Corridors Office at WSDOT, five HOT segments are implemented in the VISSIM model from SR-167 & 15th St. SW in Auburn to SR-167 & I-405 Interchange Bridge in Renton. The locations of the HOT lane segments are marked in Figure 4-3. Also two overall travel sections are indicated and will be used for performance measures later. Special care is taken to employ the HOV lanes along SR-167 and I-405 Bridge in the network. In this project, traffic composition is represented by the numbers of vehicles from the three categories: SOVs, HOVs, and trucks. Traffic composition for SR-167 is inputted to the simulation model in the format of three Origin-Destination (OD) Matrices.

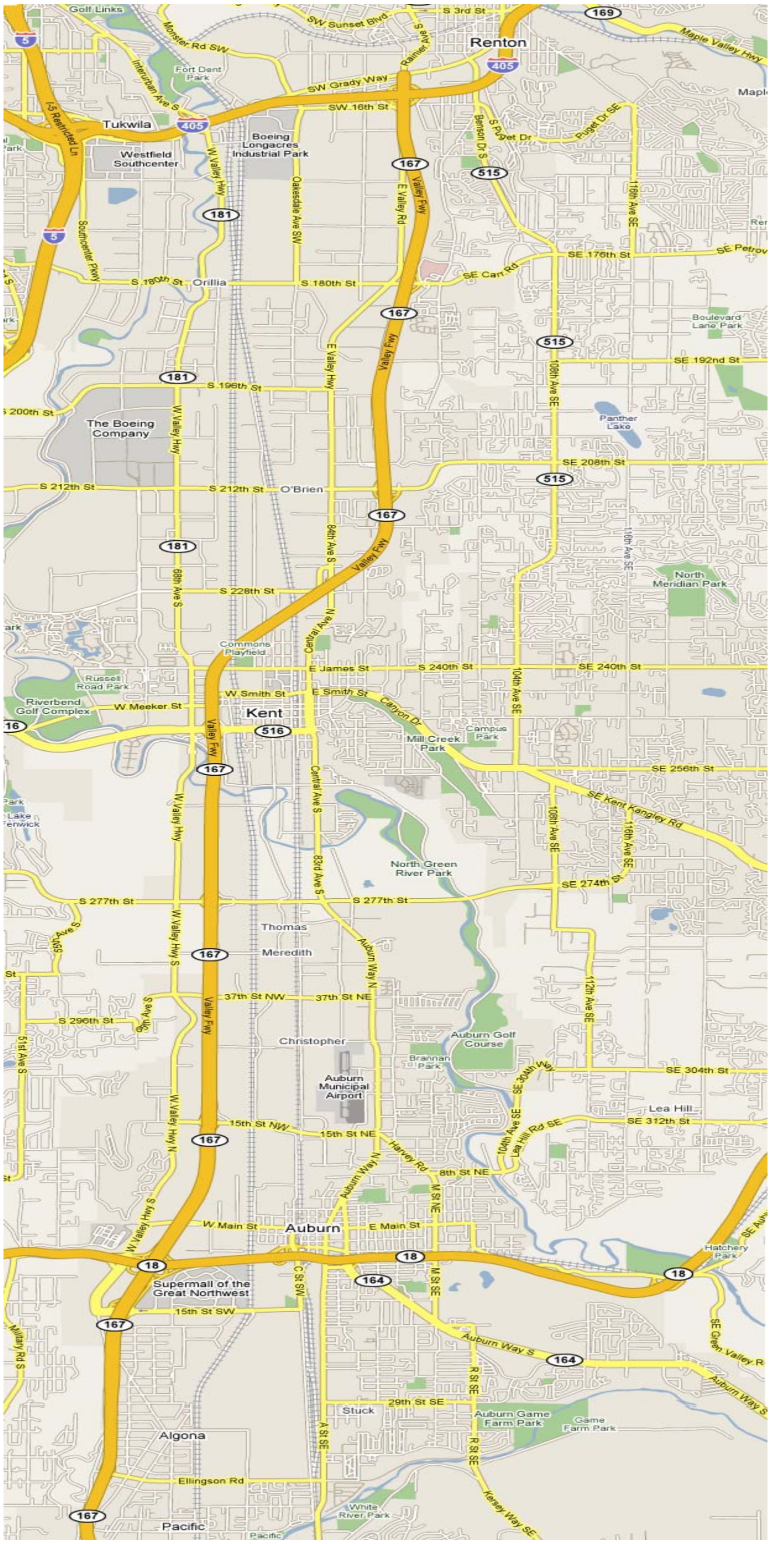

Figure 4-2 A geographic map for the arterial of SR-167

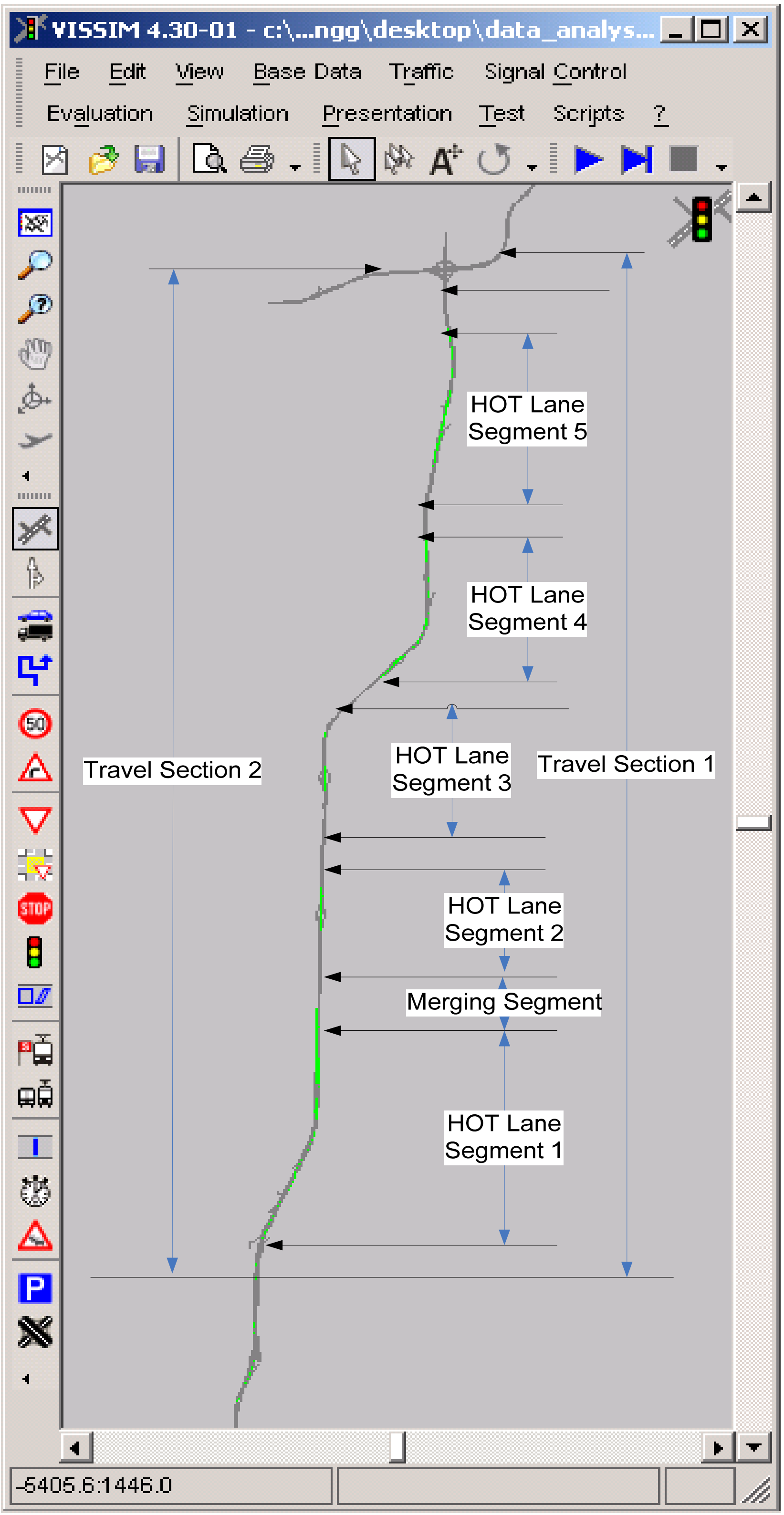

Figure 4-3 A sketching overview of HOT lane simulation network

Before the simulation model is used for simulating the HOT lane operations, it is important to calibrate the simulation model so that it can reproduce the existing traffic conditions. For calibration purposes, ground-truth traffic data are needed. In this study, such reference data are collected from two major sources:

1) *Traffic Management Center Summary Report: SR-167 Ramp and Roadway 2006 Traffic Volumes*. This report provides major information about hourly volumes on the SR-167 arterial and on each ramp. These data are important for calibrating traffic demand inputs.

2) *SR-167 and I-405 Annual Average Traffic Volumes and Speeds in 2005*. This data source offers a favorable dataset of traffic volumes and speeds with a high resolution. Aggregated 5-minute traffic counts and speeds are measured each half mile along SR-167. These data play significant roles in calibrating driving behavior parameters and network settings.

4.3.3 Simulation of HOV lane operations

Currently, one HOV lane and two GP lanes are in use along northbound SR-167 from Auburn to Renton in Washington State. The simulation model is originally configured to represent current HOV lane operations as the basic test scenario. In VISSIM, two alternatives of traffic assignment are executable: static assignment and dynamic assignment. In this study, dynamic traffic assignment is utilized to strengthen the practicality and validity of the simulation model.

1) Dynamic Traffic Assignment

With its built-in dynamic assignment module, VISSIM can dynamically assign and equilibrate traffic in the network based on the demand of trips from origins to destinations. In VISSIM, a set of possible routes between two zones is established, and then travel costs (e.g., travel time and distance) for each route are calculated. Based on the assessment of optional routes, a discrete choice model is exploited to allocate traffic demands on all possible routes to model the route choice behavior of drivers. Such assignment processes are iterated dynamically until traffic assignment reaches the equilibrium status. This module greatly enhances the operational capabilities of simulation models.

With the dynamic traffic assignment module incorporated, the simulation model is capable of simulating present traffic operations appropriately. The entire network needs to be redefined by the components of nodes and edges along each route for dynamic assignment. An abstract network is recognized by the dynamic assignment module. In VISSIM the traffic equilibrium status is called convergence. The criteria for convergence can be specified by users. In this study, strict convergence conditions were set to ensure the balanced traffic assignment: the difference in travel times and volumes on each route should be less than 3% from one iteration to its next. Traffic dynamic assignment is closely associated with the configuration of the simulation model. After adjusting any parameters in the calibration process, traffic assignment needs to be updated until a new equilibrium status is achieved.

2) HOV lane Implementation

One important feature of the network settings is the employment of HOV lanes. VISSIM provides the function to close a particular lane of a roadway segment to a certain type of vehicle. As introduced above, the traffic consists of vehicles from three categories in this study: SOVs, HOVs, and trucks. HOV-only restrictions are enforced by opening the specific lane to HOVs and closing it to SOVs and trucks. This HOV lane configuration is used to create the corresponding HOV lanes on the SR-167 arterial as well as the HOV bypass lanes on the on-ramps.

4.3.4 Simulation model calibration

Calibration efforts are required to accomplish reasonable correspondence between observed field data and simulation outputs. During the model calibration process, related parameters are adjusted to make the outputs reasonably represent field conditions. The simulation model was calibrated for SR-167 HOV lane operations. The schematic flow chart of the proposed calibration procedure is illustrated in Figure 4-4. Based on the base-year traffic planning survey data, SOV, HOV, and truck OD matrices are established and inputted to the simulation model. Through multiple iterations of traffic assignment, these traffic demands are allocated to the whole network and the assignment equilibrium is achieved. To check the fidelity of this simulation model, virtual loop sensors are placed in the simulation model according to their real positions on ramps and arterial roadways. Traffic counts and speeds are collected from these virtual loop detectors and compared to the reference data. If they are significantly different, then trip attraction and production in the OD matrices are rebalanced so that the difference can be reduced. These steps are iterated until the volume difference is reasonably small (less than 10%).

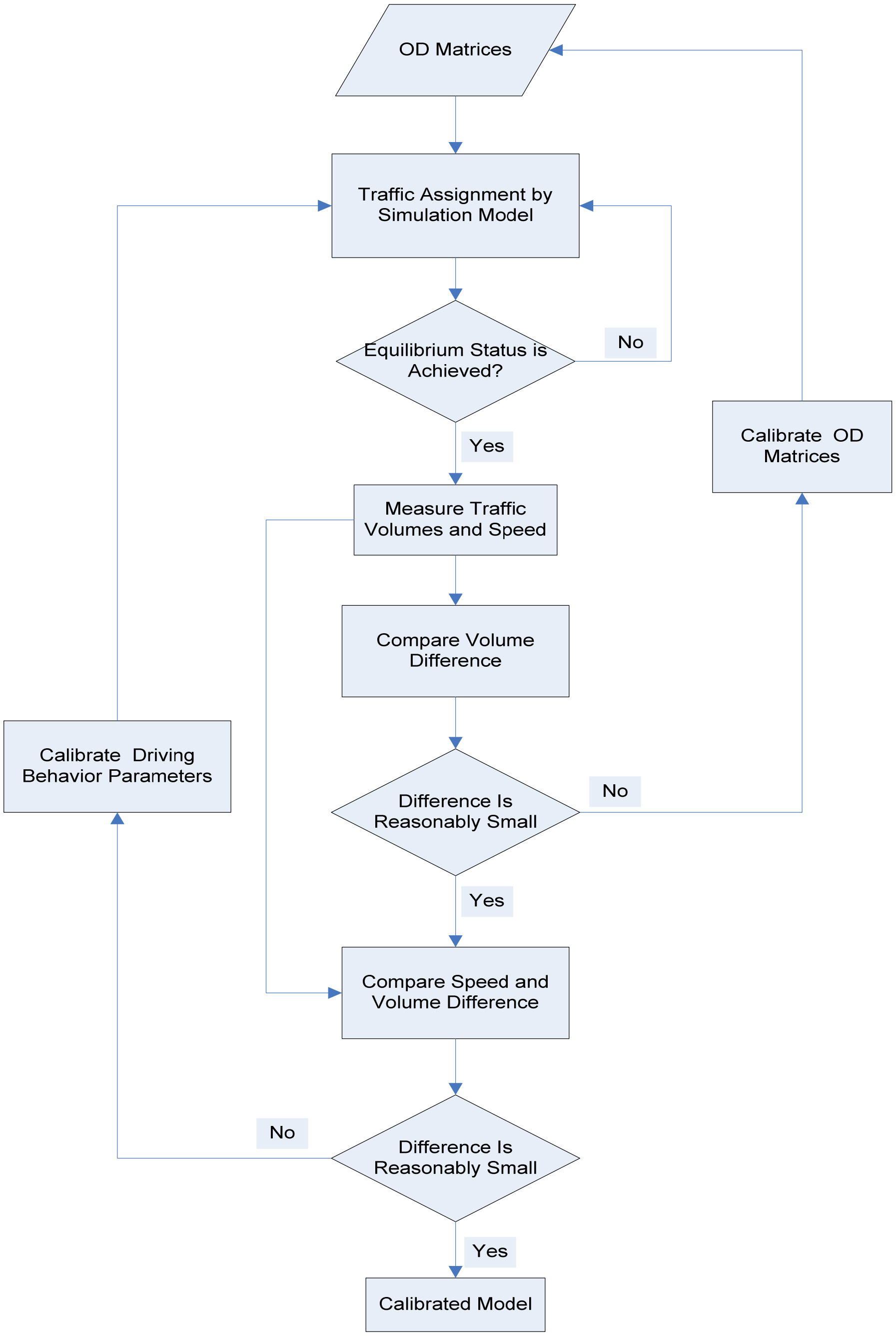

Figure 4-4 Schematic flow chart of the calibration procedure

Annual average daily traffic volumes and speeds are utilized to calibrate the driving behavior parameters. In VISSIM, traffic flow is modeled as a discrete and stochastic process, in which each driver-vehicle-unit is treated as a single entity. The freeway car following logic uses the Wiedemann 99 Model (PTV 2007, Wiedemann 1991) and involves ten parameters, including standstill distance, headway time, etc. In this study, three major parameters: standstill distance, headway time, and minimum lane changing headway, are adjusted according to the observed field headway data. Also, other parameters, such as the look-back distance, are modified separately for weaving areas. A detailed driving behavior calibration procedure for freeway operations can be found in Gomes's research (2004). After tuning up these parameters, the simulation model is iteratively executed until traffic assignment is equilibrated in the network. Based on the comparisons between the simulation results and the corresponding reference data, such calibration processes are repeated. Once the difference is small enough, the model is considered reasonably calibrated and is ready for HOT lane simulations.

To verify the overall reliability of the calibrated simulation model, five important locations on the northbound SR-167 corridor and two locations on the I-450 interchange bridge are chosen as checkpoints as illustrated in Figure 4-5. Simulated traffic volumes and speeds are compared with ground-truth data at these checkpoints. Figures 4-6 through 4-19 provide visual comparisons of traffic volumes and speeds at these locations.

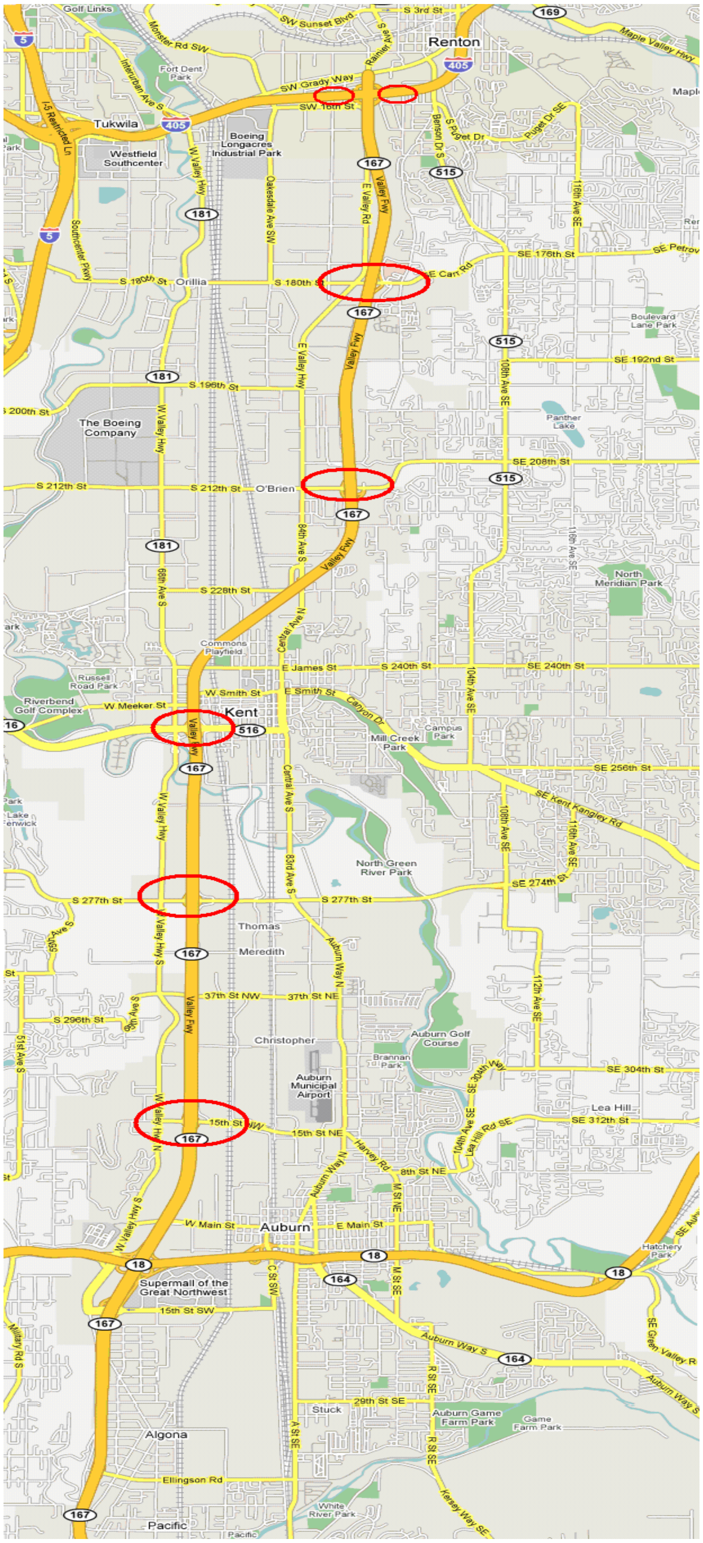

Figure 4-5 Diagrammatic locations of checkpoints on SR-167 and I-405 interchange bridge

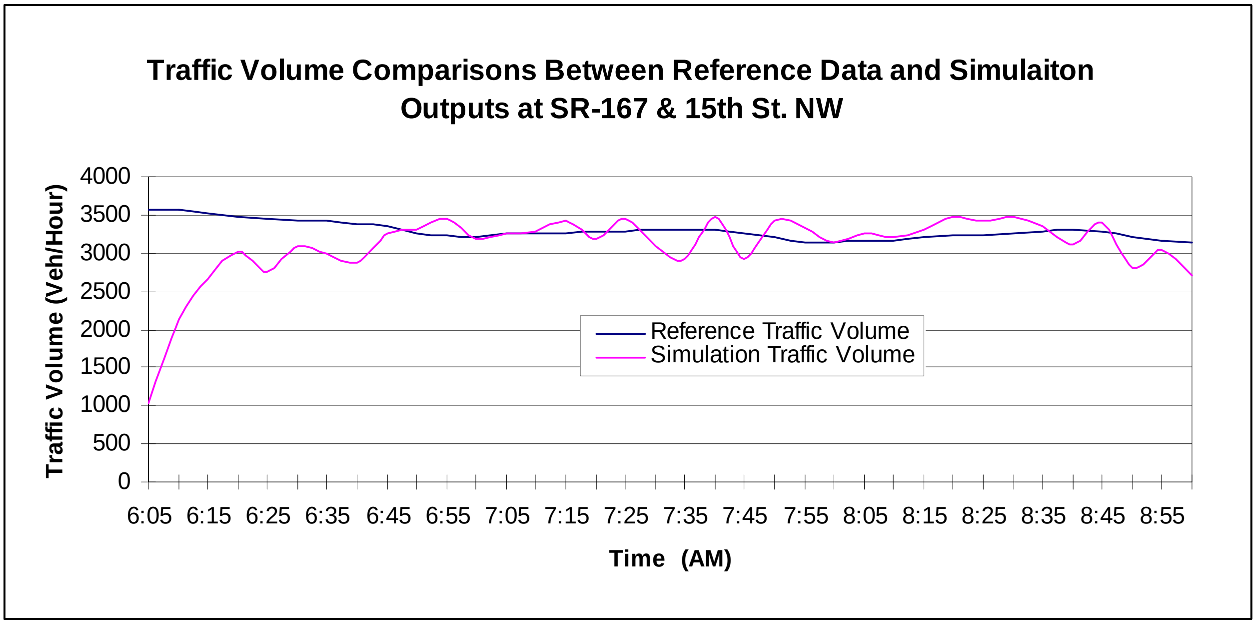

Figure 4-6: Traffic volume comparisons between reference data and simulation outputs at the location of SR-167 & 15th St. NW

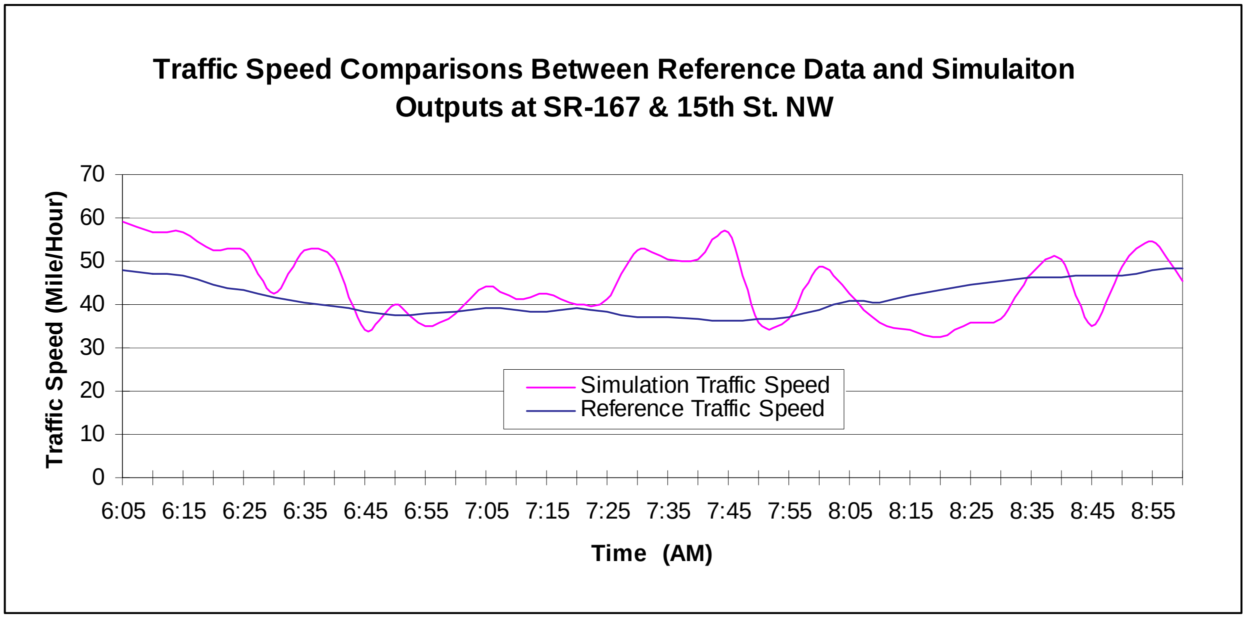

Figure 4-7: Traffic speed comparisons between reference data and simulation outputs at the location of SR-167 & & 15th St. NW

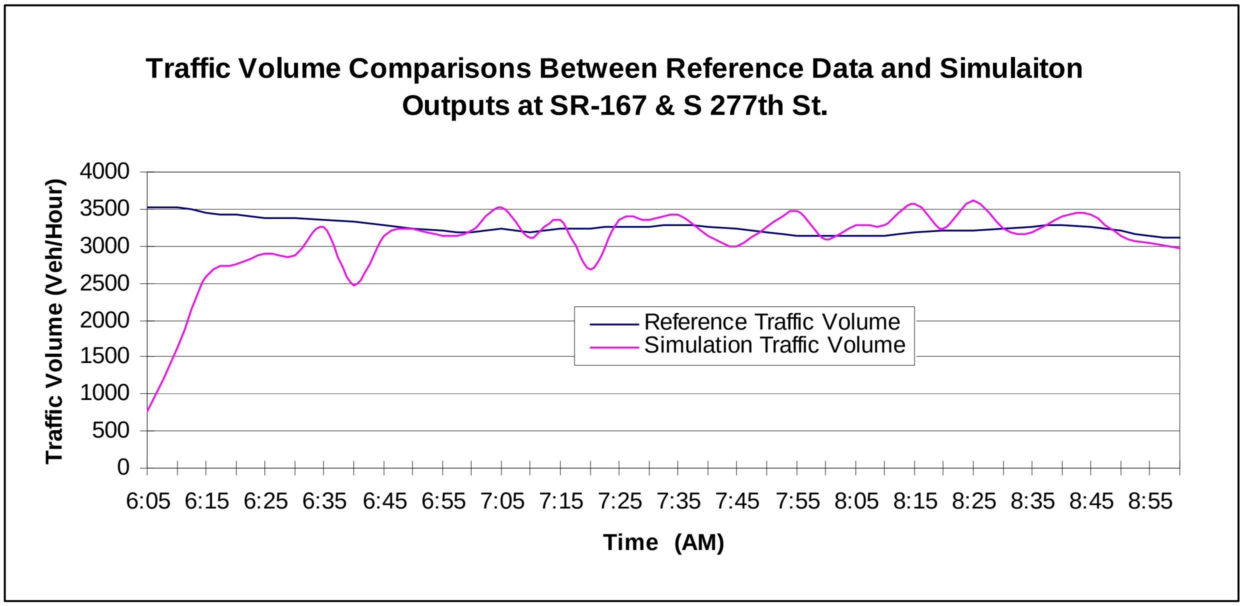

Figure 4-8: Traffic volume comparisons between reference data and simulation outputs at the location of SR-167 & 277th St.

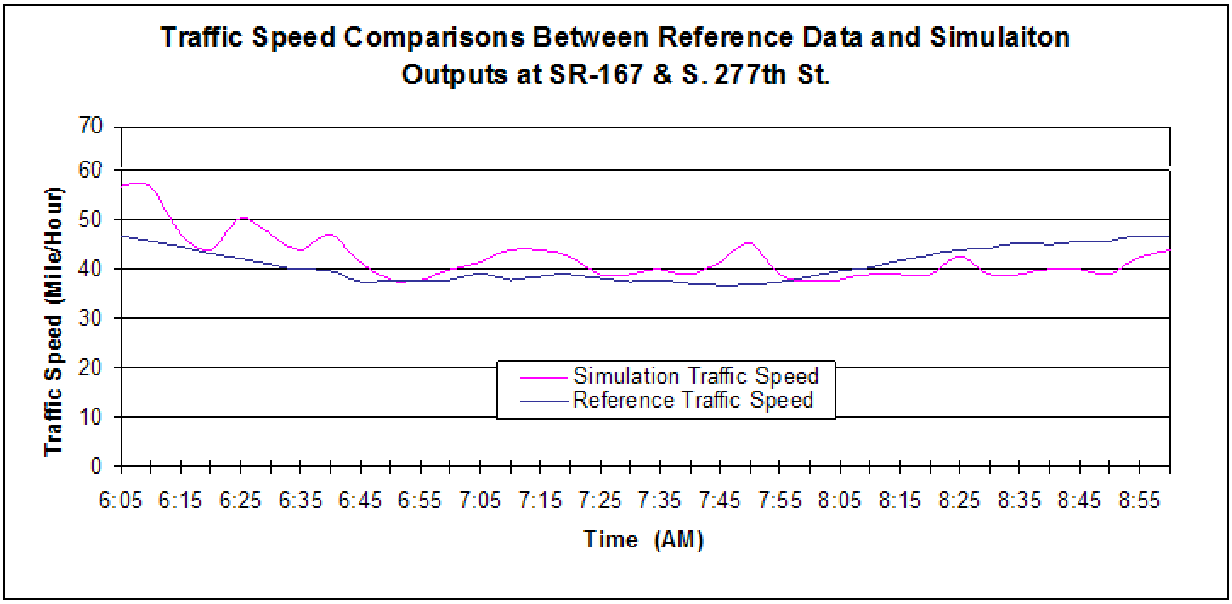

Figure 4-9: Traffic speed comparisons between reference data and simulation outputs at the location of SR-167 & 277th St.

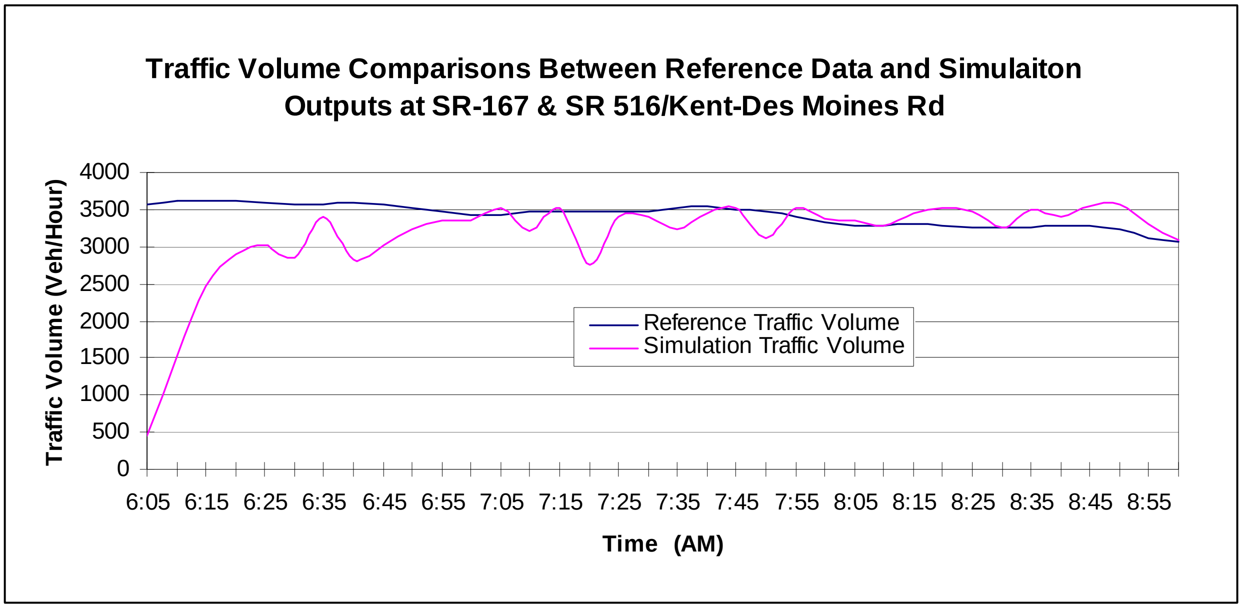

Figure 4-10: Traffic volume comparisons between reference data and simulation outputs at the location of SR-167 & SR 516/Kent-Des Moines Rd.

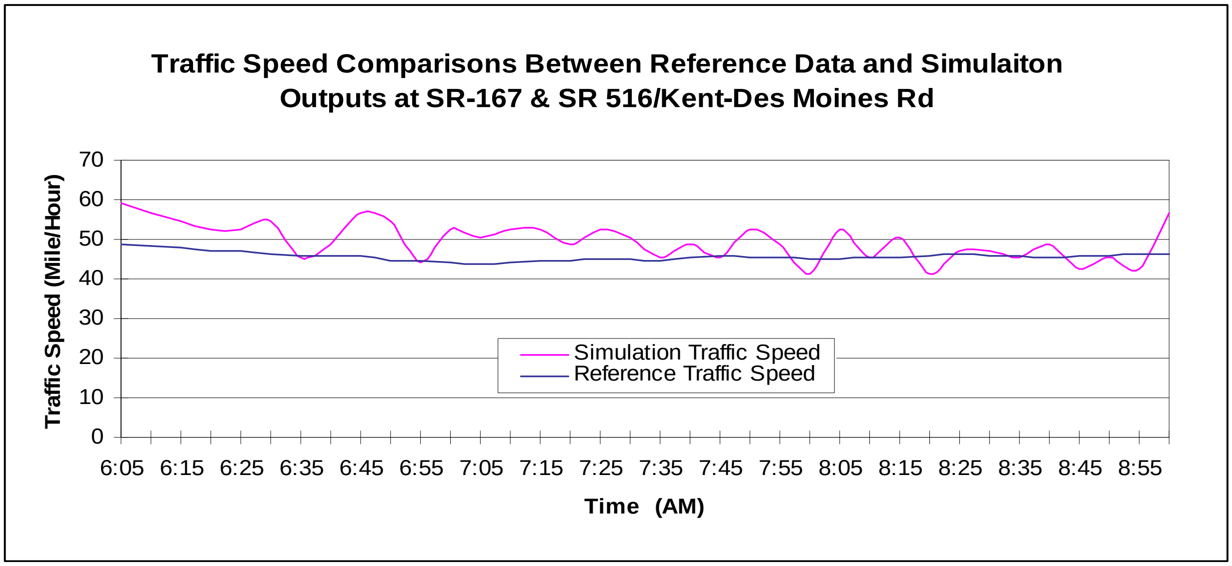

Figure 4-11: Traffic speed comparisons between reference data and simulation outputs at the location of SR-167 & SR 516/Kent-Des Moines Rd.

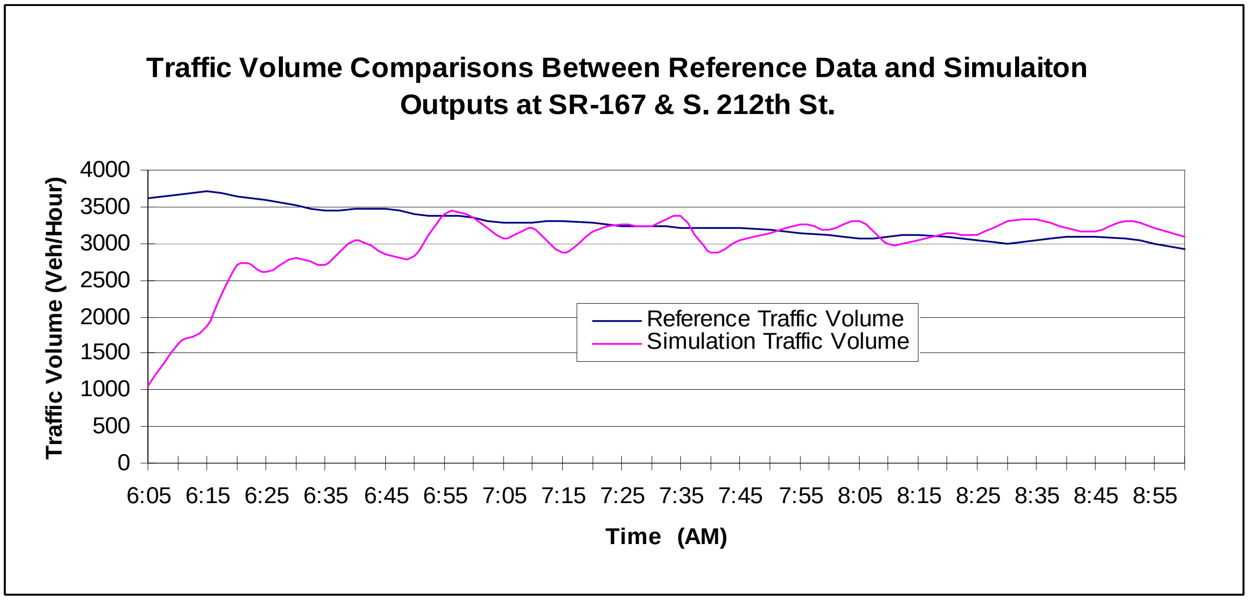

Figure 4-12: Traffic volume comparisons between reference data and simulation outputs at the location of SR-167 & S. 212th St.

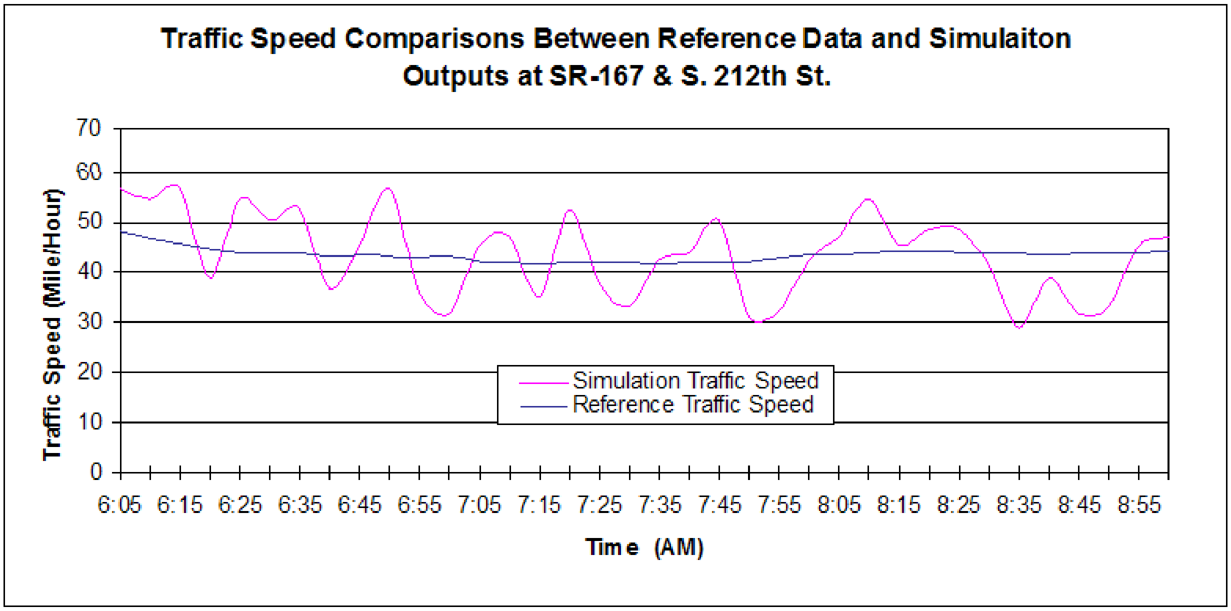

Figure 4-13: Traffic speed comparisons between reference data and simulation outputs at the location of SR-167 & S. 212th St.

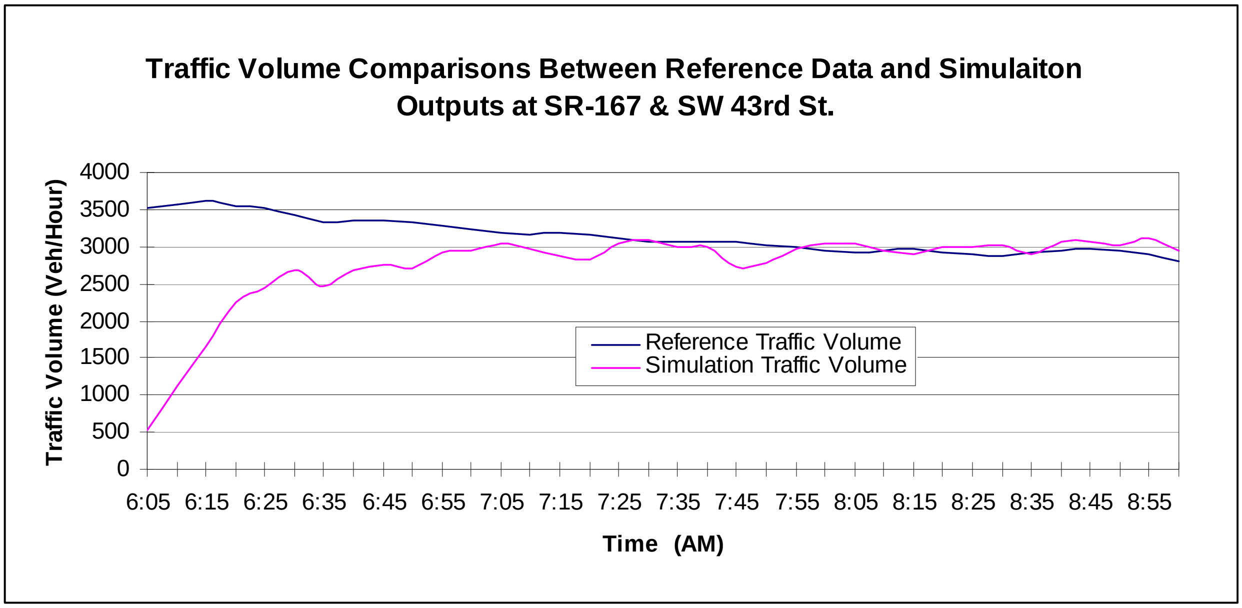

Figure 4-14: Traffic volume comparisons between reference data and simulation outputs at the location of SR-167 & SW 43rd St.

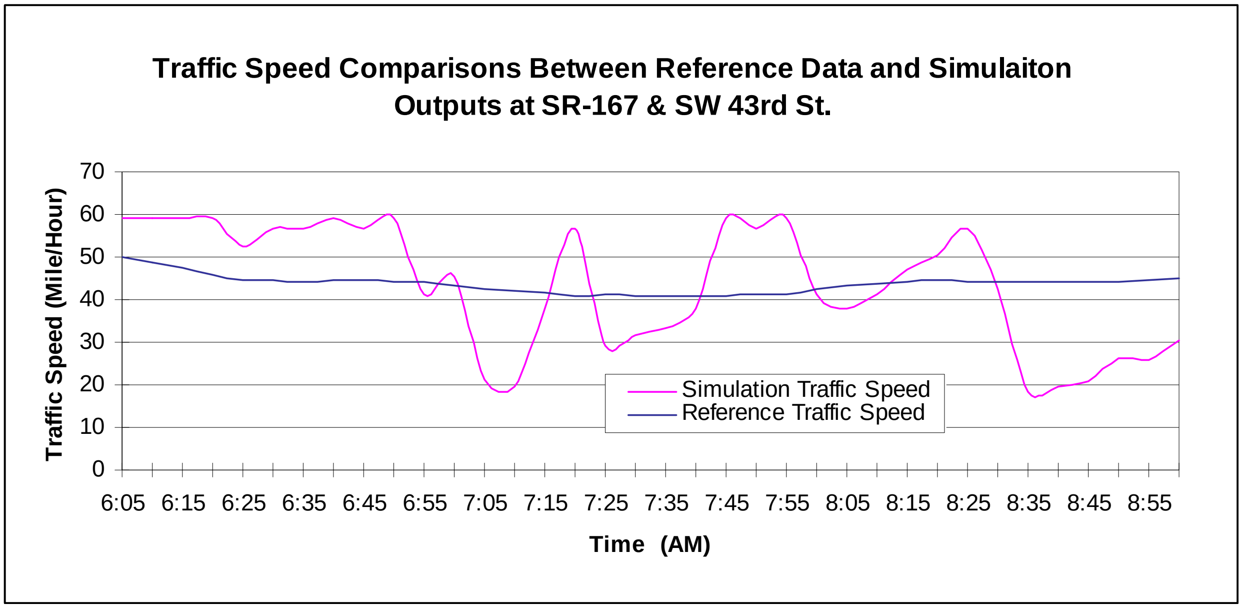

Figure 4-15: Traffic speed comparisons between reference data and simulation outputs at the location of SR-167 & SW 43rd St.

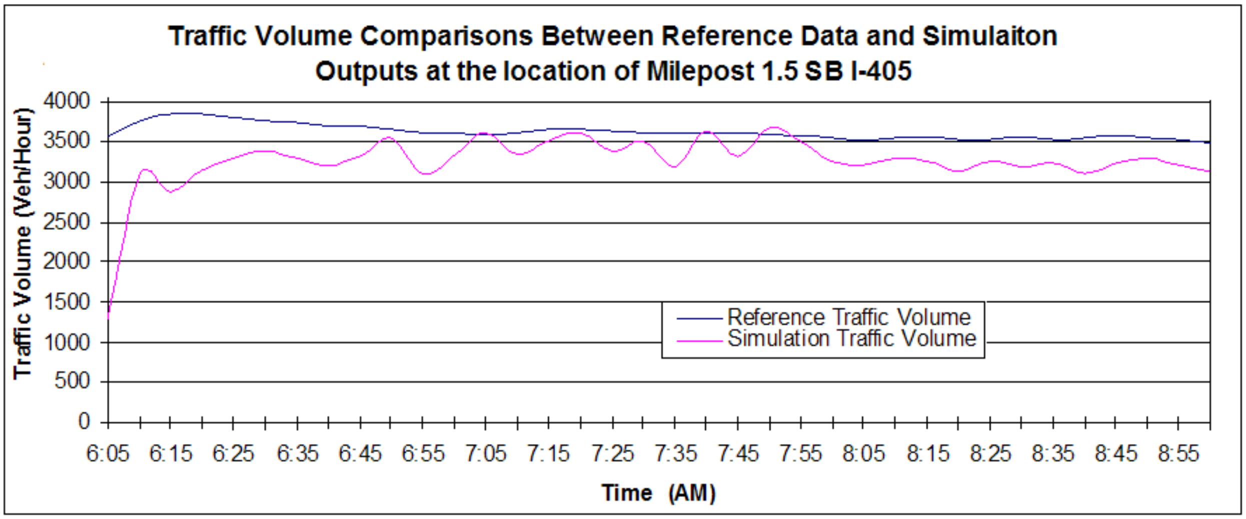

Figure 4-16: Traffic volume comparisons between reference data and simulation outputs at the location of milepost at 1.5 miles SB I-405

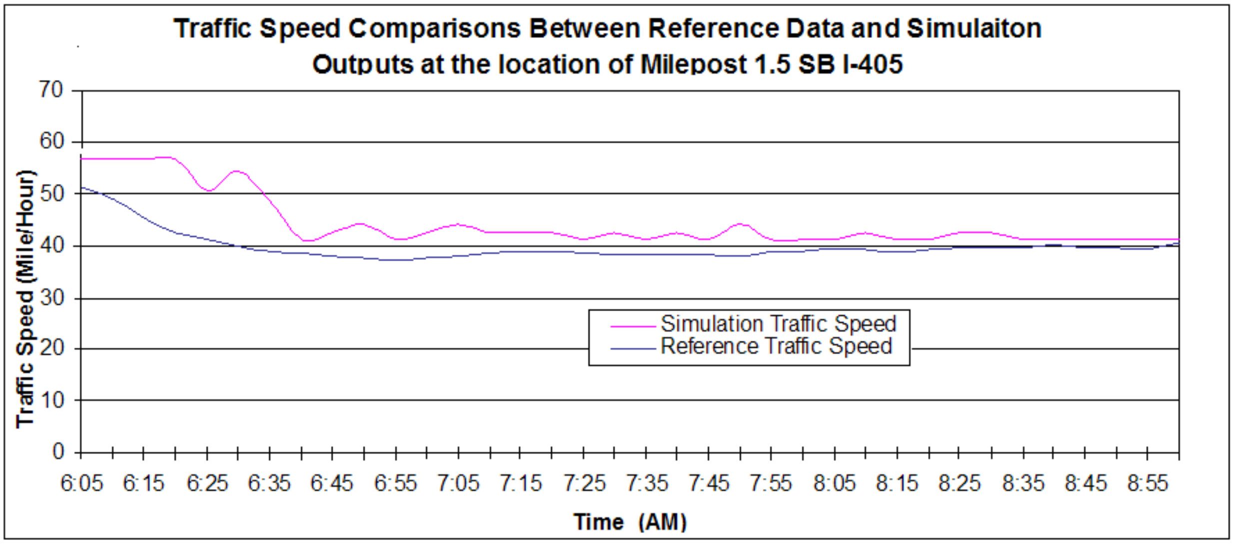

Figure 4-17: Traffic speed comparisons between reference data and simulation outputs at the location of milepost at 1.5 miles SB I-405

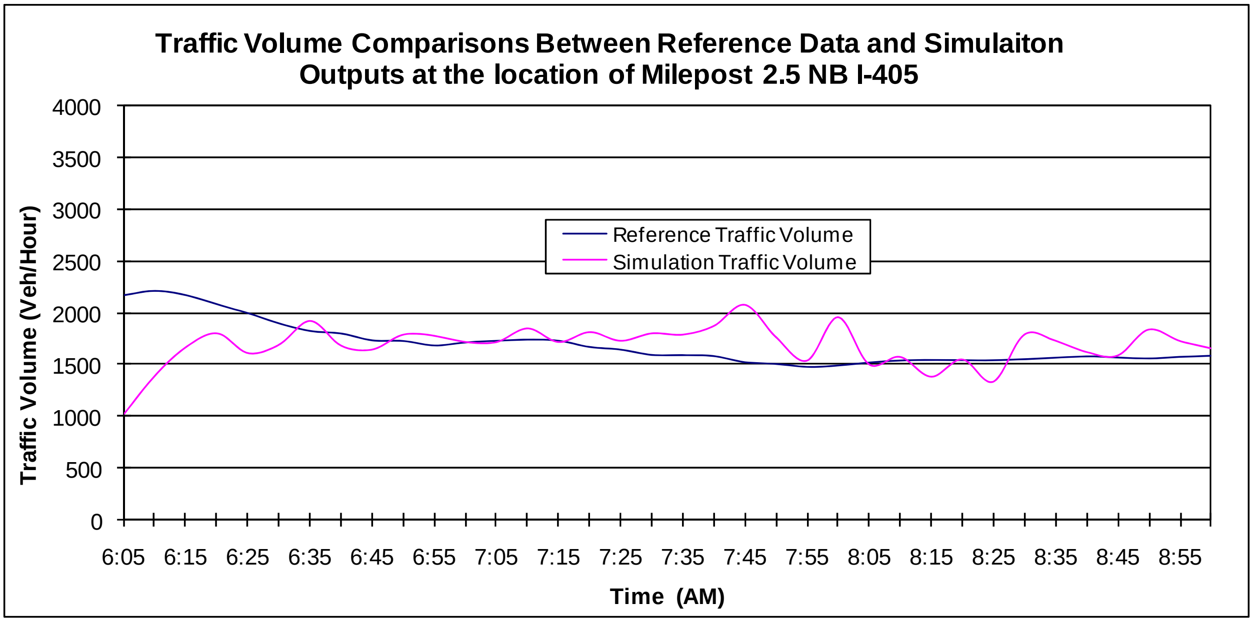

Figure 4-18: Traffic volume comparisons between reference data and simulation outputs at the location of milepost at 2.5 miles NB I-405

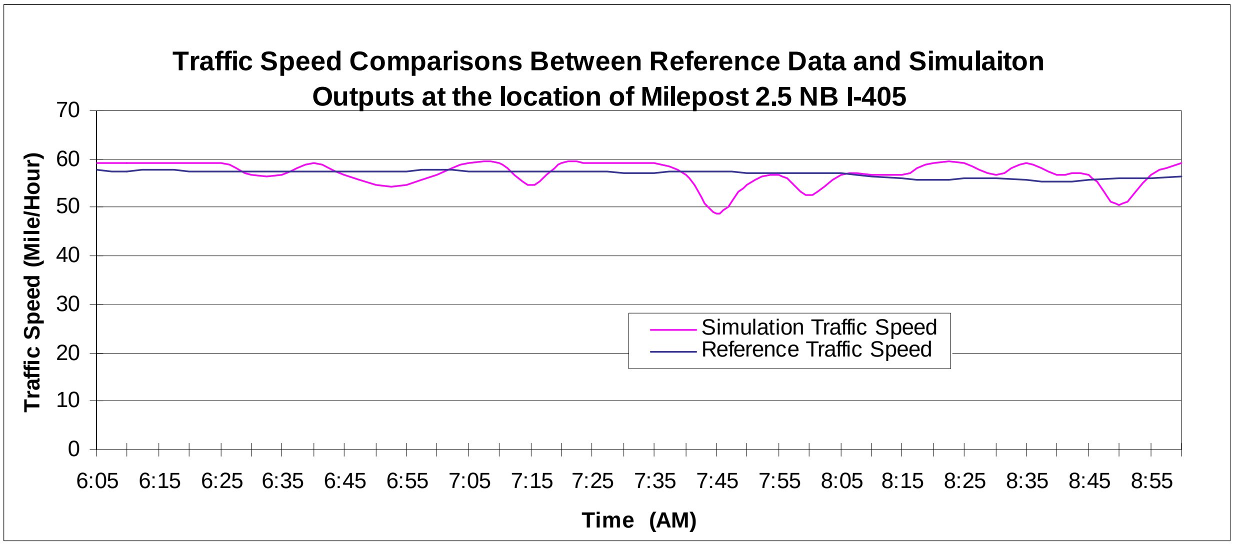

Figure 4-19: Traffic speed comparisons between reference data and simulation outputs at the location of milepost at 2.5 miles NB I-405

We can see that traffic volumes and speeds produced by the simulation model slightly fluctuate around the corresponding ground-truth annual average values. Considering the randomness of simulation outputs, such minor discrepancies are acceptable. Note that within the three-hour simulation period from 6:00 am to 9:00 am, traffic takes some time to gradually flow into the network and become stable. Also, vehicles generated near the end of the simulation period may not be able to complete their journey. Therefore, to avoid possible biased results, our analysis concentrates on one representative hour from 7:30 am to 8:30 am to screen out unfavorable disturbances. Table 4-1 shows descriptive statistics for both simulation outputs and their corresponding observed annual average values. Although simulation outputs have a bigger variation than the annual average ground-truth values, their mean values are reasonably close for both volumes and speeds. Based on both volume and speed comparisons at several vital locations, the overall simulation outputs are reasonably consistent with the reference data. Therefore, the author concludes that the model is well calibrated and can produce reliable analyses and results.

Table 4-1 Descriptive Statistics for Both Simulation Outputs and Their Corresponding Annual Average Values

Time: 7:30am-8:30am		Simulation Outputs				Annual Average Traffic Data			
		Volume[a]		Speed[b]		Volume		Speed	
		Mean	Std[c]	Mean	Std	Mean	Std	Mean	Std
SR-167	15th St. NW	3266	196.6	42.3	8.4	3224	61.9	39.8	3.3
	S. 277th St.	3303	177.7	39.7	2.8	3200	50.6	39.8	2.1
	SR 516/Kent-Des Moines Rd.	3381	127.1	47.4	3.6	3379	108.7	45.4	0.4
	S. 212th St.	3155	144.8	43.3	7.3	3128	75.9	43.1	1.0
	SW 43rd ST.	2964	102.7	45.8	9.9	2985	70.1	42.5	1.5
I-405	SB Milepost 1.5	3342	179.9	42.0	0.9	3571	32.8	38.8	0.5
	NB Milepost 2.5	1700	232.8	56.4	3.1	1535	35.8	56.7	0.7

[a] Vehicle Per Hour, [b] Mile Per Hour, [c] Standard Deviation

4.3.5 Simulation of HOT lane operations

The dynamic tolling algorithm proposed in Chapter 3 is implemented in the external HOT lane model controller module. Virtual loop detectors are employed in the simulation model. Real-time traffic movement data can be read by this external HOT lane module via the COM interfaces. Based on the toll rate and traffic conditions on the HOT and GP lanes, a lane choice decision is made for each individual vehicle being monitored in the merging area. During this process the coefficient α of Equation 3-1 needs to be determined. In this study, the value of time of $11.7 per hour is applied. This ratio value is obtained from the traffic survey in the greater Seattle area. The traffic network is abstracted by the node-edge components in VISSIM. In coding the external HOT lane module, each optional route is expressed by an ordered sequence of nodes consistent with the model configuration. After a new route decision is transmitted to each individual vehicle, its original route will be replaced so that appropriate HOT lane operations can be simulated under the dynamic tolling strategy. In this simulation model, five HOT lane sections are established. Our tests on this module indicate that the HOT lane module is able to handle all five HOT lane segments simultaneously.

Although VISSIM 4.30 is widely utilized for freeway modeling due to its ability to simulate various common transportation operations, it cannot sufficiently handle the HOT lane operation issues using its built-in modules. In this study, an independent functional module is developed to realize HOT lane simulation through the VISSIM COM interfaces. Microsoft Visual Basic is used as the external program to develop the HOT lane module in which the proposed tolling algorithm is implemented. A simulation model is established to emulate the HOT lane operation for the Washington SR 167 HOT lane pilot project.

Five HOT lane sections on northbound SR-167 from SW 15th Street in Auburn to Interstate 405 in Renton, WA, are configured in the simulation model by following the exact geographic features in reality, including the location of on-ramps and off-ramps, freeway curvature and length, weaving sections, the number of lanes, and so on. A sketch map for the overall simulation network is shown in Figure 4-3. These five HOT lane sections were selected because they represent diversified HOT lane features. For example, two off-ramps and three on-ramps are distributed along HOT Lane Segment 1, and its length is about 2.8 miles; HOT Lane Segment 2 is about 1.3 miles with one off-ramp and one on-ramp. The morning-peak hours of 6:00 to 9:00 am is chosen as the simulation time period. Three kinds of vehicles are adopted to represent a general traffic composition: SOVs, HOVs, and trucks. Dynamic traffic assignment is utilized to strengthen the practicality and validity of the simulation model. Based on the observed ground-truth data, including traffic volume and speed, the simulation model is well calibrated to properly reproduce the existing traffic conditions.

To acquire accurate speed data needed by the tolling algorithm, each HOT lane section has virtual loop detectors deployed evenly along the HOT and GP lanes in the simulation model. Based on these real-time speed data, the space-mean speed is calculated for the travel time estimation and toll determination. Based on network characteristics of this HOT lane system and the efforts of trial and error, the toll update interval is specified as 5 minutes to balance the control stabilization and timeliness. Additionally, to minimize the randomness of simulation results and enhance the credibility of the simulation models, a total of 7 simulation runs were conducted, each with a different random seed arbitrarily selected. The integrated results from these simulation runs are considered statistically reliable and unbiased.

4.4 Simulation Experimental Design

Using the external HOT lane module, simulation tests are conducted to quantify the HOT lane system performance and identify the potential problems with the SR-167 HOT lane project. Two basic test scenarios are used: current HOV lane operations and the proposed HOT lane operations. Based on our simulation results, two bottlenecks are identified under the proposed HOT lane operations, one at the northbound SR-167 exit ramp to northbound I-405, and the other at the northbound SR-167 exit ramp to southbound I-405. Both bottlenecks are marked in red squares in Figure 4-20. Due to the enhanced traffic capacities of upstream roadway sections, severe congestion is predicted to form up at the two SR-167 exit ramps to I-405.

To address these issues, two improvement plans have been developed by WSDOT. The first plan is to reconfigure the merging segments to allow vehicles in the NB I-405 Connection Distributor (CD) lane to merge into the I-405 mainline early. This can mitigate the congestion at the first bottleneck by eliminating the section where vehicles from both directions of SR-167 jointly merge into the I-405 mainline. A diagrammatic sketch of this improvement is illustrated by the right red square in Figure 4-21. Analogously, the second plan is to add a lane to each direction on I-405 just west of the SR 167 & I-405 interchange. The added lane on SB I-405 will directly receive traffic moving from SR 167 NB to I-405 SB as shown in the red rectangle on the left side. This will eliminate the merging in the SB CD lane and reduce the merging movements downstream compared to the existing condition. To fully examine the feasibility of the two improvement plans and quantitatively analyze the overall system performance, these two improvement plans are tested and evaluated.

Figure 4-20 Two bottlenecks resulted from the enhanced capacities of upstream HOT lane sections

Figure 4-21 A diagrammatic sketch of the proposed improvements with the existing infrastructure

Additionally, to fully investigate the robustness and applicability of the proposed tolling algorithm, simulation tests were conducted under various traffic demands for HOV and HOT lane operations. Based on the calibrated simulation model, the current peak-hour traffic demand from 6:00 to 9:00 am serves as the benchmark data set, and then traffic volumes change in 10% increments from 80% to 140% of benchmark. Such wide-ranging test conditions provide a reliable platform to demonstrate the effectiveness of the tolling algorithm and quantify HOT lane system performance. In brief, test scenarios are listed as follows:

Scenario 1: HOV lane and HOT lane operations under the current traffic demand;

Scenario 2: HOT lane operations plus reconfiguring the NB 167-NB to I-405 exit ramp under the current traffic demand;

Scenario 3: HOT lane operations with one lane added to each direction of I-405 just west of the SR 167 & I-405 interchange under the current traffic demand; and

Scenario 4: HOV lane and HOT lane operations under various traffic demands.

4.5 Simulation Model Development Summary

VISSIM-based simulation models were developed to examine the effectiveness of the proposed tolling algorithms. A COM-based tolling controller module is developed for dynamically optimizing HOT lane operations. Simulation models are configured and calibrated using ground-truth data collected from the study site. Verification results indicate that simulation models can reasonably represent the traffic operations in reality and are ready for further simulation experiments and analysis. Also, representative experimental test scenarios are designed. The test results and analyses are provided in the next chapter.

CHAPTER 5 SIMULATION TESTS AND ANALYSES

Simulation experiments are conducted to examine the performance of the proposed tolling algorithm for HOT lane system operations. Experiment results and analyses are detailed in this chapter.

5.1 Simulation tests under current traffic demands

First, simulation experiments are conducted for Scenarios 1 through 3 under the current traffic demand. In VISSIM, traffic generation is manipulated by a random seed number. By employing different random seeds, simulation results change correspondingly, but within a certain range. To minimize the randomness of simulation results and enhance simulation models' credibility, multiple simulation runs are necessary. In this study, for Scenarios 1, 2, and 3, a total of 12 simulation iterations are conducted, each with a different random seed arbitrarily selected. The integrated results from these simulation runs are considered statistically reliable and unbiased. To suitably measure the system performance, traffic volumes and speeds are collected at multiple travel sections, including each HOT lane segment, merging areas, and the two overall travel sections (travel sections 1 and 2) covering the entire HOT lane corridors and I-405 interchanges as shown in Figure 4-3.

Simulation results are partially summarized in Table 5-1, including travel time, throughputs, and space-mean speeds by predefined segments. Selection of HOT Lane Section 2 is determined by the fact that it represents a typical HOT lane segment. In Table 5-1, we can see that under HOV lane operations, the average speed of the GP lanes is 39 MPH (63 KM/H), and that of the HOV lane is 60 MPH (96 KM/H), or the posted speed limit. The average speed for both GP and HOV lanes is about 42 MPH (68 KM/H). Under the HOT lane scenario, the number of vehicles choosing the HOT lane increases from 558 to 910, and consequently the average speed of the GP lanes increases to 50 MPH (80 KM/H). However, the speed of the HOT lane stands at the same level, about 59 MPH (95 KM/H), and the overall average speed of both HOV and GP lanes increases to 52 MPH (84 KM/H). Such results demonstrate that substantial benefits can be achieved through HOT lane operations. Analogous analysis can be conducted for the on-ramp and off-ramp traffic. Note the speed of the merging segment drops from 55 MPH (89 KM/H) to 47 MPH (76 KM/H) due to the increased weaving movements. Considering the short length of the merging area, however, such negative influence is not enough to offset the significant benefits accomplished from HOT lane sections. In general, under HOT lane operations, the excess capacities of the HOV lane are effectively utilized. Meanwhile, there are no obvious negative impacts on the HOVs because the desired travel speed and reliability are preserved.

Due to the increased throughput of upstream HOT lane sections, the two bottlenecks become more acute at two exit ramps from SR-167 to the NB and SB I-405 Bridge as shown in Figure 4-20. When more vehicles pass through the upstream HOT lane sections and overflow into the exit ramps, the current discharging capacities are exceeded. Compared to the HOV operation, the queued traffic would accumulate faster and extend to HOT Lane Section 5. Tables 5-1 and 5-2 show the degraded performance of HOT Lane Section 5. Compared to HOV lane operations, traffic speeds and total throughputs decrease significantly under HOT lane operations. The overall average speed of both HOV and GP lanes reduces from 54 MPH (87 KM/H) to 32 MPH (51 KM/H), and the total throughput decreases from 2618 to 2588 vehicles.

Because of the severe congestion at the two bottlenecks, the net benefit gained from the upstream HOT lane operations is almost canceled. The total travel time for Overall Travel Section 1 increases slightly from 1384.8 to 1405.3 seconds, correspondingly, average speed drops to some extent from 34 MPH (55 KM/H) to 33 MPH (53 KM/H). Analogous analyses can be conducted for Overall Travel Section 2. These simulation results indicated that the proposed HOT lane operations can considerably improve traffic efficiencies (increased speed and throughput) upstream, but such gains would be significantly compromised by limited discharging capacities at the current terminus exit if the planned improvements are not implemented.

Indeed, our simulation results indicate that Scenarios 2 and 3, both with the improved exit ramps, significantly improve overall corridor performance. Test results of these two prospective scenarios confirm the applicability and necessity of the two improvement plans. In Scenario 2, after the terminus exit of the HOT lane is modified, traffic is diverged before it merges into the I-405 corridor and congestion is mitigated remarkably. The travel time of Overall Travel Section 1 is 1083.6 seconds, a decrease of 312 seconds when compared to Scenario 1. However, because NB SR-167 to SB I-405 ramp improvements are not included in this scenario, traffic on Overall Travel Section 2 is still in the severely congested condition. The average speed is about 30 MPH (48 KM/H). This problem is relieved in Scenario 3 with an additional lane added to each direction of I-405 just west of the interchange. The average speed of Overall Travel Section 2 increases from 30 MPH (48 KM/H) to 53 MPH (85 KM/H), and the total throughput increases from 228 to 248 vehicles. Note that this improvement also helps to improve the traffic on Overall Travel Section 1. Its travel time reduces further from 1083 to 910 seconds and the average speed increases to 52 MPH (84 KM/H).

Table 5-1 Integrated Simulation Results for Operation Scenario 1 from 12 Simulation Runs

Time : 7:30-8:30 AM		Scenario 1: HOV Operation			Scenario 1: HOT Operation		
		TT^a	TP^b	SP^c	TT	TP	SP
Merging Area 2		39.7	3568	55	49.2	3559	46
HOT Segment 2: Length =1.30 Mile	GP+HOV/HOT	112.0	3190	42	89.3	3226	52
	GP Lane	119.1	2634	39	93.5	2318	50
	HOV/HOT Lane	77.9	558	60	78.6	910	59
	On-Ramp	43.8	552	42	40.3	554	46
	Off-Ramp	41.7	283	50	39.0	280	53
Merging Area 5		35.2	3495	56	43.4	3540	48
HOT Segment 5: Length =1.38 Mile	GP+HOV/HOT	92.4	2618	54	155.1	2588	32
	GP Lane	94.9	2053	52	184.9	1569	27
	HOV/HOT Lane	83.1	567	60	108.8	1022	46
	On-Ramps	17.1	839	47	68.5	784	18
	Off-Ramps	52.2	816	45	55.7	833	44
NBSectionTo405Bridge		109.2	3429	37	284.3	3176	14
NBRampToNB405Bridge		212.3	960	15	217.9	908	17
NBRampToSB405Bridge		419.8	718	12	544.3	651	10
OVERALL 167NB-405NB: Length = 13.04 Mile	GP+HOV/HOT	1384.8	214	34	1405.3	208	33
	GP Lane Only	1432.7		33	1448.8		32
	HOV Lane Only	1132.9		41	1332.6		35
OVERALL 167NB-405SB: Length = 13.52 Mile	GP+HOV/HOT	1558.3	119	31	1630.2	117	30
	GP Lane Only	1606.1		30	1673.6		29
	HOV/HOT Lane Only	1306.4		37	1557.5		31

^{a} Travel Time (Sec.), ^{b} Throughputs, ^{c} Speed (MPH)

Additionally, two reference travel times are calculated and provided for Overall Travel Section 1 and 2, respectively. For instance, if a user chooses to pay to travel across Section 1 using the entire HOT lanes, the total travel time is expected to be 879 seconds, less than the travel time of 927 seconds that he/she would spend in using GP lanes without paying. These data collected from different simulation scenarios are helpful to update the proper toll rates as feedback information before HOT lane operations are executed in reality.

Table 5-2 Integrated Simulation Results for Operation Scenarios 2 and 3 from 12 Simulation Runs

Time : 7:30-8:30 AM		Scenario 2: HOT Operation with NB Exit Ramp Improvement			Scenario 3: HOT Operation with NB and SB Exit Ramp Improvements		
		TT[a]	TP[b]	SP[c]	TT	TP	SP
Merging Area 2		45.4	3568	48	46.7	3596	47
HOT Segment 2: Length =1.30 Mile	GP+HOV/HOT	88.7	3242	53	89.2	3277	52
	GP Lane	92.5	2332	51	93.4	2325	50
	HOV/HOT Lane	78.9	912	59	78.9	954	59
	On-Ramp	39.7	554	47	39.7	554	47
	Off-Ramp	39.1	281	53	39.1	283	53
Merging Area 5		41.9	3568	48	41.3	3589	49
HOT Segment 5: Length =1.38 Mile	GP+HOV/HOT	113.9	2659	44	88.2	2703	56
	GP Lane	126.2	1576	39	91.0	1594	55
	HOV/HOT Lane	95.9	1085	52	84.0	1111	59
	On-Ramps	41.8	806	38	14.6	840	54
	Off-Ramps	50.1	842	47	49.4	845	48
NBSectionTo405Bridge		204.8	3276	22	65.0	3549	56
NBRampToNB405Bridge		72.9	961	45	77.6	1025	43
NBRampToSB405Bridge		638.7	652	8	91.3	836	55
OVERALL 167NB-405NB: Length = 13.04 Mile	GP+HOV/HOT	1083.6	228	43	910.5	248	52
	GP Lane Only	1110.0		42	927.0		51
	HOV Lane Only	1039.2		45	879.7		53
OVERALL 167NB-405SB: Length = 13.52 Mile	GP+HOV/HOT	1629.8	118	30	924.1	177	53
	GP Lane Only	1656.2		29	940.6		52
	HOV/HOT Lane Only	1585.4		31	893.3		54

[a] Travel Time (Sec.), [b] Throughputs, [c] Speed (MPH)

Then, simulation experiments are conducted under current traffic conditions. The integrated simulation results are summarized in Table 5-3, including travel time, throughputs, and space-mean speeds for the entire HOT lane system. To facilitate the comparison of system performance under HOV lane operations and HOT lane operations, an improvement ratio is defined. For traffic speed analysis, the improvement ratio, IR_{speed}, can be computed as follows

$$IR_{speed} = \frac{SP_{HOT} - SP_{HOV}}{SP_{HOV}} \tag{5-1}$$

Where, SP_{HOT} denotes the average traffic speed under HOT lane operations; SP_{HOV} denotes the average traffic speed achieved under HOV lane operations. Similarly, an analogous variable is defined for analyzing traffic throughputs. Table 5-3 shows these variables quantifying the improvement for throughputs and speeds under the “improvement” column. As we can see, for example, Lane Segment 2, under HOV lane operations, the average speed of the GP lanes is 41.2 MPH, and that of HOV lane is 60.0 MPH. The average speed for both GP and HOV lanes is about 43.6 MPH. Under HOT lane operations, the number of vehicles choosing the HOT lane increase from 1574 to 2430 within 3 hours, and, consequently, the average speed of the GP lanes increases to 53.5 MPH. However, the HOT lane speed stands at the same level, about 59.2 MPH, and the overall average speed of both HOT and GP lanes increases to 55.0 MPH from 43.6 MPH, an improvement of 26.2%. The total throughputs maintain the same level, although there is a slight increase from 9153 to 9226. Although there is congestion under HOV lane operation, the existing traffic system is capable of handling all through vehicles within present traffic demands. Hence, switching HOV to HOT operations does not have significant enhancement in terms of traffic throughputs. Similar analysis can be conducted for on-ramp and off-ramp traffic for HOT lane Segment 2.

For other HOT lane segments, similar results can be obtained from Table 5-3. The overall traffic efficiency is improved remarkably under HOT lane operations. Note that for HOT Lane Segment 5, traffic operates reasonably well under the present HOV lane system. The average speed for both GP and HOV lanes is about 53.9 MPH. Therefore, no considerable improvements are expected under HOT lane operations.

Table 5-3 Integrated Simulation Results under Existing Traffic Demands from Seven Simulation Runs

Simulation Time Period: 6:00-9:00 Am		HOV Operation			HOT Operation			Improvement	
		TT[a]	TP[b]	SP[c]	TT	TP	SP	TP	SP
Merging Area 1		57.9	7747	34.2	64.3	7732	30.8	-0.2%	-9.9%
HOT Segment 1: Length = 2.8Mile	GP+HOV/HOT	230.0	5588	43.6	176.1	5586	56.9	0.0%	30.6%
	GP Lane	242.0	4677	41.4	180.8	2573	55.4	-45.0%	33.8%
	HOV/HOT Lane	168.4	912	59.5	172.1	3013	58.3	230.5%	-2.1%
	On-Ramps	71.7	5401	24.5	32.7	5445	52.2	0.8%	113.0%
	Off-Ramps	22.5	2712	34.2	20.7	2684	36.9	-1.0%	7.9%
Merging Area 2		44.6	10142	48.7	44.6	10210	48.7	0.7%	0.0%
HOT Segment 2: Length = 1.3Mile	GP+HOV/HOT	107.3	9153	43.6	85.0	9226	55.0	0.8%	26.2%
	GP Lane	113.3	7579	41.2	87.3	6796	53.5	-10.3%	29.8%
	HOV/HOT Lane	77.9	1574	60.0	78.9	2430	59.2	54.4%	-1.2%
	On-Ramps	42.8	1588	43.6	38.7	1592	48.0	0.2%	10.0%
	Off-Ramps	43.6	893	48.6	39.0	899	53.1	0.7%	9.3%
Merging Area 3		40.5	10695	44.0	44.0	10789	40.5	0.9%	-8.0%
HOT Segment 3: Length = 1.2Mile	GP+HOV/HOT	86.0	8511	49.9	74.7	8614	57.4	1.2%	15.1%
	GP Lane	88.5	7272	48.5	75.5	7151	56.9	-1.7%	17.2%
	HOV/HOT Lane	71.3	1239	60.2	71.0	1463	60.0	18.1%	-0.3%
	On-Ramps	35.1	1573	52.5	30.8	1575	57.2	0.1%	9.0%
	Off-Ramps	39.8	2092	47.6	38.1	2109	49.3	0.8%	3.7%
Merging Area 4		37.5	10033	47.1	33.5	10155	52.7	1.2%	11.9%
HOT Segment 4: Length = 2.4Mile	GP+HOV/HOT	225.4	7288	37.7	149.8	7435	56.8	2.0%	50.5%
	GP Lane	239.7	6207	35.5	152.1	4852	55.9	-21.8%	57.6%
	HOV/HOT Lane	143.5	1081	59.3	145.2	2583	58.6	138.9%	-1.2%
	On-Ramps	40.4	3310	44.7	33.3	3352	53.6	1.3%	19.9%
	Off-Ramps	34.2	2715	38.2	25.5	2760	49.9	1.7%	30.6%
Merging Area 5		35.2	9905	56.2	41.4	10062	47.8	1.6%	-15.0%
HOT Segment 5: Length = 1.4Mile	GP+HOV/HOT	92.1	7445	53.9	86.4	7581	57.4	1.8%	6.6%
	GP Lane	94.7	5783	52.4	88.0	4583	56.4	-20.8%	7.6%
	HOV/HOT Lane	83.0	1663	59.8	83.9	2998	59.1	80.3%	-1.1%
	On-Ramps	16.0	2475	50.1	14.3	2476	55.8	0.0%	11.4%
	Off-Ramps	53.3	2366	44.5	48.6	2410	48.8	1.9%	9.6%

[a] Travel Time (Second), [b] Throughputs, [c] Speed (Mile Per Hour)

5.2 Simulation tests under various traffic demands

Further simulation tests were conducted on broadly changing traffic demands. Based on the present traffic condition, six additional test scenarios are proposed with the demands distributing from 80% to 140% of the current demand. Simulation results for HOT Lane Segment 2 are shown in Table 5-3. This segment is representative for a typical HOT lane operation. As can been seen from Table 5-4, under HOV lane operations the maximum throughputs that can be efficiently handled by the existing infrastructure is about 9153 vehicles with the current demand. When the demand increases, overall traffic conditions deteriorate, and traffic speeds and throughputs decrease notably. However, under HOT lane operations, due to the enhanced traffic capacities, the maximum throughputs increase to 9489 vehicles, corresponding to 110% of the current demand. The improvement of traffic throughputs and speed accomplished by HOT lane operations is progressively noticeable with the increasing demand. The maximum improvements are 11.8% and 61.5% for traffic throughputs and speed, respectively, corresponding to 130% of the current demand. Note that immunizing from the negative impacts of the increased demands, the HOT lane speed is preserved in the desired range. The minimum speed is about 47.1 MPH, slightly higher than the HOT lane speed criterion of 45 MPH. These analytical results clearly indicate enhanced system performance of the HOT lane system and further clarify that the proposed tolling algorithm is capable of optimizing the overall traffic operation and ensuring travel reliability on the HOT lane under various traffic conditions.

Table 5-4 Integrated Simulation Results for HOT Lane Segment 2 under Various Traffic Demands from Seven Simulation Runs

Simulation Time Period: 6:00-9:00 Am		HOV Operation			HOT Operation			Improvement	
		TT[a]	TP[b]	SP[c]	TT	TP	SP	TP	SP
80%	GP+ HOV/HOT	80.7	7976	57.9	80.5	7945	58.1	-0.4%	0.2%
	GP Lane	81.4	6384	57.4	81.2	6287	57.6	-1.5%	0.2%
	HOV/HOT	77.8	1592	60.0	77.7	1659	60.1	4.2%	0.1%
	On-Ramps	35.7	1321	51.9	35.5	1321	52.1	0.1%	0.5%
	Off-Ramps	38.5	776	53.9	38.4	774	53.9	-0.3%	0.0%
90%	GP+HOV/HOT	83.2	8576	56.1	81.7	8560	57.2	-0.2%	1.9%
	GP Lane	84.4	6985	55.3	82.8	6568	56.4	-6.0%	1.9%
	HOV/HOT	77.9	1591	60.0	78.0	1992	59.9	25.2%	-0.2%
	On-Ramps	37.6	1443	49.3	36.7	1444	50.5	0.0%	2.5%
	Off-Ramps	38.9	833	53.3	38.8	832	53.5	-0.1%	0.3%
100%	GP+HOV/HOT	107.3	9153	43.6	85.0	9226	55.0	0.8%	26.2%
	GP Lane	113.3	7579	41.2	87.3	6796	53.5	-10.3%	29.8%
	HOV/HOT	77.9	1574	60.0	78.9	2430	59.2	54.4%	-1.2%
	On-Ramps	42.8	1588	43.6	38.7	1592	48.0	0.2%	10.0%
	Off-Ramps	43.6	893	48.7	39.0	899	53.2	0.7%	9.2%
110%	GP+HOV/HOT	134.6	9117	34.7	93.4	9489	50.0	4.1%	44.0%
	GP Lane	145.7	7621	32.1	98.7	6547	47.3	-14.1%	47.7%
	HOV/HOT	78.1	1496	59.8	81.8	2942	57.1	96.7%	-4.5%
	On-Ramps	47.5	1691	39.1	41.8	1700	44.3	0.5%	13.3%
	Off-Ramps	53.4	889	39.1	39.3	913	52.8	2.6%	35.0%
120%	GP+HOV/HOT	183.1	8764	25.5	117.6	9279	39.7	5.9%	55.8%
	GP Lane	202.2	7410	23.1	127.8	6643	36.5	-10.4%	58.2%
	HOV/HOT	78.4	1354	59.6	88.5	2636	52.8	94.7%	-11.4%
	On-Ramps	55.0	1819	33.8	46.8	1812	40.4	-0.4%	19.5%
	Off-Ramps	75.3	897	27.6	46.6	924	45.4	3.0%	64.9%
130%	GP+HOV/HOT	211.5	8330	22.1	131.0	9311	35.7	11.8%	61.5%
	GP Lane	234.8	7087	19.9	146.0	6350	32.0	-10.4%	60.8%
	HOV/HOT	78.9	1243	59.2	96.3	2961	48.5	138.2%	-18.0%
	On-Ramps	75.4	1949	24.9	57.1	1947	34.4	-0.1%	38.5%
	Off-Ramps	90.3	893	23.0	52.3	942	41.2	5.6%	79.2%
140%	GP+HOV/HOT	255.2	7859	18.3	157.6	8277	29.6	5.3%	62.0%
	GP Lane	284.3	6747	16.4	176.8	6093	26.4	-9.7%	60.8%
	HOV/HOT	79.1	1112	59.1	99.2	2184	47.1	96.3%	-20.3%
	On-Ramps	103.0	2073	18.2	59.2	1910	31.5	-7.8%	73.3%
	Off-Ramps	112.2	846	18.5	60.8	857	35.5	1.3%	92.1%

[a] Travel Time (Second), [b] Throughputs, [c] Speed (Mile Per Hour)

Visual comparisons on speed between the HOV/HOT and GP lanes under different operation scenarios confirm the analytical results achieved above. For instance, Figure 5-1 shows the comparison curves of traffic speed aggregated in 5-minute intervals for the HOV and GP lanes of Lane Segment 1 under HOV lane operations with the current traffic demand. Figure 5-2 shows the corresponding speed curves under HOT lane operations. The changing patterns of the GP lane speed in both figures indicate that by employing the tolling algorithm proposed in this study, the excess capacities of the HOT lane are effectively utilized and the GP lane speed is considerably improved; meanwhile, there are no obvious negative impacts on the HOV travel time because the desired travel speed and reliability are preserved on the HOT lane. Because the HOT and GP lane speeds are relatively consistent, and the toll is stable around \$0.10 to \$0.20 for SOVs to use this HOT lane.

Similar comparisons were conducted with the increasing demands. Figures 5-3 and 5-4 illustrate the speed comparison curves for the HOV/HOT lane and the GP lane with 140% of the current demand. We can see that under HOV lane operations, although the HOV lane speed maintains at the ideal level, traffic congestion generated by the dramatic increase of traffic demand severely corrupts the GP lane speed. This problem can be partially solved under HOT lane operations. Some SOVs are discharged through the HOT lane and the GP lane speed is improved to some extent. Figure 5-4 shows the HOT lane speed was suitably adjusted to adapt to the changing traffic conditions and optimize the overall traffic operations. Figure 5-5 demonstrates the changing pattern of the corresponding toll rate. Operated by the proposed tolling algorithm, the toll rate is self-adaptive to traffic conditions on GP and HOT lanes. For example, a maximum toll rate of about \$3.90 per mile is immediately applied when the HOT lane speed drops to 30 MPH, then the HOT lane condition rapidly improves, and the toll rate is back to the normal value, e.g., $0.50 per mile. Such matching patterns between the toll rate and HOT lane speed indicate the appropriate sensitivity and robustness of the proposed tolling algorithm.

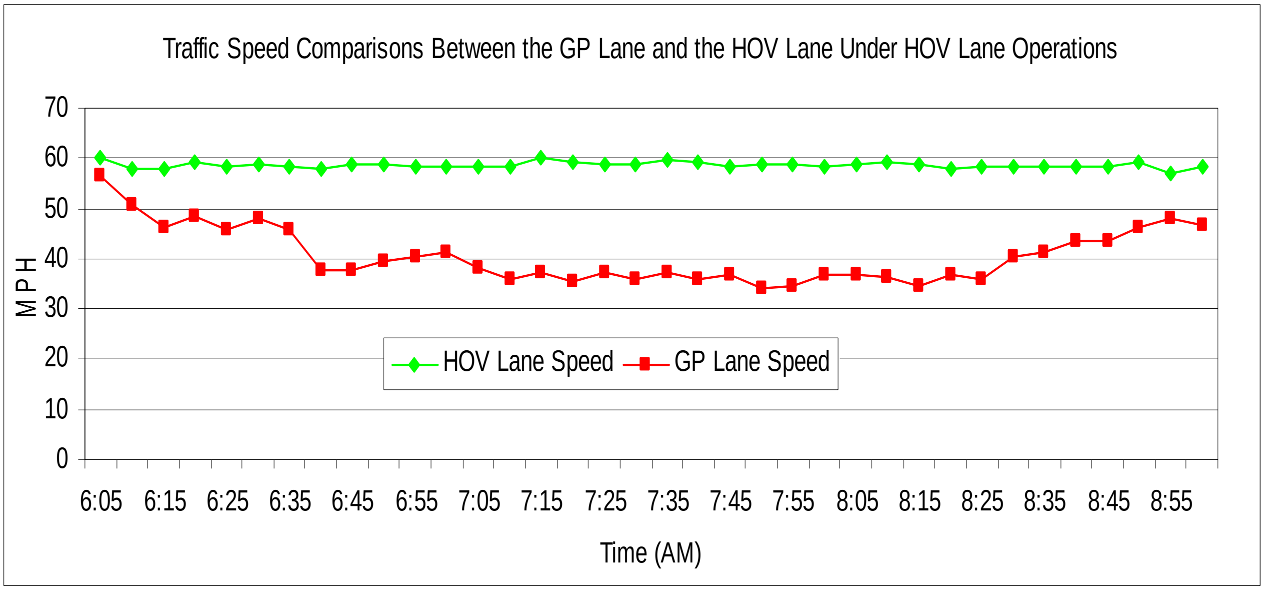

Figure 5-1 Traffic speed comparisons between the GP and HOV lanes for Lane Segment 1 under HOV lane operations with the current demand

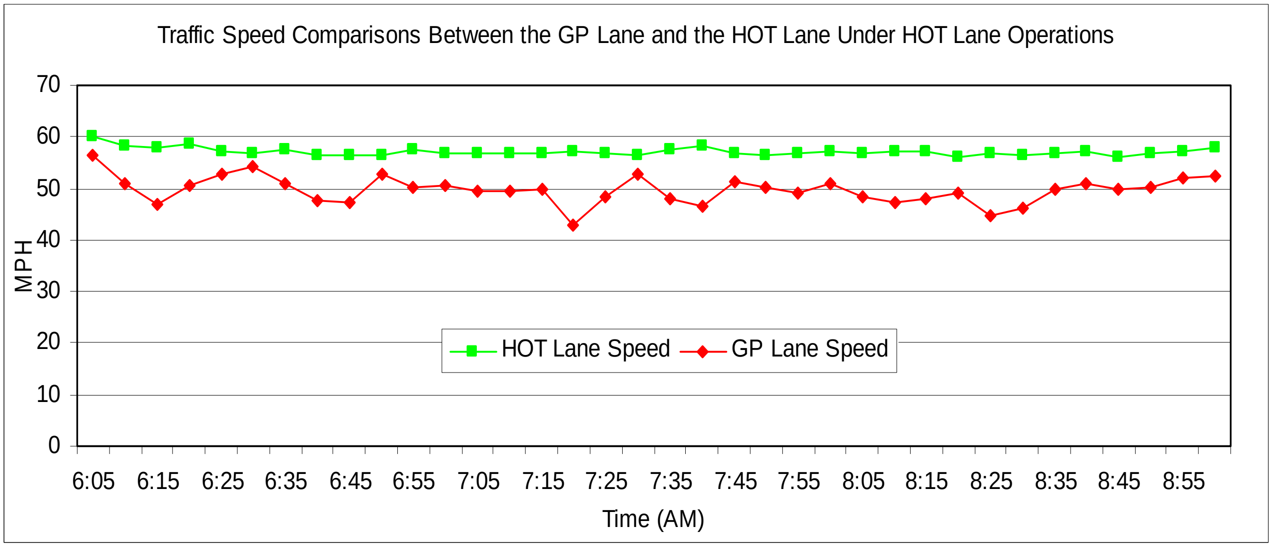

Figure 5-2 Traffic speed comparisons between the GP and HOT lanes for Lane Segment 1 under HOT lane operations with the current demand

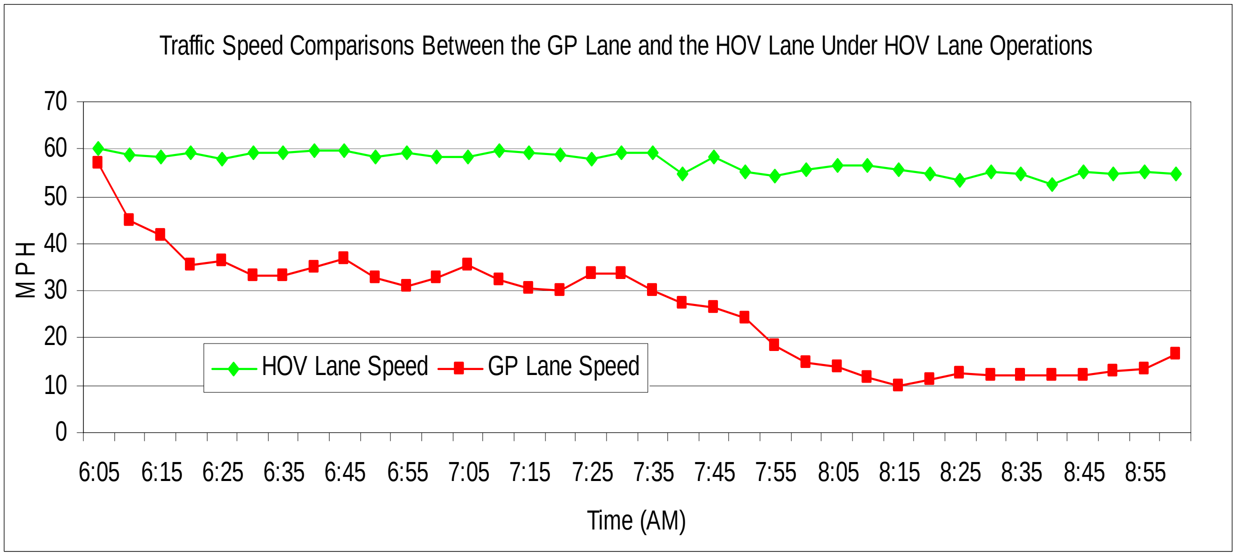

Figure 5-3 Traffic speed comparisons between the GP and HOV lanes for Lane Segment 1 under HOV lane operations with 140% of the current demand

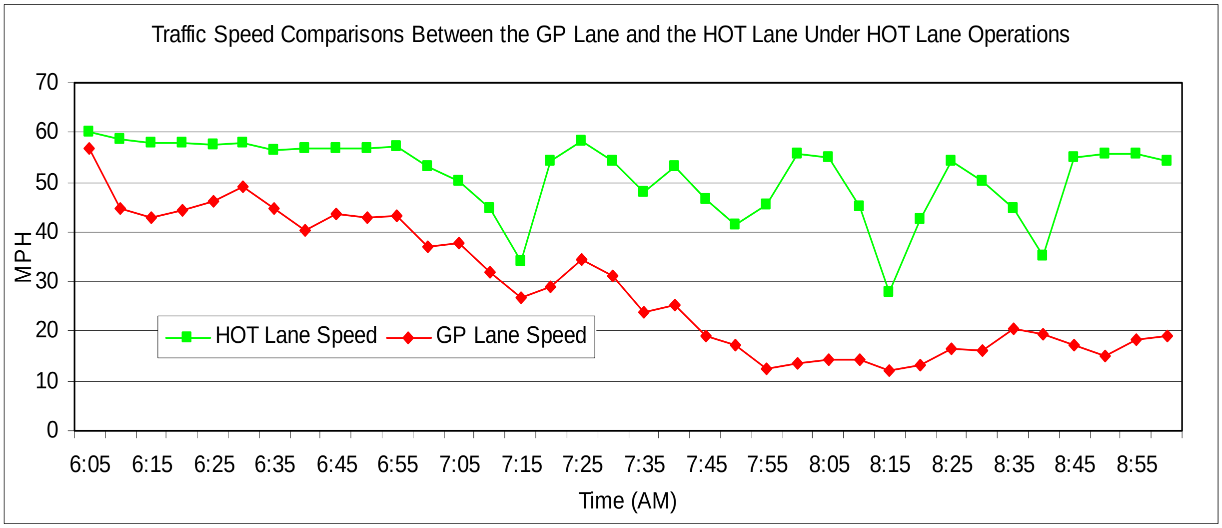

Figure 5-4 Traffic speed comparisons between the GP and HOT lanes for Lane Segment 1 under HOT lane operations with 140% of the current demand

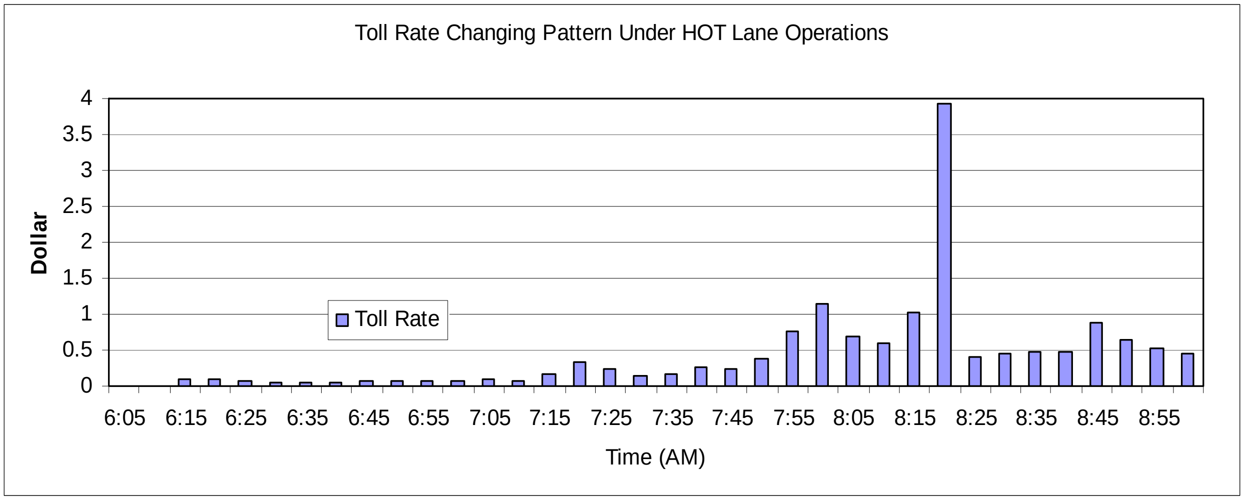

Figure 5-5 Toll rate changing pattern for Lane Segment 1 under HOT lane operations with 140% of the current demand

5.3 Tolling impacts on HOV travelers

Simulation experiments are conducted to investigate HOT lane system impacts on regular HOV travelers. The operation performance of HOVs is quantified under two test scenarios: previous HOV lane operations, and corresponding HOT lane operations with the current traffic demand. A total of 10 simulation runs are conducted, each with a different random seed arbitrarily selected. The integrated results from these simulation runs are collected by multiple travel sections summarized in Table 5-5, including travel time, throughputs, and space-mean speeds for HOVs. As we can see, HOV operations degrade significantly along the merging areas in the HOT lane system. For example, weaving movements decrease the average speed of HOVs from 53.1 MPH to 47.8 MPH in Merging Area 2 when HOV lanes are converted to HOT lanes, which correspond to an negative improvement of -9.98%. And total HOV throughputs maintain at the same levels. Similar results can be obtained for other merging areas. These data show that due to weaving movements majorly generated by tolled SOVs accessing in and out of HOT lanes, remarkable negative impacts are observed for HOV operations. The average HOV speeds noticeably drop from 5.50% (Merging Area 1) to 27.85% (Merging Area 3), although the throughputs fluctuate slightly. Additionally, note that the average speed of HOVs in Merging Area 1 is about 32.1 MPH which is considerably lower than that of other merging areas. This is because two off-ramps are very close to Merging Area 1, and the unfavorable weaving movements remarkably influence the smooth movements of vehicles. For the operation performance of HOVs on the HOV/HOT lanes, marginal deteriorations are observed. For instance, in Segment 3, the average speed of HOVs is about 60.2 MPH under HOV lane operations, and it slightly decreases to 58.2 MPH in the HOT lane system. Although more vehicles are carried by the HOT lane compared to the HOV lane, no severe interactions between vehicles, such as standstill and slowdown for changing lane, are introduced on the HOT lane. For the entire HOT lane system, the decrease in speed ranges from 1.46% (Segment 1) to 4.75% (Segment 2). Considering the randomness of simulation runs, such difference is not statistically significant.

For on-ramp and off-ramp trips, HOV operations are closely associated with specific geometric characteristics, traffic demand levels, traffic compositions, and driver behavior patterns. The separation between HOT and GP lanes deployed in HOT lane systems compromises the flexibility of HOVs for lane changing, however, due to the improvements in service conditions on GP lanes, the losses in travel time and trip reliability for HOVs could be compensated to some extent. Two representative examples are illustrated as follows. For HOT lane Segment 2, one on-ramp and one off-ramp are distributed along this 1.3-mile segment. The average speed of on-ramp HOVs is 50.3 MPH under HOV lane operations, which is appreciably higher than the speed of 45.6 MPH under HOT lane operations.

Table 5-5 Integrated Simulation Results for HOV Operation Evaluation from 10 Simulation Runs

Simulation Time		HOV Lane System			HOT Lane System			Improvement	
Period: 6:00-9:00 Am		TT[a]	TP[b]	SP[c]	TT	TP	SP	TP	SP
Merging Area 1		35.2	1268	32.1	37.3	1236	30.3	-2.55%	-5.50%
HOT Segment 1: Length = 2.8 Mile	HOV/HOT	179.3	920	58.1	182.3	927	57.1	0.71%	-1.64%
	On-Ramps	189.3	788	28.8	146.2	770	37.3	-2.40%	29.48%
	Off-Ramps	176.6	357	36.9	140.1	363	46.6	1.68%	26.09%
Merging Area 2		100.2	1751	53.1	111.4	1777	47.8	1.51%	-9.98%
HOT Segment 2: Length = 1.3 Mile	HOV/HOT	84.5	1476	55.2	88.7	1454	52.6	-1.51%	-4.75%
	On-Ramps	39.3	107	50.3	43.3	109	45.6	1.87%	-9.35%
	Off-Ramps	46.1	278	53.1	47.9	283	51.1	1.73%	-3.81%
Merging Area 3		50.0	1577	57.1	69.4	1569	41.2	-0.55%	-27.85%
HOT Segment 3: Length = 1.2 Mile	HOV/HOT	71.0	1172	60.2	73.5	1131	58.2	-3.50%	-3.29%
	On-Ramps	35.1	410	56.5	34.7	417	57.1	1.81%	1.12%
	Off-Ramps	37.4	390	53.3	41.2	426	48.3	9.15%	-9.33%
Merging Area 4		37.2	1578	59.4	43.9	1542	50.3	-2.31%	-15.22%
HOT Segment 4: Length = 2.4 Mile	HOV/HOT	144.1	1067	58.9	147.3	1074	57.6	0.65%	-2.20%
	On-Ramps	74.2	794	55.2	78.6	797	52.1	0.35%	-5.55%
	Off-Ramps	74.5	466	52.1	72.1	442	53.9	-5.09%	3.40%
Merging Area 5		46.9	1842	59.2	58.1	1861	47.8	1.02%	-19.26%
HOT Segment 5: Length = 1.4 Mile	HOV/HOT	83.8	1671	59.1	86.3	1653	57.4	-1.04%	-2.92%
	On-Ramps	14.8	543	58.8	16.2	543	54.0	-0.06%	-8.09%
	Off-Ramps	62	176	47.3	60.2	183	48.5	4.27%	2.43%

[a] Travel Time (Second), [b] Throughputs, [c] Speed (Mile Per Hour)

Similar results can be obtained for off-ramp HOVs. This can be explained by the fact that due to limited access points for ingress and egress movements, HOVs may have to travel longer distance on GP lanes before entering the HOT lane or exiting the freeway under inferior travel conditions. However, as an opposite example, HOVs on Segment 1 demonstrate different characteristics. Segment 1 is 2.8-mile long with two off-ramps and three on-ramps. Simulation results indicate that considerable improvements on the average speeds of HOVs are achieved for on-ramps and off-ramps under HOT lane operations as shown in Table 5-5. Under HOV lane operations, a large number of weaving movements along the corridor significantly deteriorate traffic conditions on GP lanes. When the HOT lane system is implemented, some SOVs are re-allocated to the HOT lane, and the GP lane travel condition can be improved. This improvement definitely facilitates traffic operations which more than offset the time loss caused by extra travel of HOVs on GP lanes.

5.4 Simulation test result summary

Simulation experiments were conducted to examine the performance of the proposed tolling algorithm. A wide range of test scenarios were designed and configured to represent real traffic operations for HOT lane system operations. Simulation experimental results were analyzed. The simulation results show that the proposed tolling algorithm performed reasonably well under various demand scenarios. The overall traffic efficiency is enhanced significantly by optimizing traffic operations on HOT and GP lanes systematically. Meanwhile, travel speed and reliability of HOVs are favorably preserved to satisfy the operation requirements.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Over the past years, traffic congestion has become a frustrating problem, especially in metropolitan areas where traffic demand has been steadily increasing and transportation infrastructure has been unable to expand at the same pace. Traffic congestion costs millions of dollars of wasted fuel and millions of hours of delay as well as secondary accidents. It has been widely accepted that one of the most cost-effective solutions to traffic congestion is to manage existing traffic facilities in a more efficient manner with advanced traffic control and management technologies. HOT lane system is one of the vital traffic control technologies for freeway congestion mitigation. The HOT lane concept has been increasingly recognized and accepted as a viable measure to mitigate freeway congestion and improve travel time reliability. Optimized HOT lane management can yield significant economic returns and social benefits. However, it is difficult to quantitatively accomplish optimal HOT lane exploitation due to theoretical deficiency in these tolling schemes, although rough traffic-response-based tolling algorithms are applied to HOT lane operations based on practical experience. Therefore, developing an applicable and optimum tolling algorithm to enhance HOT lane system performance is of utmost significance.

To sufficiently handle the major problems generated by inferior tolling strategies, a new self-adaptive tolling algorithm has been developed to dynamically optimize HOT lane operations. A second-order control scheme is exploited in this algorithm. Based on the traffic speed conditions and toll changing patterns, the optimum flow ratio for HOT lane utilization is calculated using feedback control theory. The feedback increment is quantified by a piecewise optimal function of traffic speed measured from the GP and HOT lanes. Then the proper toll rate is backward estimated using the Logit model. By decomposing the calculation complexity, this tolling algorithm can satisfy the practicality and effectiveness required by the HOT lane system in reality. VISSIM-based simulation tests were conducted to examine the proposed tolling algorithm performance. An external HOT lane module was developed using Microsoft Visual Basic to implement the algorithm. All the five HOT lane sections on northbound SR 167 corridor in Washington State were simulated. The simulation results demonstrated that this tolling algorithm performs reasonably well under various traffic demands. Through optimal toll adjustment, SOVs are regulated to fully exploit the excess capacity of the HOT lane without degrading operation conditions for HOVs. Overall traffic efficiencies are improved significantly. The proposed tolling algorithm is of theoretical and practical importance for transportation researchers and engineers to optimize HOT lane system performance and enhance traffic mobility on congested freeway networks

6.2 Recommendations

The proposed tolling algorithm illustrated its promising performance for dynamically setting toll rates for HOT lane operations. However, further improvements are desired for extensive applications through fusing lane occupancy and flow rate into the feedback quantity to strengthen the robustness of the algorithm. Additionally, more research on Logit model calibration, including validation of the cash value-to travel time conversion ratio, is helpful to enhance the applicability of the proposed tolling algorithm before field implementations. Also, the proposed algorithm is better tested with data from other HOT lane projects to enhance its transferability and effectiveness.

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