Single Occupancy Vehicle (SOV) Behavior in High Occupancy Toll (HOT) Facilities

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16. Abstract

High-occupancy toll (HOT) lanes are in operation, under construction, and planned for in several major metropolitan areas. The premise behind HOT lanes is to allow single occupant vehicles (SOVs) to access high occupancy vehicle (HOV) lanes (and theoretically, a higher level of service) if they are willing to pay a toll. To maintain a high level of service in the HOT lanes, the toll rate is set dynamically to restrict the number of SOVs which access the facility as it nears capacity. Thus, HOT facilities provide operators of transportation systems with an additional tool: pricing. In order to effectively use pricing, it is critical to understand driver behavior when faced with a set of tra c conditions and toll levels. This thesis presents the results of an empirical investigation into the relationship between toll rate, tra_c conditions, and SOV driver behavior, based on data from the dynamically-tolled I-394 HOT facility in Minneapolis, Minnesota. Analysis of the empirical data indicated that of the SOVs using the HOT lanes, 87.5% use the HOT lanes at predictable rates throughout the AM peak period, even when there is no clear travel time advantage. After accounting for these “regular" users, the remaining \price-sensitive" SOV drivers utilize the HOT lanes at greater rates when the cost per hour of commute time saved is lowest. A model was developed that incorporates both of these endings, predicting HOT lane usage rates based on time savings, time of day, and toll rates with an R2 value of 0.684, n = 27831. When compared to the historic HOT utilization rates only, i.e. assuming all HOT lane SOVs are \every day" drivers, the resulting model has an R2 value of 0.675, n = 27831. Thus, the pricing structure as in place at this facility, appears to have a negligible influence on behavior. This may indicate serious implications, as many HOT facilities are two under consideration partly for their potential as track management tools.

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Abstract

High-occupancy toll (HOT) lanes are in operation, under construction, and planned for in several major metropolitan areas. The premise behind HOT lanes is to allow single occupant vehicles (SOVs) to access high occupancy vehicle (HOV) lanes (and theoretically, a higher level of service) if they are willing to pay a toll. To maintain a high level of service in the HOT lanes, the toll rate is set dynamically to restrict the number of SOVs which access the facility as it nears capacity. Thus, HOT facilities provide operators of transportation systems with an additional tool: pricing. In order to effectively use pricing, it is critical to understand driver behavior when faced with a set of traffic conditions and toll levels. This thesis presents the results of an empirical investigation into the relationship between toll rate, traffic conditions, and SOV driver behavior, based on data from the dynamically-tolled I-394 HOT facility in Minneapolis, Minnesota. Analysis of the empirical data indicated that of the SOVs using the HOT lanes, 87.5% use the HOT lanes at predictable rates throughout the AM peak period, even when there is no clear travel time advantage. After accounting for these "regular" users, the remaining "price-sensitive" SOV drivers utilize the HOT lanes at greater rates when the cost per hour of commute time saved is lowest. A model was developed that incorporates both of these findings, predicting HOT lane usage rates based on time savings, time of day, and toll rates with an R^2 value of 0.684, $n = 27831$. When compared to the historic HOT utilization rates only, i.e. assuming all HOT lane SOVs are "every day" drivers, the resulting model has an R^2 value of 0.675, $n = 27831$. Thus, the pricing structure as in place at this facility, appears to have a negligible influence on behavior. This may indicate serious implications, as many HOT facilities are

under consideration partly for their potential as traffic management tools.

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

High occupancy toll (HOT) lanes are a form of managed lanes that offer free or reduced-toll travel to high occupancy vehicles (HOVs), while allowing single occupant vehicles (SOVs) that pay a toll [12]. Some HOT lanes employ dynamic pricing strategies to control congestion and maintain high speeds, by changing toll rates in response to congestion. HOT facilities that utilize dynamic tolling are examples of the emerging approach known as "active traffic management" (ATM), in which infrastructure providers seek to manage recurrent and non-recurrent congestion based on real time traffic conditions [9]. This chapter lists the existing HOT lane facilities, as well as the expectations surrounding new HOT lanes. The chapter then explains the purpose of the research presented in this thesis.

1.1 Existing HOT Lanes

Currently, HOT lanes exist in several U.S. cities, and more are under construction or planned. Existing HOT lanes include the following:

- San Diego, I-15
- Denver, I-25/US-36
- Minneapolis, I-394
- Houston, I-10, US-290
- Seattle, SR-167
- Miami, I-95 Express
- Orange County, CA, SR-91 Express Lanes

Of these HOT lanes, only two utilize dynamic tolling to maintain speeds in the HOT lanes. HOT lane systems with dynamic tolling are:

- San Diego, I-15
- Minneapolis, I-394

Several other HOT lane systems are in various levels of planning nationwide. One planned system is the I-495 Virginia HOT Lanes, located in the Washington DC metropolitan region between I-95 and the Dulles Toll Road (Route 267). This 14-mile, $1.9B project is expected to provide substantial improvements in transportation efficiency through active traffic management [7]. In much of the documentation on planned HOT lane systems, the facilities are expected to be a substantial part of the transportation solution through active traffic management of the lanes. These HOT lane concepts continue to move forward, despite the absense of empirical data supporting the assumption that drivers will alter their behavior based on price.

1.2 Purpose of Research

The HOT lanes concept relies on the assumption that SOVs will be discouraged from entering the HOT lanes as toll rates increase, theoretically providing a control mechanism to use for preventing the HOT lanes from becoming congested. In an actively operated HOT lane system, with dynamic toll pricing, price is used as a tool to dictate traffic assignment. Driver behavior is dependent on a driver's willingness-to-pay, i.e. a the price a driver is willing to pay for perceived or actual travel time savings.

Most willingness-to-pay research has focused either on stated preference (SP) surveys [5], or has investigated the median cost per hour of commute time saved [3]. To date, no research has been conducted to analyze and model drivers' responses to minute-to-minute changes in toll rates and traffic conditions using empirical data from an operational HOT lane system. The purpose of this research was to understand and model the impact of toll rates and traffic conditions on single occupant driver behavior in a HOT lane system, through analysis of data from an operating HOT lane facility in Minneapolis, Minnesota. This research will be critical to understanding precisely how drivers react to changes in pricing and congestion. Currently, HOT lane systems are being planned without accurate information on precisely how drivers in HOT lane environments will react to changing tolls and congestion. The findings from this research will provide HOT lane developers with better information on driver decisions, allowing more accurate model development, and better feasibility information for decision-makers. Findings from this research will also provide HOT lane operators with a better understanding of how drivers in HOT lanes behave, and will allow the development of more realistic and effective dynamic toll rate algorithms, and allow for better operation of the HOT lanes.

1.3 Conclusion

Although several HOT lane facilities are planned, there exists no information as to how vehicles react to changing congestion and pricing. This research investigates and models SOV driver behavior in a HOT lane system, based on travel time savings and toll rates from an operating HOT facility. Chapter 2 reviews the relevant published literature on the topic, including attitudinal studies, revealed preference studies, stated preference studies, and general HOT lane and dynamic pricing theory and practice. Chapter 3 introduces and describes the MnPASS HOT lane facility that was studied as a part of this research. Chapter 4 describes the methodology used to collect, prepare, and analyze the toll and traffic data from the MnPASS system. Chapter 5 highlights the results obtained from the analysis described in Chapter 4. Chapter 6 presents the conclusions drawn from the research, discusses the contributions made by this research, and recommends areas for further study.

Chapter 2

Literature Review

The purpose of this chapter is to review research studies and documentation relevant to this thesis.

2.1 MnPASS HOT Lane Performance

The primary study evaluating the performance of the MnPASS HOT lanes was sponsored by Mn/DOT, with work performed by Cambridge Systematics and published in 2006 [6]. The research team found that after HOT lane deployment, vehicle throughput increased along the corridor by 5%, while decreasing along other corridors in the region. Vehicle speed also increased 6%, while violation rates (illegal use of the HOV/HOT lanes) decreased from 20% to 9% in the diamond lanes, and 9% to 4% in the reversible lanes. More information about the MnPASS facility is provided in Chapter 3.

2.2 HOT Lane Driver Behavior: Stated Preference Surveys

A study performed by Justice Appiah used survey data to determine the factors driving HOT lane utilization at a non-dynamically priced facility in Houston, Texas [2]. The study found that the primary factors determining HOT utilization among SOVs were trip length, the driver's perception of travel time savings, frequency of travel, and trip purpose. The study also found that toll was not a major deterrant to HOT lane usage, however the toll in the studied facility was a static toll of $2 per trip.

2.3 HOT Lane Behavior with Time of Day or Static Pricing: Revealed Preference

A study was conducted of a bridge in Lee County, Florida, which introduced time-of-day based variable pricing in 1999 [8]. The study found that of the users who were eligible (i.e. that had electronic toll transponders), the introduction of variably-priced tolls caused usage to increase significantly when tolls were discounted, and decrease significantly during mid-peak when tolls were not discounted. The study concluded that the time-of-day variable tolling was effective at reducing congestion at the Cape Coral and Midpoint Bridges.

2.4 HOT Lane with Dynamic Pricing Behavior: Revealed Preference

There has been some work recently to identify driver willingness-to-pay in HOT lanes using empirical data. These studies are discussed below according to the facility they focused on.

2.4.1 San Diego I-15

Brownstone, et al. [3] studied the San Diego I-15 variably-priced HOT lanes project over a two month period, in October and November 1998. Travel time data was compared with survey data asking respondents on what days and times they traveled, and whether they used HOT lanes. The study generated some interesting conclusions. First, they discovered that higher toll rates were signaling drivers, indicating increased congestion downstream. Higher tolls only served to reduce HOT lane usage when the travel time variability (measured as the 90th percentile travel time less the 50th percentile travel time) for that time period is less than 7.21 minutes. Also when drivers encountered a toll rate higher than the average for that time of day, they tended to use the HOT lanes in greater numbers. Similarly, if they encountered a toll rate lower that expected, they used the HOT lanes in lower numbers. The study found that the median cost per hour of travel time saved that drivers were willing to pay was $30 per hour. This result was substantially higher than the $3.50-$5.00 per hour observed by Calfee and Winston [5]. The authors did not consider the effect of real-time traveler information on driver behavior, likely because at the time the study was conducted (1998), smart phones and in-vehicle navigation systems were not widely used, and most travelers relied on often inconsistent radio traffic reports for minute-by-minute traffic conditions.

Brownstone and Small [4] returned to the topic in 2005, in a paper comparing Brownstone, et al.'s earlier work with San Diego's I-15 HOT lanes [3] and Small's work on the SR-91 express toll lanes in Orange County, CA, which incorporate dynamic pricing but do not have an HOV component. The combined study focused on the value of time and value of reliability shown in revealed preference studies compared with values from previous stated preference surveys.

Value of time was found to be between $20 and $40 per hour of travel time saved. The higher values came from the San Diego facility, and the lower values from Orange County. When the San Diego values were adjusted to better reflect Orange County's lower per capita income levels, both regions had similar values of time at around $25 per hour, still several orders of maginitude higher than Calfee and Winston's values [5].

Brownstone and Small [4] also studied the value of reliability. To better capture the significant expense of being late for work, they focused on the difference between the 90th and 50th percentile of morning travel time to capture the upper tail of the travel time distribution. Their findings agreed with Small et al. [14] that travel time was worth about two-thirds of overall service quality, while reliability made up another third.

In an attempt to better understand the higher values of time found in RP studies than in SP studies, Brownstone and Small [4] found that survey participants often overestimated the time savings they would get using express lanes by a value of two. The misperception of travel time savings could be a key factor in the differnece between RP and SP values of time. Brownstone and Small theorized that drivers that experience ten minutes of congestion may perceive an experience of twenty minutes, and may therefore be willing to pay a higher rate to avoid the congestion.

2.4.2 Minneapolis MnPASS

Using traffic sensor and toll count data from March 2008, Song and Smith studied the factors behind HOT lane utilization rates on the MnPASS HOT lanes in Minneapolis, Minnesota [15]. The research team used a combination of visual analysis and elasticity analysis to develop an SOV driver decision model for using the HOT lanes. Elasticity analysis indicated that driver reaction to a change in toll rate was negligible, and that many other factors were stronger contributors to the decision to use HOT lanes.

Song and Smith developed the following multinomial logit model (MNL) to explain SOV behavior in the corridor.

$$P_{HOT} = \frac{e^{u_{HOT} - u_{GP}}}{e^{u_{HOT} - u_{GP}} + 1}$$

Where

P_{HOT} = the probability of an SOV using the HOT lane
u_{HOT} = utility of the HOT lane
u_{GP} = utility of the GP lanes

The relative utility function u_{HOT-GP} is defined as

$$u_{HOT-GP} = a + b * D_{Speed} + c * D_{Toll}$$

Where

D_{Speed} = speed difference between target speed (i.e. speed limit) and the speed in the GP lanes
D_{Toll} = cost difference, i.e. the toll rate

After solving for the variables a, b, and c using multiple nonlinear regression, the corresponding R^2 was found to be 0.5114. Song and Smith concluded that although HOT operations were successful in maintaining a high level of service in the HOT lanes, SOV behavior was largely insensitive to toll level. They further concluded that while SOV behavior was influenced by speed difference and toll rates, these two variables alone were not adequate for predicting SOV behavior.

2.5 Conclusion

There has been much interest recently in HOT lanes, both as a congestion management tool and as a revenue source. Although many HOT lanes are planned, most of the recent research has studied only stated preference surveys, or has focused only on median value of time based on historic traffic conditions. To fully understand the effect of pricing on drivers, there needs to be a greater understanding of the effects of toll rate and real-time congestion on driver behavior. Chapter 3 describes the HOT lane facility that is studied in this thesis.

Chapter 3

MnPASS Facility

The purpose of this chapter is to introduce and describe the HOT facility used to support this research.

3.1 Facility Overview

The I-394 MnPASS is an 11-mile HOT lane facility in Minneapolis, Minnesota operated by the Minnesota Department of Transportation (Mn/DOT). The facility, which has been in operation since May 2005, is one of the few HOT lanes that dynamically adjusts toll rates in response to traffic conditions.

The MnPASS facility is separated into two distinct sections. In the first section, located between Central Avenue and Trunk Highway 100 (TH 100), the HOT lanes are former HOV lanes, with a single lane in each direction. These lanes are separated from the general purpose (GP) lanes by double-striped white lines. This 8-mile section, often referred to as the "diamond" lane section, operates Monday through Friday, from 6 AM to 10 AM in the eastbound direction, and 2 PM to 7 PM in the westbound direction.

In the second section, located between TH 100 and I-94, MnPASS operates as a two lane, barrier-separated reversible facility 2.7 miles in length. The reversible section collects tolls at all times, including weekends, except when the lane direction is being reversed. The HOT lanes are operated in the eastbound direction from 6 AM to 1 PM, and in the westbound direction from 2 PM to 5 AM. The reversible lanes remain westbound Friday afternoon and early Saturday morning. They are switched to eastbound at 8:30 AM Saturday morning, where they remain until 1 PM Monday. A map of the facility is provided in Figure 3.1 [10].

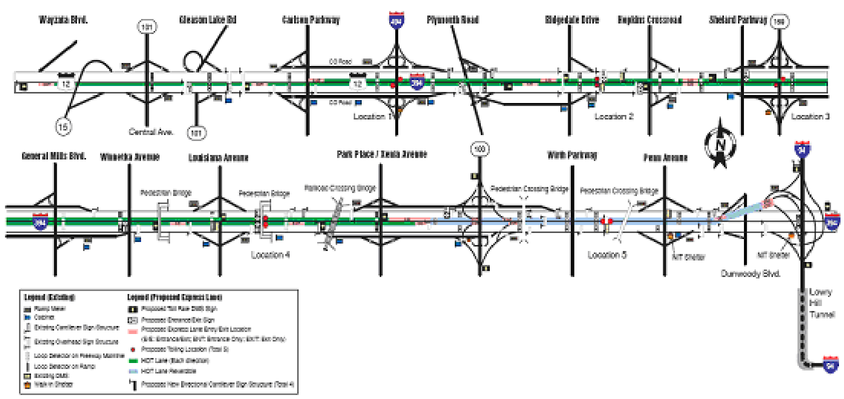

Figure 3.1: I-394 MnPASS HOT Lanes.

3.2 Tolling

Tolls for SOVs are collected electronically at five locations. Four locations are located at intervals along the diamond section, and one location is located on the reversible section. The diamond section has a single toll rate, regardless of how far the driver travels or how many toll gantries the driver passes. The reversible section has a toll rate separate from and in addition to the diamond lane toll rate. Toll rates are automatically adjusted every three minutes based on congestion in the HOT lanes, with the goal of maintaining a level-of-service C based on density (between 19 and 29 vehicles/lane/mile). Tolls range between \$0.50 and \$8.00 per trip. Operators reserve the right to restrict the HOT lanes to HOV only in extreme circumstances. The vast majority of during the study period were generally very low. Figure 3.2 shows the distribution of toll rates from November 2006 to March 2008 for the reversible section only during the AM peak period.

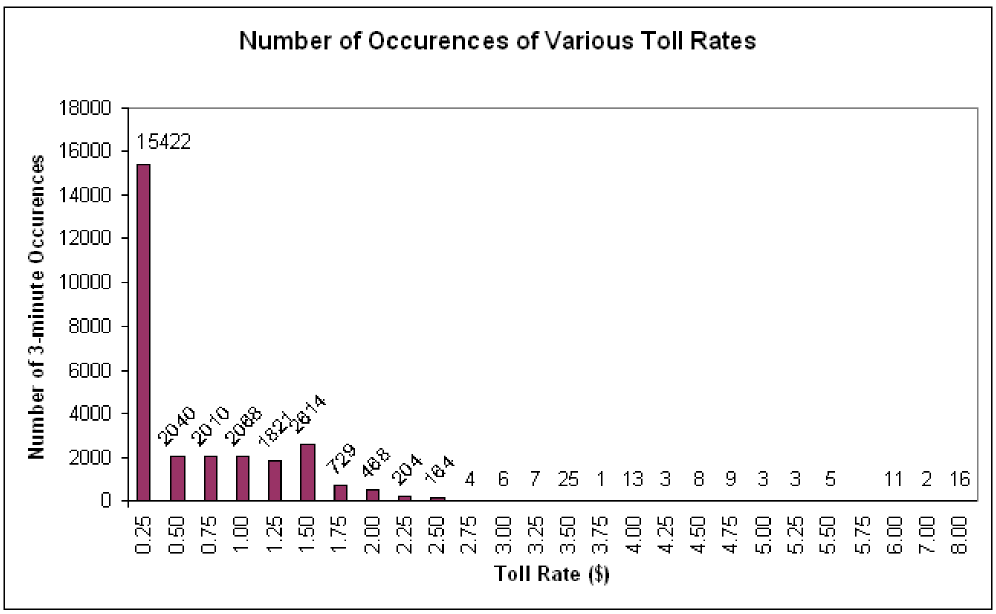

Figure 3.2: Distribution of toll rates for the reversible section of the MnPASS HOT lanes during the study period.

3.2.1 Transponders

SOVs using the HOT lanes must be equipped with MnPASS transponders. Transponders can be leased for \$1.50 per month. As of 2005, MnPASS had distributed 10,000 transponders, and were increasing at a rate of 3% annually [6]. MnPASS initially tried to limit the number of transponders issued, fearing congestion in the HOT lane from too many SOVs in the first days of operation [11]. However, over congestion was not an issue, and Minnesota continues to distribute transponders. It should be noted that MnPASS is the only toll road in the state, either electronic or traditional. MnPASS transponders are not compatible with any other other toll provider, nor does MnPASS accept other transponders.

3.2.2 Dynamic Tolling Strategy

The stated goal of MnPASS's toll rates is to maintain a level-of-service C in the HOT lanes based exclusively on density. To achieve this goal, the toll is automated, and will reevaluate itself every three minutes based on the traffic density in the HOT lanes and adjust if neccessary. To determine its new rate, first the level-of-service in the HOT lanes is determined. For each density level-of-service A through F, the toll rate initiates at a default rate. Within any particular level-of-service, the toll rate may either increase or decrease based on the increasing or decreasing traffic density. Table 3.1 below outlines the toll rate algorithm used by MnPASS.

LOS	Min Toll	Default Toll	Max Toll	Δ1	Δ2	Δ3	Δ4	Δ5	Δ6
A	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
B	$0.50	$0.50	$1.50	$0.00	$0.25	$0.50	$0.75	$1.00	$1.25
C	$1.50	$1.50	$2.50	$0.00	$0.25	$0.50	$0.75	$1.00	$1.25
D	$2.50	$3.00	$3.50	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
E	$3.50	$5.00	$6.00	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
F	$6.00	$8.00	$8.00	$0.00	$1.00	$2.00	$2.00	$2.00	$2.00

Table 3.1: MnPASS Toll Rate Algorithm Based on Current and Change in Density from Previous Three Minutes

With the density in the HOT lanes at LOS D, the default toll rate begins at $3.00. As long as the LOS remains D, the toll rate cannot go below the minimum of $2.50 or the maximum of $3.50. Should the traffic density increase by 2 vehicles/lane/mile, the toll rate will increase by the corresponding LOS D and $\Delta 2$ value of \$0.50, provided in Table 3.2.2, resulting in a total toll of \$3.50. Had the density instead *decreased* by 2 vehicles/lane/mile from the previous three minutes, the toll rate would have decreased by the same amount, from \$3.00 to \$2.50. The algorithm is designed to be sensitive to changes in densities, but still be a step-wise algorithm that avoids rapid fluctuations in toll rates.

3.3 Violations and Enforcement

Much of the revenue generated by MnPASS tolls goes towards enforcement efforts. The Minnesota Highway Patrol, and the Minneapolis and Golden Valley Police Departments assist in enforcing HOT lane restrictions, using a combination of handheld transponder readers and visual confirmation of the number of passengers [17]. Police efforts appear to be effective. Prior to MnPASS, HOV violation rates on the Diamond Lane and Reversible sections were 20% and 7% respectively. After MnPASS, rates had dropped to 9% and 4% respectively [6].

3.4 System Performance

The MnPASS corridor regularly experiences congestion during the peak period. Vehicle speeds in the GP lanes typically fall to 45 miles per hour, while speeds in the adjacent HOT lanes stay at 70 miles per hour or above. During the busiest times of a typical AM peak period, tolls in the HOT lanes average just under \$2, while 16% of SOVs use the HOT lanes. Figure 3.3 shows average speeds of the HOT and GP lanes over the study period. Figure 3.4 shows the average percentage of SOVs using the HOT lane over the study period.

Although congestion is present in the study section, it is not severe by most standards. Average speeds drop to only ten miles per hour below the speed

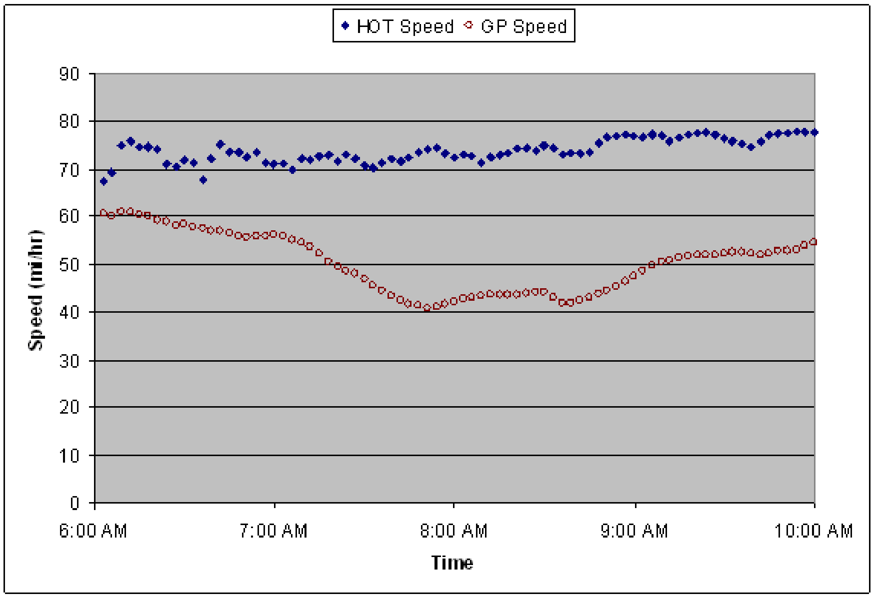

Figure 3.3: Average Speeds During the Study Period.

limit of 55 miles per hour. Minneapolis in general has slightly below average congestion compared to the 90 largest cities, with 39 hours of annual delay per traveler in 2007 compared to 41 hours nationally [13].

3.5 Revenue

MnPASS generates steady revenue, both from tolls and from various service fees. Average daily toll revenue was $5700 in September 2006 [11]. However, approximately 16% of that month's total revenue came from transponder leases ($1.50/month), new account fees, transponder replacement fees, and late-payment fees [11].

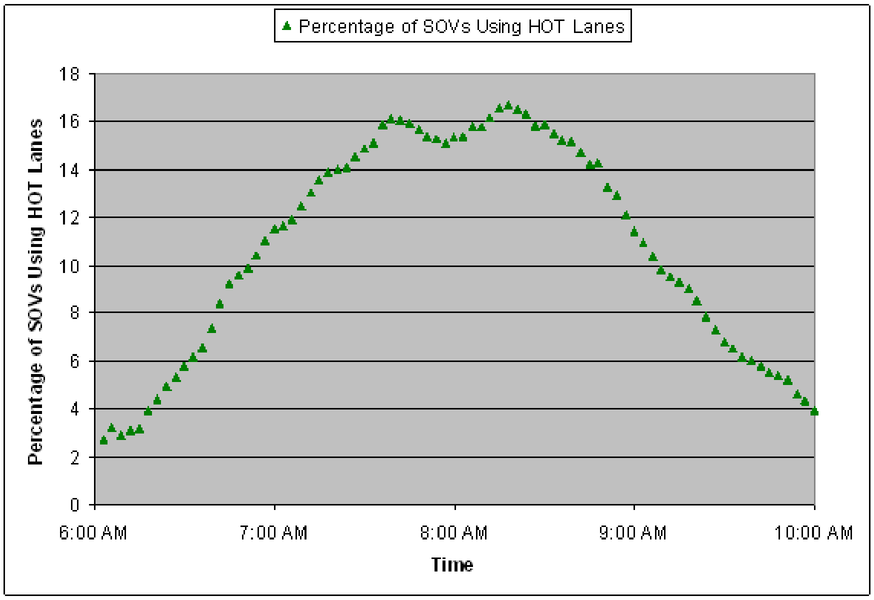

Figure 3.4: Percentage of SOVs Using the HOT Lanes During the Study Period.

3.6 Conclusion

This chapter showed that MnPASS is unique as a dynamically-tolled HOT lane facility. Travelers, while not provided with the ability to compare cost and travel time directly, are still provided a choice between the slightly faster and more reliable HOT lanes and the less reliable but toll-free GP lanes. The following chapter will explain how data from the MnPASS was collected and analyzed as a part of this research into driver behavior.

Chapter 4

Methodology

This chapter details the methods by which the data was collected, validated, and prepared for analysis. The chapter then discusses the analysis methods used to obtain the results presented in Chapter 5.

4.1 Data Sources

Two types of data were used in this study: traffic data and tolling data. These are described in detail in this section.

4.1.1 Traffic Data

Detector data were collected from twelve mainline detector stations in the 2.7 mile study section, with each station made up of several lane detectors. Six of the stations (S1125, S1126, S1127, S1128, S1129, and S1130) were in the HOT lanes, while six other stations (S280, S281, S282, S284, S286, and S288) were in the GP lanes. Data were collected from the Mn/DOT Regional Transportation Management Center's (RTMC) database using Mn/DOT's DataExtract online tool [1]. Data from each detector station were recorded in 30-second intervals, which were then smoothed to 3-minute intervals for this project. Three-minute intervals were chosen to allign with the toll rates, which are recalculated (although not neccessarily adjusted) every three minutes. A map of the detector stations locations is shown in Figure 4.1.

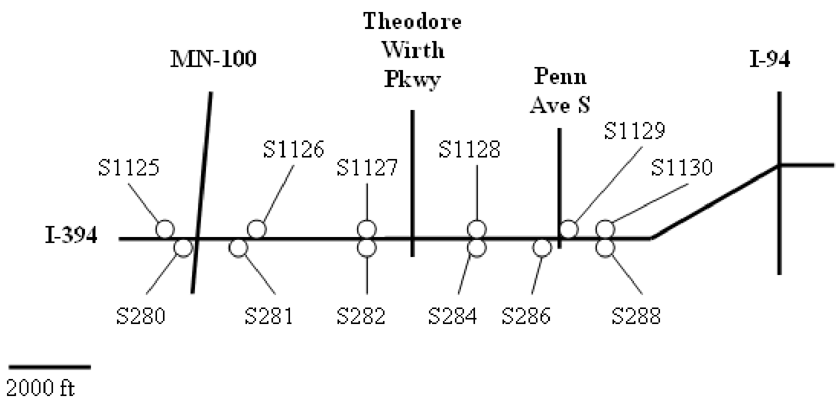

Figure 4.1: Map of the Locations of Detector Stations Used in the Study.

4.1.2 Tolling Data

Toll rates and toll counts were collected from a database provided by the contracted administrator of the MnPASS facility. The database contained individual toll records for each vehicle in the system, including a vehicle's time of entry into the HOT lane system, the toll rate paid, the first toll gantry passed, and the final toll gantry passed. A second database provided the historic toll rates. Each record in the database included the date, the start time of the toll rate, the toll rate for the diamond lane section, and the toll rate for the reversible section. The database contained no personal or identifying information of any MnPASS customer.

4.2 Calculation of Driver Decision Factors

The raw data was then validated and manipulated into usable formats. The following sections details how the raw data was validated and formulated to determine travel times, volumes, cost per hour of travel time saved by SOVs when using the HOT lanes, and the HOT lane utilization rates by SOVs.

4.2.1 Travel Time

All detector data was first validated according to several key standards used by the Texas Transportation Institute in their *Monitoring Urban Freeways in 2003* report [16]. The specific standards are described below:

- Controller error codes, where volume or speed equal a standard error code (in Mn/DOT's case, "-1") denoting a detector failure
- No vehicles present, where speed= 0 and volume= 0
- Duplicate records, where the timestamps of two or more records are identical
- Maximum speed, where speed is greater than 100 miles per hour
- Minimum speed, where speed is less than 5 miles per hour
- Consecutive identical volume, occupancy, speed values; where the values for volume, occupancy, and speed are identical across eight consecutive timesteps, as this often indicates a malfunctioning detector

Records with unacceptable data were deleted completely. Also, any time periods during which no HOT lane tolls were paid were also deleted, as these time periods included either times the toll tag readers were malfunctioning, when SOVs were prohibited from entering the HOT lanes entirely, or during holidays when tolls were not collected. Overall, 1209 3-minute records were removed from the original data set of 27,940, with 27,831 records retained for analysis (95.86% of the original data set).

The remaining data from each detector were averaged over each three minute time period to develop the overall travel time of the corridor 2.7 mile corridor, both in the HOT and GP lanes.

4.2.2 Cost per Hour of Travel Time Saved

In many transportation value of time studies [3, 5, 14], the primary factor used to measure a driver's value of time is the price paid for an hour of travel time saved. This metric was used in this study as well, partly as it is a simple, concise way to measure two separate but inextricably linked variables, and also to maintain consistency with previous projects so that the findings from this study can be easily understood by other researchers.

This thesis assumes that if highway speeds are operating above the posted speed limit, then there is no real congestion, and therefore little incentive to utilize HOT lanes. The cost per hour of travel time saved was calculated by employing the following set of equations shown in Table 4.1.

HOT Speed	GP Speed	Cost per Hour of Travel Time Saved
≥ 65 mi/hr	≥ 55 mi/hr	No advantage, value is null
≥ 65 mi/hr	< 55 mi/hr	$c = \dfrac{T}{\dfrac{D}{S_{GP}} - \dfrac{D}{L_{HOT}}}$
< 65 mi/hr	≥ 55 mi/hr	No advantage, value is null
< 65 mi/hr	< 55 mi/hr	$c = \dfrac{T}{\dfrac{D}{S_{GP}} - \dfrac{D}{S_{HOT}}}$

Table 4.1: Equations Used in Calculating Cost per Hour Travel Time Saved

Where

c = cost per hour of travel time saved ($/hr)

T = toll rate ($)

D = distance of the highway segment (mi), in this case 2.7 miles

S = speed of the HOT or GP lanes (mi/hr)

L = speed limit of the HOT or GP lanes, 65 and 55 respectively (mi/hr)

4.2.3 HOT Lane Utilization Rates

The portion of SOVs utilizing the HOT lanes at any given time period was calculated as the number of toll transactions in the corridor, divided by the combined number of toll transactions and volume in the GP lanes. This calculation assumes no HOVs in the GP lanes during the AM peak period.

4.3 Analysis Methods

The final data set consisted of 27,831 records, with each record including the following information:

- Date
- Start time
- HOT lane speed
- GP lane speed
- HOT lane volume
- GP lane volume
- Toll counts
- Portion of SOVs utilizing HOT lanes

- Toll rate
- Travel time savings along the reversible lane section
- Cost per hour of travel time saved

Each record covered three minutes from the 6:00 AM to 10:00 AM peak period.

Initially, visualization was the primary method of analysis. Several plots were created with cost per hour of travel time saved as the independent variable and average percentage of SOVs utilizing the HOT lanes.

Several other charts were created in Microsoft Excel with time of day as the independent variable, and average percentage of SOVs utilizing the HOT lanes as the dependent variable. The records used to populate these charts were subject to restrictions, as explained below.

1. In the most relevant chart, only records where GP speeds were over 55 miles per hour (the speed limit) were used, as these records assumed free flow speeds on the GP lanes, and therefore no real advantage to using the HOT lanes. These usage rates represent the portion of SOVs utilizing the HOT lanes based on historic evidence rather than real-time traffic conditions. These SOVs are referred to throughout the thesis as "every day" or "non-sensitive" drivers.

2. The resulting SOV HOT lane utilization rates for each time period (i.e. "every day" drivers) were then deducted from the entire data set, with each time period's calculated congestion-free utilization rate deducted from the same time step's actual utilization rate. For example, if 6% of SOVs use the HOT lanes at 8:33 AM when GP speeds are over 55 miles per hour, then 6% is deducted from all 8:33 AM records. The purpose of this step was to remove the "every day" drivers from the general population,

thereby isolating the drivers using real-time congestion as their decision factor.

3. The modified HOT lane utilization rates (with the congestion free rates deducted) were sorted into bins by cost per hour of travel time saved at intervals of $1 per hour up to $160/hour.

4. A chart was created with cost per hour of travel time saved as the indepedent variable, and the "modified" cost per hour saved as the dependent variable.

5. The "modified" data set was fitted with linear, power, second-order polynomial, and exponential models using Microsoft Excel. The best model was selected based on least mean squares estimation.

6. The selected model represents the portion of SOVs utilizing the HOT lanes based on real-time conditions at various levels of cost per hour of travel time saved. These SOVs are referred to throughout the thesis as "price-sensitive" drivers.

4.4 Conclusions

Congestion and toll data from a 16-month period were provided by Mn/DOT and MnPASS. The data were and validated, with a final count of 27,831 records of 3-minute time intervals. The next chapter discusses the analysis of the data and its results.

Chapter 5

Results

The purpose of this chapter is to describe the results obtained from analyzing the MnPASS data. The chapter reviews the analysis performed, and the development and performance of a model to predict real-time SOV behavior in a HOT lane facility based on congestion and price.

5.1 Aggregate Analysis

When one first examines the data, it appears that the cost per hour of travel time saved has little influence on SOV behavior. As seen in Figure 5.1, which summarizes all records during the AM peak, regardless of the cost per hour of travel time saved, roughly 14-15% of SOVs choose to travel in the HOT lanes. One notices that the speed dips near 30-33 dollars per hour saved. This is because when the GP lane speed is slightly below 55 miles per hour, the HOT lane speed is above 65 miles per hour, and the toll rate is at $0.25, the resulting cost per hour saved is in the low thirties. This situation is common in the early part of the AM peak period, between 6:00 AM and 7:00 AM, when HOT usage is very low. The spike in utilization rates comes at $34/hour represents the much higher toll rates and congestion at this price, where tolls are often over $1.

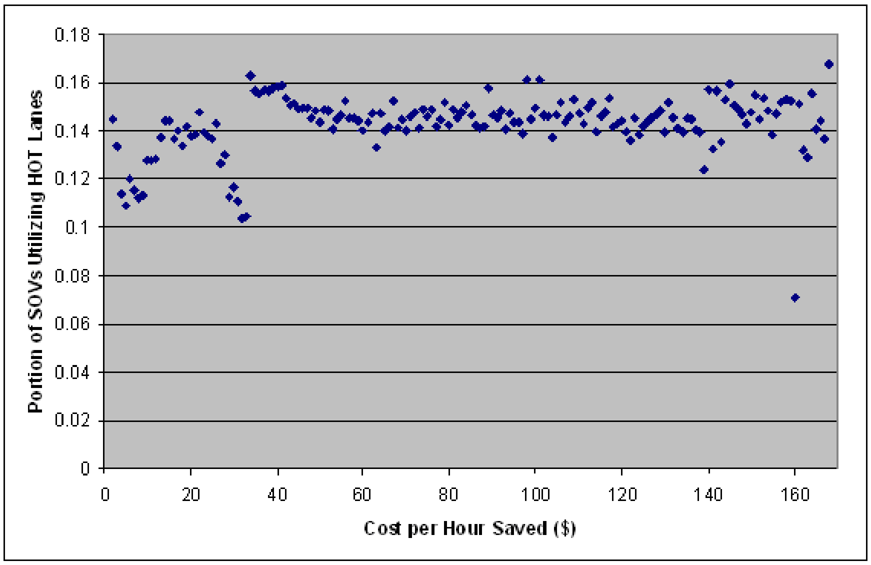

Figure 5.1: Average portion of SOVs utilizing HOT lanes vs. cost per hour saved

When plotting the time series of the percentage of SOVs utilizing the HOT lanes during the AM peak period, one will notice a clear fluctuation in HOT lane utilization, regardless of traffic conditions or toll rate. For example, Figure 5.2 shows the average HOT lane utilization when GP speeds are above 55 miles per hour, the speed limit on this facility. Even in these conditions, with very little apparent incentive to utilize the HOT lanes, drivers are almost six times more likely to use the HOT lanes at mid-peak than during early peak.

5.1.1 Possible Explanations

There are several possible explanations for this phenomenon. First, because Mn/DOT was careful not to over-market the MnPASS transponders [11], it

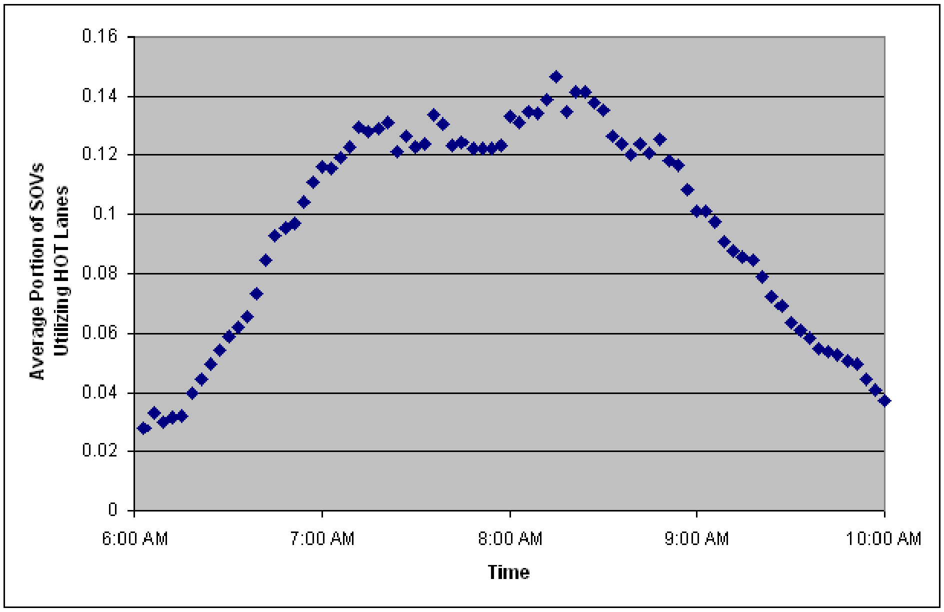

Figure 5.2: Time series of the average portion of SOVs utilizing HOT lanes, when GP speeds are greater than 55 miles per hour.

is likely that most of the MnPASS users are drivers who routinely experience heavier than average congestion. It is possible that a greater percentage of drivers during the mid-peak period have transponders, and thus explains their greater proportion in the HOT lanes. Small et al. [14] have suggested that travel time reliability is also an important factor in driver behavior. In their analysis of the I-15 dynamically-priced HOT lanes in San Diego, Brownstone et al. assumed travel time reliability to be a major decision factor for drivers [3]. In the MnPASS system, GP lane speeds are less reliable during mid-peak, as shown in Figure 5.3.

Because the GP lane speeds are less reliable during mid-peak, drivers may be using the HOT lanes as insurance against congestion, regardless of the evidence of any congestion upstream.

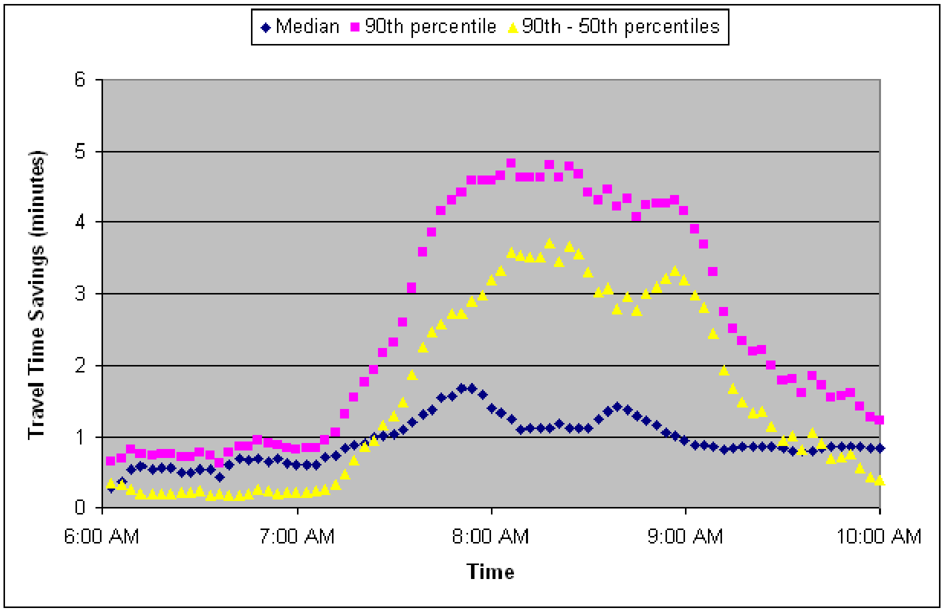

Figure 5.3: Variability of travel time savings during the AM peak.

5.1.2 Isolation of Price-Sensitive Drivers

Assuming that the drivers who use the HOT lanes even when there is no apparent benefit in travel time are insensitive to price, these drivers can be considered to be "every day" HOT lane users. In other words, these SOV users will choose the HOT lanes largely for their reliability as opposed to an improvement in current conditions. Therefore, it is reasonable to "remove" these SOVs from the data in an attempt to model behavior for the set of drivers that are sensitive to costs associated with real-time travel time savings.

By removing the average portion of "every day" drivers from each individual record based on its time-of-day, one can directly consider drivers who are more sensitive to travel time savings and conditions. Although these drivers are not provided with real time traffic conditions on the toll rate signs, drivers in the Minneapolis area are provided with general traffic information from the

Mn/DOT Regional Traffic Management Center's dynamic message signs, as well as traffic reports from local media and third party providers. Figure 5.4 shows the average portion of SOVs using the HOT lanes at various prices for travel time savings, with the "every day" drivers removed from the data. The relationship here is much clearer, as SOV drivers use the HOT lanes at greater rates when the relative cost decreases.

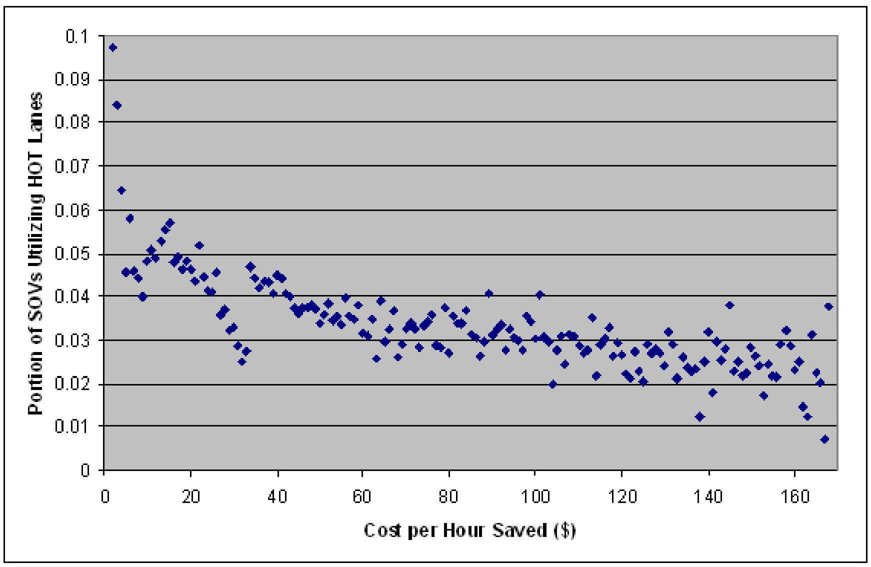

Figure 5.4: Average portion of SOVs utilizing HOT lanes vs. cost per hour saved, after removing the "every day" HOT lane SOVs.

The research team considered several functional forms for the relationship illustrated in Figure 5.4. The proposed models were fitted with least mean squares estimation, with the results shown in Table 5.1.

Based on the R^2 values, the exponential model was selected as the best functional form of the model. The relationship was modeled as shown below.

$$P(c) = \alpha \ln(c) + \beta$$

Model Type	Equation	R^2	n	F & $F_{0.05}$
Linear	$P(c) = -0.0002c + 0.0484$	0.5659	167	215>3.91
Power	$P(c) = 0.103c^{-0.2813}$	0.6108	167	257>3.06
Polynomial	$P(c) = 10^{-6}c^2 - 0.0004c + 0.0552$	0.6335	167	142>3.06
Exponential	$P(c) = -0.0107\ln(c) + 0.078$	0.7265	167	438>3.91
Where $P(c)$ is the average portion of SOVs using the HOT lanes at the cost per hour of travel time saved c.				

Table 5.1: Results of Model-Fitting Analysis of HOT Lane Utilization Data

Where $P(c)$ is the average percentage of SOVs using the HOT lanes at the cost per hour of travel time saved c. Based on a regression of average HOT lane utilizations, values of α and β were found to be -0.0107 and 0.078 respectively. The model had an R^2 value of 0.7265 with $n = 167$ after averaging.

5.2 Development of a Model to Predict Single-Occupant Vehicle Behavior in a HOT Lane Facility

Based on the results presented in the previous section, the author proposes the following two-component model of SOV behavior to account for the "every day" and price-sensitive drivers.

$$U(t, c) = E(t) + P(c)$$

Where

$U(t, c)$ = Percentage of SOVs using the HOT lanes in time interval t at cost per hour of travel time saved c

$E(t)$ = Average percentage of SOVs using the HOT lanes in time interval t when speed in the GP lanes is above 55 mi/hr (speed limit)

$P(c)$ = Average percentage of SOVs using the HOT lanes at the cost per hour of travel time saved c

When the model was applied to the entire MnPASS data set, the two-component model has an R^2 value of 0.684, $n = 27831$. Based on the model, 12.5% of SOVs utilizing the HOT lanes are price-sensitive, while 87.5% are non-sensitive "every day" users. Figure 5.5 provides an example of the model when applied to a typical day.

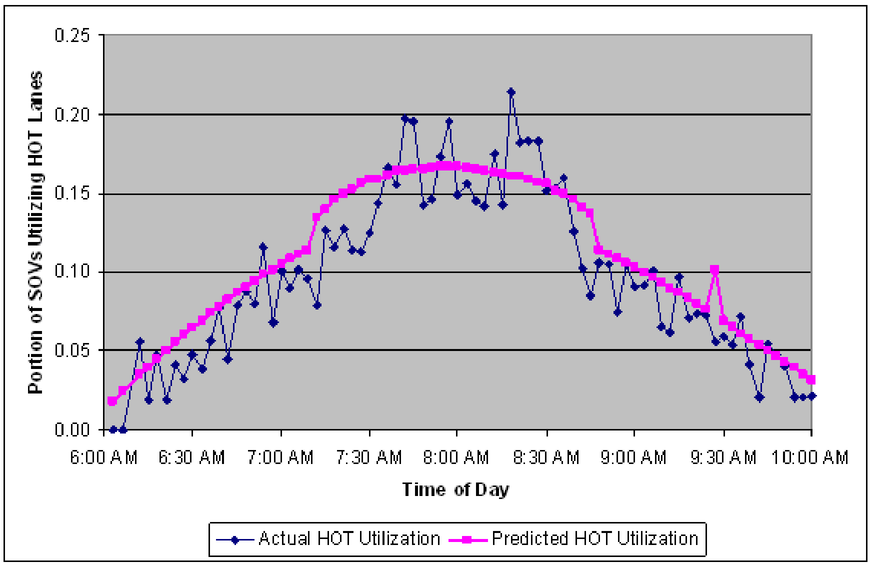

Figure 5.5: Comparison of predicted and actual HOT lane utilization on March 28, 2008.

The model behaves similarly when compared against a day with heavy congestion. Figure 5.6 provides an example of the model as applied to a day with unusually heavy congestion.

Figure 5.7 shows the average vehicle speeds in the HOT lanes and GP lanes for that day, as well as the toll rates. Both HOT lanes and GP lanes experienced significant speed reductions, and toll rates reached $8 for the reversible section.

As the reader will note, during days with typical congestion, the performance

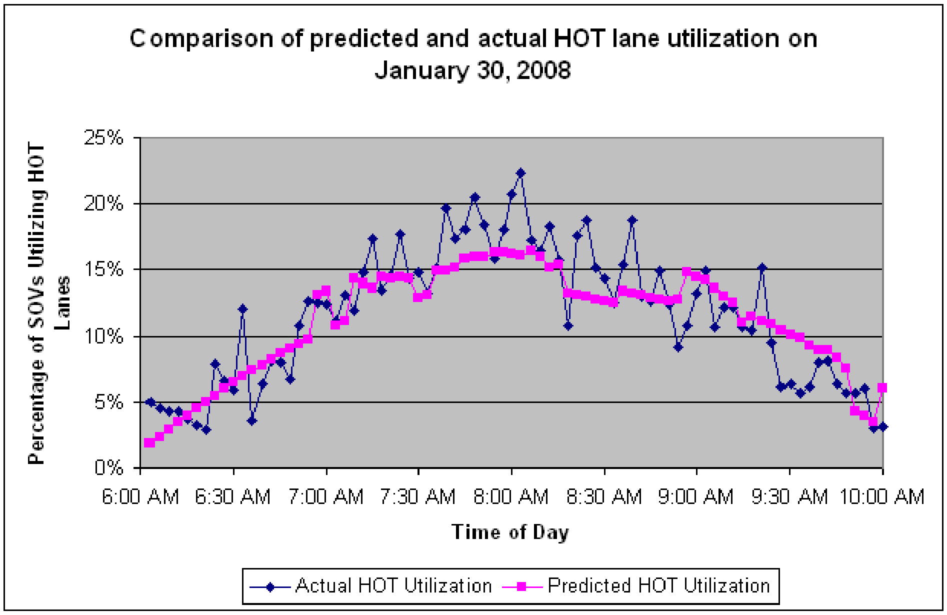

Figure 5.6: Comparison of predicted and actual HOT lane utilization on January 30, 2008.

of the multi-component model is driven largely by the everyday user component, $E(t)$. When only the historical average percentage of SOVs using HOT, under any traffic conditions (i.e. $E(t)$ without the restriction of GP lanes operating at 55 mph or higher) is used to model U, an R^2 value of 0.675 results, $n = 27831$. This varies only slightly from the R^2 value of 0.684, $n = 27831$ obtained when $P(c)$ (i.e. the price-sensitive drivers) are included in the model. Thus, under the congestion levels experienced on the MnPASS system, pricing has negligible influence on behavior. This is a very important finding in terms of future operation of HOT facilities. In this case, it is clear that the current pricing structure and population of eligible SOVs result in a situation where pricing is ineffective in preventing SOVs from using the HOT lanes when deemed necessary. While it is possible that pricing may be more effective at HOT facilities with greater congestion, the congestion levels at MnPASS are simply

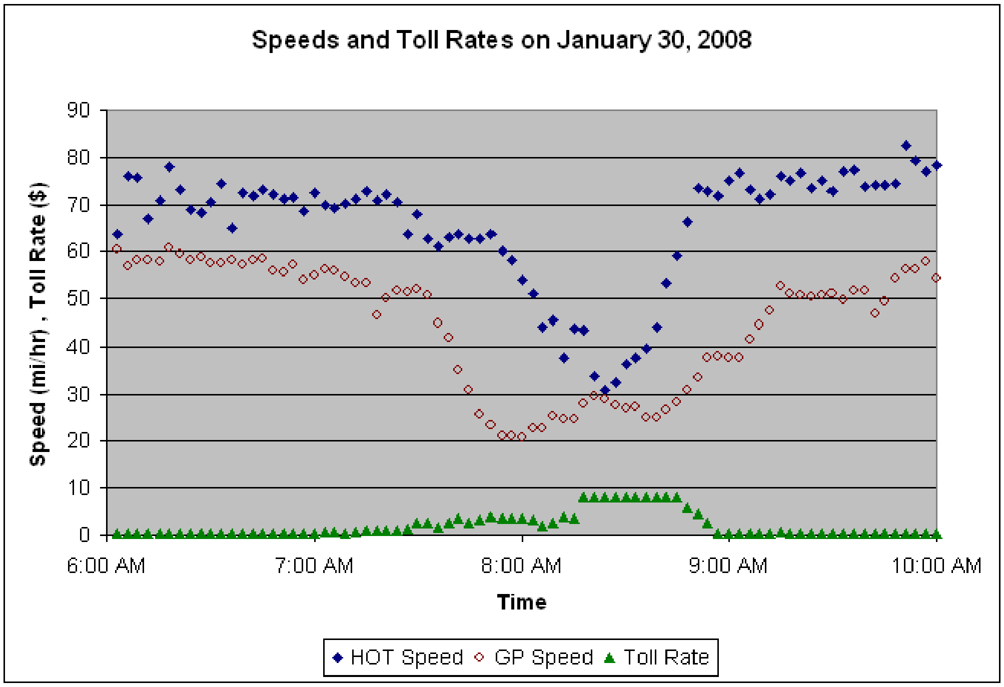

Figure 5.7: HOT lane and GP lane average speeds for January 30, 2008.

too low to suggest a strong influence of pricing on behavior.

5.3 Conclusion

The results presented in this chapter show that most driver behavior can be determined from historic data. A small percentage of drivers, approximately 10% at the most advantageous times, will utilize the HOT lanes based on real-time conditions alone. The developed two-component model, which accounts for real-time travel time costs and historic HOT utilization data, was able to predict HOT utilization rates with an R^2 value of 0.684, $n = 27831$. However, using historic data alone to predict utilization results in an R^2 value of 0.675, $n = 27831$, indicating that at the congestion levels experienced at MnPASS, pricing is not a strong influence on behavior. The next chapter presents several conclusions that can be drawn from these results, highlights the contributions of this research, and suggests potential topics for further research.

Chapter 6

Conclusions

This chapter presents the conclusions drawn from the research, the research's contributions to the field, and potential topics for future research.

6.1 Key Findings Specific to the MnPASS Facility

6.1.1 Non-Sensitive Drivers

Based on an analysis of the data from the MnPASS HOT facility, SOVs utilize the HOT lanes at different rates throughout the AM peak period, even when GP lanes are operating above the speed limit and there is no clear advantage to using the HOT lanes, as seen if Figure 6.1, repeated from Figure 5.2.

These drivers appear to place greater value on protection from possible future congestion than immediately visible travel time savings. Assuming these drivers use the HOT lanes as an "insurance" against unanticipated congestion, this portion of vehicles can be considered insensitive to price. The portion of SOV drivers who use the HOT lanes regardless of real-time conditions is significant,

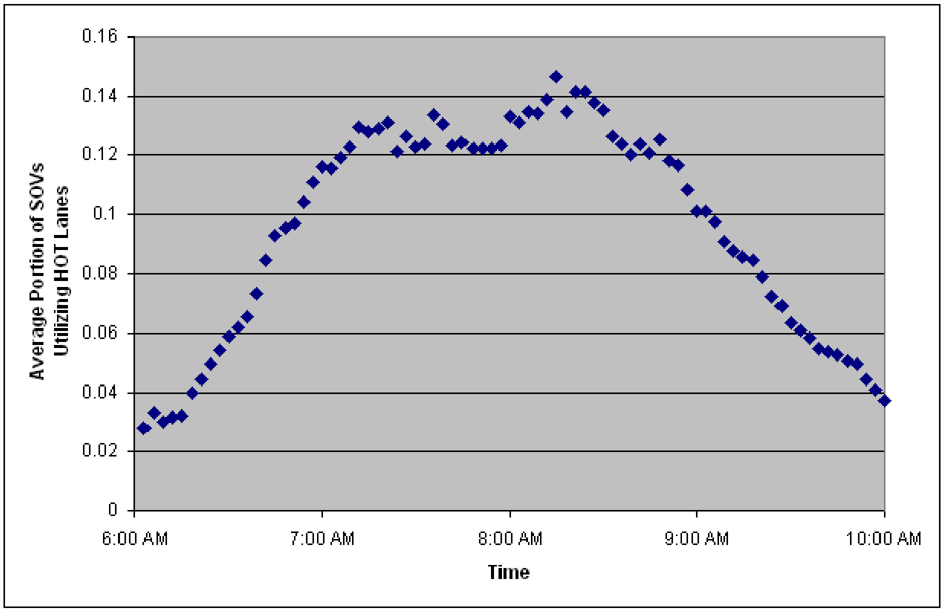

Figure 6.1: Time series of the average portion of SOVs utilizing HOT lanes, when GP speeds are greater than 55 miles per hour.

measured here as 87.5% of the entire number of SOVs that utilized the HOT lanes in this study, based on the developed model.

6.1.2 Price-Sensitive Drivers

A second group of single-occupant vehicle drivers appear willing to utilize the HOT lanes only if there is a significant travel time savings worth the cost. Of all the vehicles that entered the HOT lanes during the study period, under the model developed in this thesis 12.5% of vehicles entered based on real-time congestion and not historic congestion. These drivers utilized the HOT lanes only when the cost per hour of travel time saved reached an acceptable level. Based on the model developed in this thesis, on average 10% of all SOVs will enter the MnPASS HOT lanes in response to real-time congestion.

6.1.3 Possible Explanations for Observed Driver Behavior

Much of the variation in HOT lane usage may be explained not by cost or current conditions, but by expected traffic conditions. This is likely because most drivers are not provided with travel time savings information directly on the toll rate signs, and must make inferences about travel time savings based on perceived conditions and information from radio, dynamic message signs, and other traffic information providers. The HOT lanes experience an increase in usage during the middle of the AM peak period, even when there is little immediately apparent advantage to using HOT lanes. There are two possible explanations. First, drivers may be anticipating greater congestion during the middle of the peak period based on congestion in the past, and may be using HOT lanes to avoid potential rather than actual congestion. Drivers are likely buying reliability, as the travel time variability is greatest at mid-peak. Second, there may be a greater proportion of drivers with HOT lane transponders during this period, as drivers using the facility during this time period are the most likely to encounter congestion, and therefore have the greatest incentive to participate in the MnPASS program.

6.2 Key Findings Applicable Beyond MnPASS

This thesis has shown that pricing does in fact influence driver behavior, but that dynamic tolling itself, i.e. determing tolls based on real time conditions, appears to impact a smaller proportion of drivers. Most single occupant vehicle drivers who use the HOT lanes make their decisions based on expected rather than actual traffic conditions. However, there exists a small proportion of drivers who appear to make decisions based on toll and real-time conditions when deciding to use the HOT lanes.

6.3 Contributions

Previous analysis of HOT lane usage assumed drivers had knowledge only of displayed toll rates and historic average travel times, not real time traffic conditions [3]. This research was able to show that drivers are in fact reacting to real-time conditions, and are more willing to pay for greater travel time savings. However, only a small portion of drivers are reacting to these real-time conditions (12.5% of all SOVs using HOT lanes in the study, potentially 10% of entire SOV population). Under the current toll conditions at MnPASS, the amount of price-sensitive drivers is not enough to effectively actively manage congestion through pricing.

Agencies considering HOT lanes as a traffic solution may use the results from this thesis in three ways. First, they may implement the developed SOV HOT lane usage rate prediction model into their HOT lane transportation simulation models, to create a more accurate representation of the operation of HOT lanes in their jurisdictions. Second, they may use the findings from this research to determine the feasibility of proposed HOT lanes, specifically the utility of HOT lanes as a congestion management tool. Finally, agencies may use the HOT lane utilization model developed in this thesis to design dynamic pricing plans for HOT lane facilities.

The findings have several limitations. The first is that socioeconomics of a region may change the model. For example if the average income lower relative to tolls, drivers may become more discerning and the portion of price-sensitive drivers may increase. Another limitation is that the market penetration of these transponders is unknown. Unlike some areas in the US where electronic tolling is common, the MnPASS system is the only tolled highway in Minneapolis, electronic or otherwise. Driver unfamiliarity with electronic tolling, as well as apprehension about the $1.50 monthly leasing fee for the transponder, may have reduced demand for the transponder. Areas with higher penetration rates may see different results.

6.4 Future Research

As traveler information becomes more widely available through 511, IntelliDrive applications, smartphones, and in-vehicle navigation systems, drivers will be able to make more informed decisions. As these devices and applications become more widely available, and as travel time data become more accurate and sophisticated, drivers may begin to make decisions based more on real-time conditions rather than perceived conditions or past experiences. When these technologies and applications see substantial market penetration, this study should be repeated to determine if more drivers are reacting to real-time congestion. The more drivers that make decisions based on real-time conditions, the greater the ability of pricing to control behavior and manage congestion.

Finally, other areas should be explored to determine the effect of dynamic pricing on driver behavior, outside of HOT lanes. These areas include cordon-pricing, dynamic pricing of an entire roadway, and lane pricing.

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