POTENTIAL SINGLE-OCCUPANCY VEHICLE DEMAND FOR THE KATY FREEWAY AND NORTHWEST FREEWAY HIGH-OCCUPANCY VEHICLE LANES

A Thesis

by

LEI XU

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2005

Major Subject: Civil Engineering

POTENTIAL SINGLE-OCCUPANCY VEHICLE DEMAND FOR THE KATY FREEWAY AND NORTHWEST FREEWAY HIGH-OCCUPANCY VEHICLE LANES

A Thesis

by

LEI XU

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Approved by:

Chair of Committee,	Mark W. Burris
Committee Members,	Conrad L. Dudek
	Daniel Z. Sui
Head of Department,	David Rosowsky

August 2005

Major Subject: Civil Engineering

ABSTRACT

Potential Single-Occupancy Vehicle Demand for the Katy Freeway and Northwest Freeway High-Occupancy Vehicle Lanes. (August 2005)

Lei Xu, B.S., Northern Jiaotong University;

M.S., Texas Southern University

Chair of Advisory Committee: Dr. Mark W. Burris

Since the 1960's, high-occupancy vehicle (HOV) lanes have been successfully used as a travel demand management technique. In recent years, there has been a growing interest in the use of high-occupancy toll (HOT) lanes as an alternative to HOV lanes to help manage the increasing demand for travel. HOT lanes combine pricing and vehicle occupancy restrictions to optimize the demand for HOV lanes. As two of the four HOT lanes in the world, the HOT lane facilities in Houston, Texas received relatively low patronage after operating for over 6 years on the Katy Freeway and over 4 years on the Northwest Freeway. There existed an opportunity to increase the usage of these HOT lanes by allowing single-occupancy vehicle (SOV) travelers to use the lanes, for an appropriate toll. The potential SOV demand for HOV lane use during the off-peak periods from the Katy Freeway and Northwest Freeway general-purpose lane (GPL) travelers was estimated in this study by using the data collected from a 2003 survey of travelers on the Katy and Northwest Freeway GPLs who were not enrolled in QuickRide.

Based on survey results, more travelers would choose to drive on the HOT lanes as SOV travelers during the off-peak periods when the facilities provided higher travel time savings and charged lower tolls. Two important factors influencing travelers' use of the HOV lanes were their value of travel time savings (VTTS) and penalty for changing travel schedule (VPCS). It was found that respondents had VTTS approximately 43 percent of their hourly wage rate and VPCS approximately 3 percent of their hourly wage rate. Combining this information with current travel time savings and available capacity on the HOV lanes, it was found that approximately 2000 SOV travelers per day would pay an average toll of $2.25 to use the HOV lanes during the off-peak periods.

Dedicated to

My father, Chunlin Xu, and

My mother, Jingya Yu

ACKNOWLEDGMENTS

I would first like to thank my parents to whom this thesis is dedicated, for their love, support, and understanding in allowing me to come to the United States and devote my time to graduate studies. They deserve a special expression of gratitude that can never be expressed adequately on paper.

I thank my Committee Chairperson and advisor, Dr. Mark W. Burris, for his role in helping me with this thesis. Without Dr. Burris' advice, support, and kind help, I could never have completed it. I also appreciate the thoughtful comments of other committee members, Dr. Conrad L. Dudek, and Dr. Daniel Z. Sui. I also appreciate Texas A&M University for offering insight to ensure the education and future of each student.

I should acknowledge that this thesis research was conducted based on a Federal Highway Administration, Texas Department of Transportation, and Houston METRO project entitled the "Houston Value Pricing Pilot Program". Without the support of these sponsors, this research would not have been possible. I also appreciate all the Texas Transportation Institute staff that helped to conduct the surveys and collect the data. I want to thank Dr. Jaewook Yoo, Mr. Mark Ojah, and Mr. Justice Appiah for their suggestions on my thesis research, and I also thank all the individuals who responded to our surveys for the valuable information they provided.

TABLE OF CONTENTS

Page

LIST OF FIGURES

FIGURE Page

LIST OF TABLES

CHAPTER I

INTRODUCTION

1.1 Background

As a result of the United States' expanding population and growing economy, traffic congestion has worsened, causing significant economic costs along with increased environmental and energy concerns in many urban and suburban areas (*1*). In order to minimize traffic congestion, transportation professionals work to balance the supply of, and demand for, transportation facilities. Traditionally, more focus has been placed on increasing the supply of transportation infrastructure. However, transportation engineers and planners are now focusing additional attention on managing the increasing demand for transportation (*2*), so as to create a better balance between the demand for road capacity and the supply of infrastructure, to encourage more efficient use of the existing transportation network, and to build more capacity when and where it is most needed.

A successful travel demand management technique is the use of high-occupancy vehicle (HOV) lanes where some freeway lanes are reserved for the exclusive use of buses, carpools and other high occupancy vehicles. In recent years, there has been a growing interest in the use of high-occupancy toll (HOT) lanes as an alternative to HOV lanes to help manage the increasing demand for travel (*3*). HOT lanes provide free or reduced-cost service to HOV travelers, while also allowing travelers with fewer occupants in their vehicles to pay a toll to use the lanes. HOT lanes introduce pricing

---

This thesis follows the style and format of *Transportation Research Record*.

strategies to the use of HOV lanes, so the traffic volume on the lanes is controlled, ensuring that the lanes do not become congested while serving as many vehicles as possible.

The Houston QuickRide Program is a successful example of HOT lane implementation. QuickRide exists on the HOV lanes along Houston's Katy Freeway (I-10) and Northwest Freeway (US-290) (*4*). The Houston QuickRide Program was initially implemented on the Katy Freeway HOV lane in January 1998. This allowed a limited number of travelers in HOV-2 carpools to use the Katy Freeway HOV lane during the morning and afternoon peak periods for a toll of $2.00, while HOV-3+ travelers continued to use the lane for free. In November 2000, this program expanded to the Northwest Freeway HOV lane. The Northwest Freeway HOT lane had similar operational parameters as the Katy Freeway HOT lane except that QuickRide was only implemented during morning peak period. The Northwest Freeway HOV lane was not as congested in afternoon peak period, so all HOV-2+ travelers continued to use the lane for free at that time.

The average QuickRide demand on the Katy Freeway HOT lane in 1998 was 103 trips per day (*4*). After the introduction of QuickRide on Northwest Freeway, the total average demand on the two HOT lanes rose to 131 trips per day in 2000 and 182 trips per day in 2002, significantly below the targeted demand of 600 QuickRide vehicles per peak hour (*4*). The traffic flow on the HOV lanes usually decreased during the off-peak hours (*5*), so excess capacity existed on these HOV lanes during the off-peak hours.

Based on results from a survey of Katy Freeway QuickRide participants, people who previously traveled in single-occupancy vehicles (SOV) on the general purpose lanes were the primary source of QuickRide participants (*6*). Respondents in a more recent Houston QuickRide study indicated that the primary reason they did not use QuickRide more often was the difficulty they had forming carpools, and 80.5 percent of all survey respondents indicated they would increase their level of participation if they could drive alone on the HOV lanes (*4*). Therefore, an opportunity existed to increase the usage of the HOV lanes by allowing SOV travelers to use the lanes, for an appropriate toll.

1.2 Problem Statement

The Houston QuickRide program received relatively low patronage after operating for over 6 years on Katy Freeway and over 4 years on Northwest Freeway (*5*). Therefore, an opportunity existed to do more to achieve one of the main goals of the Houston QuickRide program, which was to optimize the usage of the existing infrastructure (*5*). There have been several studies where researchers have examined the effectiveness of the Houston QuickRide program, the participants by frequency of their QuickRide usage, and the factors affecting HOT lane demand (*4*, *5*, *6*, *7*). However, little was known about the potential demand from SOV travelers for the Katy Freeway and Northwest Freeway HOV lanes. Estimating the potential demand from SOV travelers for these HOV lanes may facilitate the adoption and implementation of strategies to further utilize the HOV lanes and improve the operation of these freeways.

The potential SOV demand for HOV lane use from Katy Freeway and Northwest Freeway general-purpose lane (GPL) travelers was estimated in this research by using the data from a recent survey of Katy Freeway and Northwest Freeway GPL travelers who were not enrolled in QuickRide. The survey included both revealed-preference (RP) questions and stated-preference (SP) questions. The survey respondents' mode choice behavior was investigated in this research with different HOT lane operational strategies, from which the potential demand from SOV travelers could be estimated by employing discrete choice modeling techniques. In addition to the estimation of potential HOV lane usage by SOV travelers, traveler's value of travel time savings and value of the penalty for changing one's travel schedule were also investigated.

1.3 Research Objectives

The objective of this research was to estimate the potential SOV demand for paid usage of the Katy Freeway and the Northwest Freeway HOV lanes by GPL travelers during off-peak periods, and to recommend strategies to increase the patronage of these HOV lanes by allowing SOV travelers to use these lanes for a toll. To accomplish these objectives, traveler's value of travel time savings and value of the penalty for changing travel schedule were examined. These characteristics were critical in determining the number of SOV travelers who were willing to travel during the off-peak times and pay a toll for HOV lane use.

1.4 Thesis Organization

This thesis is composed of 5 chapters. In Chapter 1, some background information on the Houston QuickRide program was introduced, the problem was stated, and the research objectives were defined. In Chapter 2, the available literature on HOV/HOT lane demand and the development of the Houston QuickRide program was reviewed, and the discrete choice modeling techniques and practice were introduced. In Chapter 3, the survey procedures and methods of data collection, reduction, and analysis were described. The details of the discrete choice modeling analysis and the estimation of traveler's value of travel time savings, value of the penalty for changing travel schedule, and potential SOV usage of the Katy Freeway and Northwest Freeway HOV lanes were presented in Chapter 4. The findings of this research and proposed recommendations based on the research results were summarized in Chapter 5.

CHAPTER II

LITERATURE REVIEW

This chapter contains a review of the literature regarding existing studies in the field of HOV/HOT lane congestion pricing. The trend of current urban travel demand is summarized in the first section followed by a detailed review of HOV/HOT lane implementation and relevant congestion pricing issues. The possible factors affecting HOT lane demand are explored in the third section. The final section contains an introduction to discrete choice modeling techniques and some typical applications of discrete choice modeling relevant to this research.

2.1 Trend of Urban Travel Demand

A Transportation Research Board committee (Committee for Study of Impacts of Highway Capacity Improvements on Air Quality and Energy Consumption) provided insight into the travel demand trends of the United States in their report (*8*). It was indicated in this report that the population of metropolitan areas had grown 60 percent from 1960 to 1990, while the average household size dropped sharply from 3.24 to 2.65 persons per household. Additionally, it was found that persons in smaller households made more trips on the average than if they were part of larger households (*8*). With the entrance of the baby boomers into the work force and greater employment participation by women, employment grew rapidly in metropolitan areas and the number of workers per household also increased during the same time period (*8*). The accompanying growth in personal income resulted in increased household automobile ownership and travel (*8*). All these growth trends led to the increase in travel demand in urban areas. Vehicle miles traveled (VMT) increased by 88.6 percent from 1980 to 2002 while lane miles of roads only increased by 5.1 percent (see Figure 2.1) (*9*). All of these factors have led to an increase in congestion on U.S. roadways (*1*).

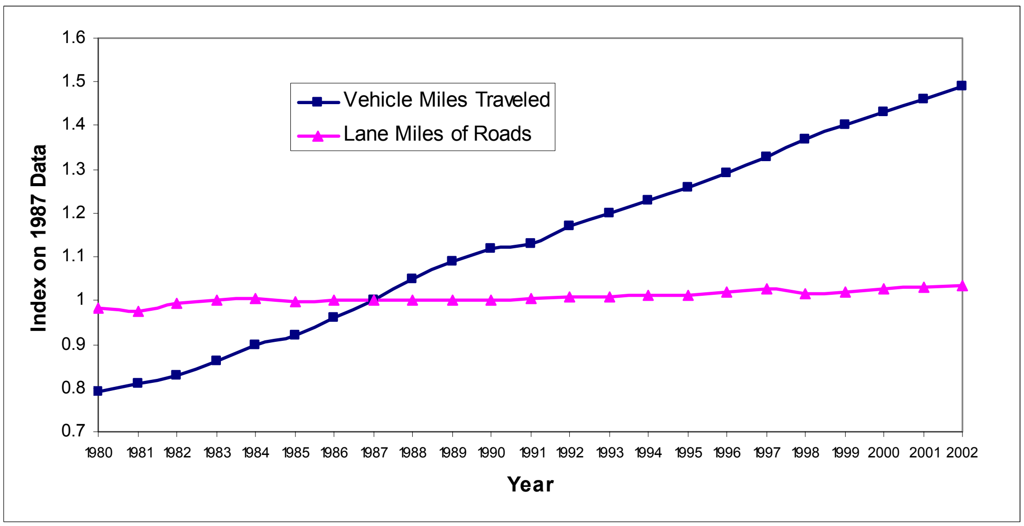


FIGURE 2.1 Vehicle miles traveled and road lane miles.

The rapid growth in VMT and inability of road construction to keep pace increases the importance of demand management strategies. Congestion pricing on HOV lanes, otherwise known as HOT lanes, was one of the alternatives considered by many transportation researchers and practitioners.

2.2 HOV/HOT Lanes

HOV lanes are lanes reserved for the exclusive usage of buses, carpools and other high-occupancy vehicles. The first HOV lane was opened on the Shirley Highway in Washington D.C. in 1969 and the second on the Route 495 approach to the Lincoln Tunnel in New Jersey in 1970 (*10*, *11*). From the mid-1980s, many HOV lane projects have been implemented across the country (*11*). In the year 2000, there were approximately 2,300 operational HOV lane-miles in 28 metropolitan regions of the country (*12*). Most of the HOV lanes were in Houston and Dallas, Texas; Seattle, Washington; the Los Angeles and Orange County area and San Francisco Bay region, California; the Newark, New Jersey, and New York City area; and the Northern Virginia, Washington, D.C., and Maryland region (*10*).

2.2.1 Objectives of HOV Lanes

Generally, the primary objective behind the introduction of HOV lanes was to maximize the person-carrying capacity of the roadway as opposed to the vehicle-carrying capacity. A recent NCHRP report (*13*) included some other common objectives of HOV lanes:

- Increase the average number of persons per vehicle;
- Preserve the person-movement capacity of the roadway; and
- Enhance bus operations.

2.2.2 Types of HOV Lanes

Many different types of HOV lanes are in use in North America. According to a recent study by the Ohio Department of Transportation (*14*), the following is a summary of the major types of HOV lanes:

(1) HOV lanes in a separate right-of-way. This type of HOV lane is developed in a separate right-of-way and designated for the exclusive use of high-occupancy vehicles, often buses only.

(2) HOV lanes on freeways. There are three different types of HOV lanes on freeways:

- Exclusive HOV Lanes

  There are two different operating strategies used with exclusive HOV lanes. The first is exclusive two-directional HOV lanes which are constructed within the freeway right-of-way, are physically separated from the GPLs, and are used exclusively by HOV travelers for all or a portion of the day. The second is exclusive reversible HOV lanes, which are separated from the general purpose lanes by concrete barriers and usually operate inbound toward the central business district (CBD) or other major activity centers in the morning and outbound in the afternoon.

- Concurrent Flow HOV Lanes

  Traffic on this type of HOV lane runs in the same direction as traffic on the adjacent GPLs and is not physically separated from the GPLs.

Concurrent flow HOV lanes are usually located on the inside lane or shoulder and are often delineated by paint striping.

- Contraflow HOV Lane

  This type of HOV lane is a freeway lane in the off-peak direction of travel which is typically the innermost lane and “borrowed” for the exclusive use by HOV travelers in the peak direction. These facilities are separated from the off-peak direction general purpose lanes by some type of changeable barrier and usually operated during the peak periods only. Some of the facilities are only operated during the morning peak period and then revert back to normal use during the rest of the day.

(3) Ingress and egress alternatives. It is very important to ensure that buses, vanpools, and carpools are able to easily and safely merge into and out of an HOV lane. Different approaches used to provide ingress and egress to HOV lanes include direct merge, slip ramps, direct access ramps, and direct freeway HOV-to-freeway HOV lane connection.

(4) Arterial street HOV lanes and priority treatments. This category of arterial street HOV applications includes bus or transit malls; bus-only lanes; lanes open to buses, vanpools, and carpools; and some other infrequently used treatments.

The HOV lanes studied in this research on the Katy Freeway and Northwest Freeway were on-freeway exclusive reversible HOV lanes separated from the GPLs by concrete barriers. Vehicles could access or exit these facilities by slip ramps at either end or T-ramps along the lanes (see Figure 2.2).

FIGURE 2.2 An access/exit T-ramp on Katy Freeway HOV lane.

2.2.3 Congestion Pricing on HOV Lanes

Although many HOV facilities have successfully increased the average number of persons per vehicle, preserved the people-moving capacity of a corridor, improved bus operations, and enhanced mobility options for travelers (*15*), not all HOV projects have achieved these desired goals (*10*). The traffic volume on some HOV facilities was significantly lower than the capacity. This precipitated the removal of occupancy restrictions on some HOV lanes, effectively converting those lanes to GPLs. Alternatively, some selected HOV facilities were converted to HOT facilities which combined pricing strategies and occupancy restrictions to manage the number of vehicles using the HOV facilities.

Congestion pricing, also known as value pricing, refers to variable road pricing intended to reduce peak-period vehicle trips by charging higher prices under congested conditions and lower prices under less congested conditions (*16*). The tolls can change based on a fixed schedule, or they can be dynamic and change based on the level of traffic congestion at that time. By implementing congestion pricing, traffic congestion and the need to add freeway capacity can be mitigated, while simultaneously generating revenues. When motorists are charged fees approximating the true marginal costs of their trips, it is believed that they will decide to use the facilities only when and where the benefits they gain equal or exceed their own average costs plus costs (primarily congestion costs) they impose on others (*17*, *18*, *19*), thus maximizing the net societal benefits of travel.

One important aspect of congestion pricing was to create an appropriate pricing scheme that would increase the efficient use of the priced facility while maintaining free-flow speeds on that facility. This required a clear insight of the value that motorists placed on travel time savings. The value of travel time savings referred to the amount of money travelers were willing to pay for travel time savings and it was usually measured in dollars per hour. The traveler's value of travel time savings could be estimated through revealed preference (RP) and/or stated preference (SP) surveys, or by observing travelers' route choices (*20*). It was a very important factor in the generalized cost of travel (*21*), and hence it was a key parameter to travel behavior analysis. Through an analysis of travelers' value of travel time savings, toll authorities could manage the travel demand for congestion priced toll roads by increasing or reducing the toll. According to recent studies (*18*, *22*), the traveler's value of travel time savings generally fell within the range of 20 to 50 percent of the traveler's hourly wage rate.

2.2.4 HOT Lanes

HOT lanes provide free access to HOV travelers while also allowing travelers with fewer occupants in their vehicles to pay a toll to use the HOV lane facilities. HOT lanes achieve better utilization of existing HOV lanes while maintaining free-flow speeds on the HOV lanes. Compared with GPLs, HOT lanes not only provide shorter and more reliable travel time (*23*) but also generate revenues. Three primary benefits of HOT lane applications include (*24*):

- Provide expanded mobility options in congested urban areas;
- Provide a source of revenues; and
- Improve HOV lane efficiency.

Several metropolitan areas have examined the feasibility of implementing HOT lanes; however, as of April 2005, there were only four HOT lanes in operation in the United States (*25*). These ongoing and completed HOT lane projects are summarized in Table 2.1 and the operational projects are discussed in the following sections.

TABLE 2.1 Current HOT Lane Projects

STATE	LOCATION	FACILITY	STATUS
Arizona	Phoenix	All Freeways	Study
California	Alameda County	1-680, I-880	Study
	Contra Costa	SR 4W	Study
	Los Angeles	Various	Post-study
	Orange County	SR 91 Express Lanes	Operational
	Orange County	SR 57	Study
	Riverside County	SR 91 Extension	Study
	San Diego County	I-15	Operational
	Santa Cruz County	SR 1	Authorized
	Sonoma County	US 101	Post-study
Colorado	Denver	I-25	Study

TABLE 2.1 Continued

STATE	LOCATION	FACILITY	STATUS
Florida	Miami	I-95, SR 836	Study
	Orlando	I-4	Study
Maryland	Baltimore Suburbs	Various	Study
Minnesota	Minneapolis	All Freeways	Study
Oregon	Portland	Various	Study
Pennsylvania	Philadelphia	US 1	Study
Texas	Austin	I-35	Study
	Dallas	I-635	MIS
	Houston	Katy Freeway (I-10)	Operational
	Houston	Northwest Freeway (US-290)	Operational
Virginia	Hampton Roads	I-64	Approved
Wisconsin	Milwaukee	I-94	Proposed Study

Source: Poole and Orski. HOT Lanes: A Better Way to Attack Urban Highway Congestion. *Regulation, Volume 23, No.1*, 2000.

2.2.5 California HOT Lane Projects

The SR 91 Express Lanes project was the first operational HOT lane in the world. It was a four-lane, 10-mile, toll facility in the median of SR 91 between SR 55 and the Orange/Riverside county line. This facility was constructed by the California Private Transportation Company (CPTC) and began operations in 1995 as a public-private partnership between Caltrans, the California Department of Transportation and CPTC. A flat toll was initially charged during the morning and afternoon peak periods until a variable pricing scheme was applied in September 1997 (*24*). In January 2003, the ownership of SR 91 Express Lanes was transferred to the Orange County Transportation Authority (*26*). As of May 2005, travelers with three or more occupants in their vehicles (HOV-3+) traveled on the lanes for free during most periods of the day except that HOV-3+ travelers paid half of the regular toll to travel eastbound between 4:00 p.m. and 6:00 p.m. from Monday through Friday (*26*).

The I-15 FasTrak lanes were an eight-mile stretch of two reversible lanes in the median of I-15, about 10 miles north of San Diego. The I-15 FasTrak project was initially called ExpressPass and was implemented in December 1996. In the first 16 months of operation, SOV travelers were allowed to utilize the HOV lane by purchasing a permit that authorized them unlimited use of the HOV lane for a flat monthly rate. In March 1998 the flat-rate monthly permit was replaced by a per-trip dynamic toll. Tolls varied from $0.50 to $8.00 per trip according to traffic volume on the HOV lane. The current toll amount was shown on electronic signs prior to the entrance of the HOV lane (*25*). I-15 FasTrak users could save up to 20 minutes of travel time over the general-purpose freeway lanes (*27*).

2.2.6 Houston QuickRide Program

As of May 2005, there were two HOT lanes on two major freeways in Houston, Texas. These two major freeways were the Katy Freeway (I-10) and the Northwest Freeway (US-290). The HOT lane projects on these two freeways were operated under the name the "Houston QuickRide Program".

The Katy Freeway HOV lane was a 13-mile, barrier-separated, reversible HOV lane located in the median of the freeway. In 1984 the lane opened, allowing transit and vanpools only. Due to excess capacity on the lane, this restriction was reduced to allowing HOV-2+ carpools by 1986. Shortly thereafter, this HOV lane became heavily congested during the peak periods. The designation for the morning peak periods reverted to HOV-3+ in 1988, and in 1991 the same change was made for the afternoon peak periods. These changes resulted in significant excess capacity on the HOV lanes during peak periods, which led to the Houston QuickRide Program. Introduced in January 1998, the program allowed a two-person carpool to use the HOV lane during peak hours (6:45-8:00 a.m. and 5:00-6:00 p.m.) for a toll of $2.00 which was collected electronically (*25*).

Following the success of the Katy Freeway QuickRide program, the Metropolitan Transit Authority of Harris County and Texas Department of Transportation also converted the Northwest Freeway (US-290) HOV lane to a HOT lane in November 2000. The Northwest Freeway HOT lane was a 15-mile, reversible, one-lane facility in the median of Northwest Freeway, and it operated in a similar manner to the Katy HOT lane except that the QuickRide program only operated during the morning peak period (*28*). HOV-2+ travelers could access the lane for free the entire day except during the morning peak hours as congestion was not a problem during the afternoon peak period on the lane.

The Houston QuickRide program received relatively low patronage after operating for over 6 years on the Katy Freeway and over 4 years on the Northwest Freeway (*5*). The total average demand on the two HOT lanes was significantly below the targeted demand of 600 QuickRide vehicles per peak hour (*4*). The traffic flow on these HOV lanes usually decreased during the off-peak hours (*5*), thus excess capacity existed on the HOV lanes during the off-peak hours (see Figure 2.3).

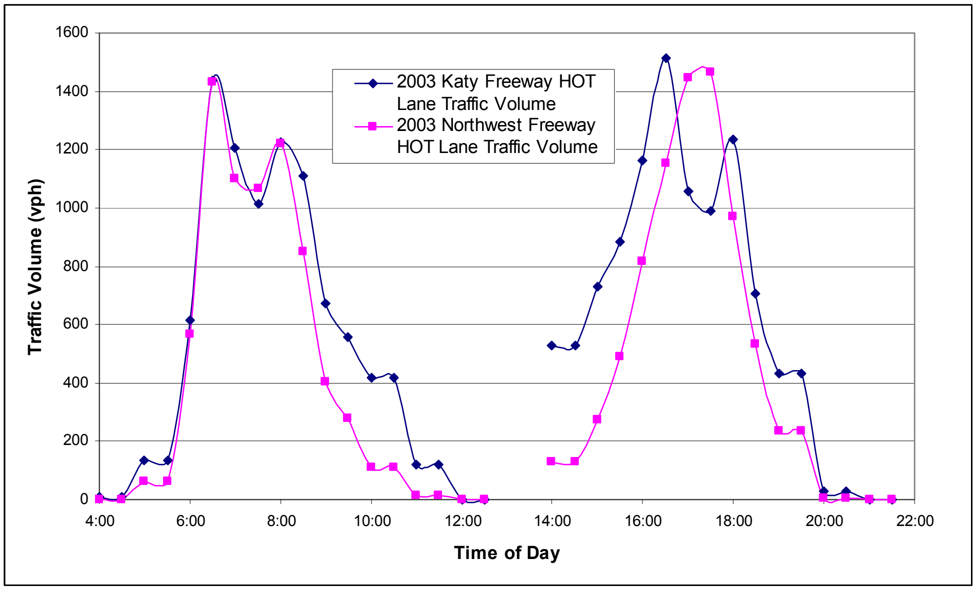


FIGURE 2.3 2003 traffic volumes on the Katy Freeway and Northwest Freeway HOT lanes.

A major difference between the HOT lane facilities in Houston and those in California was the allowance of SOV travelers. Both SR 91 Express Lanes and I-15 FasTrak allowed SOV travelers to pay to use the facility resulting in much higher usage levels. SOV travelers were not allowed to use the HOT lanes on the Katy Freeway and the Northwest Freeway in Houston. However, with the off-peak HOV lane capacity available for use, this option is now being examined.

2.3 Factors Affecting HOT Lane Demand

To begin conducting a HOT lane demand study, it was critical to identify and understand the factors which might affect traveler demand for the HOT lane. These factors could serve as a guide for policy making decisions of potential HOT lane investments and for the models developed in this research. There have been many studies examining these factors. Kim (*29*) indicated that some major factors affecting the HOT lane demand included income, toll price, trip purpose, schedule flexibility, and travel delay on adjacent general purpose lanes. Other researchers (*24*) found that the decision whether or not to use a HOT lane was based largely on the value of travel time savings. The list of factors affecting travel demand for HOT lanes (*24*) was also summarized in this FHWA report:

(1) Cost of HOT lane service.

- Amount of toll or out-of-pocket cost;
- Pricing scheme, such as the pricing function by time of day, vehicle occupancy restrictions, general levels of service on all alternative facilities;
- HOT lane travel time cost which is measured by the value of travel time of all vehicle occupants;
- Vehicle operating costs perceived by users; and
- Costs of inconvenience and opportunity cost of making the user eligible to use the HOT lane, such as automatic vehicle identification (AVI) tags for electronic tolling, account deposit, setup fees, etc.

(2) Cost of alternative modes.

- Cost of travel time when using an alternative “free” route, which is measured by the value of travel time of all vehicle occupants;

- Cost of congestion-related travel time uncertainty when using an alternative "free" facility;
- Vehicle operating costs perceived by users when using an alternative "free" facility; and
- Cost of using an alternative mode, such as transit or carpooling.

(3) Characteristics of the user.

- Socioeconomic characteristics of the user such as age, gender, education level, occupation, household size, annual household income, number of vehicles in the household, etc; and
- Attitudes and perceptions of paying tolls for travel time savings and travel time reliability.

(4) Characteristics of the trip.

- Trip purpose;
- Trip start and end times;
- Trip origin and destination locations;
- Trip length;
- Vehicle occupancy;
- Trip frequency; and
- Carpool formation time.

Mathematically, the mode choice made by a traveler can be described as a function of the factors presented above (*7*):

$$\text{Mode Choice} = f(\text{utility of HOT lane service, utility of alternative service, characteristics of the user, characteristics of the trip}). \quad (2.1)$$

In this research, focus was placed on the estimation of potential demand from SOV travelers for paying a toll to use the Katy Freeway and the Northwest Freeway HOV facilities. The review of factors affecting HOT lane demand provided insight on how travelers would choose among available mode choices and what factors were most important to their choice. This information was then used when developing discrete choice models of HOT lane use in Chapter 4.

2.4 Introduction to Discrete Choice Modeling

One of the essential elements of transportation system analysis was demand forecasting, which was primarily concerned with the behavior of users of transportation services and facilities (*30*). The development of discrete choice models was a major innovation in the analysis and prediction of transportation demand. A discrete choice model was often used to predict the mode choice decision made by an individual. The model could also be used to estimate the proportion of travelers who would change their mode choice decision in response to changes in factors such as those listed in Section 2.3. In addition, the model could be used to derive the elasticities which measured the percentage change in a variable (often demand) in response to a given change in any other particular variable (often price). The possible outputs from discrete choice models included (*30*):

- The probability for an individual to make a specific choice given particular values of variables;

- The total number or proportion of travelers who were expected to make a specific choice, if the modeling results were aggregated over a population; and
- The elasticities describing the percentage change in the variable being predicted (for example, the probability of choosing a specific alternative) for a given change in another independent variable (for example, the total cost of that alternative), holding all the other variables constant.

Development and estimation of discrete choice models has been of interest to researchers for many years within a wide range of disciplines. The method of discrete choice models was used in the biometric field since the 1940's (*31*, *32*, *33*), and shifted into the field of transportation, especially the estimation of the binary choice of travel mode, in the 1960's (*34*, *35*, *36*, *37*, *38*) and later was used to estimate the choice when more than two modes were involved (*39*, *40*, *41*, *42*, *43*, *44*).

2.4.1 Current Practice of Discrete Choice Modeling

Discrete choice models have been estimated by researchers for many of the conceivable travel decisions (*45*). It was not necessary to include all the different aspects of this research here, but some major discrete choice modeling practices applicable to this research are described below.

(1) Travel Mode Choice

"A fundamental concern of economics is understanding human choice behavior" (*46*). One of the most important contributors to this field of research was McFadden (*46*), with his classic contribution to econometric theory, "conditional logit analysis of qualitative choice behavior". This analysis intended to provide an appropriate framework for the empirical analysis of choice among finite sets of alternatives, with each alternative characterized as a bundle of attributes. McFadden (*46*) applied basic utility theory to the discrete choice problem, and supposed that each member of a population of interest faced a finite choice set and selected an alternative that maximized utility. McFadden's (*47*) research in the 1970s was primarily on the Urban Travel Demand Forecasting Project. In that project, he demonstrated disaggregate travel demand forecasting to be a practical policy-analysis tool, and the multinomial logit model was found to provide a valid functional form for a variety of transportation applications (*47*).

A series of models concerning travelers' commute mode were developed by Kenneth Train (*48*, *49*, *50*), with the household survey data collected before and after the opening of the Bay Area Rapid Transit (BART) system in the San Francisco area. His latest model was a nested logit model which examined the choice probabilities of different commuting modes (*50*).

In the late 1970s and early 1980s, researchers with the Wisconsin Department of Transportation (WisDOT) developed a series of mode-choice models to consistently assess transportation policy issues across the urban areas in the State (*51*). Kocur et al. (*51*) developed work-trip mode choice models for four sets of metropolitan areas in Wisconsin based on the results of revealed and stated-preference surveys. These models were used to estimate the effects of various policies on mode split.

Abraham and Hunt (*52*) developed and estimated a modified form of nested logit model to represent the household behavior in the selection of home location and the selection of workplace locations and commuting modes for employed household members. They used disaggregate revealed-preference observations collected in Calgary, Alberta, Canada. In their model, the choice of home location for the household, the choice of workplace location for each worker in the household, and the choice of mode for the trip to work for each worker in the household were treated as a joint choice made by the household which might have various numbers of workers.

(2) Transit Access

Discrete choice models have also been developed in many areas to predict transit mode choice. Researchers estimated the bicycle and pedestrian mode share in transit access trips for the Chicago Transit Authority (CTA) and Metra rail systems in Chicago through a real-world application of discrete choice modeling (*53*). In that study, researchers estimated two nested logit discrete choice models: one for access mode to the Metra commuter rail, and another one for access mode to the rapid rail of CTA. That research resulted in a comprehensive planning tool for evaluating the mode choice and ridership impacts of multiple changes in the transportation system, and was used by CTA to assist in prioritizing stations, selecting case study locations, identifying design improvements, and estimating the cost-effectiveness of improvements.

Another discrete choice model of transit mode choice access was developed by Loutzenheiser (*54*) in 1997, based on Bay Area Rapid Transit passenger surveys and station area characteristics. Loutzenheiser found that the individual's characteristics were more important than the urban design and station area characteristics in determining the choice to walk.

(3) Trip-Scheduling Choice by Commuters

The scheduling of a trip is one of the most important decisions affecting congestion and has been studied intensely since the early 1980s (*45*). The scheduling of the trip is usually continuous, but it is considered to be a discrete choice among a series of time intervals.

In 1982, Small (*55*) estimated the choice of work arrival time among twelve possible five-minute intervals, using the data from a set of auto commuters from the San Francisco Bay Area who had an official work-start time and stated that they usually arrived between 42.5 minutes before and 17.5 minutes after that time. The ideas of some earlier empirical models of trip scheduling were expanded upon by Small in the utility specification of this study. It was hypothesized in Small's study that the time spent for work-related activities before work officially began was relatively unproductive and unpleasant, because during this period of time people wanted to sleep and be with their families rather than at work. A linear penalty for departing early was therefore assumed. Similarly, it was hypothesized that arriving late was considered unacceptable by employers, so a much larger linear penalty was assumed for arriving late (see Figure 2.4) (*55*). Small found, from the marginal rates of substitution, that the commuter was willing to suffer an extra 0.61 minutes of congestion to reduce the amount of early arrival by one minute and an extra 2.40 minutes of congestion to reduce the late arrival by one minute (*55*). Another disutility for commuting travel was travel time disutility

(*56*). Therefore, the factors influencing the traveler's travel schedule included the penalty for early departure, the penalty for late arrival, and the travel time disutility as illustrated in Figure 2.5.

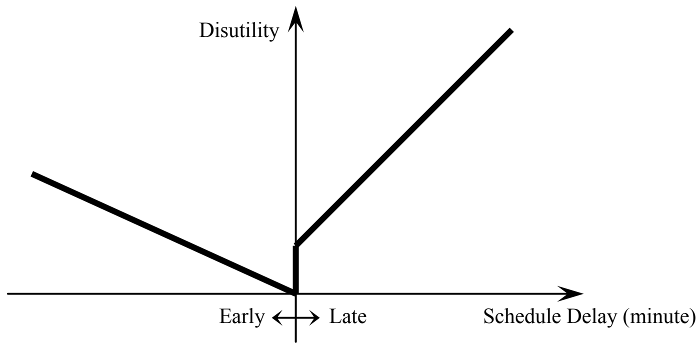


FIGURE 2.4 Disutility of schedule delay.

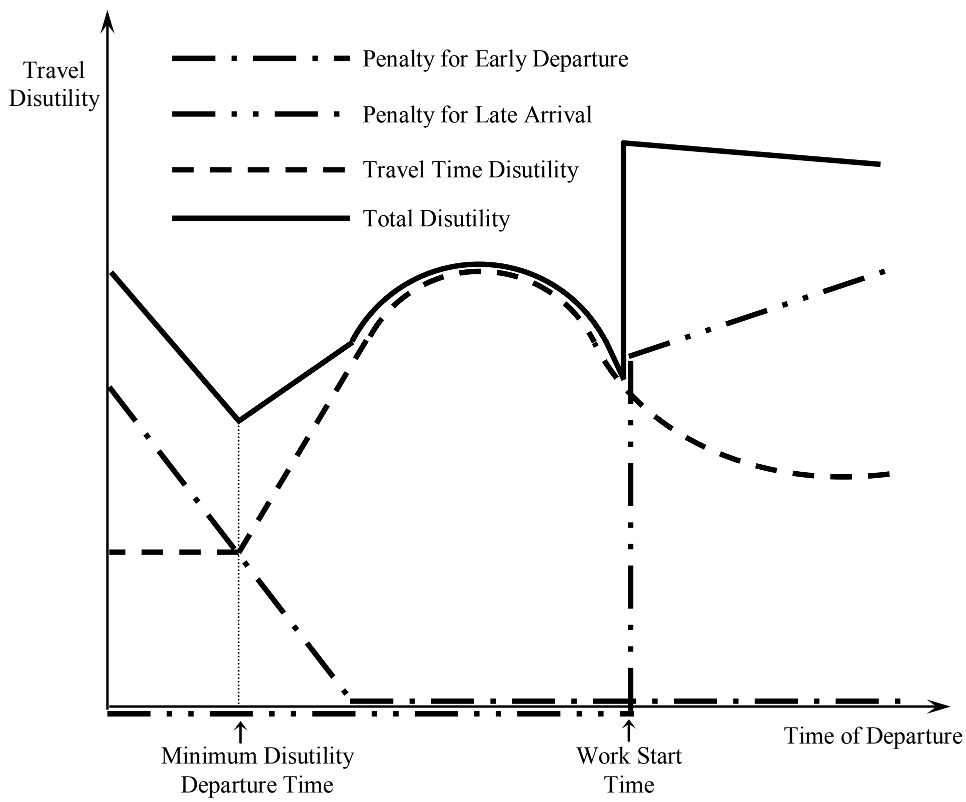


FIGURE 2.5 Commuting travel disutility by departure time.

Small compared the disutility of changing one's travel schedule to the peak period (travel time disutility) with the penalty for early departure and late arrival. This concept, a disutility for switching one's time of travel to a less preferred time of day, was employed in this thesis.

(4) Valuation of Travel Time Savings

Prior to the 1960's, the time factor was not included in the consumer behavior theory (*21*). Time was not considered to be a necessary variable in the utility function until 1965, when Becker (*57*) made the first attempt to develop a general treatment of the allocation of time in all non-work activities and suggested that households combined market goods and time to produce more basic commodities. In Becker's theory, only non-work time and goods were considered as producing utility. However, in 1966, Johnson (*58*) indicated that working time also produced pleasantness or unpleasantness and hence he introduced work time into the utility function.

In 1971, De Serpa (*59*) developed the general concept of the value of time (VOT). In his theory, time and goods were complementary instead of acting as substitutes to each other, and there were three kinds of the VOT:

(1) Value of time as a resource (VTR). VTR was defined as the value of extending the time period, which was equivalent to the ratio between marginal utility (MU) of the available time and MU of income.

(2) Value of time as a commodity (VTC). VTC was defined as the value of time allocated to a specific activity, which was equivalent to the ratio between MU of time spent in the activity and MU of income.

(3) Value of time savings (VTS). VTS was defined as the value of reducing the time needed to spend in the activity, which was equivalent to the ratio between MU of time savings and MU of income.

De Serpa (*59*) found that the VTS in an activity was equal to the VTR minus the VTC, and VTS was actually the VOT mentioned in the earlier studies. A comparison of the VOTs identified from the SR91 Express Lane data and I-15 FasTrak data was made in a study by Brownstone and Small (*60*). It was found that the models of SR91 Express Lane and I-15 FasTrak yielded very similar estimates of the VOT. Both studies found a roughly $20 per hour VOT when the I-15 FasTrak sample was weighted to match the income and commute distance distribution in the SR91 Express Lane sample. This result was surprising since the two different corridors had different pricing schemes, and the two studies used different questionnaires and different survey modes (*60*). This finding was important because a confidence could be built that the empirical findings were not just based on some particular cases, surveys or models.

This review on the valuation of travel time savings provided some important details on the estimation of a traveler's value of travel time savings. For example, the value of travel time savings was equivalent to the ratio between marginal utility of time savings and marginal utility of a monetary variable. This monetary variable was often related to the income of the traveler, so the value of travel time savings for travelers from different income levels was often estimated. This was the basic methodology of estimating the value of travel time savings used in this research. In recent research (*18*, *22*), the valuation of traveler's travel time savings were compared with the traveler's hourly wage rate, which related travelers' value of travel time savings with their incomes. This technique was also applied in the VTTS calculations in this research, as estimated using discrete choice models of travel behavior.

2.4.2 Structure of Discrete Choice Models

The principle of random utility maximization was used in the discrete choice modeling analysis. Generally, it was assumed that choices made by individuals could be predicted based on a limited set of quantifiable factors and that the decision-makers selected the alternative with the highest utility among those available at the time a choice was made (*30*, *61*). The discrete choice model was usually a mathematical utility function which predicted an individual's choice based on the value of utilities of all the competing alternatives. The modeler may not know the real value of the utility of each alternative, but the modeler could use the function of the alternative attributes, the characteristics of decision-maker, and some unobservable random components to represent the utility. The discrete choice model was usually developed from a data set containing individual trip decisions, characteristics of alternative choices for the trip, and characteristics of the traveler. The utility of an alternative i to an individual n was represented by $U_{i,n}$, and included a deterministic component $V_{i,n}$ and a random component $\varepsilon_{i,n}$ as in the following Equation (2.2):

$$U_{i,n} = V_{i,n} + \varepsilon_{i,n}. \qquad (2.2)$$

The deterministic component $V_{i,n}$ included the variables of the alternative attributes component V_i and the decision-maker characteristics component V_n:

$$V_{i,n} = V_i + V_n. \qquad (2.3)$$

Substituting Equation (2.3) into Equation (2.2), gave:

$$U_{i,n} = V_i + V_n + \varepsilon_{i,n}. \qquad (2.4)$$

It was assumed that the random component was independently and identically gumbel distributed across cases (*61*), and the number of mode choice alternatives was *J*. This assumption led to the logit model (*30*) and the probability that alternative *i* was chosen by individual *n* was calculated using the following Equation (2.5):

$$P_{i,n} = \frac{e^{V_{i,n}}}{\sum_{i=1}^{J} e^{V_{i,n}}}. \qquad (2.5)$$

Therefore, it was predicted that the individual *n* selected alternative i' which had the highest utility $U_{i',n}$ and thus the highest probability $P_{i',n}$. The utility function of an alternative *i* to an individual *n* could also be given by the following Equation (2.6):

$$U_{i,n} = \beta_i X_i + \beta_n X_n + \varepsilon_{i,n} \qquad (2.6)$$

where,

$U_{i,n}$ = utility of an alternative *i* to an individual *n*;

i = the set of alternatives available to the individual;

X_i = a vector of measurable attributes of each travel alternative;

X_n = a vector of measurable characteristics of each individual;

β_i = a vector of the coefficients of X_i;

β_n = a vector of the coefficients of X_n; and

$\varepsilon_{i,n}$ = unobservable factors (random utility).

The attributes of each travel alternative were described by the alternative-specific constants (for example, the constant of the utility function of each mode option) and the generic variables (for example, cost and travel time), and the characteristics of each individual were described by the alternative-specific socioeconomic variables (for example, age). The standard specification of a sample discrete choice model with only four choice options (A, B, C, D, and D was the reference mode) is shown in Table 2.2.

TABLE 2.2 Standard Discrete Choice Model Specification

Mode Option	X_i					X_n		
	Cost	Time	Constant			age		
			A	B	C	A	B	C
A	c_a	t_a	one	0	0	a_age	0	0
B	c_b	t_b	0	one	0	0	0	0
C	c_c	t_c	0	0	one	0	0	c_age
D	c_d	t_d	0	0	0	0	0	0

The interaction of the constants (for mode option A, B and C) with the socioeconomic and commute variables (such as age) allowed for the creation of mode-specific utility equations. The constant variable, the socioeconomic and commute variables were applicable to all the utility equations except the reference mode utility equation which contained only the cost and time attribute variables. It was also possible that the socioeconomic and commute variables were not available for some of the modes (for example, in Table 2.2, the age variable was not available for mode B).

The probability that mode option *i* was chosen by individual *n* could thus also be calculated using the following Equation (2.7):

$$P_{i,n} = \frac{e^{\beta_i X_i + \beta_n X_n}}{\sum_{i=1}^{J} e^{\beta_i X_i + \beta_n X_n}}. \tag{2.7}$$

From Equation (2.7), it could be seen that the utility function of each alternative was usually represented through a linear combination of alternative attribute variables and the decision-maker's socioeconomic variables. The estimated coefficients of the variables could be used to derive elasticities. Elasticities indicate the percentage change in a variable in response to a given change in any other particular variable, holding all the other variables constant.

The method of discrete choice modeling was applied in this research. With the appropriate datasets collected from traveler surveys, the utility functions of all the travel mode alternatives were estimated. The mode choice decision of each individual was then predicted by comparing the probabilities of all the competing mode alternatives using Equation (2.7). The estimated model could also be used to calculate the proportion of the travelers who would change their decisions in response to the changes of some important factors (for example, travel time savings and toll levels). In addition, some marginal effect variables such as traveler's value of travel time savings and value of penalty for changing travel schedule could be estimated by comparing the disutility of these variables to the disutility of a toll.

The value of travel time savings (VTTS) was a critical parameter in travel behavior and traffic assignment analysis because of its importance in a traveler's choice among multiple competing modes or routes (*21*). In neoclassical microeconomics, the VTTS was defined as the willingness to pay for a unit travel time savings, and therefore it varied with the trip characteristics and individual socioeconomic characteristics (*21*). Generally, the VTTS was also regarded as the traveler's value of time (VOT). Brownstone and Small (*60*) defined VOT as "the marginal rate of substitution of travel time for money in a travelers' indirect utility function", which linked the VOT with discrete choice modeling. Using the notations in Equation (2.6), and assuming that only two variables included in X_i measured the toll C_i and travel time T_i respectively, the VOT was therefore defined as (*60*):

$$VOT_{i,n} = \frac{\partial U_{i,n} / \partial T_i}{\partial U_{i,n} / \partial C_i} = \frac{\beta_{T_i}}{\beta_{C_i}} \tag{2.8}$$

So the VTTS could also be given by the ratio of the coefficients of travel time and toll which were two variables in the discrete choice model.

Similarly, a traveler's value of the penalty for changing travel schedule (VPCS) was defined as the marginal rate of substitution of travel schedule change for money in the utility function. Travelers who originally chose a time of travel were assumed to prefer that time unless a specific amount of monetary cost was charged to maintain their current choice. Given a variable of travel schedule, the VPCS could also be calculated by the ratio of the coefficients of a travel schedule variable and the toll variable.

2.4.3 Methods for Population Results Aggregation

In order to apply discrete choice models to the entire affected population and to estimate the proportion of all travelers who would choose a specific alternative as a result of an action, the affected population must be defined in groups for which either an average value or a distribution was known for all the variables of the model. Three alternative methods were generally used to aggregate the results of the population (*62*):

(1) The "naïve" method. By this method, the average values are assumed for each independent variable. However, significant errors may be introduced when the single aggregate values for population variables are used.

(2) The "market segmentation" method. In this method, a mode choice probability is estimated for each group of the population, multiplied by the total number of travelers of the group, and summed across all groups. This method can reduce, but can not eliminate, the aggregation errors.

(3) The "sample enumeration" method. By this method, a random sample of the total population is taken, and the mode choice probability for each person of the sample is estimated. The mode share for the entire population is hence estimated by averaging the sample probabilities. This method is the most accurate of the three but also the most difficult to apply.

The "sample enumeration" method was used in this research, because it was not practical and cost-efficient to collect the data of the entire target population. Surveys were only sent to a random sample of the total population.

2.4.4 Data Requirements

Ideally, discrete choice models were developed from sufficient data sets which contain individual trip decisions, characteristics of the individual, and characteristics of the alternative choices for the trip. There exist two types of data, revealed-preference (RP) data and stated-preference (SP) data, which were used in discrete choice modeling (*63*).

(1) Revealed-preference data. RP data usually describe the choice behavior in the actual market, based on the actual alternatives. This kind of data may be collected from a travel survey which determines the characteristics of a trip already taken, the characteristics of the decision-maker, and other influencing factors.

(2) Stated-preference data. SP data usually describe the preference statement of the decision-maker for several hypothetical scenarios. Decision-makers were asked to identify the choices they would make under various scenarios. This kind of data was capable of evaluating a wide range of alternatives which might or might not exist. However, there were still some potential sources of bias in SP data (*63*):

- Justification bias

  This kind of bias occurred when respondents answered SP questions and tried to justify their past choices.

- Omission of situational constraints

  This kind of bias occurred when respondents answered SP questions and did not consider all situational constraints of a trip, for example, travel time, non-flexible schedule, expensive parking fees, etc. This was of extra concern when the number of situational constraints was unacceptably large.

- Incomplete description of alternatives

  This kind of bias occurred when the interviewers or surveys did not explain the hypothetical alternatives and their attributes well enough.

- Cognitive incongruity with actual behavior

  This kind of bias occurred when the design of the SP questions was not user-friendly and respondents were confused or fatigued from answering the survey correctly.

Therefore, the collected RP data must describe the characteristics of decision-makers correctly and describe the characteristics of the alternatives or other factors that currently exist in the real-world. When collecting SP data, it was necessary to keep hypothetical alternatives simple and clear to the respondents and to make the survey instrument as user-friendly as possible. In the survey used for this research, effort was undertaken to minimize the potential bias in SP data. Although there were a large number of mode options (nine) along with some situational constraints (travel time and toll), by employing fractional factorial design (FFD) only four SP questions were included in each survey and there were only four choice options in each question. This minimized respondents' efforts and confusion while the main effects of the travelers' choices were still captured. One of the potential situational constraints, travel time reliability, was eliminated from the description of each travel mode, because it was very difficult for travelers to have a clear perception of travel time reliability. A graphical display of each alternative was also included in the SP questions to make it very easy for travelers to understand the hypothetical options well (see Appendix A). Further details on survey development and administration are provided in the next chapter.

CHAPTER III

METHODOLOGY

In this chapter, the design of the survey, the data collection process, and the modeling methodology are detailed. The first section includes the study locations and the current available travel mode options in the study locations. The second section includes details of the survey design, followed by how the surveys were administered. The next section contains a summary of the development of the database used in the modeling, and the final section includes specific discrete choice modeling methodologies used in this research.

3.1 Study Locations

HOV lanes have been moving travelers quickly and efficiently in the Houston metropolitan area for the past 26 years (*5*). The Houston QuickRide Program started in January 1998 on the Katy Freeway (I-10) and then in November 2000 on the Northwest Freeway (US-290). The location of the Houston QuickRide Program on a map of the Houston metropolitan area is shown in Figure 3.1.

FIGURE 3.1 Houston QuickRide program coverage areas (*64*).

Currently, the available travel mode options for travelers using the Katy Freeway and Northwest Freeway corridors include:

(1) Travel Options on the Katy Corridor

- Peak Hours (6:45 a.m. – 8:00 a.m. and 5:00 p.m. – 6:00 p.m.)
    - Drive alone (SOV) or with passengers (HOV2+) on the GPLs with no toll;
    - Drive with one passenger (HOV2) on the HOV lane for a $2.00 toll (QuickRide);
    - Drive with two or more passengers (HOV3+) on the HOV lane for free;
    - Drive a motorcycle on the HOV lane for free;

  - Take transit with fare levels ranging from $1.00 to $3.50; and
  - Join a casual carpool which travels on HOV lane for free.
- Off-peak Hours
  - SOV or HOV2+ on the GPLs with no toll;
  - HOV2+ on the HOV lane for free;
  - Drive a motorcycle on the HOV lane for free;
  - Take transit with fare levels ranging from $1.00 to $3.50; and
  - Join a casual carpool which travels on HOV lane for free.

(2) Travel Options on the Northwest Corridor

- Morning Peak Hours (6:45 a.m. – 8:00 a.m.)
  - SOV or HOV2+ on the GPLs with no toll;
  - HOV2 on the HOV lane for a $2.00 toll (QuickRide);
  - HOV3+ on the HOV lane for free;
  - Drive a motorcycle on the HOV lane for free;
  - Take transit with fare levels ranging from $1.00 to $3.50; and
  - Join a casual carpool which travels on HOV lane for free.
- Afternoon Peak Hours (5:00 p.m. – 6:00 p.m.) and Off-peak Hours
  - SOV or HOV2+ on the GPLs with no toll;
  - HOV2+ on the HOV lane for free;
  - Drive a motorcycle on the HOV lane for free;
  - Take transit with fare levels ranging from $1.00 to $3.50; and
  - Join a casual carpool which travels on HOV lane for free.

The Houston QuickRide program received relatively low patronage after operating for over 6 years on the Katy Freeway and over 4 years on the Northwest Freeway. Specifically, the total average demand on the two HOT lanes was 131 trips per day in 2000 and 182 trips per day in 2002, which was significantly below the targeted demand of 600 QuickRide vehicles per peak hour (*4*). As shown in Chapter 2.2.6, there was additional room for vehicles on these HOV lanes during off-peak periods. It was found in previous studies that people who previously traveled in SOVs on the GPLs were the primary source of QuickRide participants (*6*). According to the results of a recent survey of QuickRide participants, 80.5 percent of all survey respondents indicated that they would increase their level of participation if they could drive alone on the HOV lanes (*4*). One potential method of increasing the usage of the HOV lane would be to change the current HOV lane operating restrictions and allow some of the SOV travelers to travel on the HOV lane and take advantage of the travel time savings. The most practical way to allow SOV travelers to enter the HOV lanes was to collect an appropriate toll from those who were willing to pay for the travel time savings of the HOV lane. To do this, it was critical to estimate the potential SOV demand from the GPL travelers. To estimate this demand, discrete choice models were estimated to calculate the probabilities that travelers would pay a toll to use the HOV lanes as SOV travelers under different travel time savings and toll scenarios. This required revealed-preference and stated-preference data collected from the GPL travelers on the Katy Freeway and Northwest Freeway corridors. The data analyzed in this research were collected from QuickRide non-users in a survey conducted in November 2003.

3.2 Survey Design

The survey was designed for travelers who were driving on the GPLs of the Katy Freeway and Northwest Freeway corridors during both the peak and the off-peak hours. The survey included 35 questions (see Appendix A) regarding:

- Respondents' most recent trip;
- Respondents' general perceptions and attitudes on the QuickRide program;
- Respondents' choices among different travel scenarios; and
- Respondents' socioeconomic and demographic characteristics.

Data regarding respondents' choices among different travel modes were collected through four stated-preference questions in the survey. In theory, there were three primary factors which influenced travelers' choice of mode: travel time, travel cost, and travel time reliability (*65*). Unfortunately, when confronted with this large amount of information and mode choices, test survey respondents became confused. Therefore, to minimize respondent error due to confusion, the travel modes specified in the stated-preference questions were simplified to be characterized by only mode, travel time and toll rate factors. The travel time reliability factor was eliminated from the travel mode characteristics. Each traveler was asked to choose his/her preferred mode among four hypothesized scenarios marked as A, B, C, and D in each question, and there were four stated-preference questions in each survey (see Appendix A).

Two sets of different surveys were designed for travelers on the GPLs, one for peak period travelers and one for off-peak period travelers. Seven available mode choice options were provided in the survey for travelers who were driving on the GPLs in the peak period, as illustrated in Figure 3.2 and listed below:

(1) SOV on the GPLs in the peak period;

(2) HOV2 on the HOV lane in the peak period;

(3) HOV2 on the GPLs in the peak period;

(4) SOV on the HOV lane in the peak period;

(5) Transit, using the park and ride lot;

(6) HOV2 on the HOV lane in the off-peak period; and

(7) HOV3 on the HOV lane in the peak period.

Seven similar (but not identical) mode choice options were provided in the survey for travelers who were driving on the GPLs in the off-peak period, as illustrated in Figure 3.3 and listed below:

(1) SOV on the GPLs in the off-peak period;

(2) SOV on the HOV lane in the off-peak period;

(3) HOV2 on the GPLs in the peak period;

(4) SOV on the HOV lane in the peak period;

(5) Transit, using the park and ride lot;

(6) HOV2 on the HOV lane in the off-peak period; and

(7) SOV on the GPLs in the peak period.

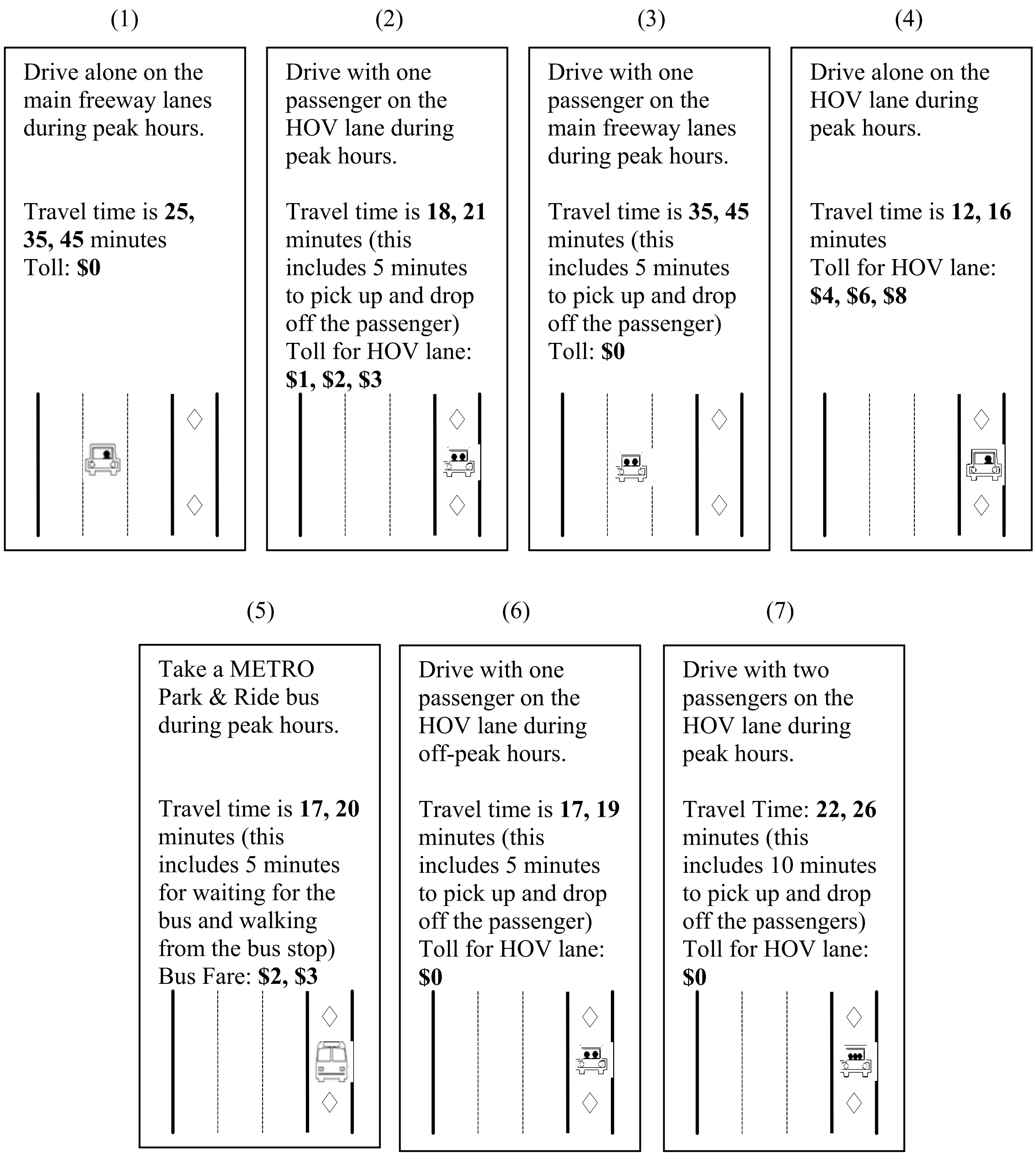


FIGURE 3.2 Travel mode options for GPL peak hour travelers.

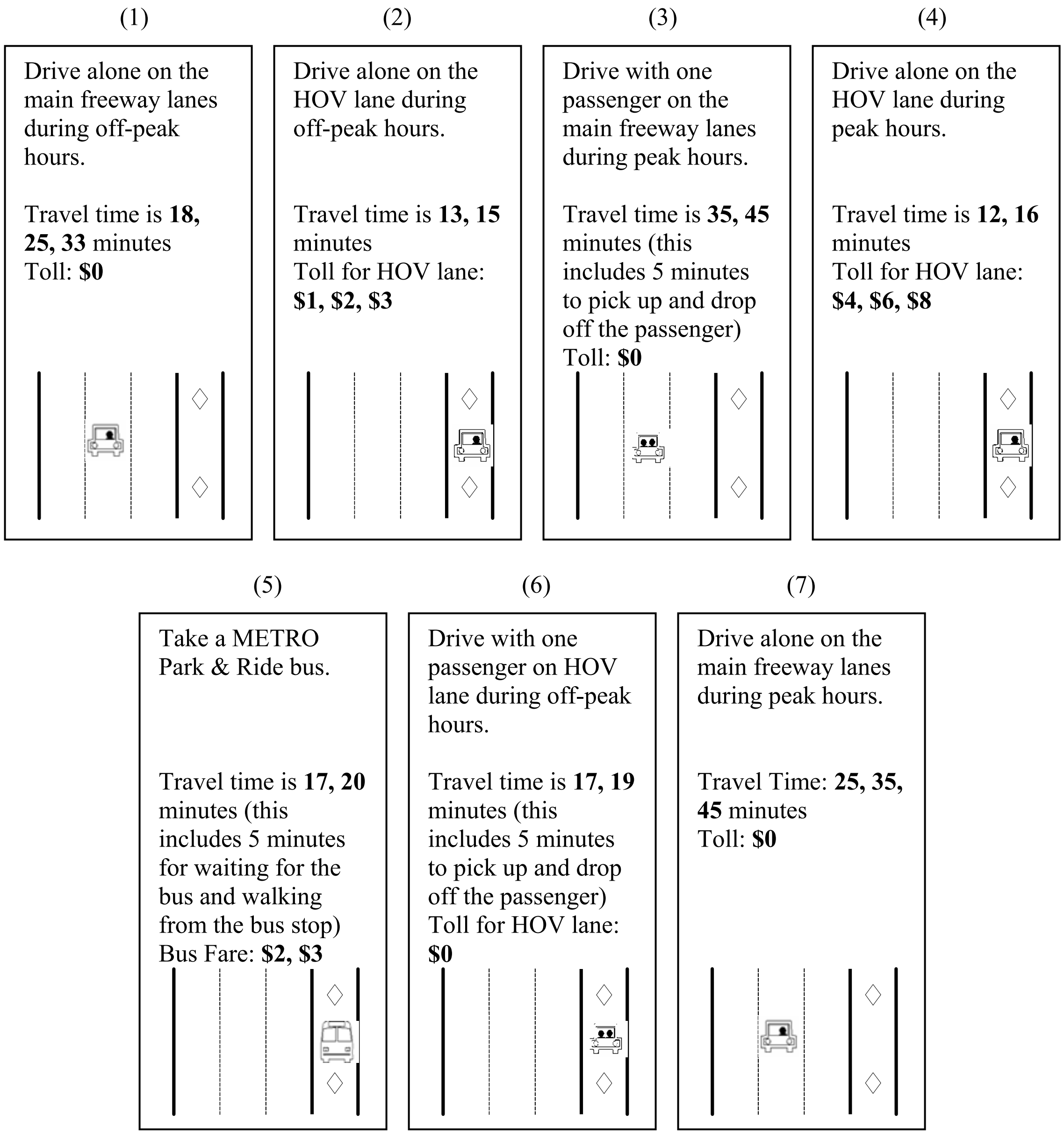


FIGURE 3.3 Travel mode options for GPL off-peak hour travelers.

There were seven available mode choice options in the surveys for travelers on GPLs in peak or off-peak hours, and each mode was characterized by two factors, that was, travel time and toll rate. It can be observed from Figure 3.2 and Figure 3.3 that each factor may also have a different number of descriptive levels (toll rates and travel times). This led to a large number of potential combinations of scenarios. However, only four questions with four alternative scenarios in each question were included in each survey to make the time required to complete a survey reasonable and the survey not overly complex. In order to resolve this problem, the method of orthogonal fractional factorial design (FFD) was applied. Orthogonal FFDs were used to define the set of scenarios in each of the four questions that were given to survey respondents to elicit their choice behavior. In this particular case, the orthogonal FFD required 36 questions to cover the main effects according to the selected orthogonal array matrix from an orthogonal array library website (*66*, *67*). Since four stated-preference questions were asked in each survey, nine different versions of surveys were required. The surveyed travelers were also divided into eight different categories according to their traveling corridors and periods:

(1) Katy Freeway – morning (inbound) peak hour;

(2) Katy Freeway – afternoon (outbound) peak hour;

(3) Northwest Freeway – morning (inbound) peak hour;

(4) Northwest Freeway – afternoon (outbound) peak hour;

(5) Katy Freeway – morning (inbound) off-peak hour;

(6) Katy Freeway – afternoon (outbound) off-peak hour;

(7) Northwest Freeway – morning (inbound) off-peak hour; and

(8) Northwest Freeway – afternoon (outbound) off-peak hour.

Therefore, there were 72 different versions of surveys (9 versions × 8 traveler categories) mailed to the travelers on Katy Freeway and Northwest Freeway GPLs. Appendix A presents a sample survey instrument for Katy freeway morning (inbound) peak hour travelers.

3.3 Survey Administration

This survey was conducted in November 2003. In order to obtain the mailing addresses of potential respondents, the license plates of vehicles on the Katy Freeway and Northwest Freeway GPLs were recorded using digital video cameras approximately four weeks before the survey was mailed, as illustrated in Figure 3.4.

FIGURE 3.4 Recording license plates using digital video camera.

The license plate numbers were captured from the videos and keyed into a database. The database of license plate numbers was sent to the Texas Department of

Public Safety (DPS), and DPS provided the travelers' name and address information based on the license plate number. As the result, the survey forms were sent to a total of 8,670 GPL travelers, and 1,441 valid responses were returned through mail. The survey instrument was also made available on a website and this survey response method was indicated on the paper-based survey forms. A total of 680 valid responses were collected from the website. A total valid response rate of 24.5 percent was obtained, and this number was within the range of the typical survey response rate for this type of transportation survey (*68*).

3.4 Data Reduction

All the survey responses were keyed into a database and reduced to identify and eliminate any erroneous data records. The data discrepancies included data entry errors, unreasonable responses, and data outliers. For example, some data records were keyed with unreasonable survey codes which were impossible to include in the dataset. After the remove of the erroneous and incomplete data records, there were 1635 valid responses obtained from the GPL travelers.

Note that, for the purpose of stated-preference data analysis, each respondent's information was recorded in 16 rows. As described in the survey design section, each respondent was asked four stated-preference questions and each question had four mode choice options. The responses to all the 16 mode choice options were therefore recorded in 16 rows of the data for each respondent. The socioeconomic profile data of each respondent was duplicated in all of the 16 rows.

After the combination of the two datasets of peak hour and off-peak hour travelers, the total number of available mode choice options became nine instead of seven, since these two datasets shared five mode choice options. The potential mode choices were relabeled as follows:

A. SOV on the GPLs in the off-peak period (SOV-GPL-OP);
B. SOV on the HOV lane in the off-peak period (SOV-HOV-OP);
C. HOV2 on the GPLs in the peak period (HOV2-GPL-P);
D. SOV on the HOV lane in the peak period (SOV-HOV-P);
E. Transit, using the park and ride lot (P&R-T);
F. HOV2 on the HOV lane in the off-peak period (HOV2-HOV-OP);
G. SOV on the GPLs in the peak period (SOV-GPL-P).
H. HOV2 on the HOV lane in the peak period (HOV2-HOV-P); and
I. HOV3 on the HOV lane in the peak period (HOV3-HOV-P).

Option C, D, E, F, and G were the five shared mode choice options. Option A and B were the mode choice options for off-peak hour travelers only, and option H and I were the mode choice options for peak hour travelers only.

Option B (SOV-HOV-OP) was particularly important when calculating the potential SOV demand for the HOV lane during the off-peak period. Currently, the traffic volume on the HOV lanes during the peak hours has been close to the capacity of the lanes, so excess HOV lane capacity generally exists only during off-peak hours and thus option B was the option that was of most interest to both encourage HOV lane usage and increase revenues.

3.5 Discrete Mode Choice Modeling

Based on the dataset collected from the GPL traveler surveys, the method of discrete choice modeling (multinomial logit model) was applied to estimate the potential SOV demand for driving on the Katy Freeway and Northwest Freeway HOV lanes during the off-peak periods. The probability of choosing the travel mode option B (SOV on HOV off-peak) was calculated using a discrete mode choice model. As part of the research task, the traveler's value of travel time savings (VTTS) and value of penalty for changing travel schedule (VPCS) were also calculated. Two different models were estimated, one for the Katy Freeway and the other for the Northwest Freeway.

The utility function value for each of the nine modeled travel modes was calculated, and the probability of travelers choosing to drive on the HOV lane during the off-peak periods as SOV travelers (option B) was also calculated. Each mode option's utility function consisted of two parts: a revealed-preference part (trip characteristics and traveler socioeconomic characteristics) and a stated-preference part (choice among hypothesized scenarios). In the model specifications, all the utility functions of different mode options contained travel time and toll information for each mode but were distinguished by the revealed-preference responses from travelers.

The traveler's VTTS could be estimated as the ratio of the coefficient of the travel time variable to the coefficient of the toll variable in the stated-preference part of the utility function. It was important to estimate the traveler's VTTS before making a congestion pricing policy on the HOV lanes, as it was a realistic indication of how the SOV travelers would choose between travel time savings and toll rates.

Similarly, by introducing the variables *peak* and *offpk* to represent the travel time period (if *peak* = 1 or *offpk* = 0, the respondent traveled during the peak period; and if *peak* = 0 or *offpk* = 1, the respondent traveled during the off-peak period), the traveler's VPCS could also be estimated through the marginal effect of the variable *peak* or *offpk* with respect to the toll variable. This indicated the monetary value at which travelers felt indifferent to the penalty they would suffer from changing their travel schedule or paying that penalty. The traveler's VPCS is an indication of how the travelers judge the levels of importance between monetary cost and penalty for travel schedule shift. If the toll rate is too high (greater than VPCS) for the travelers at their preferred time of travel, the travelers will be more likely to shift their time of travel to another time. Therefore, it was very meaningful to estimate the traveler's VPCS before making any congestion pricing policy on the HOV lanes.

CHAPTER IV

MODELING ANALYSIS AND RESULTS

This chapter begins with the details of the modeling specifications. Results from the models that were used to estimate potential SOV demand for the HOV lanes by the Katy Freeway and the Northwest Freeway GPL travelers were then provided. This is followed by a discussion of model results. Potential HOV lane off-peak pricing levels are recommended in the final section. In this study, the discrete mode choice modeling calculations were conducted within the platform of *LIMDEP 7.0*. This program was developed in 1980, initially to provide an easy tool to estimate *LIM*ited *DEP*endent variable models. *LIMDEP* is now widely used in many scientific fields for analysis of descriptive statistics, linear regression, logit models, discrete choice models, parametric duration models, and nonlinear regressions (*69*). *LIMDEP 7.0* was selected as the software platform for this modeling study due to its powerful functions of building discrete choice models.

4.1 Modeling Analysis and Results: Katy Freeway Travelers

4.1.1 Discrete Mode Choice Modeling for Katy Freeway Travelers

To begin building the discrete choice model for Katy Freeway GPL travelers, the variables in the dataset were adjusted for use in the utility function of each travel mode alternative. In general, discrete choice models required that the data set be arranged with a row of data (an observation) for each alternative in the model. The alternative-specific constants (for example, the constant in the utility function of each mode option) and the alternative-specific socioeconomic variables (for example, age, income, etc.) were distinguished by having individual coefficient for each different mode option. The generic variables (for example, cost and travel time) appeared in the utility functions of all modes with the same coefficient each time. It was critical to choose an appropriate set of alternative-specific socioeconomic variables from the dataset for the purpose of modeling. Based on the review of the literature, many potentially influential socioeconomic variables were tested in numerous preliminary discrete choice modeling trials. Only those variables that were statistically significant at the 95 percent level and showed negligible correlation with other variables were used in the final model. Additionally, many combinations of variables were tested to develop the model with the greatest predictive ability. The specification of the model for Katy Freeway travelers and the explanatory variables used in the model are defined in Table 4.1.

TABLE 4.1 Model Specification for Katy Freeway Travelers

Utility Function for Mode:	Variable Name	Description	Coefficient
All	trtime	The travel time savings obtained by using the HOV lane (minutes); the value was 0 for mode A, C, and G, because there were no travel time savings if the trip occurred on the GPLs.	β_9
	tollinc	Toll / (annual household income / 20000)	β_{10}
A (SOV on GPL Off-peak)	one	The alternative-specific constant	β_1
	apeak	The dummy variable used to describe if the traveler was driving during peak hours, yes = 1, no = 0	β_{11}
	aeduhs	The dummy variable used to describe if the traveler's education level was high school graduate, yes = 1, no = 0	β_{12}
B (SOV on HOV Off-peak)	one	The alternative-specific constant	β_2
	brtttime	The total travel time of the traveler's most recent trip (minutes)	β_{13}
	beduhs	The dummy variable used to describe if the traveler's education level was high school graduate, yes = 1, no = 0	β_{14}

TABLE 4.1 Continued

Utility Function for Mode:	Variable Name	Description	Coefficient
C (HOV-2 on GPL Peak)	one	The alternative-specific constant	β_3
	cacage	The dummy variable used to describe if the traveler's age was from 25 to 54 years old, yes = 1, no = 0	β_{15}
	ceducv	The dummy variable used to describe if the traveler's education level was some college / vocational, yes = 1, no = 0	β_{16}
	chtpm	The dummy variable used to describe if the traveler's household type was married without children, yes = 1, no = 0	β_{17}
D (SOV on HOV Peak)	one	The alternative-specific constant	β_4
	drtttime	The total travel time of the traveler's most recent trip (minutes)	β_{18}
	dtprec	The dummy variable used to describe if the traveler's trip purpose was recreational, yes =1, no = 0	β_{19}
E (Park & Ride Transit)	one	The alternative-specific constant	β_5
	ertttime	The total travel time of the traveler's most recent trip (minutes)	β_{20}
	eynage	The dummy variable used to describe if the traveler's age was from 16 to 24 years old, yes = 1, no = 0	β_{21}
	ehtpm	The dummy variable used to describe if the traveler's household type was married without children, yes = 1, no = 0	β_{22}
	envehs	The number of motor vehicles (including cars, vans, trucks, and motorcycles) available in the traveler's household	β_{23}
	eeducv	The dummy variable used to describe if the traveler's education level was some college / vocational, yes = 1, no = 0	β_{24}
	etpcom	The dummy variable used to describe if the traveler's trip purpose was commuting, yes =1, no = 0	β_{25}
	etprec	The dummy variable used to describe if the traveler's trip purpose was recreational, yes = 1, no = 0	β_{26}
F (HOV-2 on HOV Off-peak)	one	The alternative-specific constant	β_6
	ftprec	The dummy variable used to describe if the traveler's trip purpose was recreational, yes = 1, no = 0	β_{27}
G (SOV on GPL Peak)	one	The alternative-specific constant	β_7
	goffpk	The dummy variable used to describe if the traveler was driving during off-peak hours, yes = 1, no = 0	β_{28}
	gtpcom	The dummy variable used to describe if the traveler's trip purpose was commuting, yes =1, no = 0	β_{29}
	ghtpm	The dummy variable used to describe if the traveler's household type was married without children, yes = 1, no = 0	β_{30}
H (HOV-2 on HOV Peak)	one	The alternative-specific constant	β_8
	htpcom	The dummy variable used to describe if the traveler's trip purpose was commuting, yes =1, no = 0	β_{31}
I (HOV-3 on HOV Peak)	The utility function of mode I only contained the generic variables, trtime and tollinc, because mode I was specified as the reference mode		

The modeling calculation was conducted through LIMDEP 7.0, and the results from the Katy Freeway GPL travelers are summarized in Table 4.2.

TABLE 4.2 Modeling Results for Katy Freeway Travelers

Variable	Coefficient		Standard Error	T-stat	P-value
trtime	β_9	-0.072	0.007	-10.555	0.000
tollinc	β_{10}	-1.074	0.119	-9.061	0.000
apeak	β_{11}	-0.311	0.159	-1.951	0.051
aeduhs	β_{12}	-1.008	0.466	-2.166	0.030
brtttime	β_{13}	0.007	0.003	2.467	0.014
beduhs	β_{14}	-1.660	0.622	-2.669	0.008
cacage	β_{15}	-1.088	0.391	-2.784	0.005
ceducv	β_{16}	2.170	0.392	5.534	0.000
chtpm	β_{17}	0.853	0.406	2.099	0.036
drtttime	β_{18}	0.015	0.004	4.079	0.000
dtprec	β_{19}	-1.329	0.450	-2.954	0.003
ertttime	β_{20}	0.016	0.007	2.347	0.019
eynage	β_{21}	2.410	0.465	5.183	0.000
ehtpm	β_{22}	1.449	0.364	3.984	0.000
envehs	β_{23}	0.413	0.169	2.450	0.014
eeducv	β_{24}	0.955	0.389	2.456	0.014
etpcom	β_{25}	2.657	1.055	2.518	0.012
etprec	β_{26}	3.108	1.179	2.637	0.008
ftprec	β_{27}	-1.139	0.636	-1.790	0.073
goffpk	β_{28}	-0.229	0.133	-1.726	0.084
gtpcom	β_{29}	0.747	0.179	4.176	0.000
ghtpm	β_{30}	0.389	0.155	2.516	0.012
htpcom	β_{31}	1.516	0.512	2.958	0.003
constant_A	β_1	3.040	0.273	11.118	0.000
constant_B	β_2	1.728	0.329	5.254	0.000
constant_C	β_3	0.422	0.493	0.855	0.392
constant_D	β_4	0.845	0.347	2.435	0.015
constant_E	β_5	-5.179	1.257	-4.119	0.000
constant_F	β_6	0.236	0.292	0.806	0.420
constant_G	β_7	2.413	0.307	7.869	0.000
constant_H	β_8	-0.291	0.543	-0.536	0.592
$\rho^2 = 0.584$			Log likelihood function = -1686.5		
$\bar{\rho}^2 = 0.582$			Number of observations = 1845		

Therefore, the utility functions of all the travel mode options were as follows:

$$U_{\text{SOV-GPL-OP}} = 3.0400 - 1.0739 tollinc - 0.3105 apeak - 1.0080 aeduhs$$

$$U_{\text{SOV-HOV-OP}} = 1.7282 - 0.0724 trtime - 1.0739 tollinc + 0.0074 brtttime - 1.6600 beduhs$$

$$U_{\text{HOV2-GPL-P}} = 0.4217 - 1.0739 tollinc - 1.0881 cacage + 2.1702 ceducv + 0.8529 chtpm$$

$$U_{\text{SOV-HOV-P}} = 0.8449 - 0.0724 trtime - 1.0739 tollinc + 0.0146 drtttime - 1.3286 dtprec$$

$$U_{\text{P\&R-T}} = -5.1786 - 0.0724 trtime - 1.0739 tollinc + 0.0159 erttime + 2.4100 eynage + 1.4486 ehtpm + 0.4129 envehs + 0.9550 eeducv + 2.6567 etpcom + 3.1082 etprec$$

$$U_{\text{HOV2-HOV-OP}} = 0.2356 - 0.0724 trtime - 1.0739 tollinc - 1.1394 ftprec$$

$$U_{\text{SOV-GPL-P}} = 2.4131 - 1.0739 tollinc - 0.2289 goffpk + 0.7474 gtpcom + 0.3889 ghtpm$$

$$U_{\text{HOV2-HOV-P}} = -0.2909 - 0.0724 trtime - 1.0739 tollinc + 1.5158 htpcom$$

$$U_{\text{HOV3-HOV-P}} = -0.0724 trtime - 1.0739 tollinc$$

The numerical values of the utility functions depended on attributes of the available options and the socioeconomic characteristics of the individuals. It was assumed that the individual always chose the most preferred option which was the one with the highest utility function value. Therefore, variables with positive coefficients (β's) increased the likelihood of a traveler selecting that mode, and vice-versa.

4.1.2 Estimation of Potential SOV Demand for the HOV Lane on Katy Freeway

Next, the travelers' selection of HOV lanes and GPLs was investigated, and the probability of travelers choosing the mode of SOV on the HOV lane during off-peak periods (option B) was calculated.

The model estimated in Section 4.1.1 was used to predict the percentage of respondents who were originally driving on the GPLs but would choose to pay to use the HOV lane as SOV travelers during the off-peak periods. As discussed above, this decision was based on the assumption that the traveler chose the travel mode option that provided him or her with the greatest benefit/utility (or the least disutility). Since there were a large number of potential unknown variables, it was necessary to set the toll rate of other mode options to a constant value while letting the travel time savings and the toll rate of mode option B vary. Therefore, the tolls for option A, C, F, G, and I were all set equal to $0 as they required no toll. The toll for option D was set equal to $6 which was the middle value of the three alternatives from the survey ($4, $6, and $8). The bus fare for option E was set equal to $2.5 which was the average value of the two survey alternatives ($2 and $3). The toll for option H was set equal to $2 which was the middle value of the three survey alternatives ($1, $2, and $3). Different toll levels for option B were used with different travel time savings to calculate multiple likelihoods of travelers selecting to pay to use the HOV lane during the off-peak periods (option B) under different scenarios (combinations of toll level for option B and travel time savings for the HOV lane versus the GPL).

Note that options E, F, H, and I in the model were all on the HOV lane, but required extra time to complete the travel. This extra time included 5 minutes to pick up and drop off the single passenger for options E, F, and H; and 10 minutes to pick up and drop off multiple passengers for option I. Therefore, in the utility equations for choices E, F, H, and I, the values of "trtime" (the travel time savings due to HOV lane use) were reduced by 5 minutes and 10 minutes, respectively.

Based on the estimated utility functions, the utility of each mode option was calculated for both the 415 off-peak respondents and the 341 peak respondents who were driving on the Katy Freeway GPLs during the off-peak and the peak periods. The option with the highest utility value was recorded as each individual's predicted mode choice. Probabilities for travelers to choose option B (SOV on HOV off-peak) under different scenarios of travel time savings and toll levels for option B were then calculated for the off-peak respondents group and the peak respondents group. In this manner, the potential SOV demands from these two groups of travelers were estimated independently, as there could be considerable difference between the willingness of the peak and off-peak SOV GPL travelers to pay to use the HOV lane during the off-peak periods (see Table 4.3, Figure 4.1, Table 4.4, and Figure 4.2).

Not surprisingly, as the travel time savings decreased or the toll increased, the proportion of travelers who chose SOV-HOV-OP decreased. As shown in the following section, the relationship between these two variables indicated the traveler's value of travel time savings and was an important aspect in the mode choice of these travelers.

TABLE 4.3 Percentage of the Off-Peak Respondents Predicted to Use the Katy HOV Lane as SOV Travelers during the Off-Peak Periods

Travel Time Savings	Percentage of Respondents Choosing SOV on the HOV Lane Off-Peak						
	Toll Levels						
	$0	$1	$2	$3	$4	$5	$6
8 minutes	4	2	0	0	0	0	0
9 minutes	6	2	1	0	0	0	0
10 minutes	7	2	2	0	0	0	0
11 minutes	12	3	2	1	0	0	0
12 minutes	15	5	2	2	1	0	0
13 minutes	26	7	3	2	1	1	0
14 minutes	42	9	4	2	2	1	1
15 minutes	49	17	6	4	2	1	1
16 minutes	64	25	10	5	3	2	1
17 minutes	78	32	14	6	5	3	1
18 minutes	83	41	22	10	5	4	2
19 minutes	85	56	26	13	7	5	3
20 minutes	88	64	36	19	10	7	4
* Estimated using the data from Katy Freeway GPL off-peak travelers							

TABLE 4.4 Percentage of the Peak Respondents Predicted to Use the Katy HOV Lane as SOV Travelers during the Off-Peak Periods

Travel Time Savings	Percentage of Respondents Choosing SOV on the HOV Lane Off-Peak						
	Toll Levels						
	$0	$1	$2	$3	$4	$5	$6
8 minutes	6	0	0	0	0	0	0
9 minutes	7	2	0	0	0	0	0
10 minutes	9	3	0	0	0	0	0
11 minutes	11	4	1	0	0	0	0
12 minutes	13	7	2	0	0	0	0
13 minutes	16	9	3	1	0	0	0
14 minutes	21	10	5	2	0	0	0
15 minutes	24	12	9	3	1	0	0
16 minutes	32	14	9	6	3	0	0
17 minutes	43	16	10	7	3	2	0
18 minutes	50	20	12	9	5	3	1
19 minutes	60	32	14	9	6	4	2
20 minutes	73	38	20	11	8	5	3
* Estimated using the data from Katy Freeway GPL peak travelers							

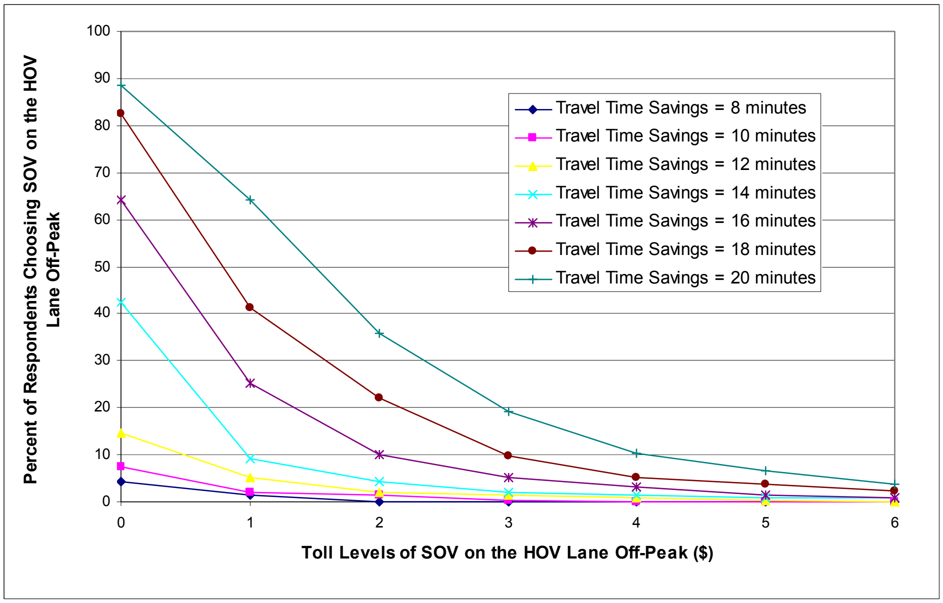


FIGURE 4.1 Potential SOV demand for driving on the Katy Freeway HOV lane during the off-peak periods from the off-peak GPL travelers.

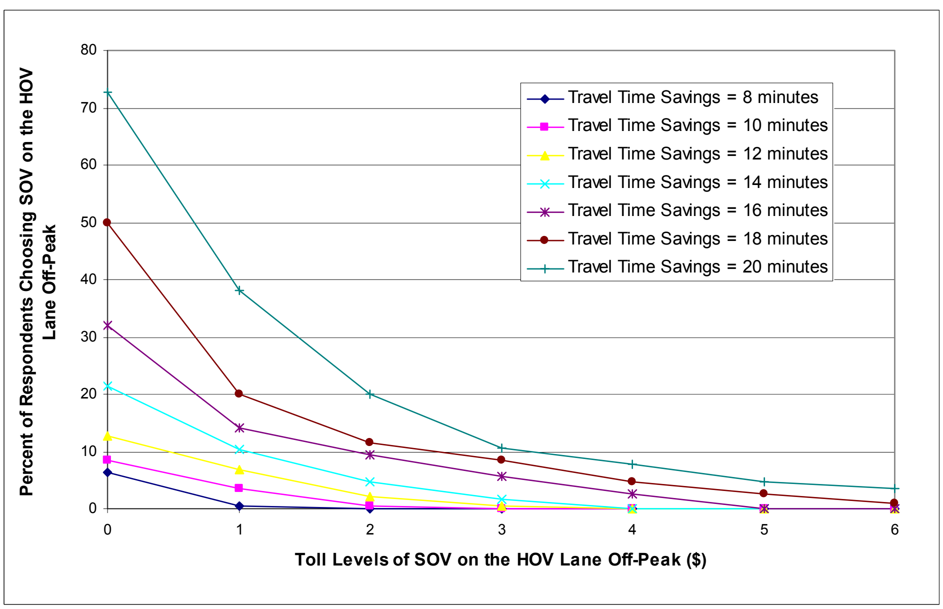


FIGURE 4.2 Potential SOV demand for driving on the Katy Freeway HOV lane during the off-peak periods from the peak GPL travelers.

4.1.3 Katy Freeway Traveler's Value of Travel Time Savings

As discussed in the review of the literature, travelers' VTTS often varies with their wage rates. To accommodate this in the models, the toll variable (*tollinc*) was defined as an integration of toll rate and traveler's annual household income:

$$tollinc = \frac{\text{Toll}}{\frac{\text{Annual Household Income}}{20000}} \tag{4.1}$$

The equation for calculating the VTTS was therefore:

$$\begin{aligned} VTTS &= \frac{\partial U / \partial trtime}{\partial U / \partial tollinc} \\ &= \frac{\beta_{trtime}}{\beta_{tollinc}} \times \frac{\text{Annual Household Income}}{20000} \times \frac{\text{60 minutes}}{\text{1 hour}} \end{aligned} \tag{4.2}$$

where, *VTTS* = the value of travel time savings, dollars/hour;

U = the utility function;

β_{trtime} = coefficient of the variable "*trtime*"; and

$\beta_{tollinc}$ = coefficient of the variable "*tollinc*".

In this survey, nine different annual household income levels were designated, and the average value of each household income level was used in Equation (4.2) to calculate the VTTS (see Table 4.5). The calculated VTTS for Katy Freeway data is summarized in Table 4.5 and Figure 4.3.

TABLE 4.5 Traveler's VTTS on the Katy Freeway

Household Income ($/year)		*VTTS* ($/hour)
Survey Range	Value Used	
<10,000	7,500	1.50

TABLE 4.5 Continued

Household Income ($/year)		*VTTS* ($/hour)
Survey Range	Value Used	
10,000-14,999	12,500	2.50
15,000-24,999	20,000	4.00
25,000-34,999	30,000	6.10
35,000-49,999	42,500	8.60
50,000-74,999	62,500	12.60
75,000-99,999	87,500	17.70
100,000-199,999	150,000	30.30
>200,000	250,000	50.50
Approximate % of Wage Rate		40%

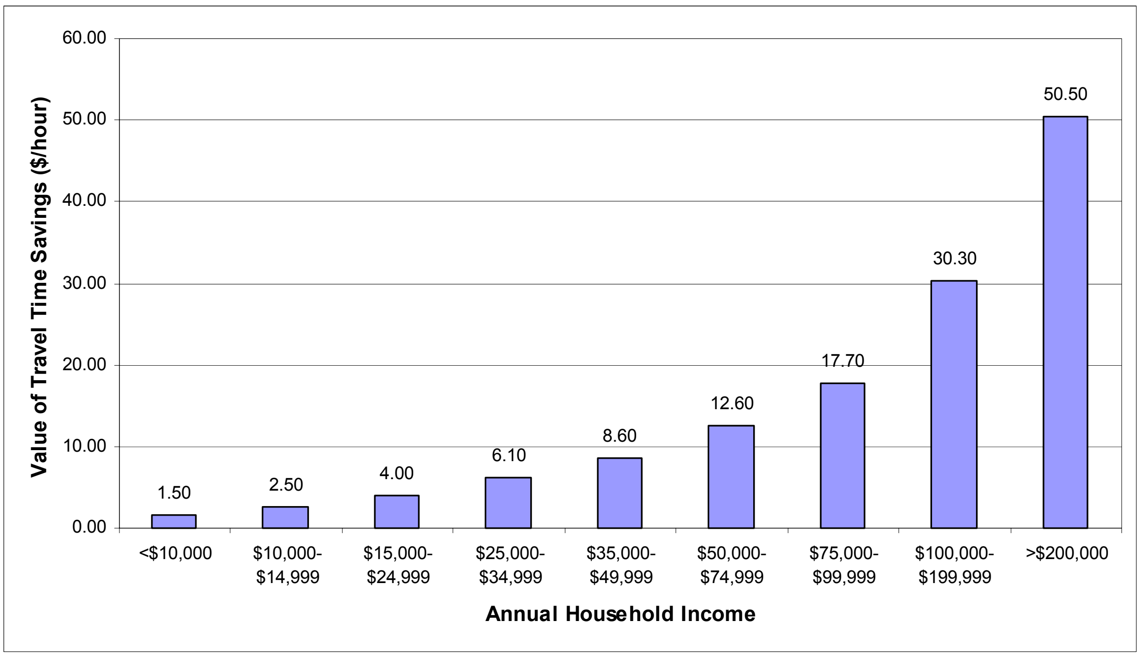


FIGURE 4.3 Traveler's VTTS on the Katy Freeway.

The calculated VTTS of Katy Freeway travelers was approximately 40 percent of their equivalent hourly wage. Note that the traveler's hourly wage rate was not recorded in the survey and a surrogate measure was used. In this case the annual household income was divided by 2000 work hours per year. This provided a fairly accurate estimate for households with a single wage earner, but overestimated wages in the case of multiple wage earner households. According to recent research (*18*, *22*), a traveler's VTTS generally ranged from 20 percent to 50 percent of the traveler's hourly wage rate. The VTTS found in this research was comparable with results of previous studies.

4.1.4 Katy Freeway Traveler's Value of Penalty for Changing Travel Schedule

As described in the literature review, the factors influencing a traveler's travel schedule included a penalty for changing one's travel schedule to a less preferred time of travel. For peak period travelers, the penalty for changing their travel schedule to off-peak periods included the penalties for early departure or late arrival. For off-peak period travelers, the penalty for changing their travel schedule to peak periods was primarily from travel time disutility. Theoretically, all travelers attempted to select the minimum disutility departure time to minimize the total cost of their trips, and this was the source of commuting traffic congestion. Even though a heterogenous group of travelers may have had departure times slightly different from one another, the work start times of many travelers were similar enough to cause traffic congestion. While many travelers chose to travel during peak periods to avoid the penalty for early departure and late arrival, there were also a number of travelers who chose to travel during off-peak periods to avoid the disutility for driving in traffic congestion (travel time disutility) because of their flexible work schedule.

There existed a monetary value (toll) that, if charged only during the peak periods, travelers who normally chose to travel during the peak time would be indifferent to changing their peak time of travel to an off-peak time of travel. Conversely, there also existed a monetary value that, if charged only during the off-peak periods, travelers who normally chose to travel during the off-peak time would be indifferent to changing their off-peak time of travel to a peak time of travel. This monetary value was defined as a traveler's value of penalty for changing travel schedule (VPCS). The equations for calculating the VPCS in this study were:

$$\begin{aligned} VPCS_{\text{Peak to Off-Peak}} &= \frac{\partial U_{\text{SOV-GPL-OP}} / \partial apeak}{\partial U_{\text{SOV-GPL-OP}} / \partial tollinc} \\ &= \frac{\beta_{apeak}}{\beta_{tollinc}} \times \frac{\text{Annual Household Income}}{20000} \end{aligned} \tag{4.3}$$

$$\begin{aligned} VPCS_{\text{Off-Peak to Peak}} &= \frac{\partial U_{\text{SOV-GPL-P}} / \partial goffpk}{\partial U_{\text{SOV-GPL-P}} / \partial tollinc} \\ &= \frac{\beta_{goffpk}}{\beta_{tollinc}} \times \frac{\text{Annual Household Income}}{20000} \end{aligned} \tag{4.4}$$

where, $VPCS_{\text{Peak to Off-Peak}}$ = the value of penalty for changing travel schedule from the preferred peak period to the off-peak period (dollars);

$VPCS_{\text{Off-Peak to Peak}}$ = the value of penalty for changing travel schedule from the preferred off-peak period to the peak period (dollars);

$U_{\text{SOV-GPL-OP}}$ = the utility function of mode option A (SOV on GPL off-peak);

$U_{\text{SOV-GPL-P}}$ = the utility function of mode option G (SOV on GPL peak);

β_{apeak} = coefficient of the variable "apeak";

β_{goffpk} = coefficient of the variable "goffpk"; and

$\beta_{tollinc}$ = coefficient of the variable "tollinc".

The interpretations of $VPCS_{\text{Peak to Off-Peak}}$ and $VPCS_{\text{Off-Peak to Peak}}$ were as follows. $VPCS_{\text{Peak to Off-Peak}}$ was the monetary amount that would be charged during the peak periods at which travelers who normally chose to travel in the peak time would be indifferent to changing their peak time of travel to an off-peak time of travel. Conversely, $VPCS_{\text{Off-Peak to Peak}}$ was the monetary amount that would be charged during the off-peak periods at which travelers who normally chose to travel in the off-peak time would be indifferent to changing their off-peak time of travel to a peak time of travel. These values, along with VTTS, play an important role in determining the mode travelers selected as option B (SOV on the HOV lane during the off-peak periods) required peak period travelers to alter their departure time. The calculated VPCS for Katy Freeway travelers is summarized in Table 4.6 and Figure 4.4.

TABLE 4.6 Traveler's VPCS on the Katy Freeway

Household Income ($/year)		$VPCS_{\text{Peak to Off-Peak}}$ ($)	$VPCS_{\text{Off-Peak to Peak}}$ ($)
Survey Range	Value Used		
<10,000	7,500	0.10	0.10
10,000-14,999	12,500	0.20	0.10
15,000-24,999	20,000	0.30	0.20
25,000-34,999	30,000	0.40	0.30
35,000-49,999	42,500	0.60	0.50
50,000-74,999	62,500	0.90	0.70
75,000-99,999	87,500	1.30	0.90
100,000-199,999	150,000	2.20	1.60
>200,000	250,000	3.60	2.70
Approximate % of Wage Rate		3%	2%

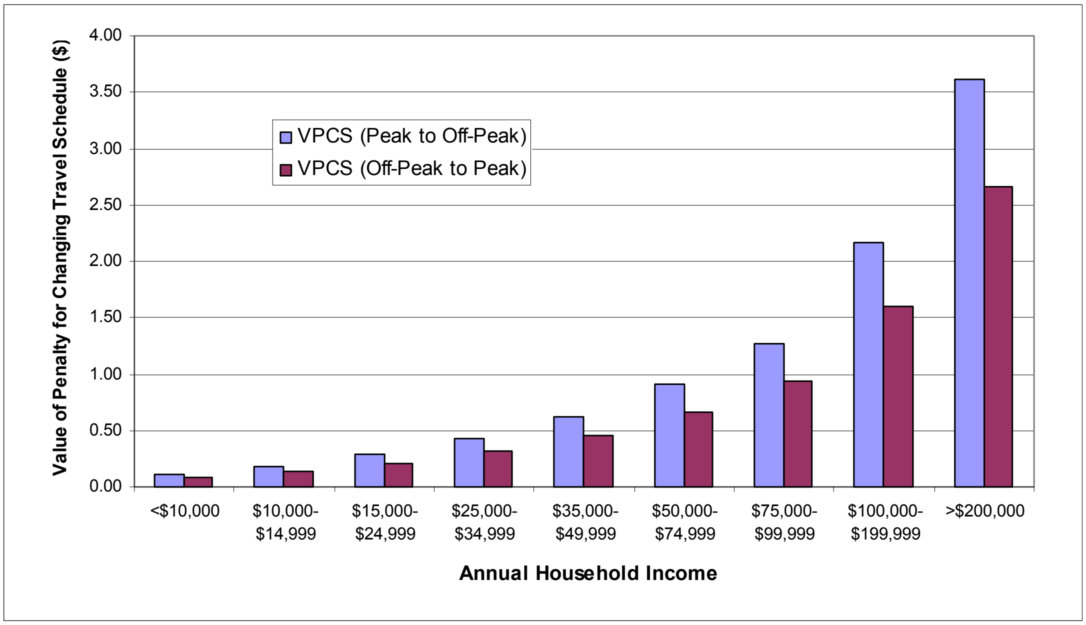


FIGURE 4.4 Traveler's VPCS on the Katy Freeway.

For example, consider a traveler with an annual household income of $75,000 to $99,999 who originally traveled during the peak periods on the Katy Freeway. A toll of less than $1.30 added to peak period would cause no change in this traveler's time of departure. However, a peak period toll in excess of $1.30 would cause this traveler to switch to a toll-free off-peak period. Conversely, if this traveler originally traveled during the off-peak periods, a toll of more than $0.90 during the off-peak would make him or her change this travel schedule from the off-peak to the peak period.

4.2 Modeling Analysis and Results: Northwest Freeway Travelers

A similar analysis was conducted using the data collected from the Northwest Freeway travelers. All the modeling processes were similar to those employed to estimate the model of Katy Freeway travelers. The specification of the model for the Northwest Freeway travelers and the explanatory variables used in the model are defined in Table 4.7, and the modeling results are summarized in Table 4.8.

TABLE 4.7 Model Specification for Northwest Freeway Travelers

Utility Function for Mode:	Variable Name	Description	Coefficient
All	trtime	The travel time savings obtained by using the HOV lane (minutes); the value was 0 for mode A, C, and G, because there were no travel time savings if the trip occurred on the GPLs.	β_9
	tollinc	Toll / (annual household income / 20000)	β_{10}
A (SOV on GPL Off-peak)	one	The alternative-specific constant	β_1
	apeak	The dummy variable used to describe if the traveler was driving during peak hours, yes = 1, no = 0	β_{11}
	ahtpm	The dummy variable used to describe if the traveler's household type was married without children, yes = 1, no = 0	β_{12}
	atsqr	The total time between midnight and the traveler's trip start time (minutes)	β_{13}
	ahtpmc	The dummy variable used to describe if the traveler's household type was married with child(ren), yes = 1, no = 0	β_{14}
	ahsize	The number of people in the traveler's household	β_{15}
B (SOV on HOV Off-peak)	one	The alternative-specific constant	β_2
	bhsize	The number of people in the traveler's household	β_{16}
	btsqr	The total time between midnight and the traveler's trip start time (minutes)	β_{17}
	bsnage	The dummy variable used to describe if the traveler's age was 55 years old or above, yes = 1, no = 0	β_{18}
C (HOV-2 on GPL Peak)	one	The alternative-specific constant	β_3
	csex	The dummy variable used to describe if the traveler's gender was male or female, male = 1, female = 0	β_{19}
	cnvehs	The number of motor vehicles (including cars, vans, trucks, and motorcycles) available in the traveler's household	β_{20}
D (SOV on HOV Peak)	one	The alternative-specific constant	β_4
	dacage	The dummy variable used to describe if the traveler's age was from 25 to 54 years old, yes = 1, no = 0	β_{21}
	deducg	The dummy variable used to describe if the traveler's education level was college graduate, yes = 1, no = 0	β_{22}
	docppr	The dummy variable used to describe if the traveler's occupation was professional/managerial, yes =1, no = 0	β_{23}
E (Park & Ride Transit)	one	The alternative-specific constant	β_5
	ealert	The dummy variable used to describe if the traveler allowed extra travel time due to possible traffic congestion, yes = 1, no = 0	β_{24}
	esnage	The dummy variable used to describe if the traveler's age was 55 years old or above, yes = 1, no = 0	β_{25}
	ehtpmc	The dummy variable used to describe if the traveler's household type was married with child(ren), yes = 1, no = 0	β_{26}
	eocpad	The dummy variable used to describe if the traveler's occupation was administrative/clerical, yes =1, no = 0	β_{27}

TABLE 4.7 Continued

Utility Function for Mode:	Variable Name	Description	Coefficient
F (HOV-2 on HOV Off-peak)	one	The alternative-specific constant	β_6
	fsex	The dummy variable used to describe if the traveler's gender was male or female, male = 1, female = 0	β_{28}
	feducg	The dummy variable used to describe if the traveler's education level was college graduate, yes = 1, no = 0	β_{29}
G (SOV on GPL Peak)	one	The alternative-specific constant	β_7
	goffpk	The dummy variable used to describe if the traveler was driving during off-peak hours, yes = 1, no = 0	β_{30}
	ghtpua	The dummy variable used to describe if the traveler's household type was unrelated adults, yes = 1, no = 0	β_{31}
H (HOV-2 on HOV Peak)	one	The alternative-specific constant	β_8
	htsqr	The total time between midnight and the traveler's trip start time (minutes)	β_{32}
I (HOV-3 on HOV Peak)	The utility function of mode I only contained the generic variables, trtime and tollinc, because mode I was specified as the reference mode		

TABLE 4.8 Modeling Results for Northwest Freeway Travelers

Variable	Coefficient		Standard Error	T-stat	P-value
trtime	β_9	0.070	0.006	-12.428	0.000
tollinc	β_{10}	-0.901	0.098	-9.162	0.000
apeak	β_{11}	-0.373	0.130	-2.866	0.004
ahtpm	β_{12}	0.557	0.157	3.542	0.000
atsqr	β_{13}	0.001	0.000	4.245	0.000
ahtpmc	β_{14}	0.661	0.177	3.737	0.000
ahsize	β_{15}	-0.155	0.069	-2.243	0.025
bhsize	β_{16}	-0.260	0.066	-3.919	0.000
btsqr	β_{17}	0.001	0.000	4.110	0.000
bsnage	β_{18}	-0.451	0.208	-2.169	0.030
csex	β_{19}	-1.145	0.333	-3.434	0.001
cnvehs	β_{20}	0.471	0.122	3.865	0.000
dacage	β_{21}	0.695	0.221	3.141	0.002
deducg	β_{22}	-0.501	0.154	-3.258	0.001
docppr	β_{23}	0.384	0.166	2.305	0.021
ealert	β_{24}	-0.875	0.254	-3.450	0.001
esnage	β_{25}	-1.493	0.529	-2.824	0.005
ehtpmc	β_{26}	-0.625	0.255	-2.449	0.014
eocpad	β_{27}	0.759	0.326	2.329	0.020
fsex	β_{28}	-0.480	0.206	-2.328	0.020
feducg	β_{29}	-0.565	0.209	-2.702	0.007
goffpk	β_{30}	-0.185	0.110	-1.689	0.091
ghtpua	β_{31}	-1.436	0.342	-4.202	0.000

TABLE 4.8 Continued

Variable	Coefficient		Standard Error	T-stat	P-value
htsqr	β_{32}	0.001	0.001	2.581	0.010
constant_A	β_1	1.971	0.328	6.016	0.000
constant_B	β_2	1.510	0.350	4.313	0.000
constant_C	β_3	-0.456	0.416	-1.096	0.273
constant_D	β_4	0.188	0.308	0.612	0.541
constant_E	β_5	0.995	0.287	3.467	0.001
constant_F	β_6	0.634	0.236	2.693	0.007
constant_G	β_7	2.736	0.189	14.478	0.000
constant_H	β_8	-0.993	0.480	-2.068	0.039
$\rho^2 = 0.584$			Log likelihood function = -2589.7		
$\bar{\rho}^2 = 0.583$			Number of observations = 2836		

The utility functions of the Northwest Freeway model were as follows:

$$U_{\text{SOV-GPL-OP}} = 1.9709 - 0.9008 tollinc - 0.3735 apeak + 0.5573 ahtpm + 0.0011 atsqr + 0.6607 ahtpmc - 0.1545 ahsize$$

$$U_{\text{SOV-HOV-OP}} = 1.5096 - 0.0698 trtime - 0.9008 tollinc - 0.2603 bhsize + 0.0012 btsqr - 0.4511 bsnage$$

$$U_{\text{HOV2-GPL-P}} = -0.4560 - 0.9008 tollinc - 1.1448 csex + 0.4714 cnvehs$$

$$U_{\text{SOV-HOV-P}} = 0.1883 - 0.0698 trtime - 0.9008 tollinc + 0.6953 dacage - 0.5008 deducg + 0.3835 docppr$$

$$U_{\text{P\&R-T}} = 0.9952 - 0.0698 trtime - 0.9008 tollinc - 0.8752 ealert - 1.4931 esnage - 0.6247 ehtpmc + 0.7590 eocpad$$

$$U_{\text{HOV2-HOV-OP}} = 0.6343 - 0.0698 trtime - 0.9008 tollinc - 0.4796 fsex - 0.5647 feducg$$

$$U_{\text{SOV-GPL-P}} = 2.7359 - 0.9008 tollinc + 0.1852 gpeak - 1.4360 ghtpua$$

$$U_{\text{HOV2-HOV-P}} = -0.9933 - 0.0698 trtime - 0.9008 tollinc + 0.0013 htsqr$$

$$U_{\text{HOV3-HOV-P}} = -0.0698 trtime - 0.9008 tollinc$$

Based on the estimated utility functions, the utility of each mode option was calculated for both the 453 off-peak respondents and the 426 peak respondents who were driving on Northwest Freeway GPLs during the off-peak and the peak periods. The option with the highest utility value was recorded as each individual's predicted trip mode choice. Probabilities for travelers to choose option B (SOV on HOV off-peak) under different scenarios of travel time savings and toll levels for option B were then calculated for the off-peak respondents group and the peak respondents group, so the potential SOV demand from these two groups of travelers were estimated separately (see Table 4.9, Figure 4.5, Table 4.10, and Figure 4.6).

TABLE 4.9 Percentage of the Off-Peak Respondents Predicted to Use the Northwest HOV Lane as SOV Travelers during the Off-Peak Periods

Travel Time Savings	**Percentage of Respondents Choosing SOV on the HOV Lane Off-Peak**						
	Toll Levels						
	$0	**$1**	**$2**	**$3**	**$4**	**$5**	**$6**
8 minutes	3	0	0	0	0	0	0
9 minutes	6	0	0	0	0	0	0
10 minutes	6	1	0	0	0	0	0
11 minutes	7	2	0	0	0	0	0
12 minutes	8	3	0	0	0	0	0
13 minutes	9	3	1	0	0	0	0
14 minutes	11	4	2	1	0	0	0
15 minutes	12	5	2	1	0	0	0
16 minutes	14	7	3	2	1	0	0
17 minutes	25	8	4	2	1	0	0
18 minutes	27	10	4	2	1	1	0
19 minutes	37	16	5	2	2	1	1
20 minutes	46	20	10	3	2	1	1
* Estimated using the data from Northwest Freeway GPL off-peak travelers							

TABLE 4.10 Percentage of the Peak Respondents Predicted to Use the Northwest HOV Lane as SOV Travelers during the Off-Peak Periods

Travel Time Savings	Percentage of Respondents Choosing SOV on the HOV Lane Off-Peak						
	Toll Levels						
	$0	$1	$2	$3	$4	$5	$6
8 minutes	8	3	1	0	0	0	0
9 minutes	8	3	1	1	0	0	0
10 minutes	8	4	1	1	0	0	0
11 minutes	14	4	1	1	0	0	0
12 minutes	20	5	2	1	0	0	0
13 minutes	21	11	3	1	1	0	0
14 minutes	26	14	4	1	1	0	0
15 minutes	31	15	8	2	1	1	0
16 minutes	32	23	9	3	1	1	0
17 minutes	37	25	13	8	1	1	1
18 minutes	49	26	18	8	6	1	1
19 minutes	50	30	19	9	7	2	1
20 minutes	54	36	23	16	8	6	1

* Estimated using the data from Northwest Freeway GPL peak travelers

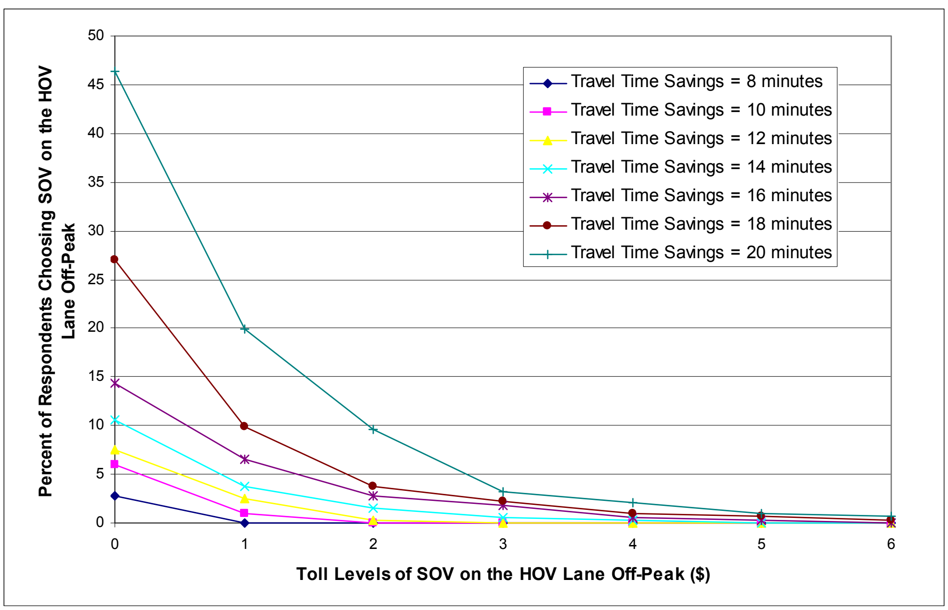


FIGURE 4.5 Potential SOV demand for driving on the Northwest Freeway HOV lane during the off-peak periods from the off-peak GPL travelers.

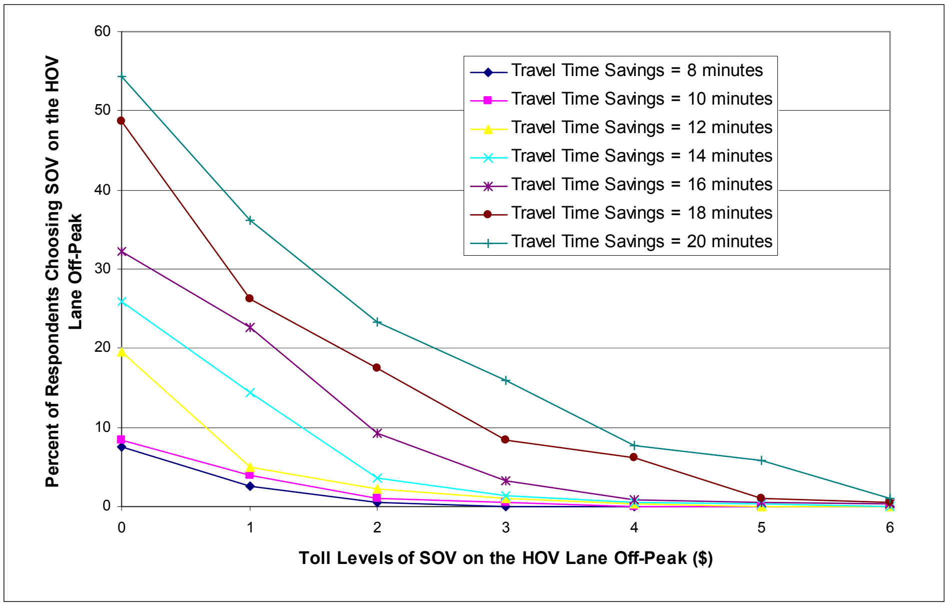


FIGURE 4.6 Potential SOV demand for driving on the Northwest Freeway HOV lane during the off-peak periods from the peak GPL travelers.

The calculated VTTS for Northwest Freeway travelers is summarized in Table 4.11 and Figure 4.7. The calculated VPCS for Northwest Freeway travelers is summarized in Table 4.12 and Figure 4.8.

TABLE 4.11 Traveler's VTTS on the Northwest Freeway

Household Income ($/year)		*VTTS* ($/hour)
Survey Range	Value Used	
<10,000	7,500	1.70
10,000-14,999	12,500	2.90
15,000-24,999	20,000	4.70
25,000-34,999	30,000	7.00
35,000-49,999	42,500	9.90
50,000-74,999	62,500	14.50
75,000-99,999	87,500	20.40
100,000-199,999	150,000	34.90
>200,000	250,000	58.10
Approximate % of Wage Rate		46%

TABLE 4.12 Traveler's VPCS on the Northwest Freeway

Household Income ($/year)		$VPCS_{\text{Peak to Off-Peak}}$ ($)	$VPCS_{\text{Off-Peak to Peak}}$ ($)
Survey Range	Value Used		
<10,000	7,500	0.20	0.10
10,000-14,999	12,500	0.30	0.10
15,000-24,999	20,000	0.40	0.20
25,000-34,999	30,000	0.60	0.30
35,000-49,999	42,500	0.90	0.40
50,000-74,999	62,500	1.30	0.60
75,000-99,999	87,500	1.80	0.90
100,000-199,999	150,000	3.10	1.50
>200,000	250,000	5.20	2.60
Approximate % of Wage Rate		4%	2%

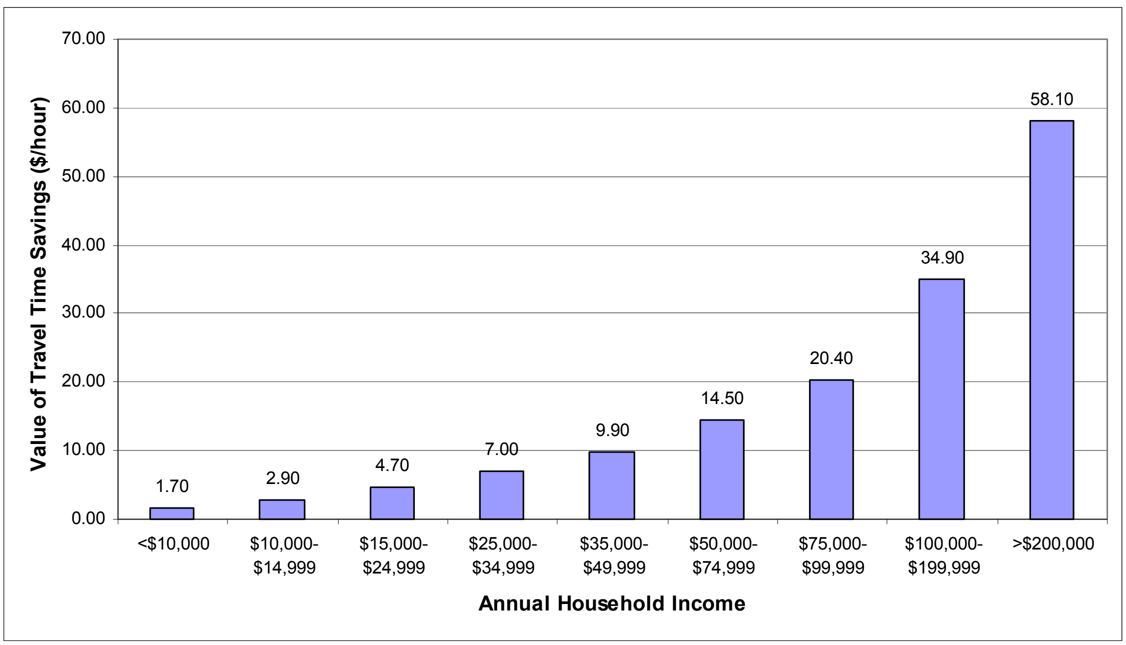


FIGURE 4.7 Traveler's VTTS on the Northwest Freeway.

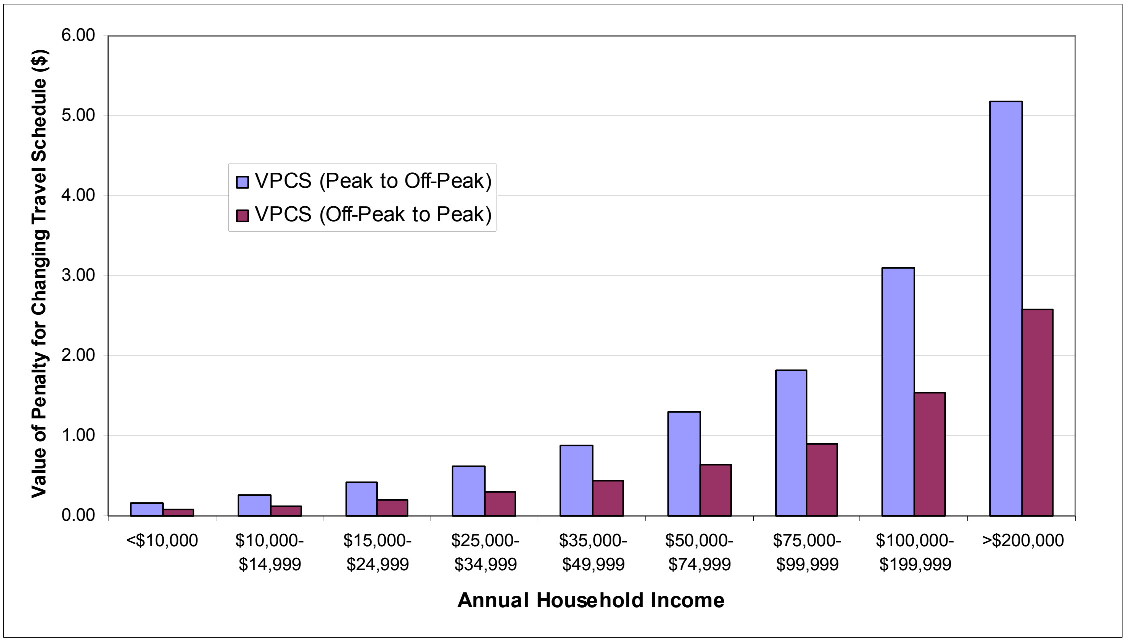


FIGURE 4.8 Traveler's VPCS on the Northwest Freeway.

4.3 Discussion of Modeling Results

Next, the modeling results from the travelers on the Katy Freeway and the Northwest Freeway were compared. Given the same travel time savings and toll, the percentage of travelers who were willing to switch their travel mode to SOV-HOV-OP on the Katy Freeway was higher than on the Northwest Freeway (see Figure 4.9).

To determine why Katy Freeway travelers were more likely to choose to travel as SOV travelers on the HOV lane for a toll, the VTTS on the two freeways were compared. Travelers on the Northwest Freeway had a slightly higher VTTS (as a percent of wage rate) than the travelers on the Katy Freeway, as illustrated in Figure 4.10. Theoretically, travelers with higher VTTSs would be more willing to pay to use the HOT lane. However, travelers on Northwest Freeway had higher VTTSs, but were still less willing to pay to use the HOT lane compared with the travelers on Katy Freeway. To explain this conflicting result, the distribution of the population by annual household income levels on these two corridors was examined (see Figure 4.11). The distribution of travelers by household income on the Katy Freeway and the Northwest Freeway were similar, except that the percentage of travelers with annual household incomes of $200,000 or more was almost three times larger on the Katy Freeway.

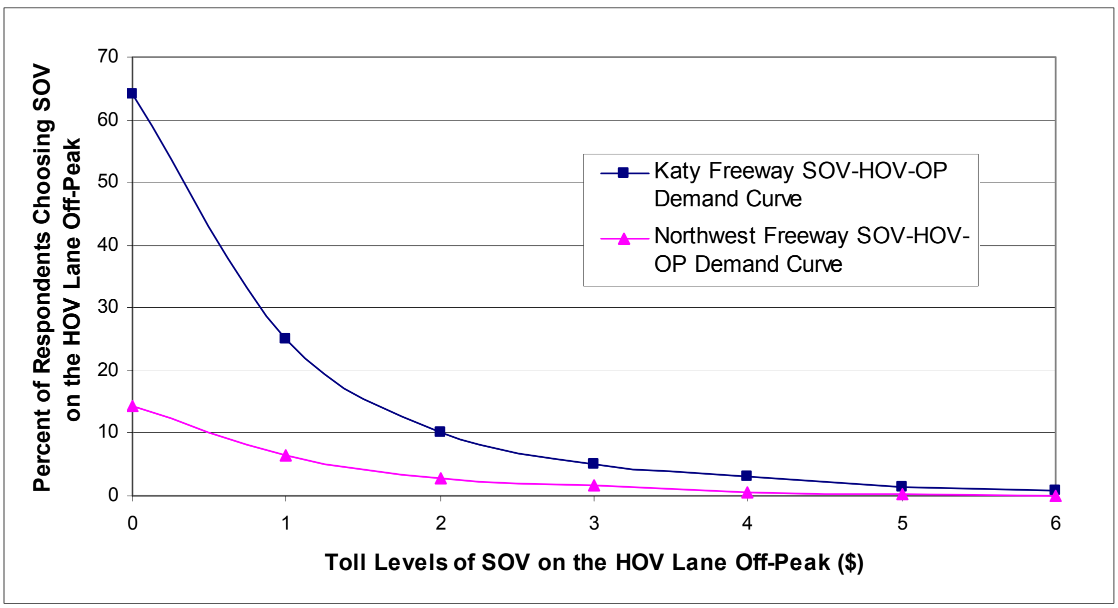


FIGURE 4.9 Example comparison of the SOV-HOV-OP demand curves (using 16-minute travel time savings and only for the off-peak travelers).

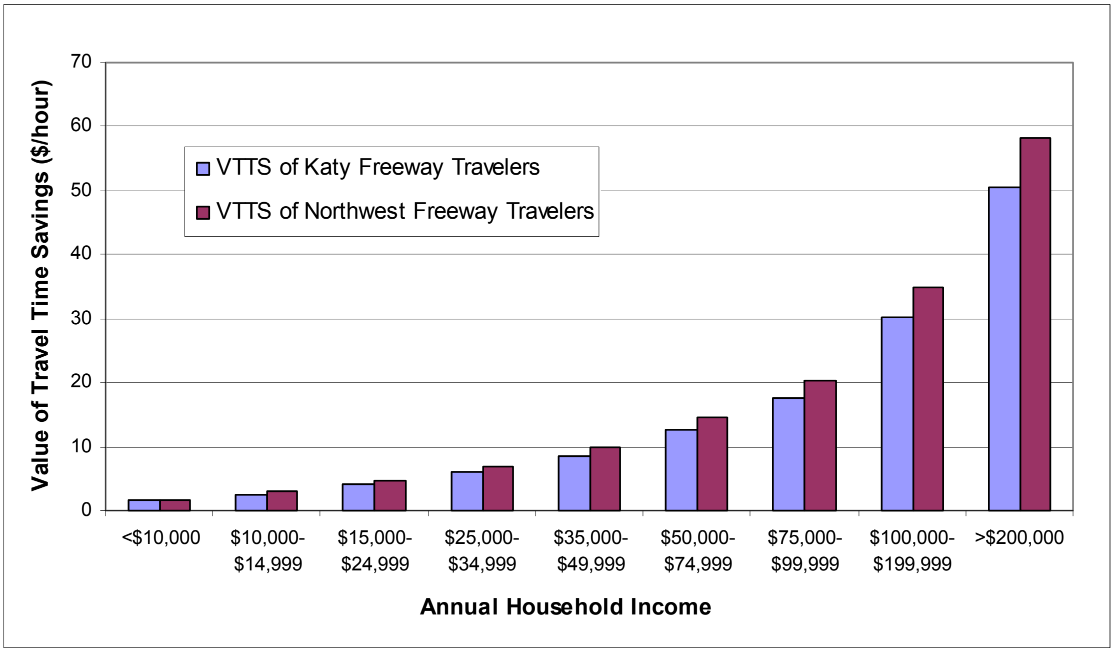


FIGURE 4.10 Comparison of VTTSs on Katy Freeway and Northwest Freeway.

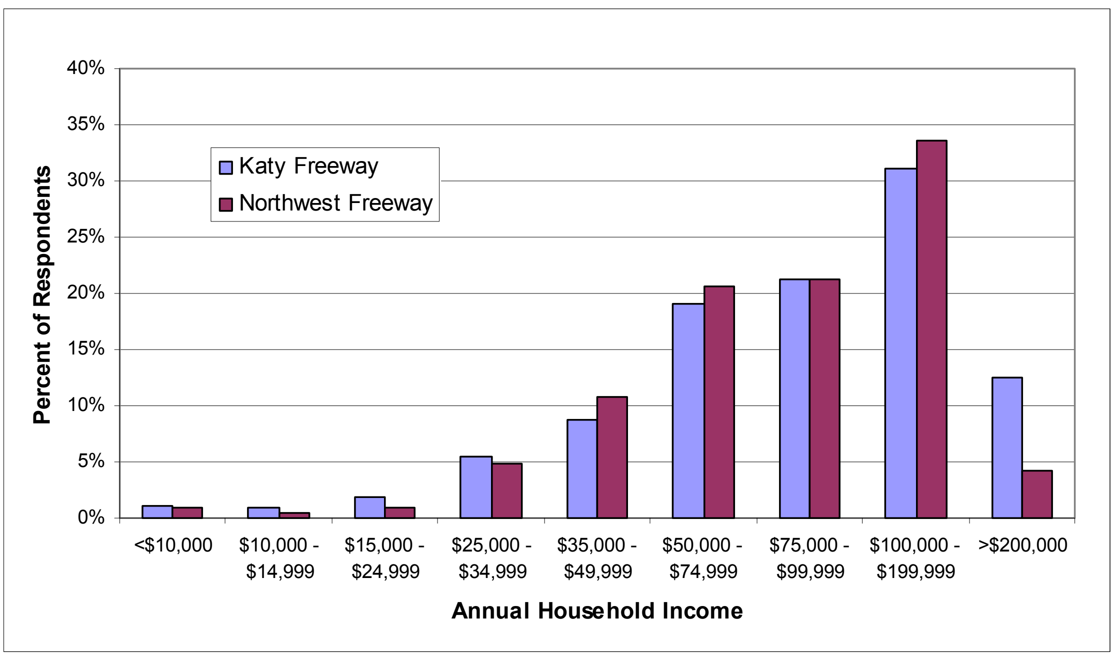


FIGURE 4.11 Comparison of household incomes.

To examine what impact these high income travelers would have on the models, the different mode choice behaviors between the travelers whose annual household incomes were $200,000 or more and the other travelers with lower incomes was examined for both Katy Freeway and Northwest Freeway travelers (see Figure 4.12 and Figure 4.13). The travelers with higher incomes were more likely to choose the tolling mode options. This may partially explain why GPL travelers on the Katy Freeway were more willing to pay to use the HOV lane as SOV travelers during off-peak periods. A larger percentage of those travelers had very high VTTS and were significantly more likely to choose travel options that saved travel time despite a toll. Another potential explanation may be based on the comparison of Katy Freeway and Northwest Freeway traveler's VPCSs, as illustrated in Figure 4.14 and Figure 4.15.

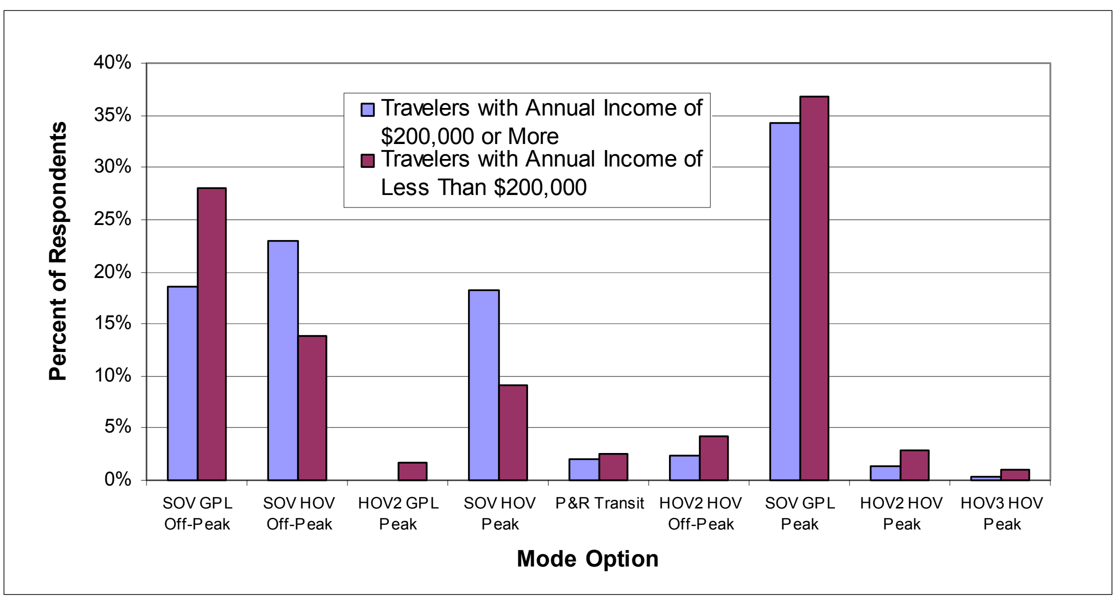


FIGURE 4.12 Comparison of different income level respondents' mode choices on the Katy Freeway.

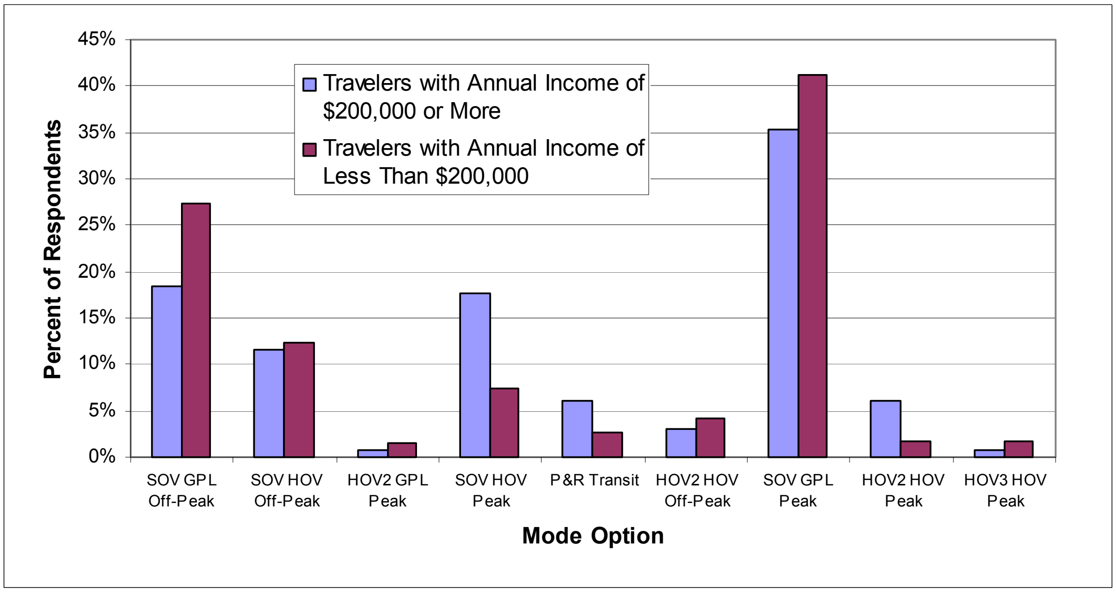


FIGURE 4.13 Comparison of different income level respondents' mode choices on the Northwest Freeway.

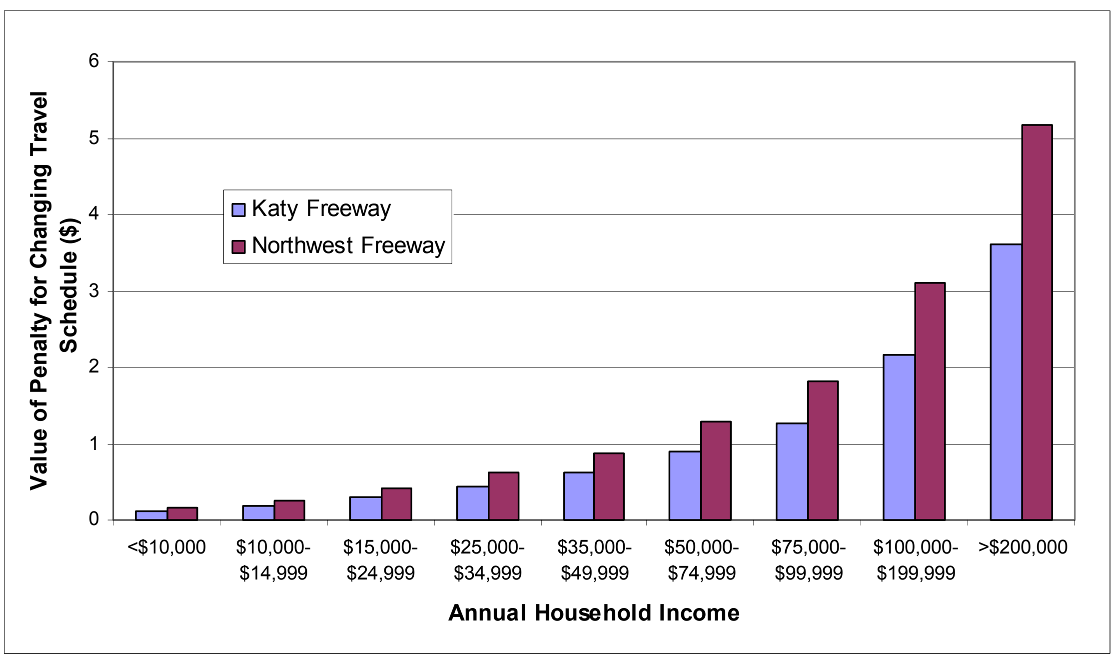


FIGURE 4.14 VPCS$_{\text{Peak to Off-Peak}}$ on the Katy Freeway and the Northwest Freeway.

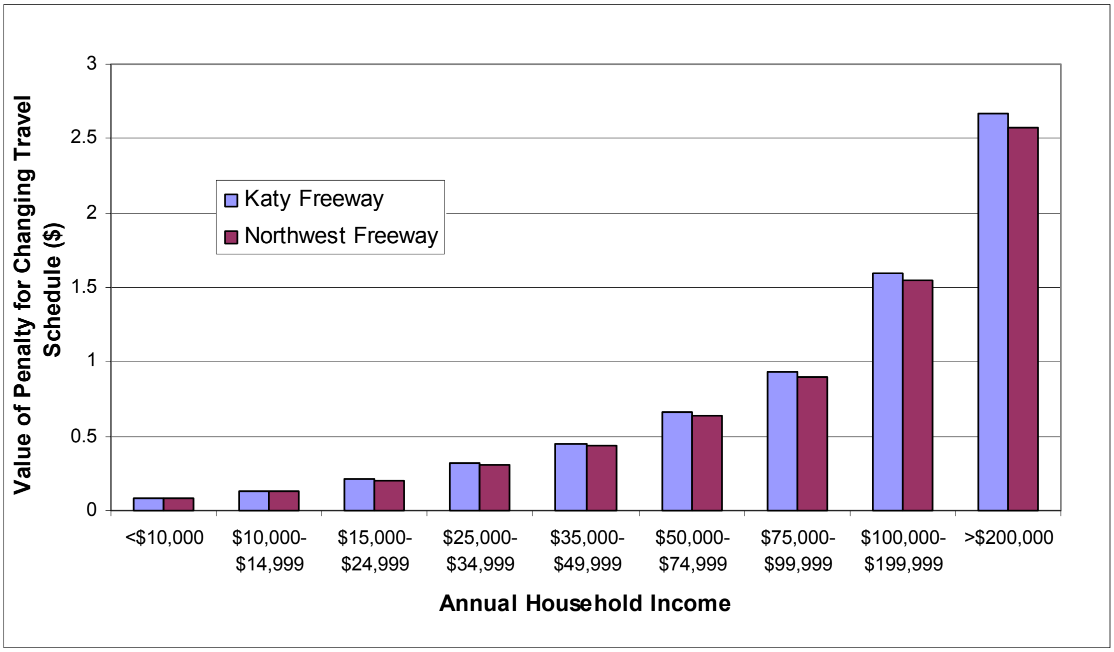


FIGURE 4.15 $VPCS_{Off\text{-}Peak\ to\ Peak}$ on the Katy Freeway and the Northwest Freeway.

Travelers on the Northwest Freeway had higher $VPCS_{Peak\ to\ Off\text{-}Peak}$ and lower $VPCS_{Off\text{-}Peak\ to\ Peak}$ than travelers on the Katy Freeway. Therefore, it could be inferred that travelers on the Northwest Freeway found switching their time of travel from the peak period more arduous (had a higher disutility) than travelers on the Katy Freeway. This was not surprising as travel during the off-peak periods on the Katy Freeway involved more congestion than on the Northwest Freeway. This was likely another reason why travelers on the Katy Freeway were more willing to pay to use the HOV lane as SOV travelers during the off-peak periods.

4.4 Potential HOV Lane Off-Peak Pricing Levels

Based on the estimated models, travel time savings data, and traffic volumes on the HOV lanes and GPLs, the optimal HOV lane pricing scheme for SOV travelers during the off-peak periods was calculated. Data from 2003 containing average travel time, travel time savings, and traffic volumes for both the Katy Freeway and the Northwest Freeway HOV lane corridors were obtained from another Houston QuickRide study conducted by the Texas Transportation Institute (TTI) (*70*). Based on a limited number of data samples from the two HOV lanes, approximately 1600 vehicles per hour could use the lanes prior to significant degradation of speed (*70*). For this research, the maximum number of vehicles on the HOV lane was assumed to be 1500 per hour. Limiting additional SOV demand such that SOVs did not cause lane volumes to exceed 1500 vehicles per hour ensured HOV lane congestion due to excessive SOV volumes would not occur. Subtracting the current HOV lane volumes from 1500 vehicles per hour yielded the volume of potential SOVs needed on the HOV lane to make full use of the available capacity. Based on average vehicle occupancy counts conducted on the two freeways for the QuickRide project, approximately 90 percent of all vehicles on the GPLs were SOVs (*70*). The available SOV volume on the GPLs was therefore 90 percent of the total GPL volume.

Note that the GPL travelers from the off-peak periods would possibly be interested in switching from the GPLs to the HOV lane while still traveling in the same time schedule. It would also be possible for the peak period GPL travelers to change their travel mode to SOV on the HOV lane during the off-peak periods. Therefore, it was necessary to estimate the potential SOV demand from the off-peak GPL travelers and the peak GPL travelers separately, and the sum of them yielded the total SOV demand for using the HOV lane during the off-peak periods. It was assumed that peak GPL travelers would only switch to the off-peak times when there existed extra capacity on the HOV lane and was close to their previous time of travel, and therefore they did not have to change time of travel too much while enjoying the travel time savings for a toll. For example, the morning peak periods (6:45 a.m. to 8:00 a.m.) contained five 15-minute intervals. It was assumed that travelers who used to travel within 6:45-7:00 a.m. and 7:00-7:15 a.m. intervals would switch their travel schedules to 6:15-6:30 a.m. and 6:30-6:45 a.m. intervals, respectively (as long as traveling during these new time intervals could save travel time and there was extra capacity on the HOV lane). Similarly, it was assumed that travelers who used to travel within 7:15-7:30 a.m., 7:30-7:45 a.m., and 7:45-8:00 a.m. intervals would switch their travel schedules to 8:00-8:15 a.m., 8:15-8:30 a.m., and 8:30-8:45 a.m. intervals, respectively. Similarly, for the four 15-minute intervals in the afternoon peak periods (17:00 p.m. to 18:00 p.m.), it was assumed that travelers who used to travel within 17:00-17:15 p.m., 17:15-17:30 p.m., 17:30-17:45 p.m., and 17:45-18:00 p.m. intervals would switch their travel schedules to 16:30-16:45 p.m., 16:45-17:00 p.m., 18:00-18:15 p.m., and 18:15-18:30 p.m. intervals, respectively.

If the off-peak time interval, t, was not considered close to any peak time interval, t', the potential SOV demand in that time interval t (N_{SOVt}) was assumed to include only the GPL SOV vehicles switching from the same off-peak time interval

(N_{OPt}). Given the GPL volume in time interval t (V_{GPLt}) and the predicted percentage of SOVs switching from the GPLs in time interval t (P_{SOVt}), N_{SOVt} could be calculated by:

$$N_{SOVt} = N_{OPt} = V_{GPLt} \times P_{SOVt}, \tag{4.5}$$

where, N_{SOVt} = potential SOV demand during time interval t (vehicles);

N_{OPt} = number of GPL off-peak SOV vehicles switching to the HOV lane during time interval t (vehicles);

V_{GPLt} = number of vehicles on GPLs during time interval t traveling in the correct direction (vehicles); and

P_{SOVt} = predicted percentage of SOVs switching from GPLs during time interval t (%).

P_{SOVt} could be estimated from the discrete choice model using the travel time savings at time t (TTS_t) and some hypothesized toll levels. In this case, only off-peak respondents' data were estimated in the model. Different toll levels were tested until P_{SOVt} equaled the maximum allowable percentage of SOVs that could switch to the HOV lane during time interval t ($P_{maxSOVt}$). The equation to calculate $P_{maxSOVt}$ was:

$$P_{maxSOVt} = \frac{\min\{V_{SOVroomt}, V_{SOVsupplyt}\}}{V_{GPLt}}, \tag{4.6}$$

where, $P_{maxSOVt}$ = maximum allowable percentage of SOVs switching to the HOV lane during time interval t (%);

$V_{SOVroomt}$ = SOV volume required to fill the HOV lane during time interval t (vehicles); and

$V_{SOVsupplyt}$ = SOV volume available on the GPLs to be added into the HOV lane during time interval t (vehicles).

The equation to calculate $V_{SOVroomt}$ was:

$$V_{SOVroomt} = 1500\text{ vph} \times t - V_{HOVt}, \tag{4.7}$$

where, V_{HOVt} = number of vehicles on HOV lane during time interval t (vehicles).

If $V_{SOVroomt}$ was found to be equal to or less than 0, the value of $P_{maxSOVt}$ was also equal to 0 as no SOV traveler would be allowed on the HOV lane at that time. The equation to calculate $V_{SOVsupplyt}$ was:

$$V_{SOVsupplyt} = V_{GPLt} \times P_{GPLSOVt}, \tag{4.8}$$

where, $P_{GPLSOVt}$ = SOV percentage on GPLs (%), assumed to be 90% during time interval t.

The equation to calculate revenue was:

$$R_t = N_{SOVt} \times toll_t, \tag{4.9}$$

where, R_t = the revenue generated during time interval t (\$); and

$toll_t$ = toll rate selected during time interval t (\$).

If the off-peak time interval, t, was considered close to a peak time interval, t', the potential SOV demand in time interval t (N_{SOVt}) was then assumed to include the vehicles from both the off-peak time interval (N_{OPt}) and the nearby peak time interval (N_{Pt}). The equation to calculate N_{SOVt} was as below, given the predicted percentage of SOVs from the GPLs in time interval t (P_{SOVt}) and t' ($P_{SOVt'}$), and the GPL volume in time interval t' ($V_{GPLt'}$):

$$N_{SOVt} = N_{OPt} + N_{Pt} = V_{GPLt} \times P_{SOVt} + V_{GPLt'} \times P_{SOVt'}, \tag{4.10}$$

where, N_{Pt} = number of GPL peak SOV vehicles switching from time interval *t'* to time interval *t* (vehicles);

$V_{GPLt'}$ = number of vehicles on GPLs during time interval *t'* traveling in the correct direction (vehicles); and

$P_{SOVt'}$ = predicted percentage of SOVs switching from GPLs during time interval *t'* (%).

In this case, the sum of the GPL SOVs during time intervals *t* and *t'* was always larger than 1500 vehicles per hour, so the maximum number of SOVs switching during time interval *t* ($N_{maxSOVt}$) was calculated by:

$$N_{maxSOVt} = 1500\text{ vph} \times t - V_{HOVt}, \tag{4.11}$$

where, $N_{maxSOVt}$ = maximum number of SOVs switching during time interval *t* (vehicles).

If $N_{maxSOVt}$ was found to be equal to or less than 0, no SOV traveler would be allowed to use the HOV lane during time interval *t*. TTS_t was the travel time savings for the off-peak GPL travelers to switch to the HOV lane while keeping the same travel schedule *t*. $TTS_{t'}$ was defined as the travel time savings for the peak GPL travelers to switch to the HOV lane and also change the travel schedule from *t'* to *t*. The equation to calculate $TTS_{t'}$ was provided in Equation 4.12:

$$TTS_{t'} = TT_{GPLt'} - TT_{HOVt}, \tag{4.12}$$

where, $TTS_{t'}$ = travel time savings for the peak GPL travelers to switch to the HOV lane and also change the travel schedule from *t'* to *t* (minutes);

$TT_{GPLt'}$ = travel time on the GPLs during time interval *t'* (minutes); and

TT_{HOVt} = travel time on the HOV lane during time interval t (minutes).

Using TTS_t and $TTS_{t'}$, the off-peak and peak respondents' data were estimated in the model separately to get P_{SOVt} and $P_{SOVt'}$. Different toll levels were tested and different values of P_{SOVt} and $P_{SOVt'}$ were obtained until N_{SOVt} equaled $N_{maxSOVt}$. This yielded the optimal toll rate ($toll_t$) and toll revenue was calculated by:

$$R_t = N_{SOVt} \times toll_t . \quad (4.13)$$

The summary of the recommended off-peak toll schedule is presented in Table 4.13 and Table 4.14. Additional data used for these calculations are available in Appendix B. Note that a minimum toll of $0.50 was assumed even when that resulted in 0 travelers choosing the option. This is standard practice for the other variable priced HOT lanes (I-15 FasTrak and SR-91 Express Lanes) to keep a sudden influx of SOV vehicles out of the HOV lane and some travelers still choose to pay the $0.50 despite the small travel time savings.

TABLE 4.13 SOV Off-Peak Toll Schedule on the Katy Freeway HOV Lane

Time of Day	Toll ($)	SOV Demand (veh)	Approximate Revenue ($)
5:00-6:00	0.50	0	0.00
6:00-6:15	0.50	0	0.00
6:15-6:30	0.50	63	32.00
6:30-6:45	0.50	67	34.00
8:00-8:15	2.50	109	273.00
8:15-8:30	5.10	31	158.00
8:30-8:45	3.50	64	224.00
8:45-9:00	0.50	53	27.00
9:00-9:15	0.50	23	12.00
9:15-9:30	0.50	5	3.00
9:30-10:00	0.50	5	3.00

TABLE 4.13 Continued

Time of Day	Toll ($)	SOV Demand (veh)	Approximate Revenue ($)
10:00-11:00	0.50	11	6.00
14:00-15:00	0.50	23	12.00
15:00-15:15	0.50	32	16.00
15:15-15:30	0.50	50	25.00
15:30-15:45	0.50	79	40.00
15:45-16:00	0.50	105	53.00
16:00-16:15	0.96	111	107.00
16:15-16:30	2.81	53	149.00
18:00-18:15	12.00	33	396.00
18:15-18:30	8.05	97	781.00
18:30-18:45	1.05	159	167.00
18:45-19:00	0.50	48	24.00
19:00-20:00	0.50	0	0.00
	Total:	**1221**	**2542.00**

TABLE 4.14 SOV Off-Peak Toll Schedule on the Northwest Freeway HOV Lane

Time	Toll ($)	SOV Demand (veh)	Approximate Revenue ($)
5:00-6:00	0.50	0	0.00
6:00-6:15	0.50	0	0.00
6:15-6:30	0.50	68	34.00
6:30-6:45	1.05	63	66.00
8:00-8:15	2.70	76	205.00
8:15-8:30	3.80	65	247.00
8:30-8:45	1.96	114	223.00
8:45-9:00	0.50	0	0.00
9:00-9:15	0.50	0	0.00
9:15-9:30	0.50	0	0.00
9:30-10:00	0.50	0	0.00
10:00-11:00	0.50	0	0.00
14:00-15:00	0.50	0	0.00
15:00-15:15	0.50	0	0.00
15:15-15:30	0.50	0	0.00
15:30-15:45	0.50	0	0.00
15:45-16:00	0.50	0	0.00
16:00-16:15	0.50	0	0.00
16:15-16:30	0.50	9	5.00

TABLE 4.14 Continued

Time	Toll ($)	SOV Demand (veh)	Approximate Revenue ($)
16:30-16:45	2.03	102	207.00
16:45-17:00	4.80	64	307.00
18:00-18:15	3.31	115	381.00
18:15-18:30	1.90	162	308.00
18:30-18:45	0.50	0	0.00
18:45-19:00	0.50	0	0.00
19:00-20:00	0.50	0	0.00
	Total:	**838**	**1983.00**

According to these calculations, allowing SOV travelers to pay to use the HOV lane during the off-peak periods could attract more participants (approximately 2000 vehicles per day) and generate more revenue (approximately $4500.00 per day) on the Katy Freeway and the Northwest Freeway. The potential demand was larger on the Katy Freeway than on the Northwest Freeway, which was consistent with the demand analysis developed in the previous sections. Part of the reason for this difference was that the travelers on the Northwest Freeway had a higher $VPCS_{\text{Peak to Off-Peak}}$ and a lower $VPCS_{\text{Off-Peak to Peak}}$, so they would prefer choosing the peak time travel modes rather than traveling during the off-peak periods. This was also partially due to the fact that the travel time savings provided by the Northwest Freeway HOV lane were generally less than those provided by the Katy Freeway HOV lane. Additionally, a larger percentage of travelers on the Katy Freeway were part of the highest household income category and more willing to pay for travel time savings.

CHAPTER V

FINDINGS AND RECOMMENDATIONS

5.1 Findings

Discrete choice models based on traveler responses to a 2003 survey conducted on the Katy Freeway and the Northwest Freeway were used to estimate the potential demand from SOV travelers for paying to use the HOV lanes during the off-peak periods. As part of this analysis, the traveler's VTTS and VPCS on these two corridors were estimated, and an optimal pricing scheme for allowing SOV travelers to use the HOT lanes during the off-peak periods was determined.

Travelers were more likely to choose to drive on the HOT lanes as SOV travelers during the off-peak periods if the facilities provided higher travel time savings and charged lower tolls. Travelers on the Katy Freeway were more likely to pay to drive on the HOT lane alone during the off-peak periods compared with travelers on the Northwest Freeway. The predicted SOV traveler off-peak demand and toll revenues on the Katy Freeway HOT lane (approximately 1200 travelers and $2500.00 per day) were also higher than those on the Northwest Freeway HOT lane (approximately 800 travelers and $2000.00 per day). Travelers on the Northwest Freeway had a higher VTTS (approximately 46 percent of their hourly wage rate) and $VPCS_{Peak\ to\ Off\text{-}Peak}$ (approximately 4 percent of their hourly wage rate) than those on the Katy Freeway (approximately 40 percent and 3 percent of their hourly wage rate, respectively).

The results of this study provided insight into some of the traveler's characteristics, for example, VTTS and VPCS, which helped to predict travelers' mode choice behaviors. Generally speaking, travelers with higher VTTS were more likely to pay to use the HOT lane facilities. However, in this case, fewer travelers on the Northwest Freeway were predicted to pay to use the HOT lane during the off-peak periods but had a higher VTTS as a percentage of their hourly wage rate. This was partially explained by the fact that travelers on the Northwest Freeway had a higher $VPCS_{\text{Peak to Off-Peak}}$. With higher $VPCS_{\text{Peak to Off-Peak}}$, these travelers found switching their time of travel to the off-peak particularly costly. Another reason for this result was that although the calculated VTTS as a percent of wage rate was found to be higher on the Northwest Freeway, the proportion of very high income travelers (with annual household incomes of $200,000 or more) was higher on the Katy Freeway than on the Northwest Freeway. Therefore, the proportion of travelers who had a higher VTTS on the Katy Freeway was higher than that on the Northwest Freeway. Additionally, the average travel time savings provided by the Katy Freeway HOV lane was higher than that provided by the Northwest Freeway HOV lane, and the travel time savings perceived by travelers was a very important factor in making a mode choice decision.

Finally, significant revenue (approximately $4500.00 per day) could be obtained from charging SOV travelers to use the HOV lanes on the Katy Freeway and the Northwest Freeway during the off-peak periods. This would increase the utilization of the HOV lanes (by approximately 2000 additional travelers per day) as well.

5.2 Recommendations

It is important to note that this analysis was based on travelers who were driving on the GPLs of the Katy Freeway and the Northwest Freeway in October 2003, so the survey responses might not reflect the entire population of travelers on these two corridors. Only potential GPL SOV travelers who might choose to pay to travel on the HOV lanes during the off-peak periods were examined in this study. Although this group likely constitutes the majority of travelers who would choose this option, there are likely a small number of current HOV lane users (transit riders and HOV-2+ travelers) who would choose to pay to travel as SOV travelers on the HOV lane in the off-peak period. Additional research should be undertaken to determine the size of this group and to gain an understanding of their characteristics, including VTTS and VPCS.

REFERENCES

1. Schrank, D., and T. Lomax. *The 2004 Urban Mobility Report*. Texas Transportation Institute, College Station, Texas, 2004. http://mobility.tamu.edu, Accessed, February 20, 2004.
2. Domencich, T., and D.L. McFadden. *Urban Travel Demand: A Behavioral Analysis*. North-Holland Publishing Co., Amsterdam, Netherlands, 1975.
3. Li, J. Explaining High-Occupancy Toll Lane Use. *Transportation Research Part D*, Vol. 6. Pergamon, Amsterdam, Netherlands, 2001, pp. 61-74.
4. Burris, M.W., and J. Appiah. Examination of Houston's QuickRide Participants by Frequency of QuickRide Usage. *Transportation Research Record, No. 1864*, Transportation Research Board, National Research Council, Washington, D.C., 2004, pp. 22-30.
5. Burris, M.W., and B.R. Stockton. HOT Lanes in Houston – Six Years of Experience. *Journal of Public Transportation*, Vol. 7, No. 3, 2004, pp. 1-21.
6. Stockton, B. HOV Lane Conversion – Texas: HOT Lanes on Two Radial Corridors in Houston (I-10 and US 290). Texas Transportation Institute, College Station, Texas, January 2004. http://knowledge.fhwa.dot.gov/cops/hcx.nsf/0/3ca94786bf8fb 10485256dc5006a3611?OpenDocument, Accessed, October 22, 2004.
7. Appiah, J. *An Examination of Factors Affecting High Occupancy/Toll Lane Demand*. M.S. thesis, Department of Civil Engineering, Texas A&M University, College Station, 2004.

8. Committee for Study of Impacts of Highway Capacity Improvements on Air Quality and Energy Consumption. *Expanding Metropolitan Highways: Implications for Air Quality and Energy Use – Special Report 245*. Transportation Research Board, National Research Council. National Academy Press, Washington, D.C., 1995.
9. Office of Highway Policy Information, Federal Highway Administration. *Highway Statistics 2002: Vehicle Registrations, Fuel Consumption, and Vehicle Miles of Travel as Indices*. 2000. http://www.fhwa.dot.gov/policy/ohim/hs02/mvfvm.htm. Accessed, April 13, 2005.
10. Turnbull, K.F. *History of HOV Lanes*. Committee on High Occupancy Vehicle Systems, Transportation Research Board, 2002. http://www.hovworld.com. Accessed, December 25, 2004.
11. Kain, J., R. Gittel, S. Daniere, T. Sumerville, and L. Zhi. *Increasing the Productivity of the Nation's Urban Transportation Infrastructure: Measures to Increase Transit Use and Carpooling*. U.S. Department of Transportation, Washington, D.C., 1992.
12. Turnbull, K.F., and T. DeJohn. *New Jersey I-80 and I-287 HOV Lane Case Study*. Report No. FHWA-OP-00-018, Federal Highway Administration, Washington, D.C., 2000.
13. Texas Transportation Institute, Parsons Brinckerhoff, Pacific Rim Resources. *HOV Systems Manual, National Cooperative Highway Research Program (NCHRP) Report 414*. Transportation Research Board, Washington, D.C., 1998.

14. The Ohio Department of Transportation. *High Occupancy Vehicle (HOV) Alternatives in Ohio: A Summary and Assessment of HOV as a Transportation System Alternative*. October 16, 2000. http://www.dot.state.oh.us/planning/Studies %20&%20Reports/HOVAlternatives/HOVAlternatives.htm. Accessed, December 25, 2004.

15. Stockton, W.R., G. Daniels, D.A. Skowronek, and D.W. Fenno. *The ABC's of HOV – The Texas Experience*. Research Report 1353-1. Texas Transportation Institute, College Station, Texas, 1999.

16. Vickrey, W. *Public Economics: Selected Papers by William Vickrey* (R. Arnott, A.B. Atkinson, K. Arrow, and J.H. Drèze, eds.). Cambridge University Press, Cambridge, U.K., 1994.

17. Gomez-Ibanez, J.A., and K.A. Small. *Road Pricing for Congestion Management: A Survey of International Practice, National Cooperative Highway Research Program (NCHRP) Synthesis 210*. Transportation Research Board, National Research Council, National Academy Press, Washington, D.C., 1994.

18. Small, K.A. *Urban Transportation Economics*. Hardwood Academic Publishers, Philadelphia, Pennsylvania, 1992.

19. Burris, M.W. The Toll-Price Component of Travel Demand Elasticity. *International Journal of Transport Economics,* XXIX(1), 2003, pp. 45-59.

20. Hensher, D.A. Measurement of the Valuation of Travel Time Savings. *Journal of Transportation Economics and Policy*, Vol. 35, Part 1, 2001, pp. 71-98.

21. Jiang, M., and T. Morikawa. Theoretical Analysis on the Variation of Value of Travel Time Savings. *Transportation Research Part A*, Vol. 38/8, 2004, pp. 551-571.

22. Calfee, J., and C. Winston. The Value of Automobile Travel Time: Implications for Congestion Policy. *Journal of Public Economics*, No. 69, 1998, pp. 83-102.

23. Murray, P.M., H.S. Mahmassani, and K.F. Abdelghany. Methodology for Assessing HOT Lane Usage and Network Performance. *Transportation Research Record 1765*, National Academy Press, Washington, D.C., 2001, pp. 8-15.

24. Perez, B.G., and G.-C. Sciara. *A Guide for HOT Lane Development*. FHWA-OP-03-009FHWA, Federal Highway Administration, Washington, D.C., 2003.

25. Poole, R.W., Jr., and C.K. Orski. HOT Lanes: A Better Way to Attack Urban Highway Congestion. *Regulation*, Vol. 23, No. 1, 2000, pp. 15-20.

26. Sullivan, E. *Continuation Study to Evaluate the Impacts of the SR 91 Value-priced Express Lanes: Final Report*. 2000. http://ceenve.calpoly.edu/sullivan/sr91/sr91.htm, Accessed, December 28, 2004.

27. Supernak, J., C. Kaschade, D. Steffey, and G. Kubiak. *I-15 Congestion Pricing Project, Monitoring and Evaluation Services, Phase II Year Three Traffic Study*. 2001. http://www.sandag.org/fastrak/pdfs/yr3_traffic.pdf. Accessed, December 28, 2004.

28. Burris, M.W., and R.L. Hannay. Equity Analysis of the Houston QuickRide Program. *Transportation Research Record 1859*, Transportation Research Board, National Research Council, Washington, D.C., 2003, pp. 87-92.

29. Kim, E.J. *HOT Lanes: A Comparative Evaluation of Costs, Benefits and Performance*. Ph.D. dissertation. University of California at Los Angeles, 2000.

30. Ben-Akiva, M., and S.R. Lerman. *Discrete Choice Analysis: Theory and Application to Travel Demand*. The MIT Press, Cambridge, MA, 1985.

31. Berkson, J. Application of the Logistic Function to Bioassay. *Journal of the American Statistical Association*, Vol. 39, 1944, pp. 357-365.

32. Finney, D. *Probit Analysis*, 3rd Edition. Cambridge University Press, Cambridge, England, 1971.

33. Cox, D.R. *Analysis of Binary Data*. Methuen, London, 1970.

34. Warner, S.L. *Stochastic Choice of Mode in Urban Travel: A Study in Binary Choice*. Northwestern University Press, Evanston, Illinois, 1962.

35. Lave, C.A. A Behavioral Approach to Modal Split Forecasting. *Transportation Research*, Vol. 3, No. 4, 1969, pp. 463-480.

36. Stopher, P.R. A Probability Model of Travel Mode Choice for the Work Journey. *Highway Research Record*, Vol. 283, 1969, pp. 57-65.

37. McGillivray, R.G. Binary Choice of Urban Transport Mode in the San Francisco Bay Region. *Econometrica*, Vol. 40, 1972, pp. 827-848.

38. Watson, P.L. *The Value of Time: Behavioral Models of Modal Choice*. D.C. Heath, Lexington, Massachusetts, 1974.

39. Rassam, P.R., R.H. Ellis, and J.C. Bennett. The N-Dimensional Logit Model: Development and Applications. *Highway Research Record*, Vol. 369, 1971, pp. 135-147.

40. Ben-Akiva, M. *Structure of Passenger Travel Demand Models*. Ph.D. dissertation. Department of Civil Engineering, MIT, Cambridge, Massachusetts, 1973.

41. Brand, D., and M.L. Manheim, eds. *Urban Travel Demand Forecasting*. Special Report 143. Highway Research Board, Washington, D.C., 1973.

42. Richards, M., and M. Ben-Akiva. *A Disaggregate Travel Demand Model*. D.C. Heath, Lexington, Massachusetts, 1975.

43. McFadden, D.L. The Measurement of Urban Travel Demand. *Journal of Public Economics*, Vol. 3, 1973, pp. 303-328.

44. McFadden, D.L., and F. Reid. *Aggregate Travel Demand Forecasting from Disaggregated Behavioral Models*. Working Paper No. 228, University of California, Berkeley, 1974.

45. Small, K.A. *Urban Transportation Economics*. Harwood Academic Publishers, Chur, Switzerland, 1992.

46. McFadden, D.L. Conditional Logit Analysis of Qualitative Choice Behavior. In *Frontiers in Econometrics* (P. Zarembka, ed.), Academic Press, New York, 1973.

47. McFadden, D.L., A.P. Talvitie, and Associates. *Demand Model Estimation and Validation*. Urban Travel Demand Forecasting Project Phase 1 Final Report Series, Vol. V, Institute of Transportation Studies, University of California, Berkeley, California, 1977.

48. Train, K. A Validation Test of a Disaggregate Mode Choice Model. *Transportation Research*, Vol. 12, 1978, pp. 167-174.

49. Train, K. A Comparison of the Predictive Ability of Mode Choice Models with Various Levels of Complexity. *Transportation Research*, Vol. 13A, 1979, pp. 11-16.

50. Train, K. A Structured Logit Model of Auto Ownership and Mode Choice. *Review of Economic Studies*, Vol. 47, 1980, pp. 357-370.

51. Kocur, G., W. Hyman, and B. Aunet. Wisconsin Work Mode-Choice Models Based on Functional Measurement and Disaggregate Behavioral Data. *Transportation Research Record*, Vol. 895, 1982, pp. 24-32.

52. Abraham, J.E., and J.D. Hunt. Specification and Estimation of Nested Logit Model of Home, Workplace and Commuter Mode Choices by Multiple-Worker Households. *Transportation Research Record*, Vol. 1606, 1997, pp. 17-24.

53. Wilbur Smith Associates. *Non-Motorized Access to Transit: Final Report*. Prepared for Regional Transportation Authority, Chicago, IL, July 1996.

54. Loutzenheiser, D.R. Pedestrian Access to Transit: Model of Walk Trips and Their Design and Urban Form Determinants around BART Stations. *Transportation Research Record*, Vol. 1604, 1997, pp. 40-49.

55. Small, K.A. The Scheduling of Consumer Activities: Work Trips. *American Economic Review*, Vol. 72, 1982, pp. 467-479.

56. Burris, M.W. Trip-Scheduling. CVEN 632 Notes in Fall 2003 Semester. Department of Civil Engineering, Texas A&M University. 2003.

57. Becker, G.S. A Theory of the Allocation of Time. *The Economic Journal*, Vol. 75, 1965, pp. 813-846.

58. Johnson, M.B. Travel Time and the Price of Leisure. *Western Economic Journal*, Vol. 4, 1966, pp. 135-145.

59. DeSerpa, A.C. A Theory of the Economics of Time. *The Economic Journal*, Vol. 81, 1971, pp. 828-846.

60. Brownstone, D., and K.A. Small. Valuing Time and Reliability: Assessing the Evidence from Road Pricing Demonstrations. Presented to the International Association for Travel Behavior Research, Lucerne, Switzerland, 2003.

61. Hensher, D.A., and K.J. Button, eds. *Handbook of Transport Modelling*. Elsevier Science Ltd, Oxford, U.K., 2000.

62. Horowitz, J.L., F.S. Koppelman, and S.R. Lerman. *A Self-instructing Course in Disaggregate Mode Choice Modeling*. Prepared for Federal Transit Administration (Former Urban Mass Transit Administration), Washington, D.C., December 1986.

63. Zhang, M. PLAN 674 Lecture Notes #14: Logit Combining Revealed and Stated Preference Data. Department of Landscape Architecture and Urban Planning, Texas A&M University, College Station, Spring 2004.

64. HOT Lanes on the Katy and Northwest Freeways. Texas Transportation Institute, College Station, Texas, 2004. http://houstonvaluepricing.tamu.edu/about_hvp, Accessed, January 22, 2005.

65. König, A. *The Reliability of the Transportation System and Its Influence on the Choice Behaviour*. 2nd Swiss Transport Research Conference, March 2002.

66. Lorenzen, T.J., and V.L. Anderson. *Design of Experiments: A No-name Approach*. Marcel Dekker, Inc., New York, 1993.

67. Sloane, N.J.A. A Library of Orthogonal Arrays. http://www.research.att.com/~njas /oadir/index.html, Accessed, October 15, 2003.

68. Robertson, H.D., J.E. Hummer, and D.C. Nelson, eds. *Manual of Transportation Engineering Studies*. Prentice-Hall, Inc., Englewood Cliffs, N.J., 1994.

69. Greene, W.H. *LIMDEP Version 7.0 User's Manual Revised Edition*. Econometric Software, Inc., 1998.

70. Winn, J.R. *An Analysis of Casual Carpool Passenger Behavior in Houston, Texas*. M.S. thesis, Department of Civil Engineering, Texas A&M University, College Station, 2005.

APPENDIX A

A SAMPLE OF SURVEY INSTRUMENT FOR KATY MORNING PEAK HOUR TRAVELERS

Part I: Please tell us about your most recent trip on the Katy Freeway (I-10) traveling towards downtown Houston during the work week (Monday through Friday).

1. What was the purpose of the trip?
   - ❑ Commuting (going to or from work)
   - ❑ Recreational / Social / Shopping / Entertainment / Personal errands
   - ❑ Work related (other than going to or from work)
   - ❑ School
   - ❑ Other (*specify*): ________________________________

2. What time of day did your trip start (for example, when did you leave your driveway)?

   [ ] ***a.m. p.m.*** (*circle one*)

3. Would it have been possible to start your trip earlier or later?
   - ❑ I could have easily made the trip [ ] minutes earlier/later.
   - ❑ I could have made the trip anytime the same day.
   - ❑ I could not take the trip at any other time.

4. Do you allow for extra travel time due to possible traffic congestion on Katy Freeway (I-10)?

   □Yes □No

   If yes, how much extra time do you try to allow?_________ minutes.

5. Near what major cross streets did your trip start? *Example: Kingsland Blvd. and Mason Creek.*

   [ ] ***and*** [ ]

6. What time of day did your trip end (for example, when did you arrive at work)?

   [ ] ***a.m. p.m.*** (*circle one*)

7. Near what major cross streets did your trip end? *Example: Main St. and Texas Ave.*

[ ] ***and*** [ ]

8. Did you have to pay to park in Houston?
□Yes □No
If yes, how much does it cost per day? $_________

9. How many people, including yourself, were in the vehicle?

❑ 1	□ Motorcycle	□ Took a bus

→ *If you travel by yourself or take the bus, please skip questions10 to 12 and go to question 13.*

□ 2 □ 3 □ 4 □ 5 or more

10. Who did you travel with? (*check all that apply*)
- ❑ Co-worker / person in the same or a nearby office building
- ❑ Neighbor
- ❑ Adult family member
- ❑ Another commuter in a casual carpool (also known as slugging)
- ❑ Child
- ❑ Other (*specify*): ________________________________

11. How much extra time did it take to pick up and drop off the passenger(s)?

[ ] minutes

12. Did you use the High Occupancy Vehicle (HOV) lane? □ Yes □ No

If yes, how much travel time do you think you **saved** compared to the main lanes?

[ ] minutes.

13. How many ***total trips*** did you make during the past full work week (Monday to Friday) on the Katy Freeway? (Count each direction of travel as one trip, include trips on the HOV or main lanes)

[ ] trips

14. Do you sometimes use a route other than the Katy Freeway to make trips with a similar purpose?
□Yes □No

Part II: Questions Regarding the QuickRide Program

During most of the time the HOV lane is open, vehicles with 2 or more occupants can use the HOV lane on the Katy Freeway (I-10), free of charge. However, during peak traffic periods (from 6:45 a.m. to 8:00 a.m. and 5:00 p.m. to 6:00 p.m.) toll-free use of the HOV lane is restricted to vehicles with 3 or more occupants.

Under a program called QuickRide, vehicles with only 2 occupants are permitted to travel on the HOV lane during peak traffic periods for a $2.00 toll per trip. Participants must set up a QuickRide account with their credit card before using the program. Enrollees are issued toll transponders that electronically charge the toll each time QuickRide is used. Additionally, a $2.50 monthly administration fee is charged to each account. For more information, please call 713-224-RIDE or 1-888-606-RIDE (toll free) or visit
http://www.houmetro.harris.tx.us/services/quickride.asp

15. Prior to this survey, had you heard of the QuickRide program?
    - □ Yes → Go to Question 16
    - □ No → Go to Question 17

16. How did you hear about QuickRide? (*Check all that apply*)
    - ❑ TV
    - ❑ Radio
    - ❑ Mail
    - ❑ Newspaper
    - ❑ METRO website
    - ❑ Family / Friend
    - ❑ On the bus
    - ❑ I don't remember
    - ❑ Other (*specify*):________________________________

    → Go to Question 18

17. Now that you know about the QuickRide program would you be interested in using it?
    - □ Yes If Yes, what interests you **most** about QuickRide? (*check only one*)
        - ❑ Being able to carpool with just one other person and still use the HOV lane
        - ❑ Being able to use the HOV lane more often because it is much faster than the main freeway lanes
        - ❑ Being able to use the HOV lane more often because the travel times on the HOV lane are consistent
        - ❑ Being able to use the HOV lane more often because it is safer / less stressful than on driving main freeway lanes
        - ❑ Other (*specify*):____

□ No If No – what are the primary reasons you would not use QuickRide? (*check all that apply*)

- ❑ Participation in a carpool is difficult / undesirable
- ❑ I do not want to set up a QuickRide account
- ❑ I do not have a credit card needed to set up an account
- ❑ I do not want to pay the $2.50 monthly administration fee
- ❑ I do not want a toll transponder in my car
- ❑ Access to the HOV lane is not convenient for my trips
- ❑ The HOV lane does not offer me enough time savings
- ❑ The HOV lane is sometimes just as congested as the main freeway lanes
- ❑ The QuickRide program is complicated or confusing
- ❑ I have the flexibility to travel at less congested times
- ❑ I do not want to pay the $2.00 per trip cost of QuickRide
- ❑ Other (*specify*):____

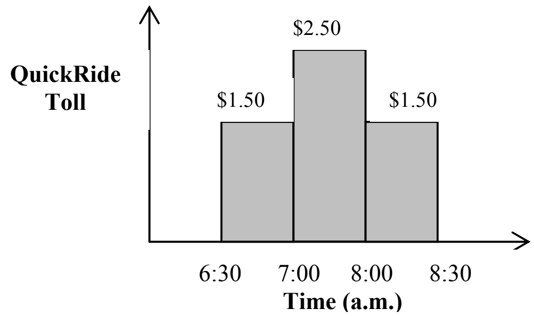
The questions in this part of the survey are to find out your views on a number of potential options for improving QuickRide. The options raised are only examples and do not represent local, state or federal policy.

18. Which of the following would cause you to try using QuickRide? (*Check all that apply*)

- ❑ Longer QuickRide operating hours
- ❑ The ability to pay to drive alone on the HOV lane
- ❑ A message sign that told me exactly how long the trip would take on the HOV lane before I paid to enter (for example, “At 7:15 a.m. travel to downtown on the HOV lane takes 14 minutes.”)
- ❑ Increased traffic on main freeway lanes
- ❑ A reduction in the $2 QuickRide toll. Please enter the toll amount you would be willing to pay to try QuickRide: $ [ ]
- ❑ Other (*specify*)______________________________

19. To maintain a smooth traffic flow, the QuickRide toll could change with the time of day. As shown in the graph below, lower tolls could be charged for travel at specific times (for example, 6:30 a.m. to 7:00 a.m.) and higher tolls during the most congested times (for example, 7:00 a.m. to 8:00 a.m.). What is your initial feeling regarding this option? (*Check only one*)

- ❑ Strongly favor
- ❑ Somewhat favor
- ❑ Indifferent
- ❑ Somewhat oppose
- ❑ Strongly oppose



20. The QuickRide toll could also change with the amount of traffic in the HOV lane. For example, if the HOV lane was not congested then the toll might be less than $2.00. However, if the HOV lane was very congested the toll might be higher than $2.00 to maintain the smooth flow of traffic. What is your initial feeling regarding this option? (*Check only one*)

- ❑ Strongly favor
- ❑ Somewhat favor
- ❑ Indifferent
- ❑ Somewhat oppose
- ❑ Strongly oppose

21. How do you feel about allowing people who drive alone to use the HOV lane for a higher toll than carpoolers?

- ❑ Strongly favor
- ❑ Somewhat favor
- ❑ Indifferent
- ❑ Somewhat oppose
- ❑ Strongly oppose

22. If you could drive alone on the HOV lane for the toll listed below, how often would you drive alone on the HOV lane?

Toll	*Number of trips per week (count each direction of travel as one trip)*
$3.00	____________
$4.00	____________
$5.00	____________
$6.00	____________

Part III: Travel Scenarios

Each of the following questions asks you to choose between four potential travel choices on the Katy Freeway (I-10). For your most recent trip, please circle the one option that you would be most likely to choose if faced with these specific options.

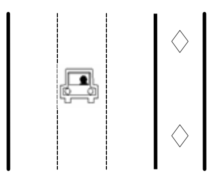
Remember that main lane traffic tends to be congested and could be slower than shown here if congestion is worse than usual. HOV lane traffic is fast moving. Peak hours are 6:45 a.m. to 8:00 a.m.

23. Circle the option you would choose:

A

Drive alone on the main freeway lanes during peak hours.

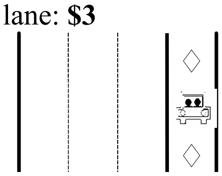
Travel time is **45** minutes
Toll: **$0**



B

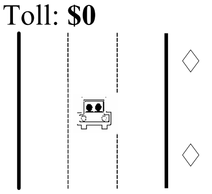
Drive with one passenger on the HOV lane during peak hours.

Travel time is **21** minutes (this includes 5 minutes to pick up and drop off the passenger)
Toll for HOV lane: **$3**



C

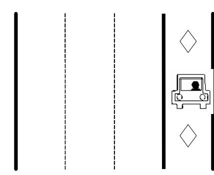
Drive with one passenger on the main freeway lanes during peak hours.
Travel time is **45** minutes (this includes 5 minutes to pick up and drop off the passenger)
Toll: **$0**



D

Drive alone on the HOV lane during peak hours.

Travel time is **12** minutes
Toll for HOV lane: **$4**

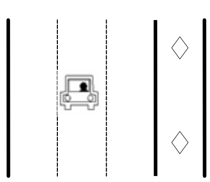


24. Circle the option you would choose:

A

Drive alone on the main freeway lanes during peak hours.

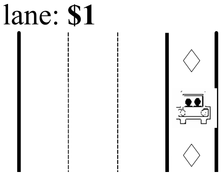
Travel time is **45** minutes
Toll: **$0**



B

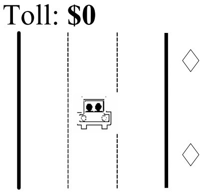
Drive with one passenger on the HOV lane during peak hours.

Travel time is **18** minutes (this includes 5 minutes to pick up and drop off the passenger)
Toll for HOV lane: **$1**



C

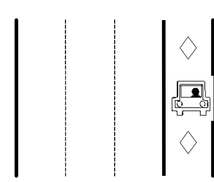
Drive with one passenger on the main freeway lanes during peak hours.
Travel time is **35** minutes (this includes 5 minutes to pick up and drop off the passenger)
Toll: **$0**



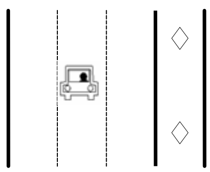
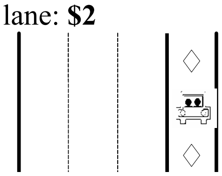
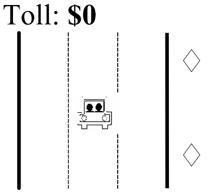
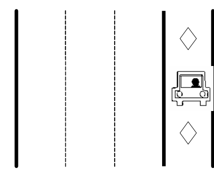
D

Drive alone on the HOV lane during peak hours.

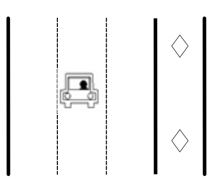
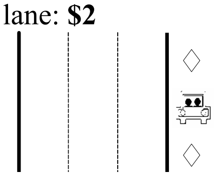
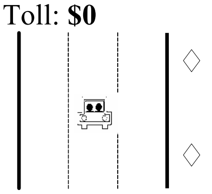
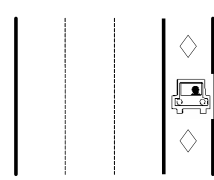
Travel time is **16** minutes
Toll for HOV lane: **$8**



25. Circle the option you would choose:

A	B	C	D
Drive alone on the main freeway lanes during peak hours. Travel time is **35** minutes Toll: **$0** 	Drive with one passenger on the HOV lane during peak hours. Travel time is **18** minutes (this includes 5 minutes to pick up and drop off the passenger) Toll for HOV lane: **$2** 	Drive with one passenger on the main freeway lanes during peak hours. Travel time is **35** minutes (this includes 5 minutes to pick up and drop off the passenger) Toll: **$0** 	Drive alone on the HOV lane during peak hours. Travel time is **16** minutes Toll for HOV lane: **$4** 

26. Circle the option you would choose:

A	B	C	D
Drive alone on the main freeway lanes during peak hours. Travel time is **25** minutes Toll: **$0** 	Drive with one passenger on the HOV lane during peak hours. Travel time is **21** minutes (this includes 5 minutes to pick up and drop off the passenger) Toll for HOV lane: **$2** 	Drive with one passenger on the main freeway lanes during peak hours. Travel time is **35** minutes (this includes 5 minutes to pick up and drop off the passenger) Toll: **$0** 	Drive alone on the HOV lane during peak hours. Travel time is **16** minutes Toll for HOV lane: **$6** 

Part IV: User Information

The following questions will be used for statistical purposes only and answers will remain confidential. All of your answers are very important to us and in no way will they be used to identify you.

27. What is your age?
- ❑ 16 to 24
- ❑ 25 to 34
- ❑ 35 to 44
- ❑ 45 to 54
- ❑ 55 to 64
- ❑ 65 and over

28. What is your gender?
- ❑ Male
- ❑ Female

29. Please describe your household type.
- ❑ Single adult
- ❑ Unrelated adults (e.g. room-mates)
- ❑ Married without child
- ❑ Married with child(ren)
- ❑ Single parent family
- ❑ Other (*specify*): ________________________________

30. Including yourself, how many people live in your household?

31. All together, how many motor vehicles (including cars, vans, trucks, and motorcycles) are available for use by members of your household?

32. What category best describes your occupation?
- ❑ Professional / Managerial
- ❑ Technical
- ❑ Sales
- ❑ Administrative / Clerical
- ❑ Manufacturing
- ❑ Stay-at-home homemaker / parent
- ❑ Student
- ❑ Self employed
- ❑ Unemployed / Seeking work

- ❑ Retired
- ❑ Other *(specify)*: ______________________________

33. What is the last year of school you have completed?
- ❑ Less than high school
- ❑ High school graduate
- ❑ Some college / Vocational
- ❑ College graduate
- ❑ Postgraduate degree

34. What was your annual household income before taxes in 2002?
- ❑ Less than $10,000
- ❑ $10,000 to $14,999
- ❑ $15,000 to $24,999
- ❑ $25,000 to $34,999
- ❑ $35,000 to $49,999
- ❑ $50,000 to $74,999
- ❑ $75,000 to $99,999
- ❑ $100,000 to $199,999
- ❑ $200,000 or more

35. Please list any comments or suggestions you have regarding travel in the Katy Freeway (I-10) corridor:

____

____

____

Thank you for your participation.

APPENDIX B

SOV ON THE HOV LANE OFF-PEAK PRICING SCHEME CALCULATION TABLES

Time of Day	Katy GPL Travel Time (min)	Katy HOVL Travel Time (min)	Katy TTS (min)	Peak to Off-Peak TTS (min)	Katy HOV Volume (vph)	SOV Needed (vph)	Katy Mainlane Volume (vph)	Katy Mainlane SOV Volume (vph)	Max SOV to Fill (veh)	Max SOV % to Switch	Toll ($)	Predicted SOV Volume From Off-peak (vph)	Predicted SOV % From Off-Peak	Predicted SOV Volume From Peak (vph)	Predicted SOV % From peak	Potential SOV Demand (veh)	Revenue ($)
5-6			0.47		134	1366	3955	3560	1366	34.5%	0.50	0.00	0.00%			0.00	$0.00
6:00			1.94		478	1022	6276	5648	256	16.3%	0.50	0.00	0.00%			0.00	$0.00
6:15	15.59	11.67	3.92	9.23	752	748	6100	5490	187	12.3%	0.50	0.00	0.00%	252.30	4.70%	63.07	$31.54
6:30	18.53	12.68	5.85	10.17	1230	270	5664	5098	68	4.8%	0.50	0.00	0.00%	267.99	5.13%	67.00	$33.50
6:45	20.89	13.26	7.64		1645	-145	5368	4965		0.0%							
7:00	22.85	12.33	10.52		1303	197	5224	4832		3.8%							
7:15	26.25	12.08	14.17		1107	393	5136	4751		7.7%							
7:30	28.50	12.31	16.18		1066	434	5032	4655		8.6%							
7:45	27.87	12.14	15.73		962	538	5100	4718		10.5%							
8:00	26.15	11.91	14.24	14.33	1066	434	5064	4558	109	8.6%	2.50	215.22	4.25%	219.31	4.27%	108.63	$271.58
8:15	25.27	11.65	13.63	16.85	1383	117	5048	4543	29	2.3%	5.10	38.87	0.77%	86.05	1.71%	31.23	$159.27
8:30	23.44	11.40	12.04	16.46	1241	259	5136	4622	65	5.0%	3.50	39.55	0.77%	217.77	4.27%	64.33	$225.15
8:45			9.68		979	521	5196	4676	130	10.0%	0.50	210.96	4.06%			52.74	$26.37
9:00			7.22		694	806	5116	4604	202	15.8%	0.50	93.62	1.83%			23.41	$11.70
9:15			6.48		653	847	5204	4684	212	16.3%	0.50	21.34	0.41%			5.33	$2.67
9:30-10			6.13		557	944	5344	4810	472	17.7%	0.50	10.69	0.20%			5.34	$2.67
10-11			4.21		420	1080	5282	4754	1080	20.4%	0.50	10.56	0.20%			10.56	$5.28
2-3			6.41		527	973	5612	5051	973	17.3%	0.50	23.01	0.41%			23.01	$11.50
3:00			7.55		719	781	5728	5155	195	13.6%	0.50	127.73	2.23%			31.93	$15.97
3:15			9.30		746	754	5832	5249	189	12.9%	0.50	201.20	3.45%			50.30	$25.15
3:30			10.27		855	645	5792	5213	161	11.1%	0.50	317.40	5.48%			79.35	$39.68
3:45			11.40		912	588	5772	5195	147	10.2%	0.50	421.36	7.30%			105.34	$52.67
4:00			12.91		1047	453	5756	5180	113	7.9%	0.96	443.79	7.71%			110.95	$106.51
4:15			14.82		1275	225	5784	5206	56	3.9%	2.81	211.12	3.65%			52.78	$148.31
4:30			16.69		1518	-18	5792	5213	0	0.0%							
4:45			18.76		1508	-8	5700	5130	0	0.0%							
5:00	38.09	13.15	24.94		1067	433	5580	5162		7.8%							
5:15	43.31	12.32	30.99		1043	457	5456	5047		8.4%							
5:30	43.13	12.14	30.99		958	542	5376	4973		10.1%							
5:45	40.21	12.10	28.11		1018	482	5372	4969		9.0%							
6:00	36.31	13.21	23.10	29.92	1369	131	5356	4820	33	2.4%	12.00	41.24	0.77%	91.93	1.71%	33.29	$399.51
6:15	31.93	12.99	18.94	27.22	1102	398	5448	4903	100	7.3%	8.05	41.95	0.77%	344.35	6.41%	96.57	$777.42
6:30			14.24		843	657	5488	4939	164	12.0%	1.05	634.41	11.56%			158.60	$166.53
6:45			9.26		566	934	5552	4997	234	16.8%	0.50	191.54	3.45%			47.89	$23.94
7-8			3.34		433	1067	5329	4796	1067	20.0%	0.50	0.00	0.00%			0.00	$0.00
8-9					29	1471	4558	4102	1471	32.3%							
9-10					0	1500	4143	3729	1500	36.2%							
															Total:	**1221.66**	**$2,536.92**

Time of Day	NW GPL Travel Time (min)	NW HOVL Travel Time (min)	NW TTS (min)	Peak to Off-Peak TTS (min)	NW HOV Volume (vph)	SOV Needed (vph)	NW Mainlane Volume (vph)	NW Mainlane SOV Volume (vph)	Max SOV to Fill (veh)	Max SOV % to Switch	Toll ($)	Predicted SOV Volume From Off-peak (vph)	Predicted SOV % From Off-Peak	Predicted SOV Volume From Peak (vph)	Predicted SOV % From peak	Potential SOV Demand (veh)	Revenue ($)
5-6			-0.01		64	1436	3080	2772	1436	46.6%	0.50	0.00	0.00%			0.00	$0.00
6:00			2.62		349	1151	5336	4802	288	21.6%	0.50	0.00	0.00%			0.00	$0.00
6:15	18.74	12.39	6.35	11.76	783	717	4224	3802	179	17.0%	0.50	0.00	0.00%	271.16	8.08%	67.79	$33.90
6:30	21.67	13.77	7.91	12.82	1262	238	3444	3100	60	6.9%	1.05	0.00	0.00%	251.77	7.52%	62.94	$66.09
6:45	24.15	14.72	9.43		1597	-97	3356	3171		0.0%							
7:00	26.59	12.75	13.84		1264	236	3348	3164		7.0%							
7:15	29.94	12.43	17.51		939	561	3304	3122		17.0%							
7:30	31.66	12.38	19.27		1092	408	3312	3130		12.3%							
7:45	29.10	12.42	16.68		1046	454	3420	3232		13.3%							
8:00	25.68	12.52	13.16	17.41	1201	299	3752	3377	75	8.0%	2.70	9.38	0.25%	294.39	8.91%	75.94	$205.04
8:15	23.27	12.05	11.22	19.61	1243	257	3948	3553	64	6.5%	3.80	0.00	0.00%	258.34	7.80%	64.58	$245.42
8:30	20.79	11.73	9.06	17.37	1046	454	4104	3694	114	11.1%	1.96	0.00	0.00%	457.25	13.37%	114.31	$224.05
8:45			6.73		654	846	4208	3787	212	20.1%	0.50	0.00	0.00%			0.00	$0.00
9:00			4.38		439	1061	4208	3787	265	25.2%	0.50	0.00	0.00%			0.00	$0.00
9:15			3.33		367	1133	4296	3866	283	26.4%	0.50	0.00	0.00%			0.00	$0.00
9:30-10			2.40		278	1223	4244	3820	611	28.8%	0.50	0.00	0.00%			0.00	$0.00
10-11			1.18		112	1388	3907	3516	1388	35.5%	0.50	0.00	0.00%			0.00	$0.00
2-3			1.41		130	1370	2947	2652	1370	46.5%	0.50	0.00	0.00%			0.00	$0.00
3:00			2.06		286	1214	3168	2851	304	38.3%	0.50	0.00	0.00%			0.00	$0.00
3:15			2.83		260	1240	3364	3028	310	36.9%	0.50	0.00	0.00%			0.00	$0.00
3:30			4.17		433	1067	3452	3107	267	30.9%	0.50	0.00	0.00%			0.00	$0.00
3:45			5.30		547	953	3580	3222	238	26.6%	0.50	0.00	0.00%			0.00	$0.00
4:00			6.88		731	769	3652	3287	192	21.1%	0.50	0.00	0.00%			0.00	$0.00
4:15			8.64		900	600	3748	3373	150	16.0%	0.50	37.85	1.01%			9.46	$4.73
4:30	22.72	12.51	10.21	16.95	1071	429	3852	3467	107	11.1%	2.03	0.00	0.00%	408.77	10.86%	102.19	$207.45
4:45	24.93	12.67	12.27	21.24	1240	260	3792	3413	65	6.9%	4.80	0.00	0.00%	254.74	6.96%	63.68	$305.68
5:00	29.46	13.02	16.44		1469	31	3764	3557		0.8%							
5:15	33.91	13.79	20.12		1426	74	3660	3459		2.0%							
5:30	33.52	14.45	19.07		1505	-5	3604	3406		0.0%							
5:45	30.54	14.54	16.00		1422	78	3640	3440		2.1%							
6:00	26.68	13.73	12.95	19.79	1099	401	3656	3290	100	11.0%	3.31	9.14	0.25%	451.58	12.53%	115.18	$381.25
6:15	22.65	12.73	9.93	17.81	840	660	3672	3305	165	18.0%	1.90	0.00	0.00%	649.01	17.83%	162.25	$308.28
6:30			6.12		642	858	3656	3290	215	23.5%	0.50	0.00	0.00%			0.00	$0.00
6:45			2.67		429	1071	3544	3190	268	30.2%	0.50	0.00	0.00%			0.00	$0.00
7-8			0.26		235	1265	2999	2699	1265	42.2%	0.50	0.00	0.00%			0.00	$0.00
															Total:	**838.35**	**$1,981.89**

VITA

Name: Lei Xu

Address: 6041 Village Bend Dr., APT 1614
Dallas, Texas 75206

Email Address: lxu@wilbursmith.com

Education: B.S., Transportation Management Engineering, Beijing Jiaotong University (former Northern Jiaotong University), 2001.

M.S., Transportation Planning and Management, Texas Southern University, 2004.

M.S., Civil Engineering, Texas A&M University, 2005.