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EVALUATION OF LANE USE MANAGEMENT STRATEGIES

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of

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Chaitanya Paleti Siva Sai Krishna

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To my family and friends

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ABSTRACT

Paleti Siva Sai Krishna, Chaitanya. M.S.C.E., Purdue University, December 2014. Evaluation of Lane Use Management Strategies. Major Professor: Srinivas Peeta.

The limited funding available for roadway capacity expansion and the growing funding gap, in conjunction with the increasing congestion, creates a critical need for innovative lane use management options. Various cost-effective lane use management strategies have been implemented in the United States and worldwide to address these challenges. However, these strategies have their own costs, operational characteristics, and additional requirements for field deployment. Hence, there is a need for systematic methodologies to evaluate lane use management strategies.

In this thesis, a systematic simulation-based methodology is proposed to evaluate lane use management strategies. It involves identifying traffic corridors that are suitable for lane use management strategies, and analyzing the strategies in terms of performance and financial feasibility. The state of Indiana is used as a case study for this purpose, and a set of traffic corridors is identified. From among them, a 10-mile stretch of the I-65 corridor south of downtown Indianapolis is selected as the study corridor using traffic analysis. The demand volumes for the study area are determined using subarea analysis. The performance of the traffic corridor is evaluated using a microsimulation-based analysis for alleviating congestion using three strategies: reversible lanes, high occupancy vehicle (HOV) lanes and ramp metering. Furthermore, an economic evaluation of these strategies is performed to determine the financial feasibility of their implementation.

Results from the simulation based analysis indicate that the reversible lanes and ramp metering strategies improve traffic conditions on the freeway in the major flow direction. Implementation of the HOV lane strategy results in improved traffic flow conditions on the HOV lanes but aggravated congestion on the general purpose lanes. The HOV lane strategy is found to be economically infeasible due to low HOV volume on these lanes. The reversible lane and ramp metering strategies are found to be economically feasible with positive net present values (NPV), with the NPV for the reversible lane strategy being the highest.

While reversible lanes, HOV lanes and ramp metering strategies are effective in mitigating congestion by optimizing lane usage, they do not generate additional revenue required to reduce the funding deficit. Inadequate funds and worsening congestion have prompted federal, state and local planning agencies to explore and implement various congestion pricing strategies. In this context, the high occupancy toll (HOT) lanes strategy is explored here. Equity concerns associated with pricing schemes in transportation systems have garnered increased attention in the recent past. Income inequity potentially exists under the HOT strategy whereby higher-income travelers may reap the benefits of HOT lane facilities.

An income-based multi-toll pricing approach is proposed for a single HOT lane facility in a network to simultaneously maximize the toll revenue and address the income equity concern, while ensuring a minimum level-of-service on the HOT lanes and that the toll prices do not exceed thresholds specified by a regulatory entity. The problem is modeled as a bi-level optimization formulation. The upper level model seeks to maximize revenue for the tolling authority subject to pre-specified upper bounds on toll prices. The lower level model solves for the stochastic user equilibrium solution based on commuters' objective of minimizing their generalized travel costs. Due to the computational intractability of the bi-level formulation, an approximate agent-based solution approach is used to determine the toll prices by considering the tolling authority and commuters as agents. Results from numerical experiments indicate that a multi-toll pricing scheme is more equitable and can yield higher revenues compared to a single toll price scheme across all travelers.

CHAPTER 1. INTRODUCTION

1.1 Background and Motivation

The growing congestion problem poses a substantial challenge to the US economy and the quality of life in the United States (US). The total congestion cost for the delay time and fuel was estimated as $121 billion in 2011, or about $818 per average commuter. Compounding the problem of congestion are the challenges of increasing funding gap and environmental concerns due to construction of new facilities (Eisele et al., 20011). The National Surface Transportation Policy and Revenue Commission (NSTPRSC) estimates that an annual investment of over $130 billion is needed for improvements and maintenance to accommodate these trends (NSTPRSC, 2007). The continued growth in travel demand, the worsening congestion, and inadequate funds have prompted the federal, state and local planning agencies to explore and implement various congestion pricing strategies to fund new capacity as well as to efficiently manage and improve performance of existing infrastructure facilities.

In the United States and worldwide, various cost-effective lane use management strategies have been implemented to address congestion. They include ramp metering, high occupancy vehicle (HOV) lanes, reversible lanes, high occupancy toll (HOT) lanes, truck-only lanes, and transit lanes. Some of them, such as lane pricing and HOT lanes, are revenue-generating strategies. However, each strategy has its own costs, operational characteristics, and additional requirements for field deployment. Hence, there is a need for systematic guidelines/recommendations to identify the specific set of lane use management strategies that are effective and select the optimal cost-effective strategy for a given corridor. Past studies (Meyer et al., 2006; Collier and Goodin, 2002; Skowronek et al., 2002; Stockton et al., 1997; Stokes and Bensen, 1987) focused on analyzing and evaluating implementation of various strategies, with respect to local or regional conditions, but they do not focus on all the aspects of simulation modeling. Therefore, a methodological framework is required to define the scope of the study, perform initial modeling and calibration, and evaluate all strategies using the developed model.

The first part of this study provides a simulation-based methodological framework to evaluate the various strategies. It involves identifying traffic corridors that are suitable for lane use management strategies, and analyzing the strategies in terms of performance and financial feasibility. Based on the needs of the Indiana Department of Transportation (INDOT), the state of Indiana is used as a case study for this purpose, and a set of traffic corridors is identified. From among these, a 10-mile stretch of I-65 south of downtown Indianapolis is selected to analyze the lane use management strategies using VISSIM microsimulation. The three lane use management strategies that are considered in this study are: reversible lanes, high occupancy vehicle (HOV) lanes and ramp metering. Performance of these three strategies is evaluated using a microsimulation based analysis in the context of alleviating congestion. Also, sensitivity analysis is conducted for different demand levels to assess the impact of these strategies. Furthermore, economic evaluation of these strategies is performed to determine the financial feasibility of their implementation.

While reversible lanes, HOV lanes and ramp metering strategies are effective in mitigating congestion by optimizing lane usage, these strategies do not generate additional revenue required to reduce the funding deficit. The continued growth in travel demand, the worsening congestion, and inadequate funds have prompted the federal, state and local planning agencies to explore and implement various congestion pricing strategies to fund new capacity as well as to efficiently utilize existing capacity and improve network performance. While various pricing schemes have been instrumental in managing demand and raising revenue, they face the issue of potential inequity. Equity is a measure to understand how benefits and costs are distributed across user groups; thereby inequity represents the uneven distribution of burden on different user groups. Equity concerns in the context of various transportation pricing scenarios are described in the review papers by Litman (2002), Ecola and Light (2009) and Levinson (2010). Ecola and Light (2009) reported that all types of congestion pricing strategies, along with the distributions of residents and jobs, have a larger impact on equity implications. Similarly, Levinson (2010) reported that pricing strategies that are appropriately implemented improve efficiency but can harm equity, particularly for the low income travelers. The decisions, in the context of road pricing, that affect equity are: (i) allocation of the burden of charges, (ii) utilization of the revenue, and (iii) distribution of the externalities such as pollution. These decisions may impact equity in more than one way. Various dimensions of equity that can be affected by these decisions are discussed in depth in the review papers by Litman (2002)and Levinson (2010).

The three dimensions of equity that are relevant in the context of pricing schemes are income, spatial and modal equities. Income equity is a measure of the extent to which the costs and benefits are distributed across commuters belonging to different categories. Spatial equity represents the degree of distribution of costs and benefits among commuters from different geographical locations, while modal equity indicates the unfair favor or costs to one mode over another. The issue of equity has been gaining greater significance in the recent past and can serve as a barrier to the development of various pricing initiatives. For instance, a congestion pricing proposal for Manhattan in the city of New York in2007was partly objected to on the grounds of spatial inequity implying that one borough would benefit disproportionately relative to the investment costs (Schaller, 2010). Similarly, a HOT lane strategy in Maryland was not implemented when it was suggested that it would be unfair to connect a better commute choice with one’s ability to pay for it, implying income inequity. Hence the potential for income inequity exists in the context of HOT lanes. Various field surveys (Patterson and Levinson, 2008; Safirova, 2003; Weinstein and Sciara, 2004) of HOT lane utilization suggest that the proportion of high income commuters using a HOT facility is high compared to that of the low income commuters, resulting in potential income inequity. However, studies that examine the equity concerns in the context of toll pricing strategies, particularly for HOT lane facilities, are limited.

Motivated by the aforementioned issues and gaps in the literature, the second part of this study proposes an income-equitable toll pricing approach for a single HOT lanes facility in a network by determining multi-tier toll prices for commuters corresponding to different income classes (high, middle and low). The methodology seeks to maximize the toll revenue for a tolling authority by determining income-equitable multi-toll prices that do not exceed pre-specified upper bounds on tolls by a regulatory authority, and ensure a minimum acceptable level-of-service (LOS) on the tolled facility. The income equitability is enabled by imposing different toll prices to different commuters groups consistent with the total savings that would be accrued by their corresponding income levels. Thereby, the proposed methodology can enable policymakers and planners to design optimal toll prices that are economically viable and socially acceptable when converting general purpose (GP) lanes to HOT lanes in an existing transportation network.

1.2 Problem Statement

The limited funding available for roadway capacity expansion and growing funding gap, in conjunction with the increasing congestion and the need to ensure the efficient utilization of the existing facilities, creates a critical need for innovative lane use management options for traffic agencies. While some lane use management strategies can be adopted seamlessly, and other may require some infrastructure/operational changes. Therefore, there is a need for department of transportation (DOT) agencies to identify which set of lane use management strategies could be adopted under different traffic situations, and the potential corridor in which to adopt them over a 5-10 year framework.

In this context, there is a need to: (i) perform an organized literature review to understand the operational characteristics and impacts of the strategies, (ii) identify the potential corridors that may require implementation of such strategies in the near future in Indiana, (iii) identify the factors affecting the operational feasibility of each strategy in Indiana for the selected corridor, (iv) assess expected costs and benefits of each strategy for the selected corridor, and (v) develop a systematic simulation-based methodology that can assist planners to evaluate various strategies on other potential corridors.

Strategies such as reversible lanes, HOV lanes and ramp metering strategies are effective in mitigating congestion by optimizing lane usage. However, these strategies do not generate additional revenue required to reduce the funding deficit. The continued growth in travel demand, the worsening congestion, and inadequate funds have prompted the federal, state and local planning agencies to explore and implement various congestion pricing strategies to fund new capacity as well as to efficiently utilize existing capacity and improve network performance. While various pricing schemes have been instrumental in managing demand and raising revenue, they face the issue of potential inequity. Equity concerns associated with various pricing schemes in transportation systems have garnered increased attention in the recent past. In the context of high occupancy toll (HOT) lanes, income inequity potentially exists whereby higher-income travelers may reap the benefits of HOT lane facilities. However, studies that examine the equity concerns in the context of toll pricing strategies, particularly for HOT lane facilities, are limited. Due to these reasons, there is a need to develop methodologies that can enable policymakers and planners to design optimal toll prices that are economically viable and socially acceptable when converting general purpose (GP) lanes to HOT lanes in an existing transportation network.

1.3 Overall Objectives

This study addresses two aspects of implementing lane use management strategies. The first part addresses operational characteristics and economic feasibility of implementing reversible lanes, HOV lanes and ramp metering strategies. The primary objectives are to: (i) identify a potential corridor to implement lane use management strategies, (ii) assess the expected costs and benefits of these strategies, (iii) provide a systematic simulation-based methodology to evaluate implementation of the three lane use management strategies, and (iv) provide recommendations to identify potential candidate strategies for analysis based on the traffic conditions.

The second part of the study addresses equity concerns associated with HOT lanes. Here, the objective is to determine optimal toll prices that maximize revenue subject to limits on toll prices, requirements on LOS, and income equity constraints, in the context of a general purpose lane being converted into a HOT lane facility.

1.4 Research Framework

To address the aforementioned issues related to the lane use management strategies, this research focuses on micro-simulation based analysis to evaluate operational and economic feasibility of the strategies, and, proposes a conceptual methodology to design an income-equitable toll prices for HOT lanes. Section 1.4.1 presents the key components of the overall methodological framework used for the microsimulation analysis. Section 1.4.2 presents the key components of optimal toll design problem for HOT lanes.

1.4.1 Work Plan for Simulation Based Analysis

The flowchart complementing the overall methodology for the micro-simulation based analysis is presented in Figure 1.1.

The overall methodology comprises of four stages: pre-modeling, model development, model calibration, and finally model application stages. Pre-modeling stage comprises of tasks such as defining the scope of the project, identifying and collecting preliminary data for project implementation, and defining the study area and its scope. Model development stage comprises of tasks such as coding the network in VISSIM, checking for errors and debugging as and when necessary. Model calibration stage includes tasks like calibration and validation of the network implemented in VISSIM to ensure that the base model replicates the existing conditions on the field. Model application is the stage where the three lane use management strategies are evaluated using the microsimulation based analysis. This stage also includes tasks such as performing economic evaluation and documenting the final report.

Figure 1.2 presents the simulation-based methodology adopted in this study. Three lane use management strategies (reversible lanes, HOV lanes and ramp metering) are identified as the feasible set of strategies based on the past studies and input from INDOT personnel. Subsequently, this is followed by literature review of the three strategies. Based on this, data required for the analysis is identified and collected from various sources such as INDOT and Indianapolis MPO travel demand model (TDM).

Using this data, traffic analysis is performed to identify the I-65 stretch south of downtown Indianapolis as a congested corridor suitable for implementation of the strategies. The boundaries of the study area are then defined by exploring routes that a commuter might consider as an alternative to the I-65 corridor. This is followed by the estimation of demand volume for the study area using subarea analysis and TransCAD tools. This along with the other data is used to code the microsimulation model in VISSIM. The final model is thoroughly checked for errors and is calibrated and validated using the orthogonal experiment design method. This is followed by the microsimulation analysis of the three lane use management strategies.

Strategies i=1, 2 and 3 (in Figure 1.2) represent the three strategies – reversible lanes, HOV lanes and ramp metering, respectively. For each of these strategies, different scenarios (j=1, 2, ……n)corresponding to different demand levels are tested. For the HOV lane strategy evaluation, additional scenarios are tested. This includes the evaluation of the HOV lane strategy under the assumption that there is a 10% increase in the HOV2+ (vehicles with two or more occupants) vehicles due to car-pooling after the first year of implementation of the HOV lane strategy.

After the simulation-based analysis, cost-benefit analysis of the three strategies is performed to evaluate the economic feasibility. Based on the findings from literature review, simulation based analysis and the economic evaluation; recommendations are developed for the consideration of each strategy.

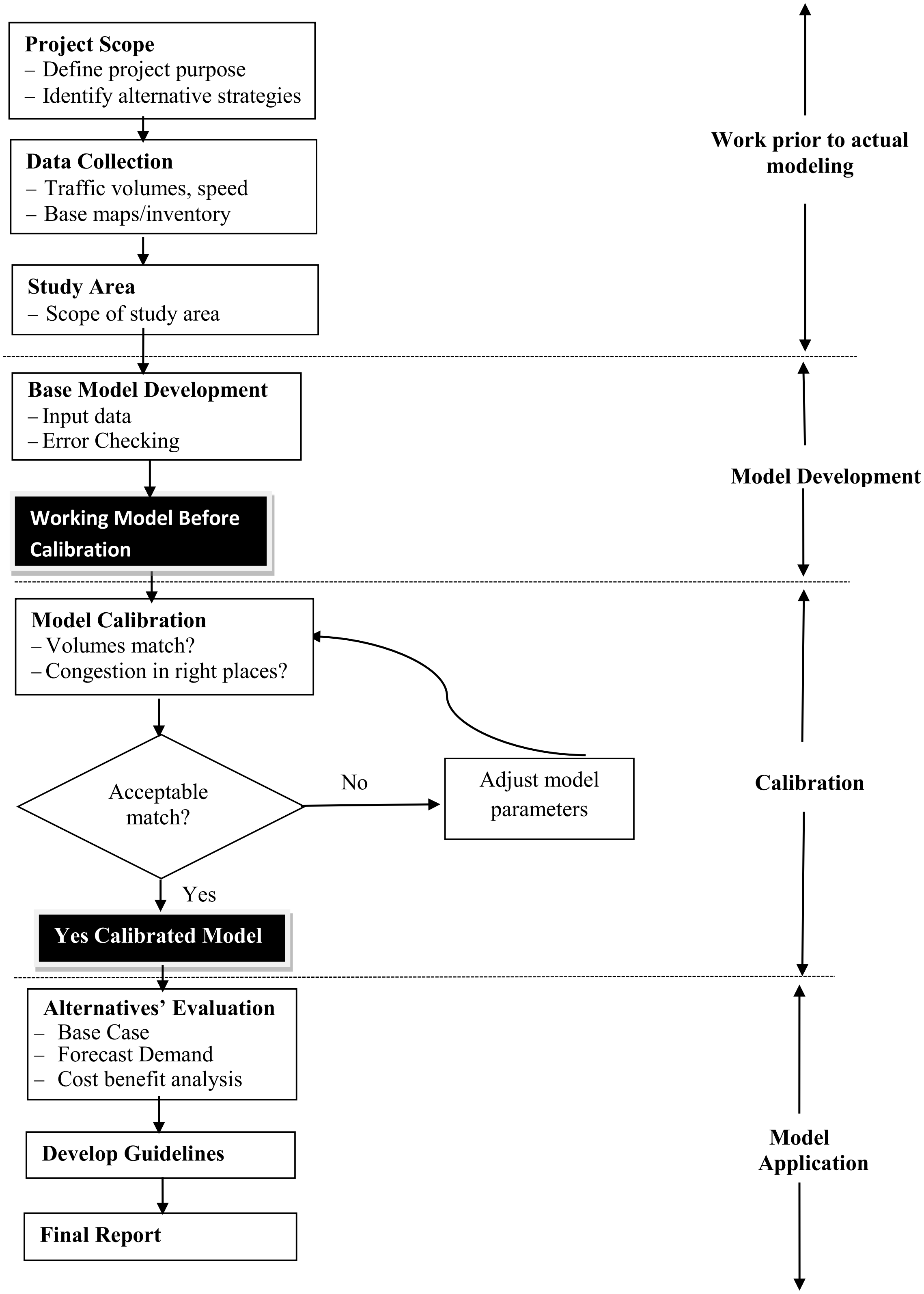

Figure 1.1 Integrated microsimulation analysis framework

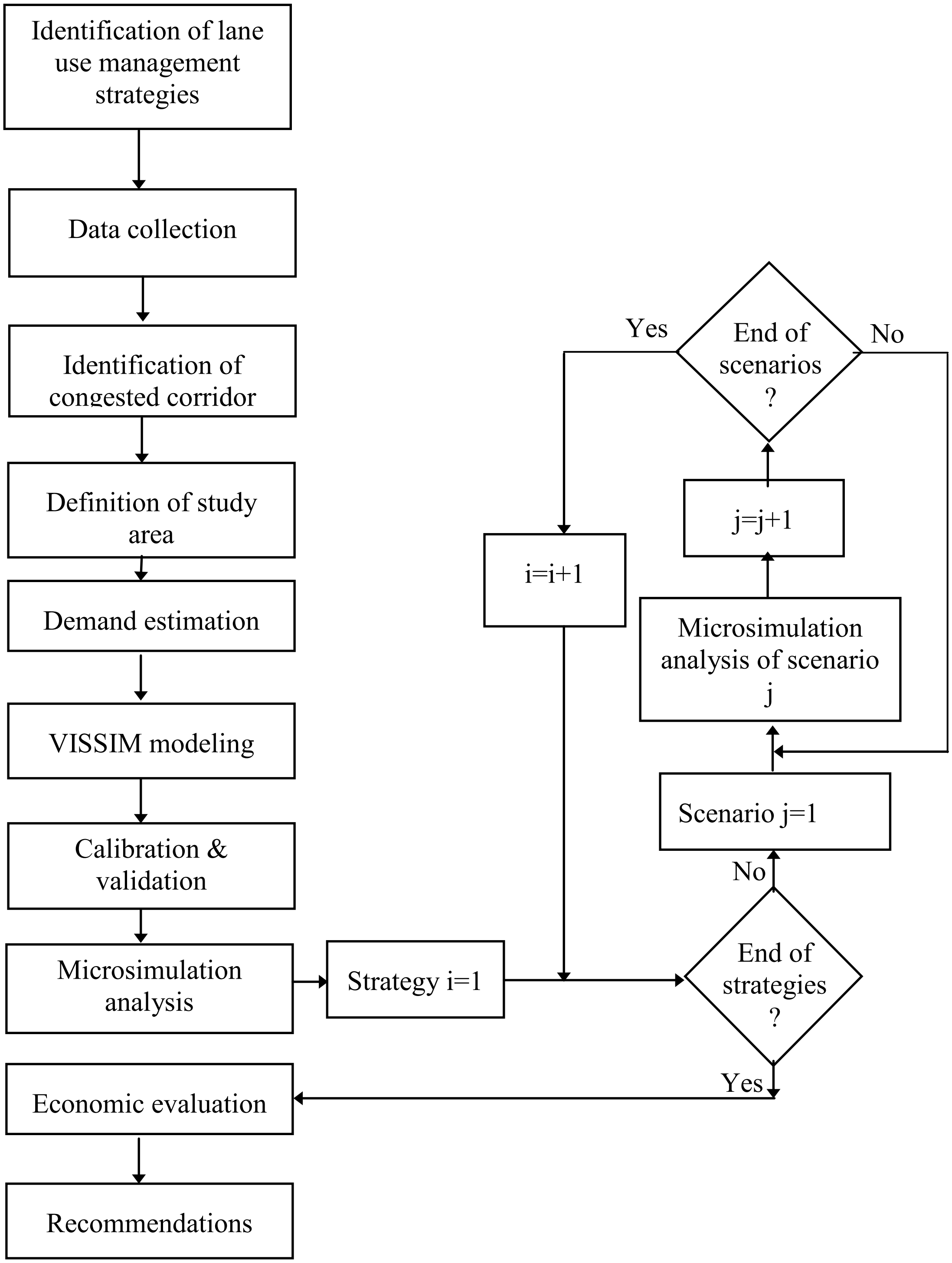

Figure 1.2 Simulation-based methodology

1.4.2 Work Plan for Optimal Toll Design Problem

This study proposes an income-equitable toll pricing approach for a single HOT lanes facility by determining multi-tier toll prices for commuters corresponding to different income classes (high, middle and low). The methodology seeks to maximize the toll revenue for a tolling authority by determining income-equitable multi-toll prices that do not exceed pre-specified upper bounds on tolls by a regulatory authority, and ensure a minimum acceptable level-of-service (LOS) on the tolled facility. The income equitability is enabled by imposing different toll prices to different commuters groups consistent with the total savings that would be accrued by their corresponding income levels. Thereby, the proposed methodology can enable policymakers and planners to design optimal toll prices that are economically viable and socially acceptable when converting general purpose (GP) lanes to HOT lanes in an existing transportation network. Mathematical formulation and the proposed solution approach along with the numerical experiments and an analysis of the results for the optimal toll design problem is presented in this study.

The remainder of this study is organized as follows. The next chapter presents the literature review in the context of the lane use management strategies under consideration. Chapter 3 presents the details of experimental setup for the microsimulation based analysis which is followed by description of the VISSIM model development in the Chapter 4. Chapter 5 discusses the results of evaluation of reversible lanes, HOV lanes and ramp metering strategies, respectively. Chapter 6 describes the optimal toll design problem, its mathematical formulation, and the proposed solution approach. This includes a section focusing on the numerical experiments and the analysis of results. The final chapter provides some concluding comments.

CHAPTER 2. LITERATURE REVIEW

This chapter provides a synthesis of existing literature on the lane use management strategies under consideration. Sections 2.1 to 2.3 present the discussion on reversible lanes, HOV lanes and ramp metering, respectively, along with the list of warrants required for implementation each of these strategies. Section 2.4 presents the review of equity concerns associated with the implementation of HOT lanes.

2.1 Reversible Lanes

Reversible lane is a lane in which traffic may travel in either direction, depending on certain traffic conditions. The advantage of this strategy is that the directional capacity of the lane can be increased without adding new lanes that usually require additional capital investment and in some cases may even have adverse environmental impacts. Also, the frequency, duration and length of maintaining reversible lanes can be decided according to the needs of the specific traffic agency. Reversible lanes have been used as strategies to address a variety of needs, particularly for unbalanced peak-period traffic flows, planned special events (work zones, football games, concerts), and emergency conditions (evacuation). In the U.S., reversible lanes are currently being implemented in several states including Alabama, Arizona, California, Connecticut, Florida, Georgia, Kentucky, Maryland, Michigan, Nebraska, New York, Ohio and Texas. Various feasibility studies and field surveys such as (CDOT, 2010; Wolshon and Lambert, 2004) indicated that reversible lanes significantly reduced (by about 50%) travel time in the direction of implementing the strategy. Also, reversible lanes are preferred in cases such as bridges and tunnels, when there is need to add capacity and it is usually not economically or environmentally feasible to add more lanes.

In addition to these benefits, reversible lanes are often associated with challenges related to safety concerns and operational difficulties. Furthermore, lack of public awareness compounds the problem of safety concerns. Past studies (Highways, 1989) also indicated that agencies are reluctant to implement reversible lanes because of the popular belief that it can be confusing to drivers, and be challenging in terms of safety and feasibility. Therefore, agencies may require additional personnel and resources to configure, enforce, and maintain safe and efficient traffic flow.

However, a 2006 synthesis study (Wolshon and Lambert, 2006) has shown that drivers not only adapt readily to the reversible lanes but also consider them as an effective utilization of transportation infrastructure. The wide appeal of reversible lane roadways was demonstrated in the 2001 WSDOT survey, in which broad public support was observed for the state's reversible freeways. Similarly, the Maryland DOT found a high level of public acceptance for reversible lanes (Wolshon and Lambert, 2004). Warrants for implementation of reversible lanes are discussed below.

2.1.1 Warrants

Warrants are guidelines that justify or "warrant" the implementation of lane use management strategies to reduce traffic congestion and improve traffic congestion by specifying conditions that must be maintained and observed prior to their application.

- AASHTO states that reversible lanes are justified when "more than 65% of traffic moves in one direction during peak hours" (Wolshon and Lambert, 2004) with no fewer than two lanes for the minor-flow direction.
- Average speed should decrease by a fourth during peak hours while the ratio of major to minor flow measured as vehicles per hour should always stay between 2:1 and 3:1.
- Other professional transportation organizations have stated that structures like bridges and tunnels warrant reversible lanes since expansion and addition of lanes is almost impossible.

- The cost of implementation and maintenance of reversible lanes should not exceed the cost of constructing/expanding existing lanes and structures.

Although few comprehensive studies such as (Allen and Rothenburg, 1997; Agent and Clark, 1980; Hemphill and Sruti, 1974) exist in literature, findings from these studies may not be generalized for implementation of reversible lanes in most locations. Due to lack of established standards and guidelines for the use of reversible lanes, there is need for traffic agencies to study the operational and the economic feasibility of reversible lanes strategy before their implementation.

2.2 HOV Lanes

In the U.S., California, Minnesota, Texas, Washington and Washington, D.C. initially implemented HOV lanes. By 2002, over 130 HOV lane projects involving 2,400 lane miles have been implemented in the U.S. Most of these projects were proposed with the preliminary objective of reducing congestion by inducing more people to travel in fewer vehicles.

The Washington DOT, Texas Transportation Institute, and Virginia DOT reported the benefits of HOV lanes ranging from induced demand for HOV lanes to travel time savings. Because HOV lanes carry vehicles with a higher number of occupants, they have the potential to move more people in fewer vehicles, in comparison to the adjoining general purpose lanes, during congested travel periods.

For example, on I-95 in northern Virginia during the morning peak travel period (6:00 to 9:00 a.m.), HOV lanes carried 54% of the people in 27% of the total vehicles on only 40% of the freeway lane capacity (two HOV lanes in comparison to three general purpose lanes). Similarly, commuters using HOV lanes in Texas saved an average of 2 to 18 minutes during the peak hours. Benefit-cost ratios for HOV lanes in Texas have been estimated to range from 6:1 to 48:1, in comparison to a base case involving the addition of the same number of general purpose lanes (FHWA, 2004).

HOV lanes enable vehicles with multiple occupants (carpools, large families, shared transit) to travel on special lanes enabling faster transit times for such vehicles while reducing the congestion in ordinary/other lanes. While capable of significantly reducing the congestion, increasing average vehicle occupancy levels, and reducing fuel consumption, a systematic implementation of such systems is necessary prevent failures as seen in the CALTRANS system in 1994 (Bhargava et al., 2006) The following are some warrants that justify the implementation of such a system, classified on the basis of design methodology.

2.2.1 Warrants on the basis of congestion, population and service levels

Following is the list of warrants for implementation of HOV lanes based on the congestion, population and level-of-service.

- The implementation of such a system should ensure significant reduction in congestion of the targeted areas.
- Certain levels of congestion should exist to justify the need for such systems. These figures depend on various factors such as number of lanes, vehicular flow volume, average speed of traffic and timing of such congestion. For example, the Texas DOT has specified that any corridors with over 25,000 vehicles per lane (daily) are prime candidates for the implementation of such a system.
- Implementation of such a system should be conducive to the adaptation of carpools and HOV methods by the local populace.
- Decisions on occupancy restrictions for use of such lanes must be based on the average occupancy rates prevalent in that region.
- Users on this section of freeway are making long trips (Stockton et al., 2000)

2.2.2 Physical design warrants

Following is the list of warrants for implementation of HOV lanes that are based on its design aspects.

- Freeway geometry should enable the modification of existing lanes or addition of a new lane for such specific use without affecting the efficiency of transit by the general populace (SOV and mass transit systems for example).
- Allow access to the HOV lanes without needing to change lanes rapidly thereby reducing the risk of collisions (Boyle, 1986).
- Construct ramps that lead directly to designated HOV lanes along with construction of optimal location of park and ride lots to increase the carpooling tendency of road users.
- General warrants that specify special programs and ideas that can be implemented to improve HOV usage (Boyle, 1986).
- Guidelines for incident management and effective response systems including real time monitoring and data collection (Cambridge Systematics, 2002).

Despite the benefits from HOV lanes, the state of Indiana is yet to implement this strategy. While the warrants discussed above provide general guidelines for implementation of HOV lane strategies, there is a need to evaluate operational characteristics, and additional requirements for their field deployment by considering regional traffic and infrastructural characteristics.

2.3 Ramp Metering

Ramp metering is the use of traffic signals at the on-ramps to control the flow of traffic entering the freeway. The primary objectives of the ramp metering include managing traffic demand to reduce congestion, improving the efficiency of merging and reducing accidents; all of which lead to improved mainline freeway flow (FHWA, 2010).

Ramp metering is advantageous because it can be implemented fairly readily, requiring only the installation of signal lights and extended lanes on entrance ramps. Furthermore, it requires coordination of these lights and freeway sensors using telemetry. The success of early ramp metering applications in the late 1950s and throughout the

1960s in US cities such as Chicago, Los Angeles, Minneapolis and Seattle led to the implementation and expansion of ramp metering systems in many states in the US including Arizona, California, Colorado, Georgian, Nevada, Ney York, Ohio, Pennsylvania, Texas, Virginia, and Florida, as well as in other countries including Australia, Canada and UK (FHWA, 2010).

Field studies (Cambridge Systematics, 2002; Kim and Cassidy, 2010) on ramp metering systems in two U.S. states (Minnesota and California) suggest that they are successful in decreasing traffic and increasing the output flow through a freeway. The Minnesota DOT reports that ramp meters have reduced freeway travel times by 22%, increased the reliability of freeway travel time by 91%, and reduced crashes by 26% (Cambridge Systematics, 2002). In Germany, ramp metering effectively prevented the drop in traffic speed normally associated with merges and enabled the harmonization of traffic flow on major access-controlled roadways. In addition, it was found that ramp metering reduced crashes involving person and property damage by up to 40% with no negative effects on the adjacent roadway network (FHWA, 2010). Based on the literature review, warrants for implementing ramp metering are identified and discussed below.

2.3.1 Warrants

Ramp metering is warranted if congestion occurs on freeways and slows down traffic by reducing the freeway operating speeds (as specified in Bhargava et al., 2006) or if there is a high frequency of crashes. It should ensure that local transportation system management objectives such as maintenance of certain levels of service (with preferential treatment to mass transit and carpools) and efficient usage of other on-ramps during peak demand times should be met. It is also useful during "special congestion", referring to short-period traffic caused by events such as concerts, rallies, and games.

These warrants are grouped into two categories: 1) individual warrants that set specific guidelines to validate the need for a ramp metering system, and 2) overall warrants that place conditions on the individual warrants for implementation.

Individual warrants describe specific conditions that can justify the implementation of ramp metering systems for sections of the freeway with high congestion and frequent crashes while maintaining a certain level-of-service. They also question the effects of implementing such a system on improving vehicle occupancy rates (by improving the persons/mobility ratio), balanced usage of the freeway and the total volume of traffic within that system. They also provide a framework for planners to determine if local social conditions (such as large gatherings) and freeway geometries allow a safe implementation of such a method.

Overall warrants provide a checklist for planners to follow in order to make an efficient decision on the implementation of such a system. If the individual warrants for collision frequencies, levels of service, mode shifts (from HOV to SOV), balancing demand for ramps and special congestion events are satisfied, then a certain method (for instance fixed signal ramp metering strategy) of implementation is justified. If the ramp plus freeway volume is greater than a certain value (exceeding 2100 vph) then another method (for instance, responsive ramp metering strategies) is specified (Bhargava et al., 2006). These warrants allow DOTs to implement these methods with relative ease.

Despite the benefits from ramp metering, the state of Indiana is yet to implement this strategy. While the warrants discussed above provide general guidelines for implementation of ramp metering strategies, there is a need to evaluate operational characteristics, and additional requirements for field deployment of ramp metering by considering regional characteristics.

2.4 High Occupancy Toll Lanes

Past studies (Dial, 2000; Lim, 2002; Verhoef, 2002; Yang and Lam, 1996) in congestion pricing have mostly focused on various pricing mechanisms and revenue forecasting. In general, most pricing studies for various transportation agencies handle inequity by proposing to invest the revenues generated through pricing into local transportation projects such as improving the transit facilities and/or reimbursing the disadvantaged commuters through revenue redistribution (for example, by exempting them from paying, or providing tax credits).

A few studies design pricing schemes that incorporate equity explicitly in their pricing methodology. Yang and Zhang (2002) studied the optimal toll design problem with multiple user classes considering income and spatial equity constraints. They used a simplistic measure to quantify equity that is equal to the ratio of the origin-destination (O-D) travel costs before and after the toll scenarios. However, this measure cannot capture the loss in consumer surplus from the reduced demand due to tolls. Therefore, it may not be appropriate for pricing studies as travel demand may reduce on tolled links. Sumalee (2003) addressed the optimal toll design problem for general urban traffic networks by factoring the potential equity impact. However, the study does not consider income equity and deals only with the spatial equity impact.

Others studies focus on a class of pareto-improving toll schemes to develop more equitable pricing mechanisms. Lawphongpanich and Yin (2010) analyzed one such pareto-improving pricing scheme; however, their model does not capture the distributional effects of pricing on different income groups. Liu et al. (2009) and, Nie and Liu (2010) proposed pareto-improving and revenue neutral congestion pricing and transit fare schemes using a general distribution of value of time (VOT) in the context of a bi-modal network with two parallel routes. However, the notion of revenue neutrality is questionable in this context as the government or some other entity plays the role of the toll collector. Yang and Wang (2010) proposed the concept of tradable credits in the context of congestion pricing which involves distribution of credits to commuters, determination of the credit prices for tolled links, and the organization of a market for trading these credits. However, this approach is conceptual, and involves complex mechanisms and the need to create special market entities, precluding implementation using existing technology and infrastructure.

Furthermore, quantifying equity is difficult because there is no single metric that captures all the dimensions of equity. The method to define and measure equity can significantly affect the results (Litman, 2002). Levinson (2010) listed a few measures of equity such as logarithmic variance, Theil’s entropy, and Kolm measure. It was also stated that none of these measures are scale invariant, and there is no consensus on which measure to use. Gini-coefficient has been successfully used in past studies (Yang and Zhang, 2002; Sumalee 2003; and Wu et al., 2012) to quantify income inequity, and hence the relevant measure in the current context of HOT lane facilities.

In summary, few studies factor equity constraints in developing implementable pricing schemes. To the author's knowledge, there is no previous study that investigated pricing schemes for HOT lane facilities considering income equity. Thus, there is a practical need to develop pricing mechanisms that consider income equity and are deployable using current infrastructure and technology for HOT lane facilities. The proposed study focuses on addressing these gaps by integrating revenue maximization and equity principles into an optimal toll design problem. A key feature of the proposed methodology is a multi-toll pricing scheme that is consistent with current technology and infrastructure, and factors income equity, social acceptance (in terms of upper bounds on imposed tolls), and LOS constraints.

CHAPTER 3. EXPERIMENT SETUP FOR MICRO-SIMULATION BASED ANALYSIS

3.1 Data Collection

This section describes the data collection efforts and the data preparation procedure used to estimate the input data of demand required for the microsimulation analysis. The type of data collected, its source, and the intended purpose for collecting such data is discussed in the data collection sub-section presented below.

Color coded maps indicating the level-of-service (LOS) of the freeways in Indiana are obtained from the INDOT Traffic Division. These LOS maps are used to identify a list of potential congested corridors.

Data from loop detectors, monitoring each lane of the freeway sections at different locations along the freeway, is obtained from the INDOT Traffic Division. The field data comprises of vehicular counts and average speed measured at 30sec intervals every day. This data, collected from January 2012 to April 2012 for each of the potentially congested freeways, is used to identify a congested corridor for the micro-simulation based analysis.

Aerial images of the study area acquired from Google maps, along with the information from the geographical files obtained from the Indianapolis MPO travel demand model are used to build the network model in VISSIM. Detailed modeling of signalized intersections is performed by incorporating the signal timing information obtained from INDOT traffic division and the Indianapolis city office.

Further, output files from the Indianapolis MPO travel demand model are acquired from the Indianapolis MPO office. These files consist of information regarding network characteristics, such as free flow speed, speed limits, origin and destination (O-D) pairs, and also information on traffic flow patterns such as daily traffic flow volume and average daily speeds. Part of this data is used to identify the congested corridor for subsequent analysis, while the rest is used for validation and calibration purposes. Additionally, demand for the Indianapolis region network, in the form of O-D matrices for the AM peak duration, is obtained from the Indianapolis MPO office. The Indianapolis regional O-D data is used to estimate the demand, for the study area under consideration.

3.2 Identification of a Congested Corridor for the Simulation Based Analysis

The objective of this section is to present the methodology adopted to identify a congested corridor for the microsimulation study. The first step is to determine the performance measures and the corresponding threshold values to quantify congestion. Previous studies (Eisele et al., 2011; Grant et al., n.d. and Qu, 2013) have used a variety of performance measures to identify congested conditions on roadways. Various performance metrics used in previous studies along with the measurements from which they are derived are listed in the Table 3.1.

Table 3.1. Performance measures to identify congested corridors

Measures Based	Performance Metrics
Traffic flow	Vehicle throughput; Lost throughput productivity
Level-of-service	LOS maps
Speed	Travel speed; % free flow speed
Travel time	Travel delay; Annual delay per person; Travel time index;
Reliability	Buffer index
Derived parameters	Density; VMT in congested area

Traditionally, long range transportation plans (LRTP), developed by MPOs, primarily use LOS based metrics. However, they alone are not effective in portraying the complete picture. For instance, while LOS based metrics can indicate presence of congestion, they cannot quantify the degree of congestion once congested conditions are reached. Consequently, some studies (Gunawardena and Sinha, 1994) attempted to address this by using traffic flow volume based metrics. However, volume based metrics may fail in cases where high traffic volume does not necessarily imply congestion, especially if vehicles are maintaining a minimum threshold speed (>45mph for instance). Therefore, a two-step process is employed to find the most congested corridor. In the first step, LOS based metrics are used to narrow down a list of potentially congested corridors. In the next step, both traffic flow volume and average speed based metrics are used to determine the most congested corridor, from the list formed in step 1. The patterns of average daily traffic volumes in the months of January and April are observed to identify a typical day of the week for the comparative analysis of freeway congestion. Duration of congestion during the typical analysis day is quantified using performance measures based on average speed. The freeway with the longest duration of congestion on a typical day of a week is used as the study corridor. The threshold values of various performance metrics used to quantify congestion are discussed below.

As mentioned above, in the first step, a LOS level of E/F is an indication of congested conditions, while a LOS level of D is used to indicate near congested corridors (Holt, 2010; Midlands Tomorrow 2035 LRTP). For the second step, speed expressed as the percentage of the free flow speed is used as the metric to quantify congestion instead of absolute speed values to account for the different speed limits on the corridors. Threshold value of percentage free flow speed less than 75% is adopted to identify congested conditions on freeway segments (Eisele, 2011).

3.2.1 Results of Analysis to Identify Study Corridor

For the analysis, six most congested corridors are identified based on the LOS maps. Freeway locations operating at LOS E or F conditions in both 2010 and 2015 are included in the list of potentially congested corridors. These potentially congested corridors identified using LOS maps are listed in Table 3.2. Typical LOS maps for the year 2010 along with the location of the congested corridors are shown in Figure 3.1. Further analysis of volume and speed data performed to identify the study corridor is presented below.

Figure 3.2 shows the typical traffic patterns, i.e. daily volumes, on these highway segments during different days of the month. It can be immediately observed that the data for a period of one week contains the necessary information for analysis, as the weekly pattern just repeats itself all through the month. Furthermore, given that traffic volumes might vary significantly within a week, the longest duration of congestion for each freeway segment, is identified by observing the distribution of traffic volumes for each day of a typical week. Figure 3.3 shows the day-to-day variation of percentage of time for which the freeway segment is congested during a typical week at different locations on I-69. Two observations can be made from this plot. Firstly, the highest percentage of time wherein the freeway is congested is at the 3.7 mile marker for all the days. Secondly, among all the days, I-69 has the longest duration of congestion on a Wednesday (i.e., Day 4) at the 3.7 mile marker. Using similarly analysis, the most congested segment and its corresponding day is identified for each of the six freeways. Additionally, in order to capture seasonal variation of traffic patterns, the aforementioned analysis is performed both for the months of January and April. Due to inclement weather in winter, the average speed is expected to be lower in comparison to April. The findings (Figure 3.4) validate the initial expectation that the congestion was more pronounced in January compared to April, for all the freeway corridors. Lastly, comparison of the congestion conditions (at the most congested freeway segment and the day-of-week) in January and April, as shown in Figure 3.4, indicates that I-65 is the most congested corridor and is therefore selected for subsequent simulation analysis.

Table 3.2 List of potentially congested corridors identified using LOS maps

Corridor	Details
I-65	South side of Indianapolis
I-65	Louisville to Clarksville
I-65	North of Indianapolis to Lebanon
I-69 / I-465	-
I-70	Through central Indianapolis
I-80 / I-94	Borman Expressway

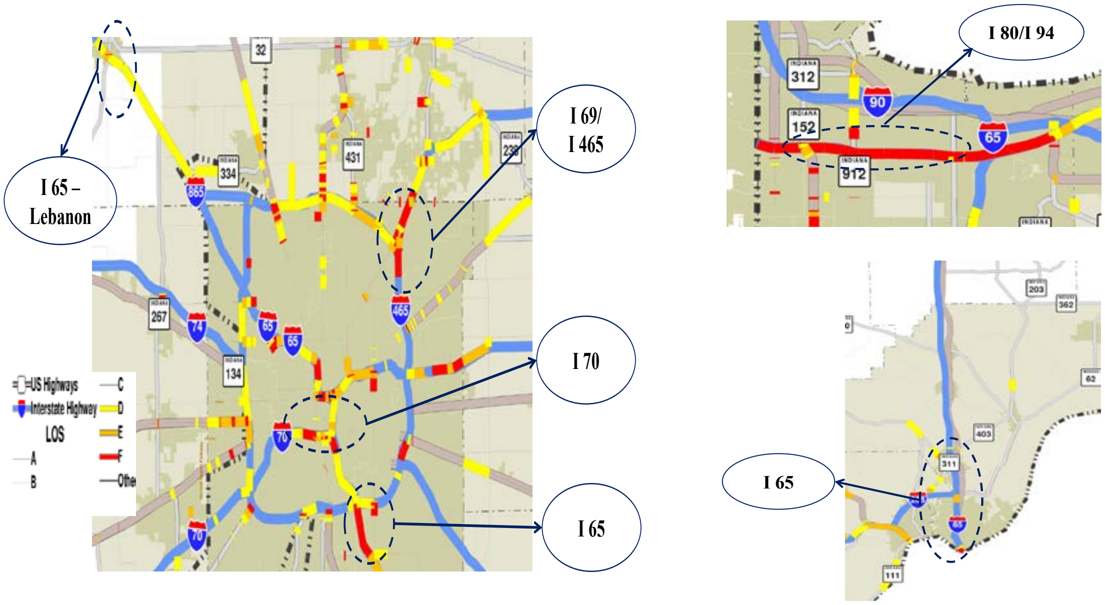

Figure 3.1 Map indicating LOS in the year 2010 on the six potential corridors considered for identification of a congested corridor for the simulation based analysis

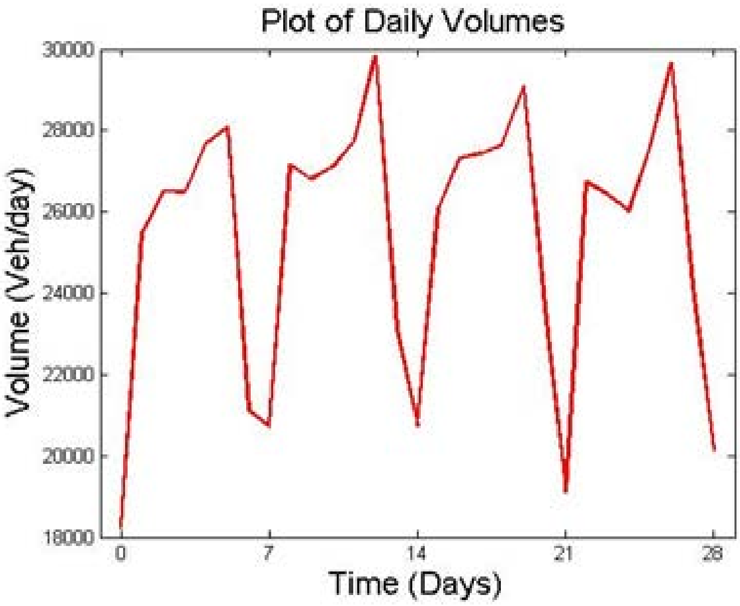

Figure 3.2 Traffic flow pattern on I-69 corridor for the month of January

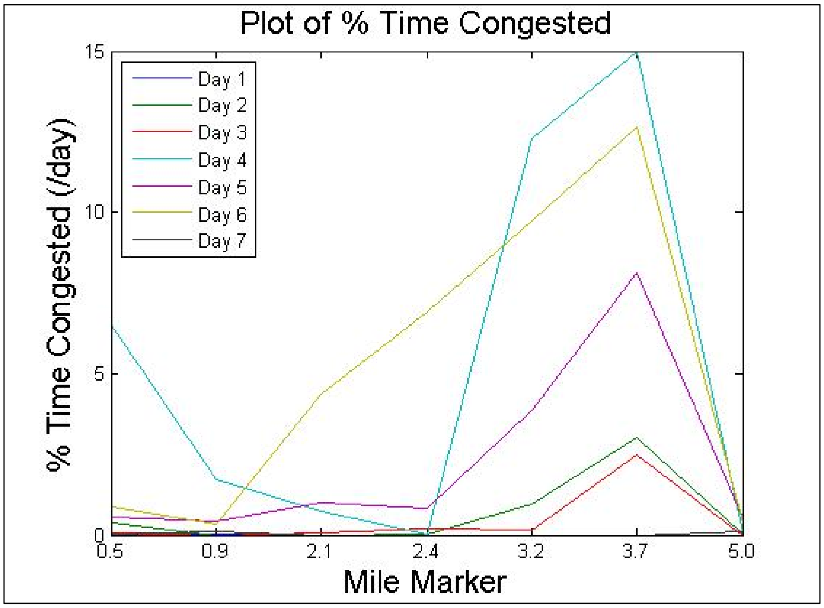

Figure 3.3 Variation of congestion conditions within a week on I-69

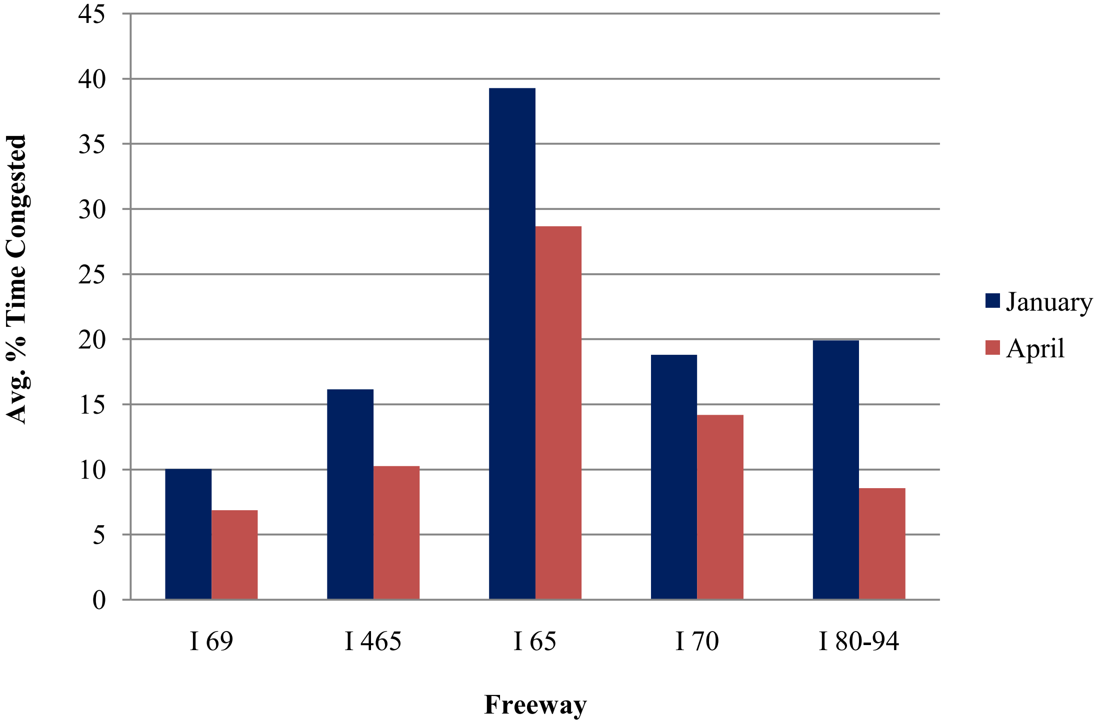

Figure 3.4 Monthly variation of congestion conditions on different freeways

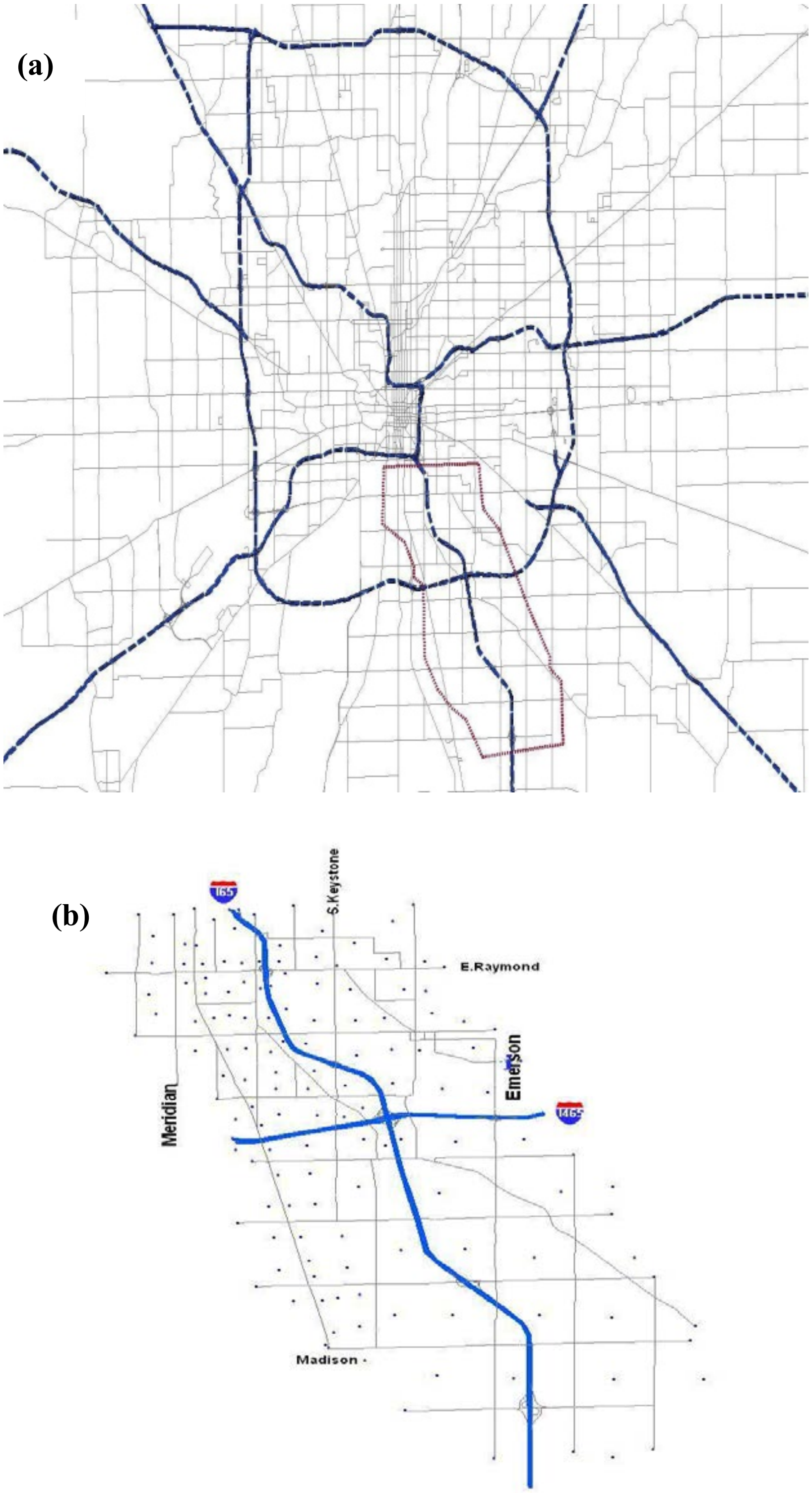

Figure 3.5 Study area (a) Indianapolis region showing the study area (b) Study area

3.3 Study Area

The location of the study area in the Indianapolis region is presented in Figure 3.5(a), while the schematic diagram of the study area is shown Figure 3.5(b). A 10-mile stretch of the I-65 corridor extending from the downtown of Indianapolis (mile post 110) to the south of Indianapolis (mile post 100) was selected for simulation based analysis.

There are four ramp locations (at mile posts 109, 107, 103, and 101, respectively) and one freeway interchange (at mile post 106) along this 10-mile section. The 10-mile stretch is selected where the potential travel time savings due to implementation of various lane use management strategies on I-65 are realized by the commuters using this facility.

Additionally, the study area comprises of all major (functionally classified as freeways, state roads, major and minor arterials) roadway facilities within a 2 mile distance on either side of the I-65 corridor. This enables holistic evaluation of lane use management strategies considering the effects of their implementation on the adjacent road network. A 2 mile boundary on the either side of I-65 corridor is identified by investigating the alternative routes to I-65 which a commuter may choose. Furthermore, the study area also comprises of all the other minor roads considered in the Indianapolis MPO TDM within the boundaries described above, utilizing the data from the MPO TDM.

3.4 Demand Estimation for the Study Area

For the simulation based analysis, the dynamic assignment (DA) module in VISSIM is used. DA in VISSIM is different from the conventional dynamic traffic assignment procedure where the latter also accounts for the temporal variation of demand during the assignment process. VISSIM's DA refers to the process of assigning vehicle routes, in a simulation model, based on traffic conditions which change during the simulation period. Unlike the static assignment case, where it is required to identify and input alternative routes and the percentage of vehicles using each route, DA module lets each vehicle select the best route based on multinomial logit models. It is an iterative process that converges to a path assignment based on vehicle travel time and delay between origin and destination (O-D) points in the network. Therefore, before the start of any calibration and model application, there is a need to estimate the existing demand, required for the DA analysis, for the study network in the form of O-D matrices.

In general, direct survey and subarea analysis models based on traffic counts on links, are the major methods used for estimating regional O-D matrices. Direct survey can be further subdivided into number plate matching, household survey, and road side survey. However, all these survey based methods are time consuming and costly. Subarea analysis methods that are based on traffic flow counts, to estimate the regional O-D matrices, can be divided into entropy based, statistical based, and heuristic based methods. However, these methods require an initial seed matrix and their accuracy depends on the proximity of the seed matrix to the actual O-D matrix.

Nonetheless, since the data for the regional O-D matrices is already available, from Indianapolis MPO's TDM, subarea analysis can be used. Subarea analysis is particularly effective for estimating the study area (sub-regional) O-D matrices, as the trips are evaluated based on an actual network. Hence, they effectively capture network interactions in and around the study area (Martchouk and Fricker, 2009)

The subarea analysis is performed using the tools available in TransCAD software. For the subarea analysis, the study area O-D trip data is subdivided into internal-internal, external-external, internal-external, and external-internal trips based on the location of the origins and destinations of trips with respect to the study area. For the internal-internal trips, since the origin and destination points are both inside the subarea, the regional values pertaining to the O-D pair can be simply retained to form the subarea O-D matrix. For the external-external trips, since both origin and destination points fall outside the study area, only O-D pairs whose paths pass through the study area are considered. The external entry and exit points are identified for each of these paths through the study area and subsequently flow values are appended to the subarea O-D matrix. For calculating the internal-external and external-internal O-D trips, first a regular traffic assignment is performed for all O-D pairs using the entire regional network and its corresponding O-D matrix. Next, the flow for all the paths for the O-D pairs is recorded. From this complete set, only paths corresponding to internal-external and external-internal trips are used. The O-D pair falling outside the study area is replaced with the external node at the point where they cut the boundary of the study area.

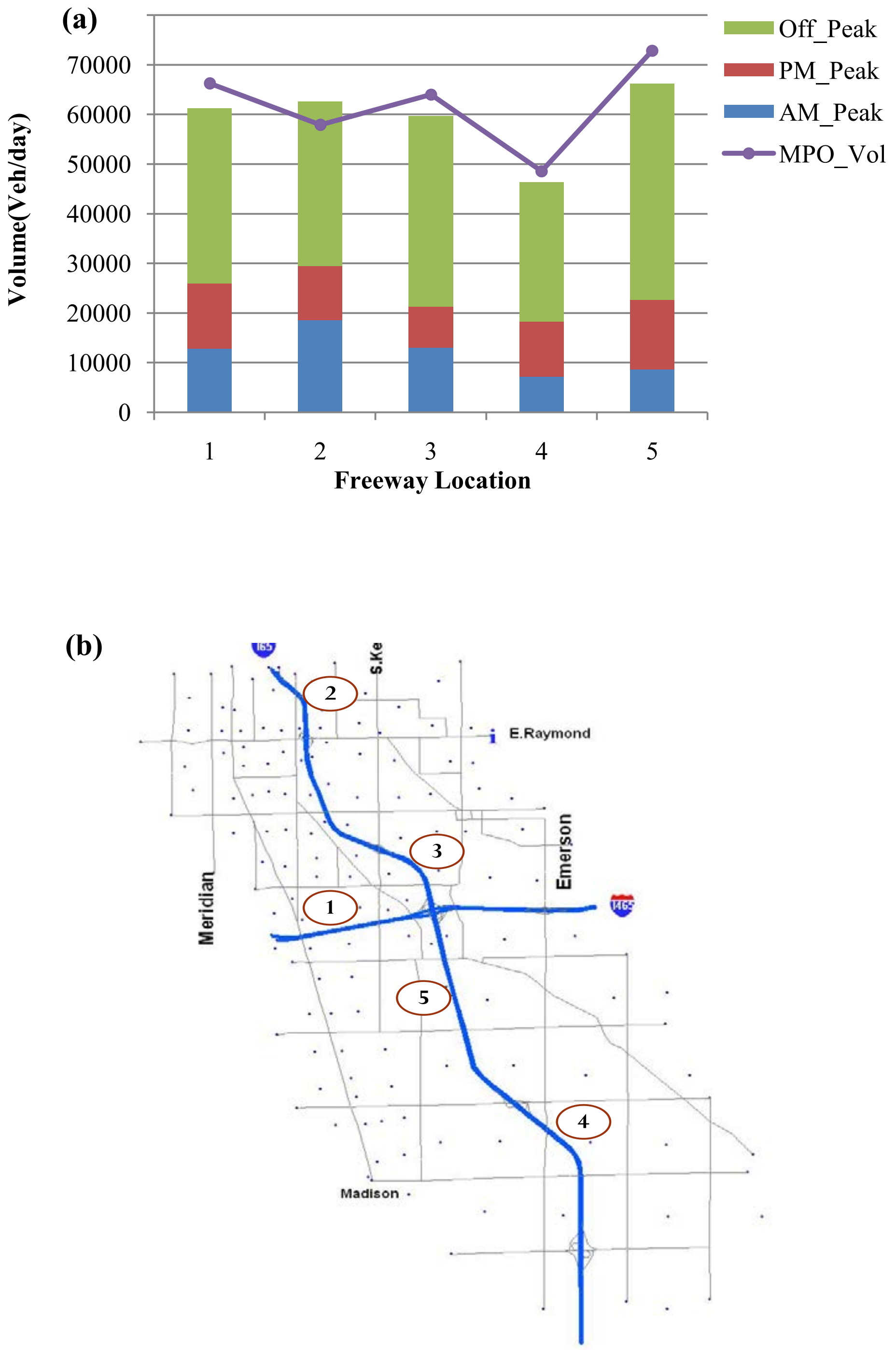

Figure 3.6 Validation of subarea analysis using traffic flow volumes on freeway links

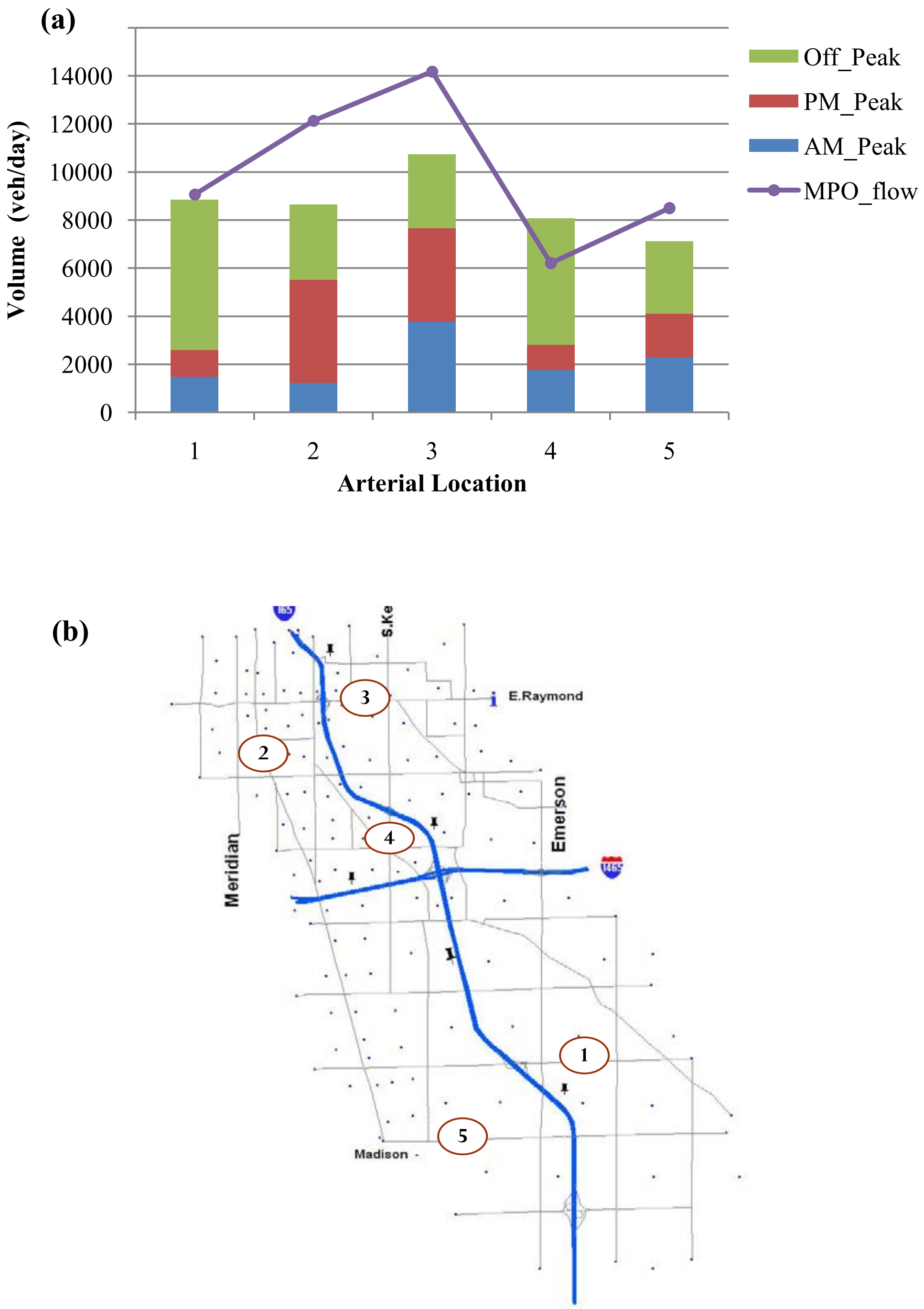

Figure 3.7 Validation of subarea analysis using traffic flow volumes on arterial links

3.4.1 Results of subarea analysis (demand estimation)

The first step of the simulation analysis is to estimate the O-D demand for all pairs among the 157 traffic analysis zones in the study region using subarea analysis. In this study, separate subarea analysis is performed for each AM Peak, PM peak, and off-peak periods. Traffic volumes obtained from the subarea analysis for different time periods are aggregated to obtain the total daily traffic volume for each O-D pair. These daily traffic volumes, obtained from subarea analysis, are then compared with the daily traffic volumes obtained from the region-wide Indianapolis MPO’s TDM. Figure 3.6(a) presents the results of this comparison analysis at different links of the freeway, while Figure 3.6(b) shows the corresponding locations in the transportation network on freeway links. The results indicate that the traffic volumes obtained from subarea analysis is closely correlated to values from the four-step model (TDM model), validating the results from subarea analysis. A similar comparative analysis is performed for different arterial links in the transportation network (Figure 3.7). While the subarea analysis results are reasonably close to the TDM volumes, the differences in traffic volumes on arterial links seem to be more pronounced compared to the freeway links.

In summary, this Chapter 3 describes the methodology adopted to select the study corridor for the simulation based analysis. In addition, this chapter presents the basis for defining the scope and boundaries of the study area. Finally, discussion on subarea analysis techniques used to estimate the demand for the study area along with its results are presented. Chapter 4 describes the details of coding the microsimulation model in VISSIM.

CHAPTER 4. MODEL DEVELOPMENT

This chapter presents details of coding the microsimulation model in VISSIM along with the description of calibration and validation methods used in this study. This includes topics such as selection of calibration parameters, performance measures, and the experimental design method used to determine parameter values for the calibration runs. Furthermore, this chapter also presents the details about how each lane use management strategies are implemented in VISSIM.

Microsimulation model to replicate the existing traffic conditions is constructed in VISSIM. Extensive error checks are performed to avoid vehicle behavior and to ensure that all the traffic controls and rules are appropriately coded in to the model. Thus verified model is used for further calibration and validation purposes. The following discussion describes the calibration methodology used to identify the set of parameter values for the microsimulation model that best represents the local traffic conditions.

The default model parameters in microsimulation software could not produce accurate results for the study area. The network model programmed in VISSIM is initially evaluated by running the model with default parameters. Link travel times on I-65 freeway are used to check for the appropriateness of the model. From these runs, it is observed that the model with default parameters overestimates travel times and therefore requires calibration. Therefore, the parameter values are adjusted to appropriately predict local traffic conditions. General guidelines provided by Dowling et al., (2004) and, Park and Qi (2005) are used to design the calibration procedure for this study. Based on the discussions in Dowling et al., (2004) and, Park and Qi (2005) and by observing the simulation model, parameters that have significant impact on the driver behavior are identified. Experimental design methods are used to define 25 different parameter sets for calibration runs. Performance measures along with goodness-of-fit test statistics are identified to evaluate the calibration parameter sets. The parameter set with the best goodness-of-fit statistic is selected. Finally, the best calibration parameter set is validated by comparing the travel times on I-65 corridor from simulation and the MPO TDM. Further description of the selection of calibration parameters, performance measures, and the experimental design method is presented below.

4.1 Identification of Calibration Parameters

This section discusses the VISSIM car following and lane changing parameters along with their acceptable ranges used in the calibration process. Based on modeling experience and guidelines in Dowling et al., (2004), the set of parameters selected for the calibration process along with their corresponding defaults values and their variation ranges are presented in Table 4.1. CC0, CC1 and CC4/CC5 represent the three car following parameters while safety reduction factor and waiting time before diffusion are the lane change parameters used during the calibration process. The ranges of parameter values used for calibration are defined using the guidelines provided in Dowling et al., (2004) and; Park and Qi (2005). Furthermore, five levels (of values) for each parameter, obtained by equally dividing the interval of variation, are used in this study.

4.2 Experimental Design

The total number of simulation runs to account for all combinations of the selected calibration parameters and their corresponding levels along with the multi-runs is large and it is practically impossible to test each such combination. Therefore, OED method is used to limit the number of combinations to a practical amount while still reasonably covering the entire parameter surface. This method provides an orthogonal array that randomly samples the entire design space broken into equal-probability regions and ensures that the complete range of every parameter is sampled (Park and Qi, 2005; Park et al., 2006). Parameter sets used for calibration are selected using the orthogonal experiment design (OED) method and each parameter set is run for three times with different random seed values to account for stochasticity of VISSIM simulation. 25

different parameter sets are identified using the OED method and their appropriateness is evaluated using the performance measures discussed below.

4.3 Selection of Performance Metrics

Two performance measures are selected for the calibration and the validation processes. The first measure of performance is the traffic volume on freeway and arterial links, and the second measure is travel time on the I-65 corridor. These measures are selected because of their ease of data collection from field and VISSIM output files, and availability of such data from the Indianapolis MPO TDM. Root mean square percentage error (RMSPE) and average GEH (Geoffrey E. Havers) statistics are used as goodness-of-fit statistics to evaluate various calibration parameter sets. Both these measures are scale independent and are most commonly used in various forecast studies (Barceló, 2010 and; Swanson, 2008). GEH, calculated according to Equation 4.1, is an empirical statistic used both in research and in practice to measure the difference between the observed and simulated values of interest Dowling et al., (2004). GEH values in the range of 0-5 convey that the simulated volume is closely correlated to the observed traffic volume, while those in the range of 5-10 convey that there is a good match between the modeled and observed traffic volume.

However, GEH values greater than 10 imply a mismatch between the modeled and observed traffic volume and needs further investigation. RMSPE is a variation of the standard RMSE norm and is computed as per Equation 4.2. Lower values of RMSPE indicate better accuracy of forecasted values.

$$GEH = \sqrt{\frac{2 \times (M - C)^2}{M + C}} \tag{4.1}$$

$$RMSPE = 100 \times \sqrt{\frac{\sum_{i=1}^{N} \frac{M_i - C_i}{M_i}}{N}} \tag{4.2}$$

where, *M* and *C* are the measured and calculated values while *N* is the number of measurements

Table 4.1 Description of parameters selected for calibration

Selected Calibration Parameters	Description	Default Values	Variation Range	
			Min.	Max.
CC0 (ft)	It is defined as the desired distance between stopped cars. This parameter impacts the capacity of the freeway during congestion.	4.90	4.0	10.0
CC1 (sec)	It represents the headway time in seconds and is defined as the time the driver wants to keep between following vehicles.	0.90	0.7	1.2
CC4 / CC5	These are dimensionless parameters which represent the coupling between leader and follower accelerations. Smaller absolute values indicate driver behaviors that are more sensitive to changes in the speed of the preceding vehicle.	-0.35	-2.4	-0.2
Safety reduction factor	The safety distance reduction factor impacts a driver's aggressiveness while making a lane change.	0.6	0.0	0.8
Waiting time before diffusion (sec)	The waiting time before diffusion is the maximum amount of time a vehicle will wait for a gap to change lanes before being removed from the network.	60	2.0	30

4.4 Calibration Results

Twenty five different sets of calibration parameters are tested during the simulation analysis. These calibration parameter sets are then ranked based on two criteria: GEH and RMSPE (Root mean squared percentage error). Figure 4.1 presents the performance of different sets of calibration parameters in the context of replicating the observed traffic volumes at 45 locations along the transportation network which includes 15 freeways sections, 10 ramp locations, and 20 arterial locations. It is found that parameter set 8 performs the best both with respect to RMPSE and GEH statistic.

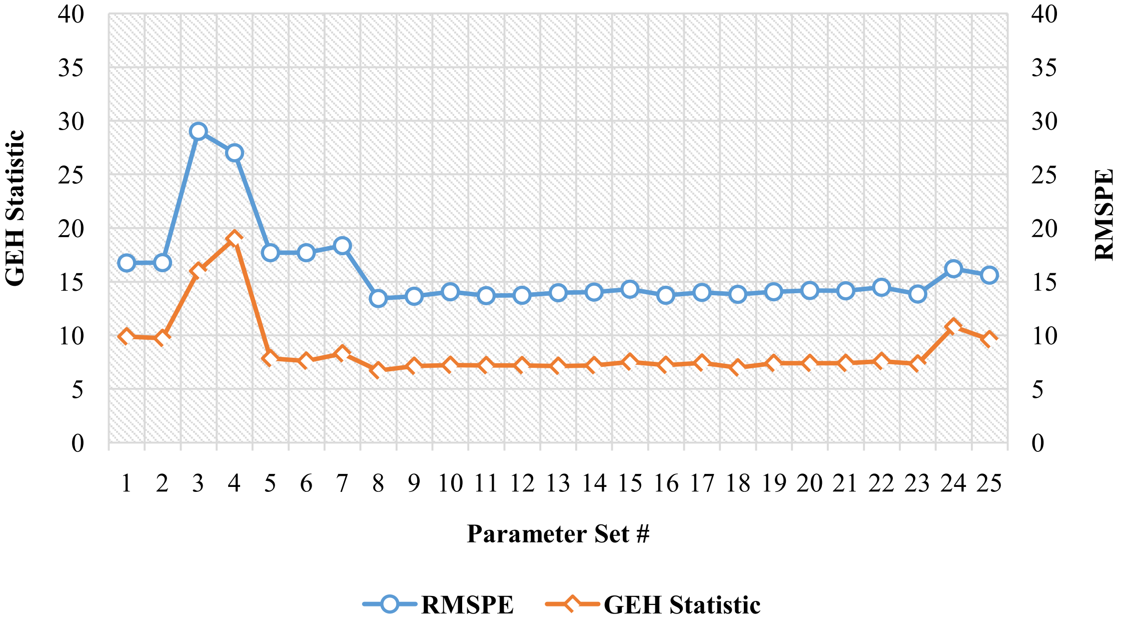

Figure 4.1 Comparison of the performance of calibration parameter sets with respect to RMSPE and GEH statistics

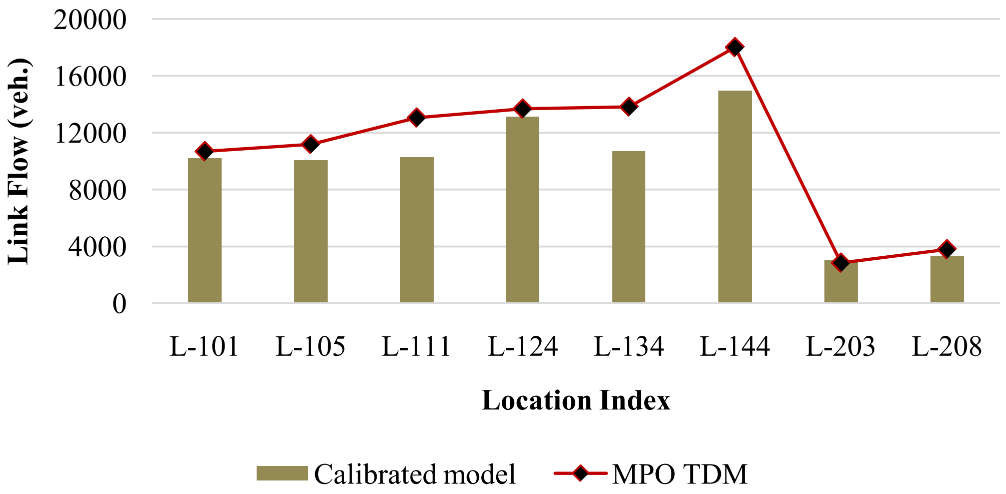

Figure 4.2 Comparison of traffic flow volumes from the MPO TDM and those obtained from the simulation

Table 4.2 Validation of model using MPO TDM travel times and the travel times from simulation

Location	MPO TDM (sec)	Simulated (sec)	% Difference	GEH Statistic
I-65 NB	779	809	3.85	1.06
I-65 SB	621	668	7.57	1.85
I-465 EB	226	251	10.88	1.59
I-465 WB	229	272	18.78	2.71
Raymond	540	527	-2.41	0.56

Figure 4.2 presents the comparison between simulated traffic flows obtained using the calibration parameter set 8 and the Indianapolis MPO TDM. X-axis represents the index for location of the link, while the y-axis presents the link flow volume during the morning peak duration. The first six indices along the x-axis represent locations along different freeway segments while L 203 and L 208 represent the ramp locations. It is observed that the calibrated model closely represented the existing traffic conditions.

Subsequently, the performance of the best parameter set identified in the earlier step (i.e., set 8) is analyzed with regard to replicating the travel times from the region-wide Indianapolis MPO travel demand model. Table 4.2 presents the validation results of this analysis for parameter set 8. It can be seen from the results that the average percentage difference in observed and simulated travel times is 7.7 and the average GEH statistic value is only 2.98 which is considered very good for such simulation analysis.

4.5 Details of Implementing Different Strategies Using VISSIM Modeling

4.5.1 Reversible Lanes

The existing I-65 facility in the study region consists of three lanes each in the northbound (NB) and southbound (SB) directions. Under the reversible lanes scenario, for the AM peak, the left most lane in the SB direction is converted into a reversible lane to serve the traffic in the NB direction. Thus, in this scenario, there are 4 lanes in the NB direction and 2 lanes in the SB direction. Moreover, the north and south bound traffic lanes are non-contiguous and are divided / median separated. Therefore, entry and exit bays are provided to access and exit the reversible lane. The reversible lane is designed as an express lane similar to that being currently implemented on I-5 in Seattle with one entry point and multiple exit points. Entry bay for the reversible lanes is provided before the I-65 NB and E county Rd interchange. Exit bays are provided before each of the off-ramp locations ensuring that there is sufficient distance to enable safe weaving and merging maneuvers.

The ten mile stretch of I-65 corridor is divided in to the following six segments to account for the variation in the traffic flow volume and the corresponding travel time savings.

a. Segment 1 is between the southern tip to the E County lane and I65 interchange
b. Segment 2 is between the Southport and E County lane ramp locations
c. Segment 3 is between I-465 interchange and Southport ramp locations
d. Segment 4 is between Keystone ramp and I-465 interchange
e. Segment 5 is between Raymond and Keystone ramp locations and
f. Segment 6 is between Raymond and north end of the study corridor.

4.5.2 HOV Lanes

Under this scenario, one of the existing lanes in each direction is converted to a continuous access HOV lane that only allows auto traffic with at least 2 passengers and transit bus services. During the implementation of HOV lanes, it is likely that travelers will change their mode of travel to get access to the high speed HOV lane. Hence, the HOV traffic is likely to increase under this scenario. To capture the effect of this change in demand, we consider two situations under which there is: (1) 0% increase in the HOV traffic due to HOV lane implementation, and (2) 10% increase in the HOV traffic due to HOV implementation.

HOV lane strategy is implemented on I-65 corridor both in north and south bound directions by converting the left most general purpose (GP) lane to a HOV lane in the respective directions. The HOV lanes are designed with continuous access which minimizes the extent of infrastructural modifications required to facilitate HOV implementation. Based on the analysis of existing SOV and HOV traffic flow patterns acquired from INDOT, a minimum of two or more passengers per vehicle is determined as the requirement to allow HOV lane access. Additionally, the model allows transit vehicles to use the HOV lanes. The economic evaluation performed in this study does not include park-and-ride facilities, transfer centers, and direct access ramps for the HOV facility. However, these factors along with ridership programs and other support facilities should be planned strategically for successful implementation of HOV lanes strategy.

4.5.3 Ramp Metering

The I-65 corridor operates at congested conditions in the NB direction during the morning peak duration and vehicles entering from the ramps aggravate the congested conditions. There are five on-ramp locations along the study corridor. The ramps in the SB direction are not considered for ramp metering as the I-65 corridor is not congested in this direction during the analysis period (AM peak). Performance of metering at each ramp location is evaluated separately in this study. This means that when evaluating implementation of the ramp metering strategy at I-65 and Raymond on-ramp, it is assumed that there are no ramp signals on the other ramps lanes.

A traffic predictive ramp metering strategy based on ALINEA algorithm is used to determine the ramp signal timings. ALINEA based traffic predictive ramp metering is more sophisticated compared to fixed time metering and unlike the responsive ramp metering algorithms, anticipates the operation problems before they occur (Bhargava et al., 2006).

The objective of ramp metering is to regulate the flow from ramps onto the freeway in order to minimize congestion on the freeway. If the freeway segment upstream of the ramp location is already congested, then the benefits due to ramp metering are minimal as the vehicles from ramp entering the freeway has longer waiting times (Bhargava et al., 2006). Also, benefits of metering are not significant when the ramp volume is below a threshold value. One of the warrants, discussed previously, requires that the freeway and ramp volume should be at least a minimum threshold value to consider metering at a ramp location.

The ramp at I-65 and I-465 is a freeway – to – freeway type ramp connector which require special considerations (Bhargava et al., 2006). One of the warrants, discussed previously, require a minimum of two ramp lanes to implement freeway-freeway ramp metering. However, the existing infrastructure is such that there exists only one ramp lane connecting the I-465 and the I-65 in the NB direction. Since objective of this study is to optimize the lane use by managing the existing infrastructure, ramp metering at this location is not considered for further study. Results of microsimulation analysis along with the economic evaluation of the traffic predictive ramp metering implemented separately at the Raymond and I-65 ramp 1 in this study. This location is selected because, it has ramp and freeway volumes greater than the minimum threshold value of 4250 vph.

In summary, this Chapter presents the details and results of calibration and validation of the microsimulation model coded in VISSIM. Furthermore, this chapter also presents the details about how each of three strategies is implemented in VISSIM.

CHAPTER 5. RESULTS OF VISSIM MICRO-SIMULATION MODELING

5.1 Results of Micro-simulation Based Analysis of Reversible Lanes

5.1.1 Impact on Average Lane Speed

Impact of the reversible lane strategy implementation on the performance of the freeway during the morning peak duration is presented in this section. Figure 5.1 and Figure 5.2 present the impact of reversible lane strategy implementation on the average speeds measured at different locations (represented by mile markers) in the NB and the SB directions along the I-65 corridor, respectively. Understandably, the additional reversible lane in the NB direction improved average traffic speeds by up to 40% whereas, the reduction in the number of lanes in the SB direction decreased average speed by up to 12%. This is due to the increased capacity in the NB direction and reduced capacity in the SB direction. Similar analysis when performed for future years using the projected traffic conditions result in trends that are consistent with those shown in Figure 5.1 and Figure 5.2. However, the amount of improvement in average lane speed reduced in the future year scenarios. This is because the freeway demand increases every year thereby further increasing the congestion on freeway regardless of the improvements due to the reversible lane. Also, congestion increases at a higher rate in the SB direction than the rate of growth of total travel time savings. In such a scenario, improvements from reversible lanes seize to exist after a while.

5.1.2 Economic Evaluation

Economic evaluation of reversible lane strategy implementation during the morning peak duration is presented in this section. Implementation of reversible lanes in the major flow direction (NB) requires disruption to the minor flow direction (SB) traffic flow in order to set up the barriers. However, the time lost to convert the SB direction lane to a reversible lane is not considered during this evaluation.

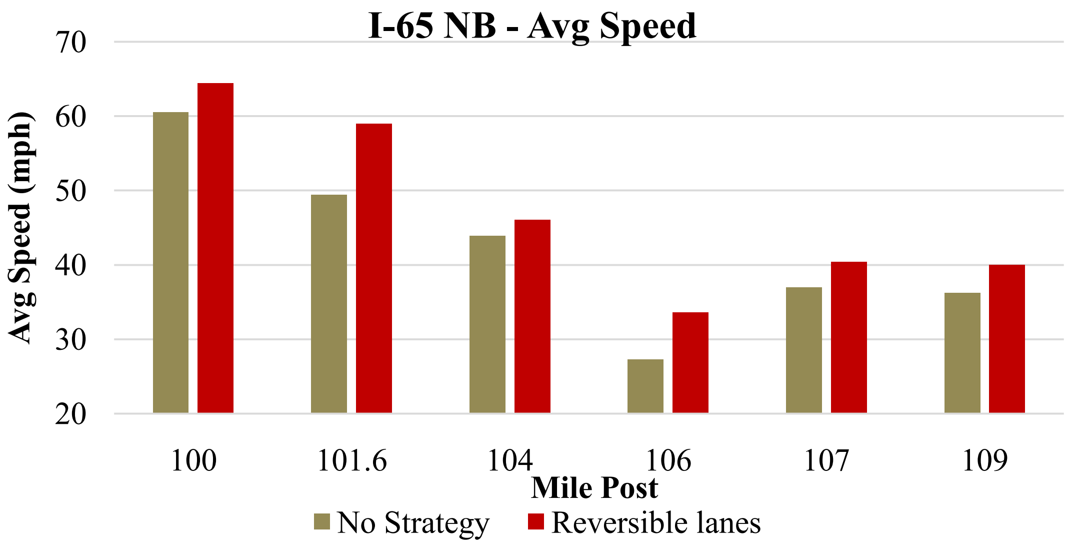

Figure 5.1 Comparison of average speeds NB I-65 before and after scenarios of implementing reversible lanes strategy

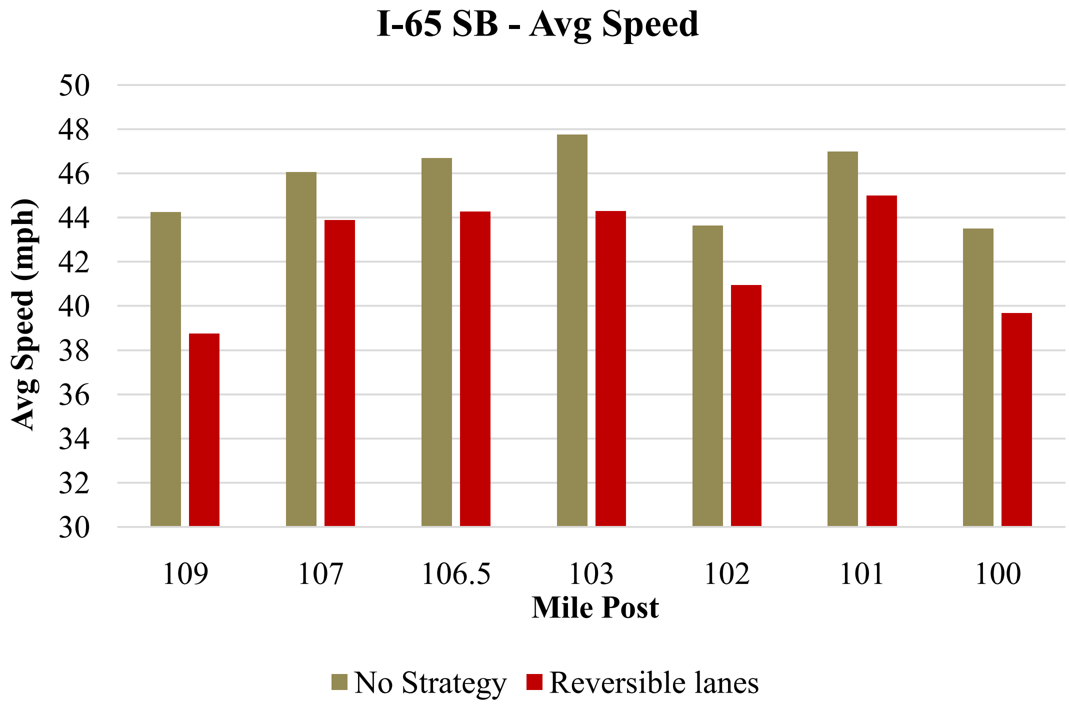

Figure 5.2 Comparison of average speeds SB I-65 before and after scenarios of implementing reversible lanes strategy

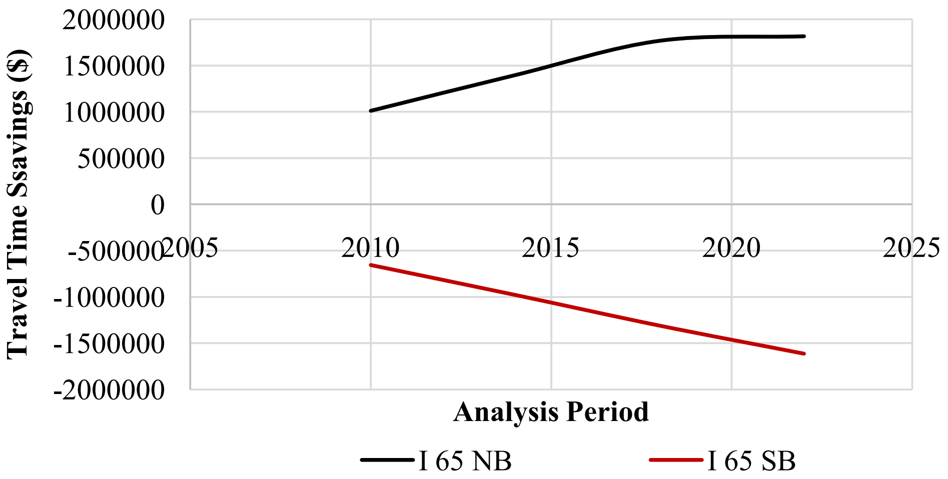

Figure 5.3 Travel time savings (in $) in NB and SB directions due to implementation of reversible lanes strategy

5.1.2.1 Travel time savings

For estimation of travel time savings during the morning peak duration, it is assumed that the trip purpose for all the automobiles is work related trips. The corresponding value of travel time (VOT) for a single occupant vehicle (SOV) is assumed to be $30/hour, while the VOT for automobiles with higher occupancy is equal to occupancy multiplied by $30/hour (NCHRP, 2012). Travel time savings due to the implementation of reversible lanes for the base and the future years' projected traffic conditions on the six segment links of I-65 are shown in the Figure 5.3. NB direction which occurs to be the major flow direction during the morning peak, has significant travel time savings, while the SB direction have negative travel time savings. This is because of the increased capacity in the NB direction and reduced capacity in the SB direction. Demand in the major flow direction (NB) is met by four lanes (3 existing NB lanes and one reversible lane) in this direction, while the demand in the minor flow direction is accommodated by two lanes (right and the center lanes of the existing SB lanes). Given that the impact of the strategy is opposite in the NB and SB directions and the rate of travel time accrual (in the SB direction) is higher than the rate of travel time savings in the NB direction, the net travel time savings follows an inverted U-shaped profile peeking during 2016-2018 period.

5.1.2.2 Vehicle operating cost (VOC) savings

A similar segment wise analysis is performed to estimate the VOC savings and the results are presented in the Table 5.2. The VOC savings are determined by estimating the fuel cost savings using the AASHTO model as described in Sinha and Labi, 2007. However, it must be noted that these VOC calculations do not take into account the impact of freeway grade, number of stops and speed changes on the VOC values. It is assumed the fuel cost is 3.5$ per gallon in 2010 dollars (OPIS, 2013). Furthermore, the free flow speed on I-65 corridor is assumed to be 55 mph and the corresponding values of average fuel consumption (in gallons) per minute of delay by vehicle type are obtained from Sinha and Labi (2007).

To calculate the VOC savings for each vehicle type, the average travel time savings are multiplied by the fuel cost per gallon and the corresponding fuel consumption values. The total annual average VOC savings are determined by summing the VOC savings for all the vehicle types. The annual VOC savings are found to decrease each year due to corresponding reduction in the travel time savings.

5.1.2.3 Emission Savings

Reversible lane strategy implementation increases the emissions in the SB direction of I-65 corridor, while it reduces the emissions in the NB directions. Vehicle emissions, in general, are influenced by vehicle age, mileage, size, engine power and VMT (vehicle miles travelled). However, in this study, it is assumed that the vehicle type and the VMT are the only factors influencing the vehicular emissions rates. Hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NO_x) related costs are estimated in this study. Typical emission rates by vehicle type and mode under average freeway operating conditions along with unit cost ($/kg) of pollutants (Bhargava et al., 2006) are presented in the Table 5.1. Using these values, the annual emission rates are calculated and presented in the Table 5.2 for each year during the analysis period.

5.1.2.4 Costs Associated with Implementing Reversible Lanes

The costs associated with reversible lane strategy for this study comprise of the following components.

- Construction cost of carriageways which connect the reversible lane and the major flow direction lanes
- Costs of putting up relevant signs and pavement markings
- Costs associated with placing barriers separating the reversible lanes from the regular flow lanes
- Operational and maintenance costs

In this study, reversible lanes are provided with one access point and multiple egress points as described previously. Since the NB and SB lanes of I-65 are non-contiguous, construction of carriageways is required to facilitate egress and ingress. Therefore a total of six segments of carriageways are required and the length of each of these carriageways is approximately 0.1 mile. Furthermore, it is assumed that the construction cost of such lanes is same as the freeway lane construction cost which is equal to $1,300,000 per lane mile (Bhargava et al., 2006). Therefore a onetime fixed cost of carriageway construction is equal to $780,000.

The cost of reversible lane signing is assumed to be approximately equal to $26,000 per lane mile (Bhargava et al., 2006). Cost of lane signs is estimated based on the reversible lane signs at the ingress and guide signs at the egress points. Furthermore, the cost of pavement markings is assumed to be equal to two percent of lane construction cost (Bhargava et al., 2006). Therefore one-time fixed costs of the new lane signs and pavement markings are calculated as $260,000 each.

Implementation of reversible lanes requires placing barriers in the minor flow direction, which in this case is SB direction during the morning peak, and removing them regularly. Moveable concrete barriers facilitate this and can be performed at a transfer rate of 12 minutes per mile (Barton, 2013).The cost of machine for placing moveable barriers cost varies from $250,000 to $400,000.In this study it is assumed that cost of acquiring a moveable barrier infrastructure is $250,000. Furthermore, it is assumed that 5 feet long concrete barriers are used to separate reversible lanes from the minor flow direction lanes and they are placed at an interval of one in every 20 feet. The cost of barriers is assumed to be 70$ per foot (Murray, 2013) and therefore adds up to a total fixed cost of $924,000 for the barriers.

Major component of the operational costs comprises of the operation of moveable barrier to place the concrete barriers. It is assumed that the operator’s wage cost is $30 per hour and is required to perform the placing and removal of barriers twice a day each corresponding to the morning and evening peak durations. The maintenance cost is assumed to be negligible. Therefore the annual cost of operation and maintenance cost is estimated as $62,400 using the previous assumption that it takes 12 minutes per mile to place / remove the barriers.

Therefore the total fixed cost is equal to $2,474,000 while the annual cost for implementing the reversible lanes is equal to 62,400. The costs for implementation for each year during the 10-year analysis period are listed in the Table 5.2.

Table 5.1 Emission rates of pollutants by mode and the corresponding unit costs (Bhargava et al., 2006)

Vehicle Type	**HC**	**CO**	**NO$_x$**
Automobiles (g/VMT)	1.88	19.36	1.41
Trucks (g/VMT)	2.51	25.29	1.84
Bus (g/VMT)	2.3	11.6	11.9
Unit cost (/Kg)	$1.28	$0.01	$1.28

Table 5.2 Annual costs and benefits of implementation of reversible lane strategy on I-65 corridor

Year	**VOC Savings ($)**	**Emission Savings ($)**	**Travel Time Savings ($)**	**Total Benefits ($)**	**PVB ($)**	**Initial Fixed Cost ($)**	**Opr. & Mnt. Cost ($)**	**Total Costs ($)**	**PVC ($)**	**NPV ($)**
0	0	0	0	0	0	2474000		2474000	2474000	-2474000
1	97,048	192,860	355,304	645,211	614,487	0	62,400	62,400	59,429	555,058
2	97,894	223,162	358,402	679,458	616,288	0	62,400	62,400	56,599	559,690
3	101,811	256,275	372,744	730,830	631,319	0	62,400	62,400	53,903	577,415
4	107,644	288,710	394,099	790,453	650,307	0	62,400	62,400	51,337	598,971
5	114,236	316,980	418,233	849,449	665,566	0	62,400	62,400	48,892	616,673
6	120,430	337,600	440,913	898,943	670,805	0	62,400	62,400	46,564	624,241
7	125,072	347,081	457,907	930,060	660,976	0	62,400	62,400	44,347	616,630
8	127,004	341,937	464,982	933,922	632,115	0	62,400	62,400	42,235	589,881
9	125,070	318,680	457,905	901,655	581,215	0	62,400	62,400	40,224	540,991
10	118,115	273,824	432,443	824,382	506,099	0	62,400	62,400	38,308	467,791
Net Present Value ($)										3,273341
Benefit Cost Ratio										1.90

5.1.3 Benefit-cost ratio (B/C) and net present value (NPV)

The annual benefits and costs associated with implementation of reversible lane strategy are listed in the Table 5.2. Total benefits (B) are calculated as the sum of VOC, emissions, and travel time savings. Similarly, total costs are determined as the sum of total initial fixed costs and the annual operation and maintenance costs. Present value of benefits (PVB) and costs (PVC) are estimated using a discount rate equal to 5%. From the above economic evaluation for 10 year analysis period, it is found that the NPV is positive and equal to \$3,273,341, while the B/C ratio is 1.90. This indicates the implementation of reversible lanes is economically viable. Although the implementation of this strategy is economically feasible, it may be criticized for increasing congested conditions in the minor flow direction due to reduction in capacity. Appropriate public awareness programs are needed to alleviate such effects.

5.2 Results of Microsimulation Analysis of HOV lanes

5.2.1 Impact on the average lane speed

Impacts of the HOV lane strategy implementation on the performance of the freeway during the morning peak duration is presented in this section. It is expected that the average speed on the HOV lane is higher than that of the GP lanes due to the lower number of HOVs compared to that of the SOVs and trucks. Microsimulation analysis yielded similar results and this trend was consistent across all the scenarios corresponding to the forecasted demands. Figure 5.4 and Figure 5.5 show the typical microsimulation results of average speed variation along the I-65 corridor in the NB and SB directions respectively, for one of the scenarios.

Another interesting observation can be made by looking at the average speed profile of traffic along the GP lanes before and after the implementation of the HOV lane strategy. It is seen from the Figure 5.6 that the speed of traffic on GP lane has reduced considerably in the HOV lane strategy. This is probably a result of the fact that "Drive Alone" auto traffic that was using all the 3 lanes before the implementation of the HOV lane strategy are forced to use only two lanes. The speeds on GP lanes are slightly higher in the HOV-10% strategy compared to the HOV-0% strategy which is consistent with the shift in the mode shares to car-pooling in the HOV-10% strategy.

5.2.2 Impact on the throughput

Although, the traffic speed on the HOV lanes improved significantly, the cost of travel on the GP lanes also increased. Therefore the overall vehicle throughput of the HOV lane and GP lane is lower compared to the before HOV implementation scenario. However, the purpose of HOV lanes is to improve the overall person throughput and not the vehicle throughput. Comparison of the person throughput before and after the implementation of the HOV lane strategy, presented in Figure 5.7 for one of the scenarios, indicating that the HOV lanes are instrumental in improving the person throughput. These trends are consistently seen in other scenarios corresponding to future years.

5.2.3 Impact on travel time savings

As expected, the increased person throughput due to HOV implementation also translated into higher overall travel time savings in the NB direction as can be noticed from the Figure 5.10. These trends are consistent for the other scenarios corresponding to future years.

These results are also consistent with the higher average HOV lane speeds and increasing demand over time (resulting in increasing HOV lane traffic over time). However, the rate of negative savings on GP lanes is higher than the rate of positive savings on HOV lanes and more significantly so in the SB direction (Figure 5.8 and Figure 5.9). This is because of the fact that the speed on the GP lanes decreased more drastically with the increasing demand over time than the improvement of speed on the HOV lanes over time.

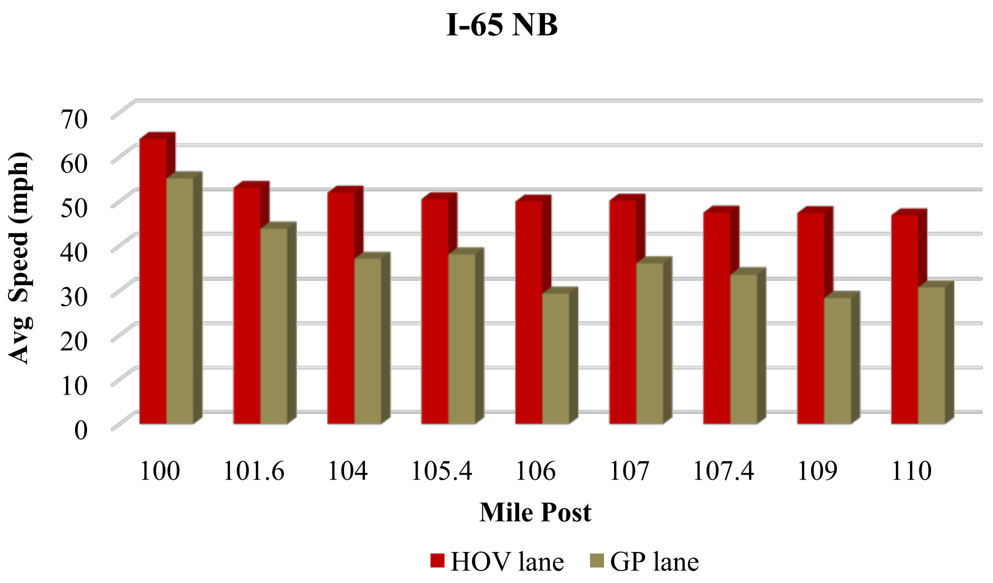

Figure 5.4 Comparison of average speed on HOV lane and GP lane in NB direction of I-65

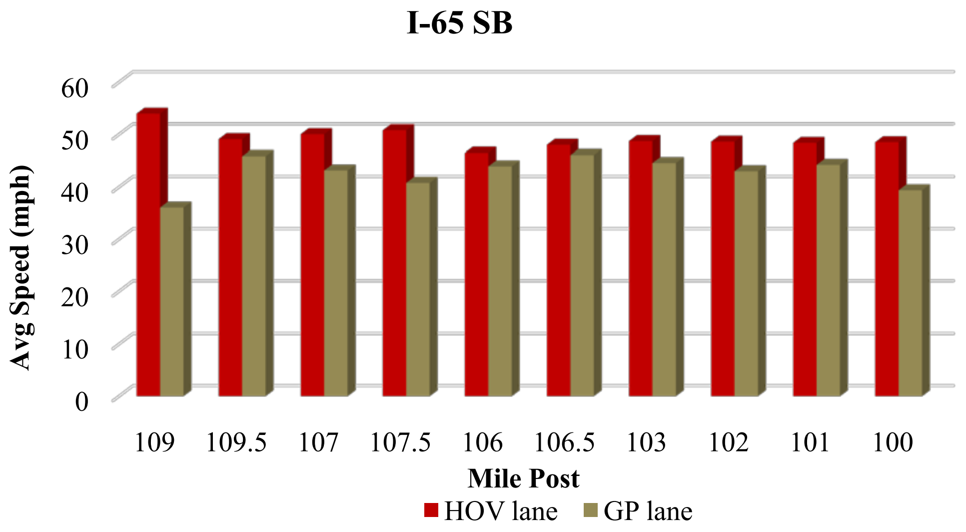

Figure 5.5 Comparison of average speed on HOV lane and GP lane in SB direction of I-65

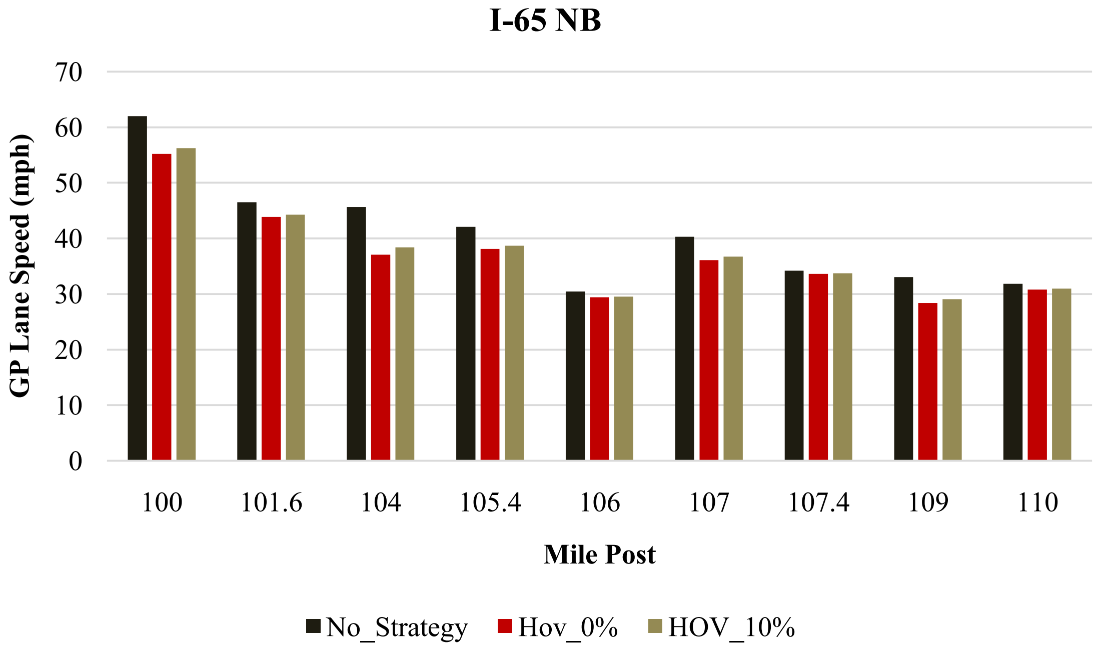

Figure 5.6 Comparison of average GP lane speed for different scenarios in NB direction of I-65

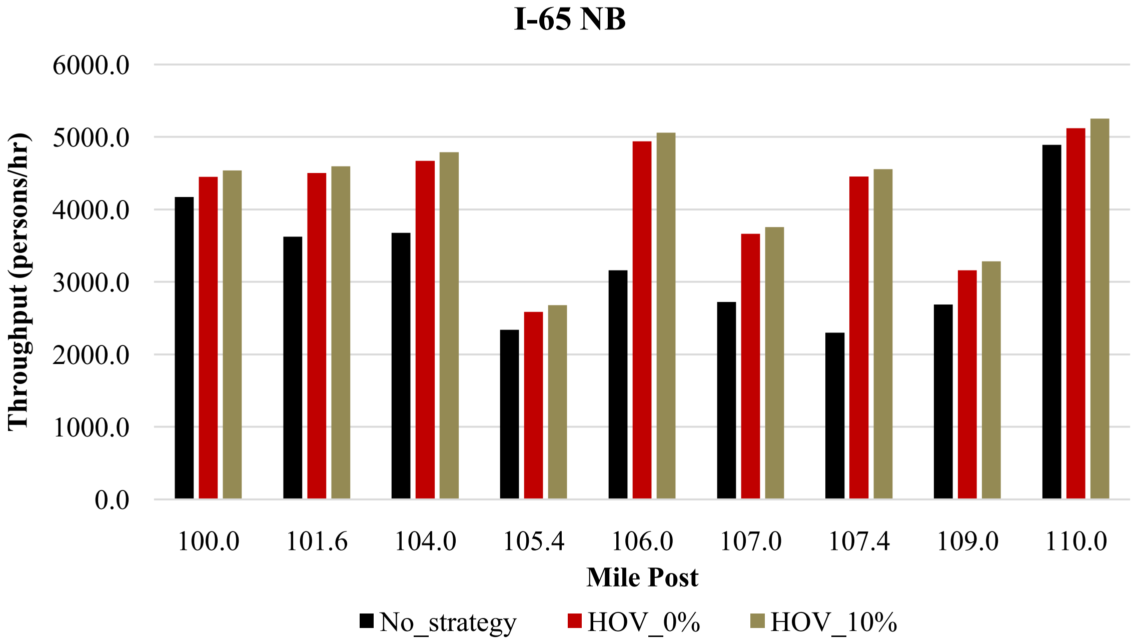

Figure 5.7 Comparison of average person throughput for different scenarios in NB direction of I-65

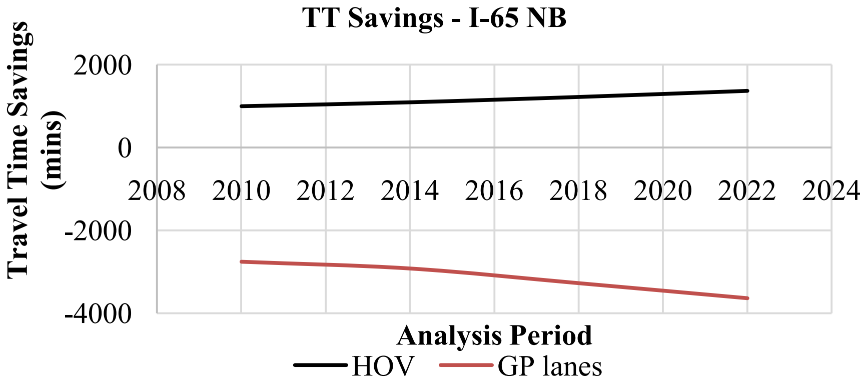

Figure 5.8 Total vehicle travel time savings from HOV implementation in NB direction

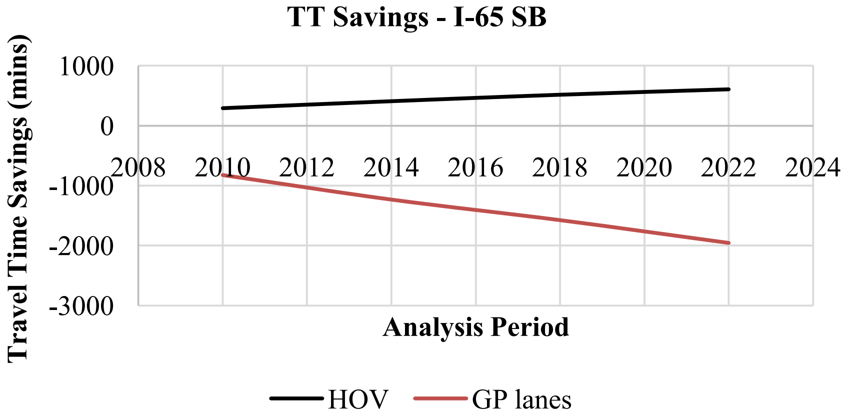

Figure 5.9 Total vehicle travel time savings from HOV implementation in SB direction

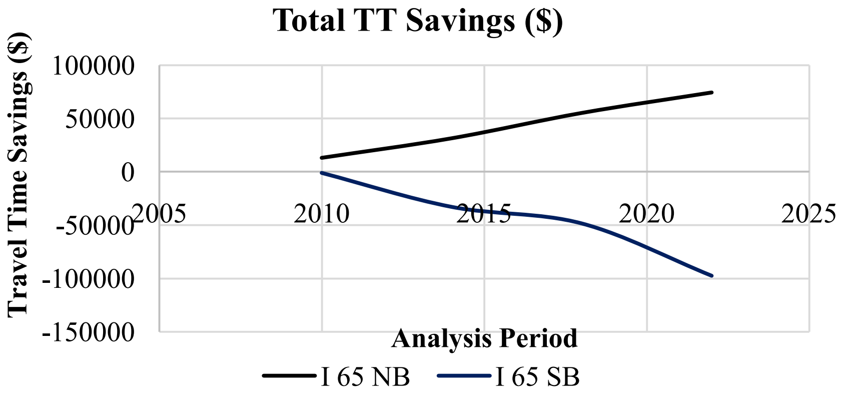

Figure 5.10 Total travel time savings ($) from HOV implementation in NB and SB directions

Table 5.3 Annual costs and benefits of implementation of HOV lane strategy on I-65 in the NB direction

	VOC Savings ($)	**Emission Savings ($)**	**Travel Time Savings ($)**	**Total Benefits(B) ($)**	**PVB**	**Initial Fixed Cost ($)**	**Mnt. Cost ($)**	**Total Cost(C) ($)**	**PVC ($)**	**NPV ($)**
0	0	0	0	0	0	520,000		520,000	520,000	-520,000
1	-375,499	-17	49,733	-325,783	-310,270	0	0	0	0	-310,270
2	-374,091	7,159	70,488	-296,444	-268,884	0	0	0	0	-268,884
3	-376,429	12,457	91,243	-272,729	-235,594	0	0	0	0	-235,594
4	-381,959	16,109	111,998	-253,852	-208,845	0	0	0	0	-208,845
5	-390,127	18,347	132,753	-239,027	-187,284	0	0	0	0	-187,284
6	-400,382	19,404	153,508	-227,470	-169,741	0	0	0	0	-169,741
7	-412,168	19,512	174,263	-218,394	-155,208	0	0	0	0	-155,208
8	-424,935	18,902	195,018	-211,014	-142,823	0	0	0	0	-142,823
9	-438,127	17,808	215,773	-204,546	-131,852	0	0	0	0	-131,852
10	-451,192	16,462	236,528	-198,202	-121,679	0	0	0	0	-121,679
Net Presesnt value										**-2,452,179**

Table 5.4 Results of micro-simulation analysis of ramp metering at Raymond ramp location

Analysis year	**With Ramp metering**				**Without Ramp metering**		**Total Net Travel Time Savings (VHT)**
	Avg. Travel Time on I-65 NB (sec)	**Avg. Travel Time on Ramp (sec)**	**Flow on I-65 at Ramp (Veh/hr)**	**Flow on Ramp (Veh/hr)**	**Avg. Travel Time on I-65 NB (sec)**	**Avg. Travel Time on Ramp (sec)**	
2010	792.55	40.7	3137	1061	809.83	26.88	10.98
2014	826.38	41.75	3216	1080	844.73	27.33	12.07
2018	842.28	42.7	3311	1116	861.41	28.2	13.10
2022	898.31	45.85	3467	1266	916.15	34.85	13.31

5.2.4 Economic Evaluation

This section presents the economic evaluation of the HOV lane strategy with 0% i.e., with the assumption that there is not additional car-pooling due to the implementation of HOV lanes.

5.2.4.1 Travel time savings

For estimation of travel time savings during the morning peak duration, it is assumed that the trip purpose for all the automobiles is work related trips. The corresponding value of travel time (VOT) for a single occupant vehicle (SOV) is assumed to $30/hour, while the VOT for automobiles with higher occupancy is equal to occupancy multiplied by $30/hour (NCHRP, 2012)

Figure 5.10 presents the net travel time savings from the HOV lane strategy in NB and SB directions. The monetary value of travel time savings is obtained by multiplying the savings by VOT corresponding to the occupancy of the vehicles. The net travel time savings after considering the travel time accrual on the GP lanes indicate that the HOV lane strategy offers significant savings only along the NB direction. Thus, the analysis in this study recommends implementation of HOV lanes only in the NB direction (major flow direction) but not in the SB direction. Similar trends were observed with HOV-10% scenario as well with the only difference being that the magnitude of savings is higher than those in the HOV-0% scenario.

SB direction of I-65 is not considered for further evaluation of economic feasibility due to the net negative travel time savings. It is therefore economically infeasible to implement HOV lanes in SB direction during the morning peak.

5.2.4.2 VOC savings

The vehicle operating cost savings are estimated as described previously in the Section 5.1.2. The values of VOC savings are listed in Table 5.3. The VOC savings are found to be negative because the negative VOC savings due to congestion on GP lanes is higher than the positive savings on HOV lanes.

5.2.4.3 Emission savings

Emission savings are estimated as described previously in the Section 5.1.2. The values of VOC are listed in Table 5.3. An interesting observation from these results is that the emission savings, although small, are positive (except for the first year) unlike the expectation that they should have been negative due to congested conditions on the GP lanes. This phenomenon is thought to be because of the lower vehicle throughput before HOV implementation scenario. Emission savings are positive probably because the savings are estimated based on the total VMT, and the total VMT is lower in the post HOV implementation scenario compared to the pre HOV implementation scenario.

5.2.4.4 Costs associated with HOV lanes

The overall cost of HOV lanes is significantly influenced by the components included in the analysis. Typical components of HOV lane cost estimation include right of way acquisition cost, HOV lane construction cost, sign and pavement markings costs, construction of access ramps and park-and-ride facilities, and, dedicated enforcement area construction costs. In this study, one (leftmost lane) of the three existing lanes in each direction is converted to HOV lane giving rise to one HOV lane and two general purpose lanes in each direction. Therefore, the cost of right of way acquisition and HOV lane construction cost is equal to zero. Furthermore, the costs of constructing park and ride facilities along with dedicated enforcement areas are not considered. Hence, signing and pavement marking costs are the only cost components associated with the HOV lane cost analysis.

The cost of HOV lane signing is assumed approximately equal to $26,000 per lane mile. Cost of lane signs is estimated based on the HOV only signs and guide signs at regular locations (every two miles) along the I-65 corridor. Furthermore, the cost of pavement markings is assumed to be equal to two percent of lane construction cost

(Bhargava et al., 2006). Therefore one-time fixed costs of the new lane signs and pavement markings are calculated as $260,000 each.

5.2.4.5 Benefit-Cost Ratio (B/C) and Net Present Value (NPV)

Economic evaluation of HOV lanes is performed for the NB and SB directions separately. The annual benefits and costs associated with implementation of HOV lane strategy in NB direction are listed in the Table 5.3. Total benefits (B) are calculated as the sum of VOC, emission and travel time savings. Similarly, total costs are determined as the sum of total initial fixed costs and the annual operational and maintenance costs. Present value of benefits (PVB) and costs (PVC) are estimated using a discount rate equal to 5%. From the above economic evaluation for 10 year analysis period, it is found that the NPV of HOV lane implementation in the NB is negative and equal to -$2,452,179 and the B/C ratio is 0.79. This indicates the implementation of HOV lanes is economically infeasible.

5.3 Results of Microsimulation Analysis of Ramp Metering

Impacts of the ramp metering strategy implementation on the performance of the freeway and ramps during the morning peak duration are presented in this section. Table 5.4 presents the vehicle hours spent on the freeway and the ramps before and after the implementation of ramp metering at the Raymond Street between 2010 and 2022. It is observed that the ramp metering improves the freeway travel conditions. The average increase in the travel time on the ramp is increased by 34% in the base year (2010). This is due to additional delay on the ramps due to the ramp metering. The net travel time savings after subtracting the additional time spent by all the vehicles along the ramps is the metric of interest and is presented in Table 5.4. Overall, the results suggest that ramp metering offers significant travel time savings during the analysis period although the rate of increase in the savings is found to decrease with time. This is because the traffic along freeway increases every year regardless of the traffic along the ramp and the delay at ramp meters increases at a higher rate compared to the travel time savings along the freeway.

Table 5.5 Cost components for implementation of ramp metering

Component	**Unit Cost ($)**	**Quantity**	**Total Cost ($)**
Ramp meter installation cost	45,000	1	45,000
Communication from detectors to meters (twisted pair wire)	100,000	1	100,000
Detector cost	2,800	5	14,000
Series processor	8,000	1	8,000
Total fixed installation costs			167,000
Annual operating and maintenance costs	10% of installation costs		16,700

5.3.1 Economic Evaluation

This section presents the economic evaluation of implementing ramp meter strategy at the I-65 and Raymond interchange. A discount rate of 5% is used to estimate the present value of various annual benefits and annual costs.

The annual travel time savings in monetary terms are obtained by multiplying the annual travel time savings, expressed as vehicle hours travelled (VHT), with the value of travel time and a factor of 780 (=3*5*52) to account for the conversion of hourly savings to annual savings.

Similarly, the vehicle operating cost savings and the emission savings are estimated as described previously for the reversible lanes. However, the emission savings due to implementation of reversible lanes are very small compared to the travel time savings. This is because of the small difference in the total VMT before and after implementing ramp metering. Therefore, emissions savings are assumed to be zero. The values of VOC, emission and travel time savings are listed in Table 5.6.

Table 5.6 Annual costs and benefits of implementation of ramp metering strategy Raymond and I-65 ramp location

Year	**VOC Savings ($)**	**Emission Savings ($)**	**Travel Time Savings ($)**	**Total Benefits ($)**	**PVB**	**Initial Fixed Cost ($)**	**Mnt. Cost ($)**	**Total Cost ($)**	**PVC ($)**	**NPV ($)**
0	0	0	0	0	0	164,200		164,200	164,200	-164200
1	81,621	0	256,137	412,465	392,824	0	18,000	16,700	15,905	305,770
2	84,229	0	264,322	425,644	386,072	0	18,000	16,700	15,147	300,999
3	86,635	0	271,870	437,800	378,188	0	18,000	16,700	14,426	295,264
4	88,838	0	278,784	448,933	369,339	0	18,000	16,700	13,739	288,704
5	90,839	0	285,062	459,043	359,672	0	18,000	16,700	13,085	281,443
6	92,637	0	290,704	468,130	349,326	0	18,000	16,700	12,462	273,593
7	94,233	0	295,712	476,194	338,422	0	18,000	16,700	11,868	265,258
8	95,626	0	300,084	483,234	327,072	0	18,000	16,700	11,303	256,529
9	96,817	0	303,821	489,251	315,376	0	18,000	16,700	10,765	247,489
10	97,805	0	306,922	494,246	303,424	0	18,000	16,700	10,252	238,215
Net Present Value ($)										**2,586,265**
Benefit Cost Ratio										**9.74**

5.3.1.1 Ramp metering costs

The cost components of traffic predictive ramp metering include ramp meter installation cost, cost to enable communication between detectors and meters, detector and series processor cost and annual operating and maintenance costs. The corresponding costs of the various components were obtained from Bhargava et al. (2006) and are listed in Table 5.5. A total of five detectors are required to implement ramp metering – three for the freeway and two for the ramp. One ramp detector is placed at the ramp meter signal to detect vehicles while the other detector is placed near the ramp entry to detect threshold queuing condition. The three detectors on freeway are to be placed on each of the three lanes upstream of the ramp meter to determine the metering rate of the ramp signal.

5.3.1.2 Benefit – cost ratio and net present value

The annual benefits and costs associated with the implementation of ramp metering strategy at Raymond and I-65 ramp location are listed in the Table 5.6. Total benefits (B) are calculated as the sum of VOC, emission and travel time savings. Similarly, total costs are determined as the sum of total initial fixed costs and the annual operation and maintenance costs. Present value of benefits (PVB) and costs (PVC) are estimated using a discount rate equal to 5%. From the above economic evaluation for 10 year analysis period, it is found that the NPV is positive and equal to $2,586,265, while the B/C ratio is 9.74. This indicates the implementation of ramp metering strategy is economically viable. Although the implementation of this strategy is economically feasible, it may be criticized for the increasing congested conditions on the ramp due to ramp metering.

CHAPTER 6. DESIGN OF INCOME-EQUITABLE TOLL PRICES FOR HIGH OCCUPANCY TOLL LANES

6.1 Optimal Toll Design Problem

This section focuses on the methodology to determine optimal toll prices that maximize revenue subject to limits on toll prices, requirements on LOS, and income equity constraints, in the context of a general purpose lane being converted into a HOT lane facility. The use of revenue maximization as the objective is based on the emerging view in transportation government agencies in the U.S. that public-private partnerships (PPPs) represent a key strategy to mitigate the looming funding gap. Hence, attracting the private sector to PPPs entails a focus on revenues in addition to the LOS. The study considers the notion that income-equitable toll pricing can be achieved when users are charged in proportion to the benefits they receive from the HOT facility. Hence, the study proposes different toll prices on the HOT lanes for commuters who are grouped based on their income levels. The proposed pricing scheme can be implemented using existing technology and current infrastructure facilities. Thereby, different toll prices can be imposed for different income-based commuter groups using electronic tolling systems and in-vehicle transponders that characterize drivers based on income levels. The income categories of commuters are determined by the tolling authority potentially using documents such as income-tax returns and driver insurance policies when commuters sign up for the transponders.

The determination of tolls depends on the objectives of two key players: the tolling authority and the commuters. The tolling authority seeks to maximize total revenue from the HOT facility while ensuring that the toll prices are in an acceptable range from a regulatory standpoint, the service levels on the HOT lanes meet some minimum standards, and income equity is ensured. To that end, the toll prices for the commuter groups will be adjusted based on the savings accrued by each of them using the HOT facility. Additionally, the tolling authority will ensure that the HOT lanes operate at a minimum LOS by regulating the entry flow into the HOT lanes when the LOS drops below a certain threshold. Commuters seek to minimize their generalized travel costs, expressed as a function of travel time and the monetary cost incurred, to reach their respective destinations. Figure 6.1 enumerates the choice alternatives for commuters where they can choose their mode of travel in conjunction with possible routes and lanes. The mode choice of commuters includes three options: driving alone (SOV), carpooling with two occupants (HOV2), and carpooling with three or more occupants (HOV3+).

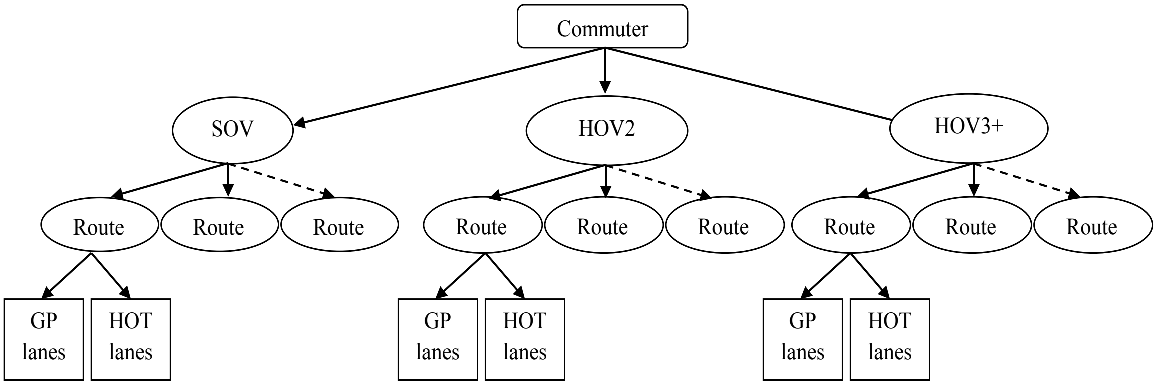

Figure 6.1 Mode, route, and lane choices of commuters

Consistent with the objectives of the tolling authority and the commuters, the optimal toll design problem can be viewed as consisting of two interacting components. The first component deals with the tolling authority's objective which is subject to commuters' choice behavior, while the second one deals with the commuters' choice selection which is influenced by the toll prices set by the tolling authority. To address these disparate objectives, the optimal toll design problem is formulated as a bi-level model (akin to Yang and Lam (1996)) to explicitly capture the interactions between the two key players. The upper level model aims to maximize the total toll revenue earned from the tolled HOT facility subject to income equity constraints, upper bounds on toll prices, and constraints on the minimum level-of-service on the tolled HOT facility. The lower level model addresses a multiclass stochastic user equilibrium (SUE) formulation using generalized travel costs. The multi-toll prices on the HOT lane facility are the decision variables for the upper level model while the decision variables for the lower level model are the link flows. These can be iteratively solved for until a pre-specified convergence criterion is satisfied. As discussed later, to enable computational efficiency given the NP-hard nature of the bi-level model, the proposed solution methodology uses an approximate mechanism to solve the bi-level model rather than iterating between the upper and lower levels.

Additionally, if the tolling authority cannot obtain a minimum acceptable revenue due to constraints arising from the need for equity, subsidies are sought from government agencies. In this case, the subsidies are determined as the difference between the cost for the HOT lane facility and revenue generated from the HOT facility at the predefined upper bound toll prices for the different income groups. The mathematical formulation of the bi-level model is described hereafter.

Consider a transportation network with a set of nodes *N* and a set of links *A*. A subset of links $A_T \subset A$ represents the links with tolled HOT lanes in the network. Let x^a and $t^a(x^a)$ represent the flow and the travel time on link *a*, respectively. The set of O-D pairs is denoted by *W*. The set of paths connecting O-D pair $w \in W$ is denoted by K^w. The number of commuter groups identified based on their income levels is represented by *M*, and the toll price for the commuter group $m = 1,...,M$ on the HOT lane is denoted by τ_m. Denote $\tau = \{\tau_m; m = 1, 2, ..., M\}$. The demand of commuter group *m* for the O-D pair *w* is represented by q_m^w. The mode choice for each commuter is represented by *p*, where *p* = 1, 2, and 3 denote the SOV, HOV2, and HOV3+ modes, respectively. In particular, let x_m^a be the vehicular flow on link *a* corresponding to commuters belonging to income group *m*, and $x_{m,p}^{a,w}$ be the vehicular flow on link *a* corresponding to commuters belonging to income group *m* and O-D pair *w* using mode *p*. The capacity of link *a* is denoted by ς_0^a.

6.1.1 Upper Level Problem

The upper level model addresses the objective of the tolling authority to maximize the revenue from the toll facility subject to the constraints of income equity and cap on toll price. It has a linear objective function and a non-linear constraint set. The multi-toll prices (τ_m) on the HOT lane facility represent its decision variables. τ_m is the toll price for commuters belonging to income group *m* and using the HOT lane facility. The mathematical formulation of the upper level model is as follows.

$$\text{Max } Z_1 = \sum_{a \in A_T} \sum_{m=1}^{M} \tau_m x_m^a \tag{6.1}$$

subject to

$$G(\tau) \le \beta \tag{6.2}$$

$$G(\tau) = \frac{1}{2} * \frac{1}{\left(\sum_{w \in W} \sum_{m=1}^{M} q_m^w \right)^2} * \frac{1}{\overline{E}(\tau)} * \sum_{w \in W} \sum_{n=1}^{M} \sum_{m=1}^{M} q_m^w q_n^w \left| E_m^w(\tau) - E_n^w(\tau) \right| \tag{6.3}$$

$$E_m^w(\tau) = \sum_{a \in A} \sum_{p \in P} x_{p,m}^{a,w}(\tau) * u_{p,m}^{a,w}(t^a, \tau_m) - \sum_{a \in A} \sum_{p \in P} x_{p,m}^{a,w}(0) * u_{p,m}^{a,w}(t^a, 0)$$

$$\forall w \in W \text{ ; } m = 1, 2, .., M \tag{6.4}$$

$$\overline{E}(\tau) = \frac{\sum_{w \in W} \sum_{m=1}^{M} E_m^w(\tau)}{\sum_{w \in W} \sum_{m=1}^{M} q_m^w} \tag{6.5}$$

$$u_{p,m}^{a,w}(t^a, \tau_m) = \lambda_m^p * t^a(x^a) + \tau_m \qquad \forall w \in W \text{; } m = 1, 2, ..M; \ p = 1, 2, 3; \ \forall a \in A \tag{6.6}$$

$$\tau_m = \frac{1}{\sum_{a \in A_T} x_m^a(\tau)} * \frac{E_m^T(\tau)}{\sum_{m=1}^{M} E_m^T(\tau)} * C \qquad m = 1, 2, ..M \tag{6.7}$$

$$E_m^T(\tau) = \sum_{a \in A_T} \sum_{w \in W} \sum_{p \in P} x_{p,m}^{a,w}(\tau) * u_{p,m}^{a,w}(t^a, \tau_m^a) - \sum_{a \in A_T} \sum_{w \in W} \sum_{p \in P} x_{p,m}^{a,w}(0) * u_{p,m}^{a,w}(t^a, 0)$$

$$m = 1, 2, .., M \tag{6.8}$$

$$\frac{x^a(\tau)}{\varsigma_0^a} \le \gamma \qquad \forall a \in A_T \tag{6.9}$$

$$0 \leq \tau_m \leq \overline{\tau} \qquad m = 1, 2, .., M \qquad (6.10)$$

Equation (6.1) denotes the objective of the tolling authority to maximize the total revenue generated from the HOT lane facilities in the network. The link flows x_m^a are dependent on the multi-toll prices τ_m and determined in the lower level model. Equation (6.2) represents the income equity constraint where equity is quantified using the Gini-coefficient *G*. The constraint requires *G* to be less than a minimum level of equity *β*, which is pre-determined by a government or regulatory entity. *G* is a commonly used measure in pricing studies (Yang and Zhang 2002; Sumalee 2004; and Wu et al. 2012) to quantify spatial and income equities. The value of *G* is calculated using Equation (6.3), ranging from a minimum of zero, which corresponds to all individuals being equal, to a theoretical maximum of one which represents maximum inequality. In Equation (6.3), E_m^w represents the savings of commuters of O-D pair $w \in W$ belonging to income group *m*. The average savings across all income groups is denoted by $\overline{E}$ which are determined by Equation (6.5). These savings (E_m^w or $\overline{E}$) can either be positive or negative, where positive savings indicate a benefit and negative savings indicate a loss.

The savings E_m^w are determined according to Equation (6.4) and calculated as the difference of the generalized costs between the tolled and no-toll scenarios for all commuters of O-D pair *w* belonging to income group *m*. In this equation, $x_{m,p}^{a,w}(\tau)$ and $x_{m,p}^{a,w}(0)$ are the link flows corresponding to the tolled and no-toll scenarios, respectively. $u_{m,p}^{a,w}(t^a, 0)$ and $u_{m,p}^{a,w}(t^a, \tau_m)$ are the generalized travel costs on link *a* under the no-toll and tolled scenarios, respectively, for commuters of O-D pair *w* belonging to income group *m* using mode *p*. The generalized cost $u_{m,p}^{a,w}(t^a, \tau_m)$, defined by Equation (6.6), is equal to the summation of the travel time and the toll price, where travel times (expressed in time units) are converted into monetary values (in \$) through VOT λ_m^p.

Equation (6.7) represents the toll determination mechanism in which the toll for commuter income group *m* is a value based on the proportional generalized cost savings accrued by that group of commuters. In equation (6.7), *C* represents the cost incurred by the tolling authority to maintain and operate the HOT facility. Equation (6.7) by itself is a fixed point problem embedded in the upper level problem which determines a set of toll patterns. To identify a toll patterns satisfying equation (6.7) relies on solving the lower level traffic assignment problem. This embedded fixed point problem induces additional computational complexity when solving the proposed bi-level toll design problem.

The savings E_m^T accrued by commuters using the HOT lane facility for each income group m are defined by Equation (8) as the total difference in the generalized costs between the tolled scenario $u_{m,p}^{a,w}(t^a,\tau)$ and no-toll scenario $u_{m,p}^{a,w}(t^a,0)$.The savings E_m^w accrued by commuters for each income group of O-D pair w for the entire network are differentiated from the savings E_m^T accrued by only those commuters who use the HOT lane facility. The former are used to estimate the Gini-coefficient while the latter are used to determine the toll prices for each commuter group.

Equation (6.9) denotes an LOS constraint, which ensures a minimum LOS on the HOT lanes facility defined by the volume-to-capacity ratio γ. By specifying the LOS of the HOT lanes as a constraint rather than in the objective function, it provides flexibility to the tolling authority/decision-maker to propose it as a user input based on the context of the specific facility and the associated stakeholders. Equation (6.10) ensures that the toll prices on the HOT lanes are less than a predefined threshold value $\overline{\tau}$ which is determined by a government or regulatory entity in typical tolling systems.

The link flow x^a is an implicit function of the multi-class link toll prices τ_m as the tolls influence the route choice decisions of travelers. The links flows used in the upper level problem are determined by solving the lower level SUE problem that is described hereafter.

6.1.2 Lower Level Model

The stochastic user equilibrium (SUE) principle is used to determine the mode and route choice behavior of commuters. The lower level model addresses the commuters' objective of minimizing their generalized travel costs which are a function of both the travel time and the toll price. Thereby, a modified form of the SUE formulation proposed by (Fisk 1980) is used for the lower level model by incorporating a term associated with the toll price. The formulation consists of a non-linear objective function with linear constraints. The decision variables are $f_{m,p}^{k,w}$ which represent the commuter flow on path k corresponding to commuter class m using mode p between O-D pair w. The analytical formulation of the lower level model is presented as follows:

$$\text{Min } Z_2 = \sum_{a\in A}\int_0^{x^a} t^a(x^a)dx + \sum_{w\in W}\sum_{a\in A}\sum_{p=1}^{P}\sum_{m=1}^{M}\frac{1}{\lambda_m^p} * \tau_m * x_{m,p}^{a,w} + \frac{1}{\theta} * \sum_{w\in W}\sum_{k\in K^w}\sum_{p=1}^{P}\sum_{m=1}^{M} f_{m,p}^{k,w} * \ln\left(f_{m,p}^{k,w}\right) \quad (6.11)$$

Subject to

$$x_{m,p}^{a,w} = \sum_{k\in K^w}\delta_k^{a,w} * \left(\frac{f_{m,p}^{k,w}}{\eta_p}\right) \quad (6.12)$$

$$x^a = \sum_{w\in W}\sum_{m=1}^{M}\sum_{p=1}^{P} x_{m,p}^{a,w} \quad (6.13)$$

$$q_w^m = \sum_{k\in K^w}\sum_{p=1}^{P} f_{m,p}^{k,w} \quad (6.14)$$

$$f_{m,p}^{k,w} \geq 0 \quad (6.15)$$

Equation (6.11) represents the objective function of lower level model which seeks to minimize the generalized cost across all the links in the network. As travelers' perceptions of the generalized cost are stochastic due to the variability in travel times and monetary costs, the objective function is formulated as the sum of systematic and stochastic components. The first two terms in the objective function, which encompass the deterministic component of the generalized cost. The third term in Equation (6.11) models the stochastic component to capture the randomness that arises due to unobserved attributes (to the modeler) of the various alternatives. A dispersion parameter θ reflects the aggregate measure of commuters' perception of generalized travel costs.

The VOT values λ_m^p are used to convert travel time into monetary value (in $). The VOT is an important parameter to capture the heterogeneity in user behavior. Commuters have different VOTs depending on their income levels and trip purpose.

Equations (6.12) to (6.14) represent the flow and demand conservation constraints. Equation (6.12) ensures that the flow contributed by commuters of income group *m* using mode *p* on all paths of O-D pair *w* that use link *a* aggregates to the corresponding link flow. $\delta_k^{a,w}$ is the link-path incidence matrix which takes a value 1 if link *a* belongs to path *k* for O-D pair *w* for a given income group *m* and mode *p*; otherwise, it is equal to 0. In the model, $\eta_p > 0$ represents the average occupancy of vehicles corresponding to mode *p*, which is used to convert the commuter flow into vehicular flow. For example, η_p is equal to 2 for HOV2 vehicles and therefore the vehicular flow is half of the commuter flow. Equation (6.13) indicates that the flow on link *a* is that aggregated across all income groups *m,* O-D pairs *w* and modes *p*. Equation (6.14) represents the conservation of the total demand in the network. Equation (6.15) denotes the non-negativity constraint on the route flows.

6.2 Solution Methodology

While a bi-level linear optimization problem is itself NP-hard, solving the inherently non-linear bi-level formulation discussed heretofore is non-trivial. Given the non-linear characteristics of the formulation, a global optimum solution cannot be guaranteed. In addition, the embedded fixed point problem, i.e. equation (6.7), introduces difficulties in deriving a good searching direction when solving the bi-level program. Therefore, we seek to obtain a local optimum solution by using an agent based modeling (ABM) approach to solve the proposed bi-level model.

ABM is a heuristic approach that enables efficient but good approximate solutions to such problems. In the study context, the key system players (the tolling authority and the commuters) can be viewed as agents in the ABM approach. In addition, it is synergistic with the need to model commuter behavior, both with regard to their interactions amongst themselves and that with the tolling authority. In the proposed ABM solution approach, the tolling authority agent, central to the upper level model, adjusts the toll prices for each commuter group so as to maximize the revenue subject to the constraints on equity and LOS. The commuter agents, central to the lower level model, seek to minimize their generalized travel costs through mode, route and lane choice decisions to reach their respective destinations subject to the constraints on network characteristics.

The proposed ABM solution approach solves the bi-level model in an approximate manner to enable computational efficiency, as illustrated conceptually in Figure 6.2. The lower level model, which corresponds to the commuter agents, is identified by dashed lines in the figure, while the rest of the figure corresponds to the tolling authority and the upper level model. Rather than iteratively solving the upper and lower level models, the toll prices are updated by incrementing them using a fixed small step size in an iteration. As discussed later in Equation (6.20), these step size increments are proportional to the savings accumulated by commuter groups using the HOT facility. This ensures that the tolling authority determines the toll prices for each commuter group based on the savings accrued by those who use the HOT lane facility. Then, the equilibrium flows are determined using the updated toll prices, and these are used to determine revenue and check for violations of the equity, LOS constraint, and toll price thresholds. If the solution is feasible, the upper level convergence criteria (which track revenue) is checked for. If the convergence criterion is not satisfied, then the iteration counter is incremented by 1 and the toll prices are incremented using Equation (6.20). The procedure is repeated until convergence of the revenue values or until the toll prices become infeasible after an increment. Hence, the proposed ABM approach can address revenue maximization. Thereby, rather than solving a computationally complex upper level model, and then solving a non-linear SUE-based lower level model, the upper level decision variable (toll price) is incremented deterministically. This substantially reduces the computational burden while being consistent with the upper level objective of maximizing revenue subject to the constraints of income equity and LOS. The ABM solution approach is described in detail hereafter.

The network properties and commuter characteristics along with the equilibrium flows for the base case (no-toll) are used as the initial input (Figure 6.2). In the initialization step *(σ=1)* of the ABM solution approach, the tolling authority agent sets the toll prices to a small fixed value equal to $0.01*\Delta$, where Δ is a fixed predefined value used to increment the toll prices, and the equilibrium traffic flows are obtained by solving the lower level model. The lower level SUE model, which uses Equations (16) to (20), is discussed hereafter.

$$\psi^{k,w}_{p,m} = \frac{\exp\left(\dfrac{\nu^{k,w}_{p,m}}{\theta^{k,w}_{p,m}}\right)}{\sum\limits_{k\in K^w}\exp\left(\dfrac{\nu^{k,w}_{p,m}}{\theta^{k,w}_{p,m}}\right)} * \frac{\exp(\bar{\nu}^{w}_{p,m})}{\sum\limits_{p=1}^{P}\exp(\bar{\nu}^{w}_{p,m})} \qquad (6.16)$$

$$\bar{\nu}^{w}_{p,m} = \ln\left(\sum_{k\in K^w}\exp\left(\frac{\nu^{k,w}_{p,m}}{\theta^{k,w}_{p,m}}\right)\right)^{\theta^{k,w}_{p,m}} \qquad (6.17)$$

$$v^{k,w}_{p,m} = \sum_{a\in A}\lambda^{p}_{m} * t^{a}(x^{a}) * \delta^{a,w}_{k} + \sum_{a\in A}\tau^{a}_{m} * \delta^{a,w}_{k} \qquad p = 1,2, .., P;\ m=1, 2,.., M \qquad (6.18)$$

$$t^{a}(x^{a}) = FFTT^{a} * \left[1+\alpha_0 * \left(\frac{x^{a}}{\varsigma^{a}_{0}}\right)^{\alpha_1}\right] \qquad (6.19)$$

$$[\tau_m]_{\sigma+1} = [\tau_m]_{\sigma} + \Delta * \left[\frac{1}{\sum\limits_{a\in A_\tau} x^{a}_{m}(\tau)} * \frac{E^{T}_{m}(\tau)}{\sum\limits_{m=1}^{M} E^{T}_{m}(\tau)}\right]_{\sigma} * C \qquad (6.20)$$

The lower level SUE model comprises of commuter agents who are grouped based on their income levels. Commuter mode and route choices are represented using a nested logit model, where they first choose their travel mode and then their routes. The nested logit model (Wu et al. 2012) used to predict the commuters' choice behavior is represented by Equations (6.16) to (6.19). The probability $\psi^{k,w}_{p,m}$ for a commuter of income group *m* to choose mode *p* and route *k* for O-D pair *w* is derived from Equation (6.16). $v^{k,w}_{p,m}$ is the deterministic observable component of the generalized cost function, while $\bar{\nu}^{w}_{p,m}$ is the expected utility for using mode *p* for a commuter of group *m* for O-D pair w. The dispersion parameter for path k of mode p for O-D pair w and commuter group m is denoted by $\theta_{p,m}^{k,w}$. $\overline{v}_{p,m}^{w}$ is determined using Equation (6.17), and $v_{p,m}^{k,w}$ is determined based on Equation (6.18). $v_{p,m}^{k,w}$ is determined as the sum of travel times (expressed in monetary terms) and monetary costs where travel time, VOT, link-path incidence matrix, and toll price incurred by the commuter are denoted by $t^{a}(x^{a})$, λ_{m}^{p}, $\delta_{k}^{a,w}$, and τ_{m}, respectively. The travel time on link a is a function of the flow on link a. It is determined using the BPR function shown in Equation (6.19). The free flow travel time on link a, the BPR function parameters, and the capacity of link a are denoted by t_{0}^{a}, α_0, α_1, and ς_{0}^{a}, respectively.

The iterative process for the lower level model is repeated until equilibrium is reached; convergence to equilibrium flows is assumed if the difference among flows for all links in two consecutive iterations is less than 10^{-5}.

As illustrated in Figure 6.2, after solving the lower level model, the minimum LOS level C is maintained on the HOT lanes by restricting the flow on the HOT lanes to a threshold value determined using the threshold V/C value γ. The flows on the HOT lanes that are higher than the threshold value are redistributed to alternative routes. This redistribution of traffic flow is performed as follows. When the threshold traffic conditions relative to the LOS are reached on the tolled facility, the utility functions for commuters are updated using the new traffic conditions. Then, the excess traffic which seeks to use the HOT lanes is redistributed among various alternative routes using the SUE principle with the updated utility functions.

The traffic flows computed are used by the tolling authority to compute revenue, generalized cost savings and the Gini-coefficient. A feasibility check is performed for the toll prices and the Gini-coefficient. If either is violated, the toll prices from the previous iteration are used in the next step to compare cost and revenue. If both are satisfied, the upper level convergence criterion in terms of whether the relative difference between the revenue earned across consecutive iterations is less than 10^{-5}. If it is satisfied, the next step checks whether the revenue is less than the HOT lane-related costs. If it is, subsidies are estimated as the difference between the cost and revenue (at the threshold G values);

if not, the ABM approach has determined the multi-toll prices. If the upper level convergence criterion is not satisfied, the iteration counter is incremented by 1, the toll prices are incremented using Equation (6.20), and the procedure is repeated starting from the lower level model to compute equilibrium flows.

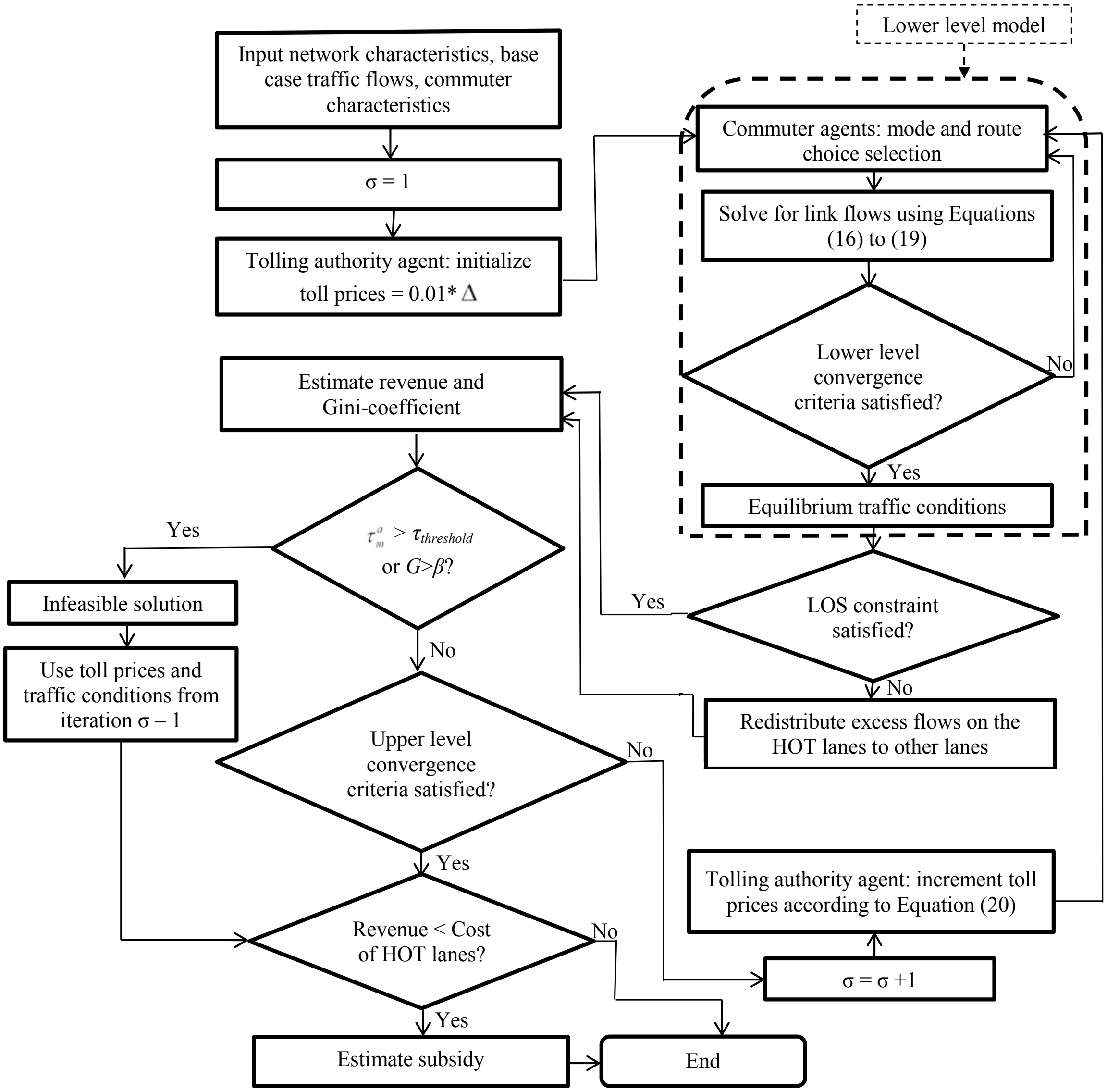

Figure 6.2 Conceptual flowchart of the proposed ABM solution approach

6.3 Numerical Experiments

The optimal toll design problem is solved for the Nguyen-Dupuis (ND) network (Nguyen and Dupis 1984) (shown in Figure 6.3), using the MATLAB environment. The network consists of 13 nodes and20 links. Table 6.1 lists the free flow travel times and capacities for each link. The coefficients and parameters of the model representing the nested structure of commuters' choice of mode and route are, in general, non-transferable. Due to the lack of data on model parameters for commuter mode and route choice for the selected network, their values are assumed for the various alternatives (combinations of mode and route choices for the O-D pair *rs*): SOV mode and route *k*, HOV2 mode and route *k*, and HOV3+ and route *k*, where *k*=1, 2, …, K^w .

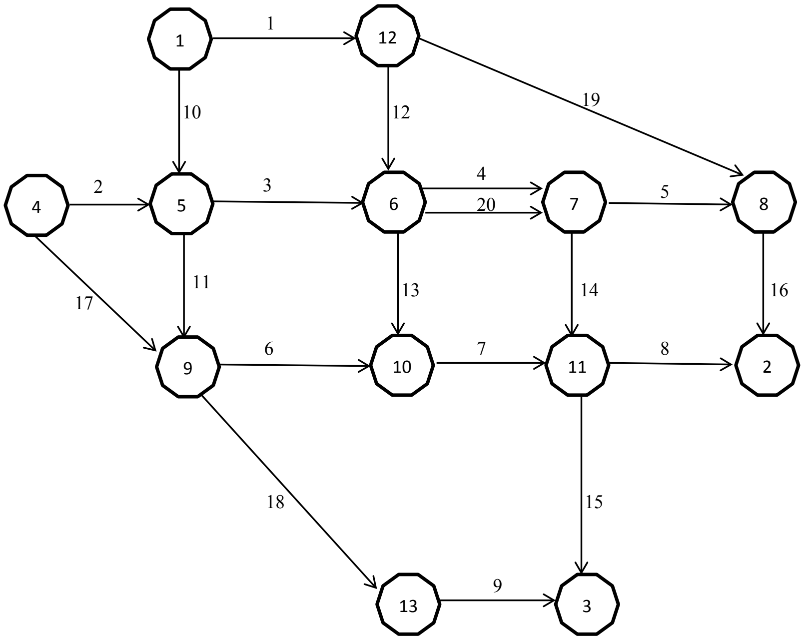

Figure 6.3. Study network

A fixed demand of 12000 with 30% low income, 40% middle income and 30% high income commuters is assumed for the O-D pair (nodes 1 and 2). Links joining nodes 6 and 7 are selected; two general purpose (GP) lanes are converted to a HOT lane facility with one HOT lane (link 4) and one GP lane (link 20). It is assumed that all trips are commuting trips and HOV3+ mode vehicles travel free on the HOT lane facility while the other two modes pay an identical toll for an income class to use this facility, though the higher income classes pay more. The VOT values corresponding to different income groups and using different modes are presented in the Table 6.2 (NCHRP 2012). In the study, the HOT lane facility is considered to be a freeway section in a suburban area and the corresponding threshold V/C value indicating LOS level C is assumed to be 0.8 (Gunawardena and Sinha 1994).

Table 6.1 Free flow travel times and capacities on the network links

Link Number	**Free Flow Travel Time (mins.)**	**Capacity (veh./hr.)**
1	45	1800
2	22	2400
3	34	2400
4	25	3600
5	22	1600
6	22	1600
7	32	1600
8	30	1600
9	20	1600
10	25	1800
11	35	1800
12	20	2400
13	35	1700
14	25	1800
15	25	1800
16	40	2400
17	22	1800
18	30	1800
19	35	1600
20	16	2000

Table 6.2 VOT for commuters of different classes for different modes of travel (NCHRP 2012)

Mode Choice Segments		**Assignment Vehicle Classes**	
Purpose	**Mode**	**Occupancy**	**Approximate VOT**[1]
Commuting: low income workers	SOV	SOV	10
	HOV2	HOV2	$10*O_2$
	HOV3+	HOV3+	$10*O_3$
Commuting: middle income workers	SOV	SOV	15
	HOV2	HOV2	$15*O_2$
	HOV3+	HOV3+	$15*O_3$
Commuting: high income workers	SOV	SOV	20
	HOV2	HOV2	$20*O_2$
	HOV3+	HOV3+	$20*O_3$
Work based sub-tours	SOV	SOV	30
	HOV2	HOV2	$30*O_2$
	HOV3+	HOV3+	$30*O_3$

[1] O_2 and O_3 in VOT column are scaling parameters accounting for vehicle occupancy and are estimated statistically.

6.3.1 Convergence and validation of lower level model results

Convergence and validation of the link flows determined from the lower level model are examined first. Convergence trajectories of the link flows are illustrated in Figure 6.4. It is observed that link flows smoothly converged to the equilibrium flow values after approximately 35 iterations. The lower level solution approach is also used to estimate link flows for the network studied by Pravinvongvuth et al. (2003). They used the paired combinatorial logit (PCL) and the multinomial logit (MNL) models to examine the effects of congestion and stochasticity in the route choice problem. The associated results are represented by MNL and PCL while the results from this study obtained by solving the lower level model (under no toll condition) are denoted by LLM in Figure 6.5. It can be observed that the link flows in this study are in good agreement (less than 5% error) with the stochastic user equilibrium results obtained by Pravinvongvuth et al. (2003).

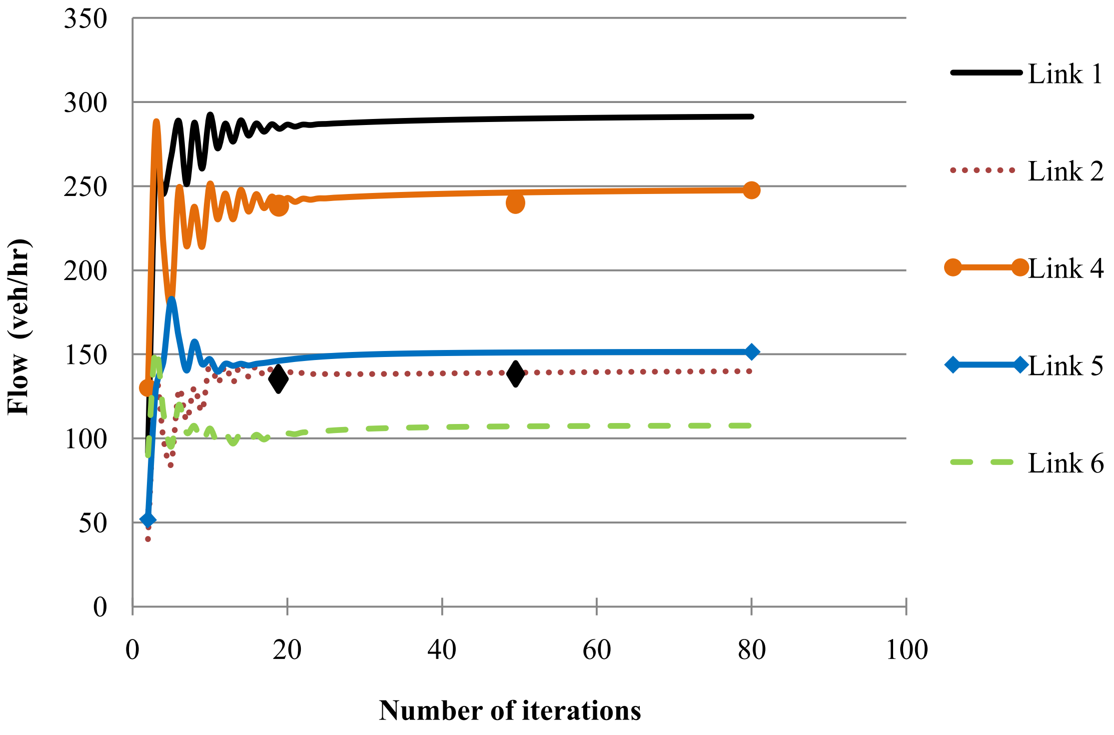

Figure 6.4 Convergence trajectories of the link flows

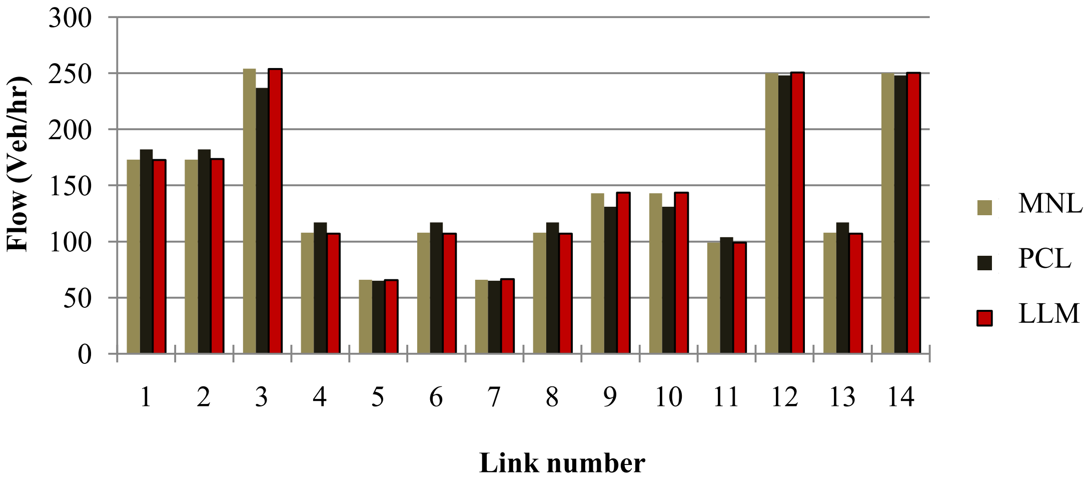

Figure 6.5 Validation of lower level model flows

6.3.2 Variation of demand for HOT lane with respect to toll price

Figure 6.6 describes the flow and toll patterns on the HOT lane relative to the toll price for the multi-toll pricing scenario. The multi-tier toll prices are incremented in each iteration as per Equation (20) and therefore increase in number of iterations is indicative of increasing toll prices, as illustrated in Figure 6.6(e). Figure 6.6(a) presents the variation of total flow on the HOT link, while Figure 6.6(b), 6.6(c), and 6.6(d) illustrate the HOT lane usage by SOV, HOV2, and HOV3+ commuters, respectively, for the different income classes. Figure 6.6 (e) presents the variation of multi-tier toll prices (for low, middle and high income groups) with the number of iterations of the upper level problem. The multi-tier toll prices corresponding to each iteration can be identified in this figure.

Figure 6.6(a) confirms that the HOT facility usage decreases with increasing toll price, even with HOV3+ commuters traveling for free on it. However, as illustrated by Figs. 6(b)-6(d), the usage of each mode varies with income class. Figure 6.6(b) illustrates that initially more middle income commuters use the HOT lane. This is because they represent a higher percentage (40%) of the travelers in this network. As toll price increases, their sensitivity to cost leads to fewer of them using the toll facility compared

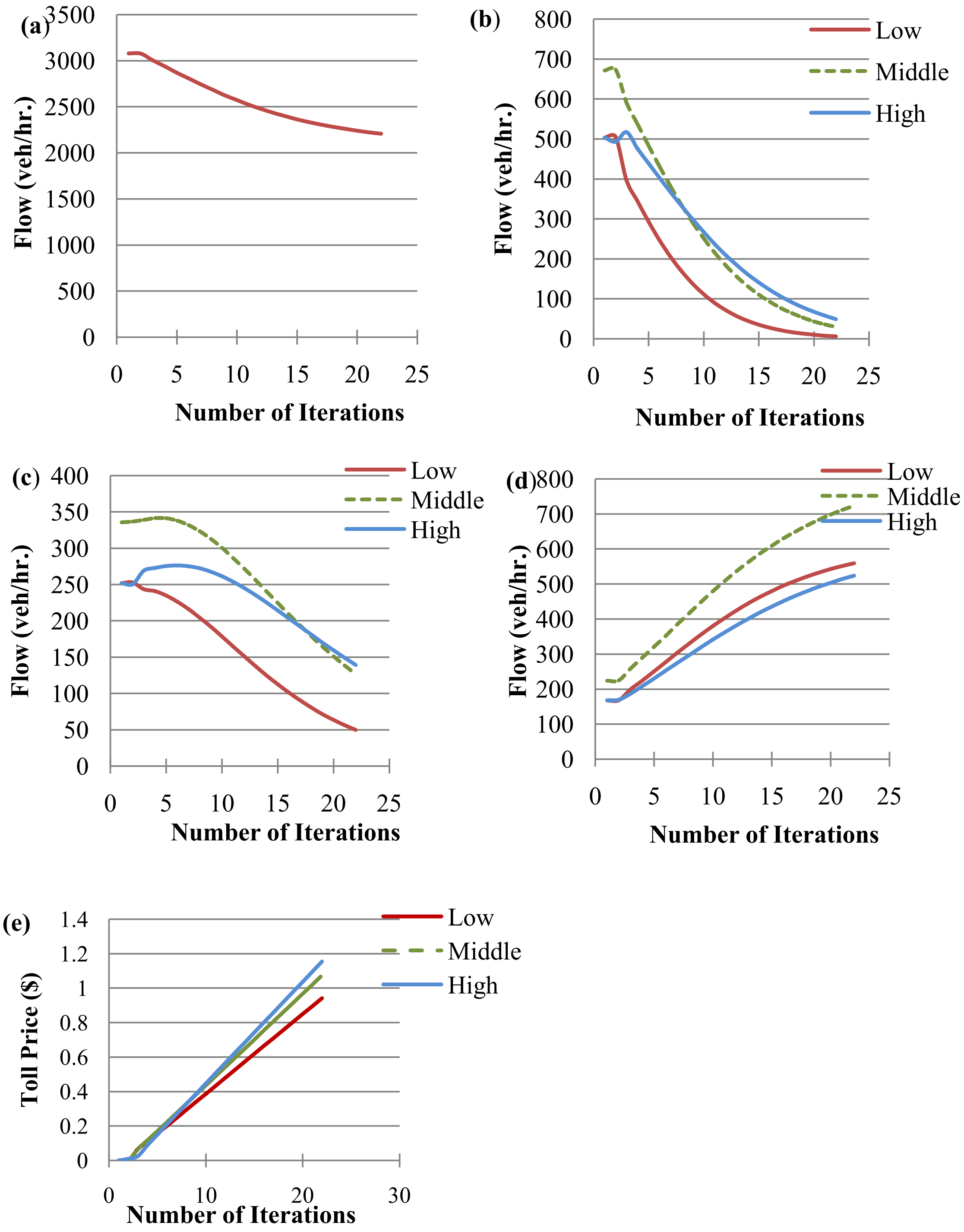

Figure 6.6. Variation of flow on tolled link relative to toll price: (a) total flow on the tolled link; (b) SOV flow for each commuter class; (c) HOV2 flow for each commuter class; (d) HOV3+ flow for each commuter class (e) Variation of multi-tier toll prices with the number iterations of upper level problem

to the higher income commuters (who have a higher VOT). A similar trend involving the middle and high income commuters is observed for the HOV2 group, as shown in Figure 6.6(c). While low income commuters show a consistent trend of decreased usage with an increase in toll, the other two income classes show an initial increase in usage followed by the decrease as toll prices continue to increase. The initial increase in the usage of the HOT lane is due to improving travel conditions and middle/high income commuters' willingness to pay at the lower toll levels.

The proportion of HOV3+ commuters using the HOT lane facility increases with the toll price for all income groups (Figure 6.6(d)). This is because of the improved travel conditions and zero toll costs to travel for the HOV3+ commuters on the HOT lane.

6.3.3 Variation of revenue and corresponding Gini-coefficient with respect to toll price

Figure 6.7 illustrates the variation of annual revenue and Gini-coefficient values with respect to toll price. The revenue and *G* are computed over all commuters; here, the multi-tier toll pattern corresponding to each iteration is shown in Figure 6.6 (e).

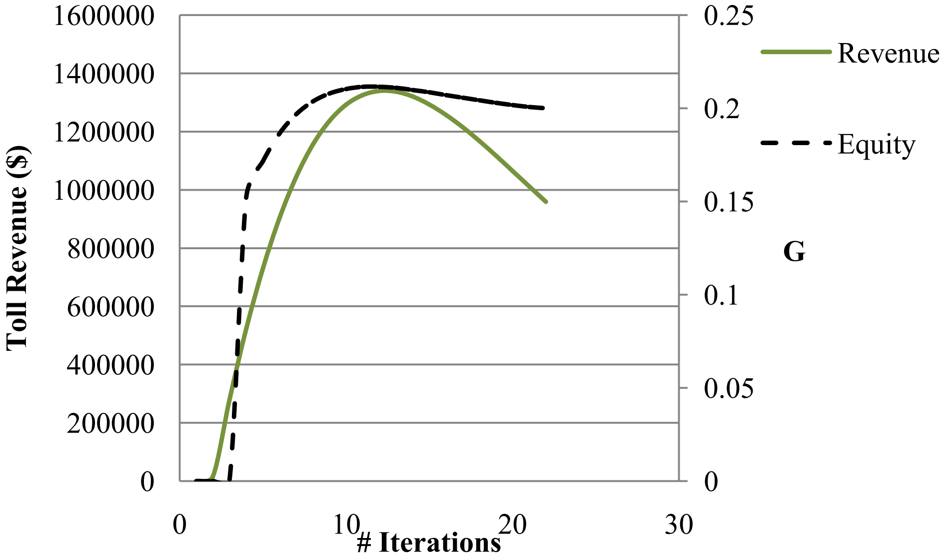

Figure 6.7. Variation of revenue and equity relative to toll price on the HOT facility

As the toll price increases, the revenue toll revenue increases initially and then decreases. The initial increase in revenue is due to increased usage of HOT facility by high and middle income commuters of the HOV2mode and reduced usage by the low income group commuters of the SOV and HOV2 modes. With the reduced demand on the HOT lane as the low income commuters shift out of it as tolls increase, and the lower toll prices initially, the higher income group commuters are more willing to pay the toll to travel faster. However, as the toll price increases beyond a certain threshold value (around \$0.55 here), revenues decrease. This is due to the corresponding decrease in flow of the high and middle income HOV2 commuters, as evident in Figure 6.6(c). While the shift of the high and middle income HOV2 users starts occurring at a toll value less than \$0.55, the revenue continues to increase for a bit more due to the increasing value of the toll price. Hence, there is an offset between the flow peaks in Figure 6.6(c) and the revenue peak in Figure 6.7.

The Gini-coefficient (G) exhibits similar trends to that of the revenue, as seen in Figure 6.7. The decreasing trend of G values (beyond a toll price of about \$0.4) is due to the differential toll values and HOT lane usage by commuters of different income groups. The number of high and middle income HOV2 commuters using the HOT lane facility decreases (Figure 6.6(c)), while the low and middle income HOV3+ commuters using the HOT lane facility increases gradually (Figure 6.6(d)). Hence, more low income commuters tend to use the HOT lane facility. After the peak of the G value, the high income commuters are charged a high toll value due to their accrued savings while lower income travelers are charged a lower value of toll. This illustrates an advantage of the multi-toll approach compared to a single flat toll approach in the context of fostering income equity.

6.3.4 Comparison of different toll scenarios

Table 6.3 summarizes the results of the optimal toll design problem for different toll scenarios: no-toll, single toll and multi-toll. The multi-toll pricing scheme yielded slightly higher (~1%) revenue and is more equitable when compared to that of the single toll scenario. Further, Gini-coefficient in the multi-toll scenario is approximately 30%

less than that of the single toll scenario indicating its higher income equity. Improvement in the equity under the multi-toll scenario is attributed to the increased usage of HOT facility by lower income commuters compared to that of the single toll scenario. Therefore, multiple toll paradigms can be are more equitable, and also effective in raising the necessary revenue from the HOT facility.

Table 6.3 Results of various toll scenarios

Variable	**No Toll**	**Single Toll**	**Multiple Tolls**
Gini-coefficient	N/A	0.274	0.211
Optimum toll price ($)	N/A	0.56	0.48,0.54,0.57*
Maximum revenue ($)	N/A	1.33E+06	1.34E+06
Total flow on HOT lane (Veh/hr)	3275.7	2462.2	2476.8

*Optimum toll prices for low, middle and high income commuters, respectively.

6.4 Summary and Conclusions

This chapter addresses income equity issues in HOT lane facilities whereby higher income commuters may reap the benefits of HOT lane facilities at the cost of lower income commuters. It seeks to incorporate income equity constraints in an optimal toll design problem for HOT lanes. A multi-tier toll pricing approach is proposed to simultaneously maximize the toll revenue and address the equity concerns, while ensuring that tolls do not exceed upper bounds pre-specified by a regulatory authority and a certain LOS on the HOT facility.

The problem is formulated as a bi-level model, in which the upper level model addresses the objectives of the tolling authority and the lower level model addresses commuter travel objectives. The notion of revenue maximization for the tolling authority is driven by and consistent with societal objectives: (i) toll prices are subject to regulatory oversight to ensure a balance between the need to mitigate congestion and tolling authority costs versus the economic burden for commuters, (ii) revenue generated should be sufficient to diffuse the cost of the tolled facility and its operation, and (iii) any excess revenue generated is used for societal solutions to reduce congestion (for example, through additional investment in transit in that region).

Agent-based modeling approach is employed to determine the optimal multi-toll prices for commuters belonging to different income classes. Results from synthetic experiments indicate that a multi-toll pricing strategy can perform better than a single flat toll strategy in terms of fostering income equity while ensuring similar revenue levels and the LOS on the facilities. A synergistic feature of the multi-toll paradigm is that it can be implemented with the currently available transportation infrastructure (e-toll automated collection systems currently in use in many cities) and technology (such as RFID transponders).

The contribution of this study is the development of a multi-tier toll pricing approach to simultaneously maximize the toll revenue and address income equity concerns, while ensuring that tolls do not exceed upper bounds pre-specified by a regulatory authority and assuring a certain LOS on the HOT facility. It is based on the notion that income equitable toll pricing can be achieved when users are charged in proportion to the benefits they receive from the HOT facility. A potential future direction is to design multi-tier toll prices for multiple facilities with HOT lanes in a network.

CHAPTER 7. SUMMARY AND RECOMMENDATIONS

7.1 Summary

Increasing travel demand and funding deficits represent key transportation challenges. In the United States and worldwide, various cost-effective lane use management strategies have been implemented to address these challenges. Some of these strategies can be adopted seamlessly, while others require additional infrastructure/operational changes. Hence, there is a need to evaluate various lane use management strategies. To evaluate the effectiveness of the various strategies, an organized framework is required to model, calibrate, validate and compare these strategies. In this context, the objective of the first part of this study is to develop a systematic simulation-based methodology to evaluate lane use management strategies. A 10-mile stretch of the I-65 corridor in Indianapolis is selected to illustrate the procedure developed in this study. The study includes the analysis performed to identify a congested corridor in Indiana, demand estimation analysis for the study area, and calibration and validation of the VISSIM microsimulation model. Furthermore, operational and economic evaluations of reversible lanes, HOV lanes and ramp metering strategies are performed.

Based on the analysis of the traffic data, the I-65 corridor in Indianapolis is selected as the study corridor for the microsimulation based analysis. The demand volumes for the study area are estimated using subarea analysis, and the results of calibration and validation of the VISSIM model are presented.

An assessment of the impacts of the reversible lane strategy on the I-65 corridor indicated that this strategy improved traffic flow conditions. The average travel speed in the major flow direction (NB I-65 stretch during the morning peak) is higher under the reversible lane scenario when compared to the base case scenario (representing existing conditions). While the minor flow direction (SB I-65 stretch during morning peak) experienced lower flow speeds and higher congestion compared to the base case, comprehensive economic evaluation indicated that this strategy is an effective and viable option.

Microsimulation analysis of high occupancy vehicle (HOV) lane strategy indicated travel speed improvement on the HOV lanes but resulted in reduced speeds on the general purpose lanes when compared to the base case scenario. Also, the person throughput increased due to the implementation of HOV lanes compared to the base case scenario. Furthermore, the travel time savings (expressed in monetary terms) in the major flow direction were positive due to the improved person throughput. However, economic analysis of the HOV lanes indicated that this strategy is not feasible for implementation.

Microsimulation analysis of the traffic predictive ramp metering strategy implemented for I-65 at the Raymond ramp location indicated improved flow speeds on the I-65 corridor. However, the average travel time on the ramp increased due to the ramp signal. The NPV was positive implying the economic feasibility of this strategy.

A comparison of the three lane use management strategies with respect to NPV is presented in the Table 7.1. It illustrates that reversible lane and ramp metering strategies are found to be economically feasible with positive NPVs. However, the NPV for reversible lane strategy is found to be the highest and therefore is the preferred lane use management strategy for the I-65 corridor stretch analyzed. HOV lane strategy was found to be economically infeasible due to low HOV volume on these lanes.

In summary, the study provides a simulation-based methodological framework to evaluate various strategies. As future congestion bottleneck areas arise in Indiana, the associated corridors could be analyzed for the effectiveness of lane use management strategies.

Table 7.1 Comparison of the three lane use management strategies

	Reversible lanes	**HOV lanes**	**Ramp metering**
NPV ($)	3,273341	-2,452,179	2,586,265

The study also addresses income equity issues in HOT lane facilities. While reversible lanes, HOV lanes and ramp metering strategies are effective in mitigating congestion by optimizing lane usage, these strategies do not generate additional revenue required to reduce the funding deficit. Inadequate funds and worsening congestion have prompted federal, state and local planning agencies to explore and implement various congestion pricing strategies. Equity concerns associated with various pricing schemes in transportation systems have garnered increased attention in the recent past. In the context of high occupancy toll (HOT) lanes, the challenge of income inequity exists whereby higher income commuters may reap the benefits of HOT lane facilities at the cost of lower income commuters.

In this context, the second part of the study seeks to incorporate income equity constraints in an optimal toll design problem for HOT lanes. A multi-tier toll pricing approach is proposed to simultaneously maximize the toll revenue and address the equity concerns, while ensuring that tolls do not exceed upper bounds pre-specified by a regulatory authority and a certain LOS on the HOT facility.

The optimal toll design problem is formulated as a bi-level model, in which the upper level model addresses the objectives of the tolling authority and the lower level model addresses commuter travel objectives. The notion of revenue maximization for the tolling authority is driven by and consistent with societal objectives: (i) toll prices are subject to regulatory oversight to ensure a balance between the need to mitigate congestion and tolling authority costs versus the economic burden for commuters, (ii) revenue generated should be sufficient to diffuse the cost of the tolled facility and its operation, implying the possibility that the government may need to subsidize cost gaps using the “public good” justification, and (iii) any excess revenue generated is used for societal solutions to reduce congestion (for example, through additional investment in transit in that region).

An agent-based modeling approach is employed to determine the optimal multi-toll prices for commuters belonging to different income classes. Results from synthetic experiments indicate that a multi-toll pricing strategy can perform better than a single flat toll strategy in terms of fostering income equity while ensuring similar revenue levels and the LOS on the facilities.

7.2 Recommendations

This section presents the recommendations developed based on the simulation-based analysis and the literature review of the three lane use management strategies: reversible lanes, HOV lanes and ramp metering. These recommendations can be used during the preliminary decision-making process involved in selecting potential lane use management strategies. However, the simulation-based analysis of the strategies under consideration should be performed using the methodology presented in this study when future congestion bottleneck areas arise.

7.2.1 Reversible Lanes

The recommendations for the implementation of reversible lanes on freeways are:

- The minor flow direction should have no fewer than two lanes.
- Implementation of reversible lanes is justified on freeways with highly directional congestion. Ratio of major to minor flow (vph) during peak hour should be greater than a threshold value.
- Although literature review suggested that the ratio of major to minor flow during the peak hours should always be between 2:1 and 3:1, in this study a flow ratio of 1.7:1 yielded positive results.
- Presence of structures like bridges and tunnels warrant reversible lanes since expansion and addition of lanes is difficult.
- The implementation of reversible lane should be economically feasible.

7.2.2 HOV Lanes

The recommendations for implementation of HOV lanes on freeways are:

- In scenarios where one or more of the existing GP lanes are converted to HOV lanes, there should be at least two GP lanes apart from the HOV lane.

- A minimum occupancy level (at least 600-800vphpl) of HOV lanes is required to justify HOV lane implementation and avoid "empty lane syndrome".
- Planning agencies should consider policies such as those encouraging car-pooling to improve the vehicle occupancy and HOV lane usage.

7.2.3 Ramp Metering

The three significant factors to be considered for implementing ramp metering are: ramp volume, freeway volume and ramp geometry. The following are the recommendations for the implementation of ramp metering:

- Single lane ramp metering should be adopted if the ramp volume is between 1200-1400 vph and dual lane metering for ramp volume greater than 1400vph.
- Also, the combined volume of the ramp and the freeway should be greater than a minimum threshold value for effectiveness of ramp metering. The threshold volumes for ramp metering are listed the Table 7.2.
- Metering on ramps connecting freeway to freeway requires at least two ramp lanes.
- Existing ramp geometry must permit safe metering by providing adequate merging distance with the freeway.
- The implementation of ramp metering should be economically feasible.

Table 7.2 Threshold volumes required for ramp metering (Bhargava et al., 2006)

No. of freeway lanes including auxiliary lanes	**Threshold freeway + ramp volume downstream of ramp**
2	2650
3	4250
4	5850
5	7450

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