Benefit and Cost Analysis of the I-394 MnPASS Program

Final Report

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CTS 12-03
In this report, we explored the benefits and costs associated with converting the I-394 High Occupancy Vehicle (HOV) lanes to High Occupancy Toll (HOT) lanes. The study focused on the I-394 corridor, with a 10-year timeframe from 2006 to 2015. The benefits included travel time savings, safety benefits, and vehicle operating cost savings, and the costs consisted of capital costs and annual operating costs. Where applicable, the implementation of this study followed the benefit-cost analysis guidance of MnDOT.

This study considered the benefits of both travel time savings and travel time reliability and the valuations of travel time savings and reliability were derived from econometric models for individual drivers' behavior. HOT lane users choose the lanes because of travel time savings and/or the reliability of the lanes whereas previous studies considered only travel time savings and exclusively relied on standardized economic value of travel time.

This study estimated safety benefits from crash reduction using the Empirical Bayes method. Previous studies scarcely considered the benefits resulting from the conversion of HOV lanes to HOT lanes. This study also showed that “naïve” approaches tended to overstate safety benefits, which highlighted the importance of using a sound methodology.

17. Document Analysis/Descriptors
Congestion pricing, Value of time, Value of reliability, Empirical Bayes, Empirical methods, Safety, High occupancy toll lanes

18. Availability Statement
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February 2012

Published by:

Intelligent Transportation Systems Institute
Center for Transportation Studies
University of Minnesota
200 Transportation and Safety Building
511 Washington Avenue SE
Minneapolis, Minnesota 55455

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Acknowledgments

The authors wish to acknowledge those who made this research possible. The study was funded by the Tech Plan program of the Intelligent Transportation Systems (ITS) Institute at the University of Minnesota’s Center for Transportation Studies (CTS). Financial support was provided by the United States Department of Transportation’s Research and Innovative Technologies Administration (RITA).

We would like to thank the following people for their assistance with the study: Ken Buckeye, Heather Gardner, Gene Hicks, Lars Impola, Julie Johnson, Jolene Servatius, and Ryan Coddington of the Minnesota Department of Transportation.

We would also like to thank Dr. Gary Davis, Dr. Chris Monsere, and Dr. Bhagwant Persaud for their help on technical questions. Comments by Dr. Mark Burris improved the report.

Thanks also to Kirti Das and Feili Hong, who helped collect and analyze GIS data.
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Executive Summary

In this study, we conducted a benefit cost analysis to evaluate the net societal benefits and costs that were brought about by the I-394 MnPASS program. Where applicable, the implementation of this study followed the benefit-cost analysis (BCA) guidance of MnDOT. The study focused on the I-394 corridor, with a 10-year timeframe from 2006 to 2015. The benefits considered included travel time savings, safety benefits, and vehicle operating cost savings, and the costs consisted of capital costs and annual operating costs.

In this study we considered the benefits of both travel time savings and travel time reliability and their valuations were derived from econometric models for individual drivers’ behavior. We estimated safety benefits from crash reduction using the Empirical Bayes method. We showed that “naïve” approaches tended to overstate safety benefits.

Overall, the BCA concludes that the I-394 MnPASS program is economically justified, with a benefit-cost ratio of 2.19. Specifically, travel time savings (not including reliability savings) can compensate only a very small share (about 7%) of total costs, and travel time reliability savings contribute to additional 23%. Different variations on these two savings do not materially change their contribution. Thus, travel time savings and travel time reliability savings are important sources of the benefits, but they are not the dominant sources.

Safety benefits dominate the total benefits of the MnPASS, especially those from fatal crash reductions. The specific contribution of safety benefits to cost compensation also depends on the standard economic values used. It is worth noting that the safety benefits of the I-394 MnPASS program are associated with converting underused HOV lanes to HOT lanes, accompanied by designating access points. Therefore, the safety benefits have limited generalizability for scenarios in which HOT lanes are added to existing freeways.

Future BCA of HOT lane projects should consider travel time reliability savings and safety benefits. Ignoring the two benefits could substantially skew the outcome.
1 Introduction

High-occupancy-toll (HOT) lanes have become increasingly popular in the U.S., in the hope that they would relieve highway congestion and generate revenues. In 2005, Minnesota converted the underused high-occupancy-vehicle (HOV) lanes on I-394 to HOT lanes (called MnPASS). Several other HOT lanes are in full operation; for example, California I-15, Colorado I-25, Houston I-10 and US 290, Utah I-15, and Washington SR-167. Further, dozens of future HOT lanes are under study. In 2006, US Department of Transportation (DOT) initiated an Urban Partnership Agreement (UPA) with cities to implement complementary and synergistic strategies to relieve urban congestion. One significant strategy of UPA is tolling. For example, in Minneapolis, the HOV lanes on I-35W have been extended and converted into HOT lanes. In Miami, a HOV lane on I-95 was converted into two HOT lanes in each direction.

HOT lanes provide a variety of benefits to users and transportation agencies (FHWA 2003). First, HOT lanes offer users reliable travel times by managing traffic volume through dynamic tolls, especially during peak hours. HOT lanes give solo drivers an option to pay for the privilege of high travel speed, instead of sitting in congested general purpose lanes. For example, after four HOT lanes were added to Route 91 in California, users were reported to save 12 to 13 minutes’ travel time (Poole and Orski 2000; Sullivan and Burris 2006). Second, HOT lanes may provide revenue for the construction and maintenance of HOV lanes and improving transit services. For instance, with about $1.85 million capital costs of conversion, the I-15 HOT project can generate about $1 million in revenue annually (Poole and Orski 2000). Third, HOT lanes may reduce fuel consumption and offer environmental benefits. (Burris and Sullivan 2006) conducted a benefit-cost analysis on the conversion of QuickRide HOT lanes in Houston. They found significant benefits from travel time saving and reduction in fuel consumption. A similar conclusion was drawn for California SR 91 (Sullivan and Burris 2006).

The I-394 MnPASS opened to solo drivers paying an electronic toll on April 11, 2005; buses, carpools and motorcycles can use it for free. It runs from the western suburbs of the region to downtown Minneapolis (Figure 1). The I-394 MnPASS contains two sections. The section from Highway 100 to downtown Minneapolis includes two reversible lanes with separations from general traffic. For each direction, the section from Wayzata Boulevard to Highway 100 includes a diamond lane, which is marked by double white lines. Typically drivers cannot cross the double lines. Drivers who want to use the MnPASS lane must access or exit it at designated areas. The HOT lane is open to MnPASS users Monday through Friday from 6 a.m. to 10 a.m. and 2 p.m. to 7 p.m. The lane is open to general traffic the rest of each week day and on weekends. Refer to http://www.mnpass.org/index 394.html for detailed information on the I-394 MnPASS.
Figure 1. Interstate Highways in the Minneapolis-St. Paul Metropolitan Area
The implementation of the MnPASS had four goals: improve the efficiency of the I-394, maintain free-flow speed in MnPASS lanes, employ new technologies for pricing and enforcement, and use revenues to improve highway and transit in the corridor (Arnebeck 2006). Although the MnPASS did well in the first three aspects, no net revenues have been provided yet. During the past few years, Minnesota Department of Transportation (MnDOT) has been subsidizing the operation of the MnPASS (Table 1). Further, MnDOT invested more than $8 million to convert the HOV lanes to the HOT lanes in 2005. Accordingly, many planners and legislators have questioned whether the conversion is economically justified.

Table 1. Toll Revenues and Operating Costs of the MnPASS

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toll revenues</td>
<td>$968,781</td>
<td>$1,096,107</td>
<td>$1,118,444</td>
<td>$1,256,380</td>
</tr>
<tr>
<td>Total costs</td>
<td>$1,294,922</td>
<td>$1,331,699</td>
<td>$1,322,489</td>
<td>$1,426,352</td>
</tr>
</tbody>
</table>

Source: MnDOT

The purpose of this study is to conduct a benefit cost analysis (BCA) to examine net societal benefits and costs resulting from the implementation of the I-394 MnPASS. The report is organized as follows. The next chapter presents the framework for the BCA. Chapter 3 focuses on travel time savings and presents a method to measure value of travel time and value of travel time reliability. Chapter 4 discusses the safety benefits associated with the conversion. Chapter 5 presents other benefits and costs. Chapter 6 discusses the BCA results and shows how sensitive the results are to a few input parameters. Chapter 7 summarizes the key findings of this study. It is worth noting that Chapters 3 and 4 are adapted from two papers presented at the Transportation Research Board Annual Meeting in Washington, D.C. (Cao, Xu et al. 2010; He, Liu et al. 2011).
Framework of MnPASS Benefit Cost Analysis

In this study, we will evaluate the net social benefits and costs that were brought about by the I-394 MnPASS program. Where applicable, the implementation of the BCA follows MnDOT’s guidance (MnDOT 2009): “Benefit-Cost Analysis for Transportation Projects”.

The scope of this study is concerned with the I-394 corridor. According to MnDOT engineers, although MnPASS improved the mobility of the I-394, it did not produce significant effects on the mobility of the regional transportation network. Thus, this study will focus on benefits and costs on the I-394. We will quantify the incremental benefits and costs of the MnPASS beyond the base case. The base case assumes that the MnPASS HOT lane would continue to operate as a HOV lane, as it did before the MnPASS program. The alternative is the current MnPASS program. Similar to (Burris and Sullivan 2006), the benefits of the MnPASS are calculated by comparing MnPASS trips to single occupancy vehicle (SOV) trips on the general purpose lanes (GPLs). The MnPASS was opened in April 2005. The timeframe of the MnPASS analysis is set to be 10 calendar years from 2006 to 2015.

According to the MnDOT guidance, the benefits of the MnPASS program include travel time savings, vehicle operating cost savings, and safety benefits. Travel time savings are calculated using two ways. The first way is to compute the differences in travel time for MnPASS users under the base case and the alternative. In particular, we compare instantaneous travel time of MnPASS users to travel time of GPL users who traveled at the same time as MnPASS users. The valuation of travel time savings is calculated using the standardized cost-per-hour-per-person values for autos. Because many MnPASS users choose the HOT lane for reliable travel time (Cho, Goel et al. 2011), the second way considers the difference in both travel time savings and reliability savings. The valuation of these two savings is calculated using the economic values derived in this study.

For vehicle operating cost savings, we consider only the reduction in fuel consumption, as a result of improved mobility. This saving is derived based on the relationship between fuel economy and travel speed, illustrated by (West, McGill et al. 1999). Because MnPASS users and GPL users drive the same distance, the MnPASS will not change vehicle ownership, and hence it is not likely to have a significant influence on other operating costs.

Safety benefits result from the reduction in accidents. The benefits are estimated for different severity type of crashes (including fatal, type A, B, C injuries, and property damages). The reduction in crashes of MnPASS, compared to the HOV lane, is estimated using an Empirical Bayes method (Hauer 1997). In particular, for a given severity type of crashes, we compute the change in the number of crashes by taking the difference between case B and case A, where case B is the expected number of accidents that would have happened in the after period without converting a HOV lane to a HOT lane, and case A is the actual number of accidents in the after period. This approach is different from a simple before-after study with control groups and is well acknowledged for the ability to produce accurate estimates for road safety. The valuation of safety benefits is calculated using the standardized economic values for different crash severities (MnDOT 2009).
The costs of MnPASS include capital costs and operating costs. The I-394 MnPASS Lanes from TH 100 West to I-494 are epoxy edgelines. The reversible lanes from TH 100 East to I-94 are epoxy edgelines and grooved contrast poly preformed marking tape for the skipline. Grooved tape can last 5 to 10 years and the epoxy edgelines can last 3 to 5 years. The tape and edgelines are needed even if there is no HOT conversion. So we will not consider replacement costs as maintenance costs unique to HOT lanes. According to the MnDOT guidance, remaining capital values will be deducted from the overall costs.

It is worth noting that the benefits and costs that were transferred between different agents will not be considered in the analysis. Such benefits and costs include, but are not limited to, tolls, leasing fees of transponders, and taxes of fuels.

The economic values from 2005 to 2010 are adjusted to 2010 constant dollars using Consumer Price Index (CPI) from Bureau of Labor Statistics and those from 2011 to 2015 are adjusted using a 3% inflation rate. According to the MnDOT guidance, a 2.9% real discount rate is used to convert economic values to present values in 2010 dollars.

Although both benefit cost ratio and net present value are shown in the spreadsheet, the former is used to evaluate whether the MnPASS program is economically justified compared to the base case.
3 Travel Time Savings

3.1 Introduction

Toll pricing has long been recognized as an effective means to balance the supply and demand of social resources. For researchers and transportation planners, a good understanding of drivers’ preference to using tolled roads is one of the key components in developing effective value pricing policies. A large number of studies have been conducted to evaluate drivers’ value of travel time (VOT) and value of travel-time reliability (VOR), both of which are believed to be the most important aspects impacting drivers’ route, departure time, and mode choices (Brownstone and Small 2005; Carrion-Madera and Levinson 2011).

Our understanding on VOT and VOR is constrained by the limitations of empirical data. In the literature, survey data, loop detector data, and GPS data are commonly-used sources for estimating VOT/VOR. The earliest modeling frameworks have been developed on the basis of information from revealed preference (RP) (Beesley 1965) or stated preference (SP) (Black and Towriss 1993) surveys. However, in the VOT/VOR studies based solely on RP (actual preferences) data, it is difficult to account for travel-time reliability and drivers’ heterogeneity resulting from unobserved sources (Small, Winston et al. 2005). Meanwhile, SP data may deviate from drivers’ actual choice because the scenarios respondents encounter are hypothetical. To overcome the inabilities in the SP and RP data, (Ghosh 2001) and (Small, Winston et al. 2006) employed both RP and SP observations to examine drivers’ preferences. Even so, the design of survey and the sampling strategy need to be carefully considered to avoid non-response bias. And since the response rate is usually low, a survey process becomes costly in order to obtain a sample large enough for statistical analysis.

Some studies employed loop detector data as an alternative data source for evaluating VOT/VOR. Loop detector data, compared to survey data, provide a simple way to reveal travelers’ actual responses to different traffic conditions on the aggregated level. For instance, (Liu, Recker et al. 2004) and (Liu, He et al. 2007) used the loop detector data from California State Route (SR) 91 to estimate drivers’ VOT and VOR. Since the data provide only aggregate link volumes, individual’s route choice preference is absent. Thus, the methodologies used in both studies are limited to simple networks (generally with single origin or destination such as SR91) due to the difficulties incurred by origin-destination demand estimation.

The recent research on VOT/VOR applies new technologies, such as Global Positioning System (GPS) or smart phones, as alternative means to collect drivers’ choice behaviors. Using GPS data, individual drivers’ route information can be exploited in VOT/VOR estimation (Li, Guensler et al. 2005; Carrion-Madera and Levinson 2011). However, the difficulties in recruiting voluntary participants and installing additional equipment (e.g., GPS devices) for the experiment often limit the number of subjects involved in the study. With a low sampling rate, studies applying GPS data generally need follow-up surveys to reduce bias. It makes the data collection process time-consuming and labor-intensive.

The dynamic toll data, such as those provided by MnPASS system in Minnesota, is an alternative data source that overcomes the shortcomings inherent in the above-mentioned sources. First, a dynamic toll database covers a large number of traffic conditions that could not possibly be
offered by a single RP or SP survey. Meanwhile, all the traffic conditions recorded are revealed preferences instead of hypothetical scenarios assumed in SP surveys. Second, different from loop detectors, the transponders leased to users in a dynamic toll system enable the identification of individual vehicles. Thus, the dynamic toll records offer the capability of modeling drivers’ route choice in a complex network with multiple origins and destinations. Third, compared to GPS data, since transponders are required to be equipped by dynamic toll system users, no additional devices are needed to collect their choice information. In addition, the non-response bias is not a concern anymore, because the data is automatically collected for all users.

Some researchers have taken advantages of dynamic toll data in evaluating VOT. For example, (Cho, Goel et al. 2011) used the I-394 dynamic toll data to estimate the VOT of HOT lane users. They found that the mean VOT for morning users was up to $78 per hour. In their study, drivers’ route choice is assumed to be solely dependent on travel time savings. They directly used the out-of-pocket toll over the travel-time saving to approximate drivers’ VOT. As they pointed out, travel time reliability should be considered in the model. However, to our knowledge, none of the models proposed for estimating VOT/VOR have been applied to the dynamic toll data. There exists a gap between the theoretical models and the reliable dynamic toll data.

To fill in the gap, in this study we propose a methodology for estimating the VOT/VOR using the dynamic toll data. The methodology is then applied to the data from the I-394 MnPASS system in Minnesota. The proposed methodology is also applicable to dynamic toll data in other metropolitan areas. Among the high occupancy toll (HOT) lanes currently operating in the US, the I-394 MnPASS program was one of the first sites applying a dynamic tolling strategy to achieve the goals of improving the efficiency of transportation network and maintaining free flow speeds for transit and carpools (Cambridge Systematics, Inc. 2006). The MnPASS program is not only a traffic management system for maintaining the service quality, but also a traffic information system providing drivers the most recent traffic condition through toll price. The more congested the downstream traffic, the higher the posted toll. Thus, drivers are aware of downstream congestion when they choose to enter the HOT lanes. This is one of the unique features embedded in the dynamic toll data that should be carefully handled by the estimation methodology.

The remainder of this chapter is organized as follows. The following section gives a brief description of the I-394 MnPASS program and the data sources for travel time saving, travel time reliability, and monetary cost. Section 3 presents the mathematical formulation of the model. Section 4 explains in details how we prepare the model inputs. Section 5 presents the results along with the implications and explanations of the estimates. The final section summarizes the key findings.

3.2 Background

3.2.1 Study Site

The I-394 is a 9.5-mile freeway that serves as a major link connecting the western suburban communities and downtown Minneapolis. With three lanes in each direction, it carries an annual average daily traffic (AADT) of up to 151,000 vehicles (Cambridge Systematics, Inc. 2006). The posted speed limit is 55 mph. MnPASS Express lanes, designed as HOT lanes, provide up
to two additional designated lanes on the I-394 between Wayzata and downtown Minneapolis. The I-394 MnPASS program was opened and became the first managed lanes in Minnesota in May 2005 (Cambridge Systematics, Inc. 2006). It converted the historical high-occupancy vehicle lanes into HOT lanes by equipping the lanes with sensors and leasing transponders to single occupancy vehicle (SOV) drivers. The general purpose lane (GPL) configuration remained unchanged. Figure 2 illustrates the schematic of I-394 Express lanes. The MnPASS lanes include two types of designs. From I-494 to Highway 100, the toll lanes were designed as diamond lanes (one lane per direction), which were separated from GPLs by double white lines and painted with diamond marks. The segment has designated access points that are controlled primarily by lane striping. On the segment from Highway 100 to Downtown, two reversible lanes are present alongside the freeway separated from the GPLs by a concrete barrier.

According to the MnPASS website (http://www.mnpass.org/), the current operation time for the HOT lanes is as follows. The eastbound of I-394 diamond lane section is operated Monday through Friday from 6 a.m. to 10 a.m. The westbound of I-394 diamond lane section is operated Monday through Friday from 2 p.m. to 7 p.m. Both eastbound and westbound lanes will open to general traffic for the rest of the day and on weekends. The eastbound of I-394 reversible section is operated from 6 a.m. to 1 p.m. The reversible lanes are closed from 1 p.m. to 2 p.m. for directional change. The westbound of I-394 reversible section is operated from 2 p.m. to 5 a.m. The reversible lanes are closed from 5 a.m. to 6 a.m. for directional change.

For value of reliability, we focus on the eastbound traffic from 6 a.m. to 10 a.m., which consists mainly morning commuting trips from residential locations to downtown Minneapolis. The study site runs from the interchange of I-394 and I-494 at the west end, to a location just prior to the Dunwoody Blvd exit on the east end. Along this segment, there are five tolling sensors and five corresponding HOT lane zones. Accordingly, the study corridor was subdivided into five
zones, or plazas. The eastbound tolling stations are labeled as 1001 to 1005. These plazas were delineated by the loop detectors that lie within the access points. This provides an accurate measure of the travel time savings of a vehicle within a given plaza. The loop detectors have a known easting and northing surveying location. This provides the geometry information for the travel time analysis.

3.2.2 Data Sources

Several data sources were used to obtain the information about drivers’ route choice decisions, traffic conditions and tolls. They are discussed in details as follows.

3.2.2.1 MnDOT Loop Detector Data

Since loop detectors have been well instrumented on the I-394 with about half mile spacing, we decided to use loop detector information to estimate travel times. Minnesota Department of Transportation (MnDOT) archives vehicle counts and occupancies at all loop detector stations in a 30-second time interval. A computer assistant tool, Data Extractor, was used to extract Microsoft Excel (.csv) files that contain speed data for all detectors for a given day, based on the archived occupancy data. We then used average traffic speeds from each detector station to compute the travel time for each trip. The locations of loop detectors were identified through MnDOT All Detector Report (http://www.dot.state.mn.us/tmc/trafficinfo/downloads/adr.pdf). The location data were required when we downloaded the appropriate data through the MnDOT Data Extractor.

3.2.2.2 MnPASS Toll Tag Database

This data set provides the information about the usage of the I-394 HOT lanes. Its data structure includes the following fields: Toll Tag Number, Start Plaza, End Plaza, Toll Price, Date, Time, Transponder Registration Zip Code, Day of Week, and Trip ID. The Start Plaza in the data refers to the toll plaza (1001 to 1005) where the driver was first detected, and the End Plaza refers to the toll plaza (1001 to 1005) where a driver was last detected. The fields Date and Time refer to the date and time the trip was detected. The toll zones were then linked to the loop detector data to produce estimated travel times for the tolled trips.

3.2.2.3 MnPASS Toll Rate Database

In addition to the price information for tolled trips provided in the toll tag database, we used a toll rate database. As toll rates are updated every three minutes, the toll rate table provides the posted toll prices at each toll zone in a three-minute time interval during the HOT lane operation time. Therefore, this table allows us to identify the posted toll prices when drivers traveled on the GPLs.

The tolls on the I-394 HOT lanes change dynamically, ranging from $0.25 to $8.00 depending on the level of congestion as determined by the volume to capacity (v/c) ratio in the HOT lanes and a predetermined curve (Cambridge Systematics, Inc. 2010). In a toll plaza, the highest v/c ratio from all detectors in that zone is used to determine the toll rate. The toll rate database includes a field, DETECTOR, referring to the detector that was used to determine the toll rate for that plaza. As the highest v/c ratio on the HOT lane increases, the toll also increases. Note that the toll is NOT a function of the distance traveled on the tolled segment. Whether a trip uses only a small
portion of the segment or the entire segment, the same toll is charged. If a trip uses multiple
tolled segments, the total toll paid is the sum of the toll on each segment.

3.3 Methodology

3.3.1 Mathematical Model

In this study, we assume that the disutility experienced by any particular driver is captured by
three components: travel time, travel-time variability and out-of-pocket monetary cost (toll).
Without any socio-demographic attributes of I-394 MnPASS users, the three characteristics are
so far the most reliable features we can obtain in estimating VOT/VOR. They have been
extensively discussed and used in previous studies (Brownstone and Small 2005). Similar to
(Liu, He et al. 2007), drivers’ disutility function is mathematically expressed as:

\[ U_{np}(t) = \beta_n x_{np}(t) + \epsilon_{np}, \]  

where

- \( U_{np}(t) \) is the total disutility of path \( p \) at time \( t \) for traveler \( n \)
- \( x_{np}(t) = [T_p(t), R_p(t), C_p(t)] \) is the cost vector of path \( p \) at time \( t \) for traveler \( n \)
- \( T_p(t) \) is the travel time of path \( p \) at time \( t \)
- \( R_p(t) \) is the variability of path \( p \) at time \( t \)
- \( C_p(t) \) is the out-of-pocket monetary cost of path \( p \) at time \( t \)
- \( \beta_n = [\beta^{T}_n, \beta^{R}_n, \beta^{C}_n] \) is the aversion parameters vector of traveler \( n \)
- \( \epsilon_{np} \) is unobserved extreme random value for traveler \( n \) using path \( p \)

Here, we assumed the coefficients \( [\beta^{T}_p, \beta^{R}_p, \beta^{C}_p] \) in the disutility function satisfy certain
distributions across the whole study period. The random term \( \epsilon_{np} \), which is assumed to be
identically and independently distributed across all drivers and routes, captures the person-
varying differences between true disutility value \( U_{np}(t) \) and deterministic disutility calculated by
the linear function \( V_{np}(t) = \beta_n x_{np}(t) \). This utility function is not used to derive time-dependent
VOT and VOR, as suggested in (Liu, He et al. 2007). The toll tag database does not contain the
departure time information when a MnPASS user traveled on the GPLs. Without drivers’
departure choice modeled in the utility function, we cannot estimate time-dependent coefficients
for VOT and VOR.

According to microeconomic theory (Varian 1978), the value of time is defined as the marginal
rate of disutility between travel time and out-of-pocket toll; and value of (un)reliability is defined
as the marginal rate of disutility between travel time (un)reliability and out-of-pocket toll.
Mathematically,

\[ \text{VOT}_n = \frac{\partial U_{np}(t) / \partial T_p(t)}{\partial U_{np}(t) / \partial C_p(t)} = \frac{\beta^{T}_n}{\beta^{C}_n}, \]  
\[ \text{VOR}_n = \frac{\partial U_{np}(t) / \partial R_p(t)}{\partial U_{np}(t) / \partial C_p(t)} = \frac{\beta^{R}_n}{\beta^{C}_n}, \]  

(2)

(3)
To accommodate taste variation across individuals, preference heterogeneity is introduced by assuming that the coefficients $\beta_n$ are realizations of random variables $\beta$. This specification, known as mixed logit, is identical to standard logit except that $\beta$ varies over decision makers rather than being fixed (McFadden and Train 2000; Bhat 2001; Small, Winston et al. 2005). Specifically, the mixed logit model follows a joint generalized extreme value distribution. Detailed explanation and application of the mixed logit model and GEV family model are covered in (Train 2009).

The mixed logit model makes it convenient to capture the heterogeneity among individuals’ preference. It approximates random utilities by assuming that the coefficients in the model are realizations of random variables. This assumption generalizes the standard multinomial logit (MNL) model and allows the coefficients to vary. Although the coefficients are generally assumed to be normally distributed, they can be extended to other distributions, e.g. lognormal or triangular distributions (Small, Winston et al. 2005). Throughout this chapter, we assume that the coefficients of travel time, its reliability and out-of-pocket cost follow a normal distribution.

Under the mixed logit model formulation, the probability that driver $n$ will choose route $P$, i.e. $P_{np}$, is expressed as:

$$P_{np} = \int \frac{e^{\beta x_{np}}}{{\sum}_{q=0}^{Q} e^{\beta x_{pq}}} f(\beta|\theta) d\beta,$$

where $f(\beta|\theta)$ denotes the density function of the coefficient vector $\beta$. The parameters that define the density of $\beta$ are denoted by vector $\theta = [b_T, W_T; b_R, W_R; b_C, W_C]$, where $b$ and $W$ are mean and standard deviation of respective coefficients for travel time, travel-time variability, and toll. The MNL part in the mixed logit model is generally expressed as:

$$MNL_{np}(\beta) = \frac{e^{\beta x_{np}}}{{\sum}_{q=0}^{Q} e^{\beta x_{pq}}}.$$

Thus the probability $P_{np}$ is a function of $\theta$, since the parameters $\beta$ are integrated out. In practice, this mixed logit model does not lend itself to an analytical probability value because it is difficult to incorporate the density function in the integral. Empirical approaches rely on simulations (Bhat 2001; Train 2009). We will discuss the solution method in the following section.

### 3.3.2 Simulated Maximum Likelihood Estimation

Compared with other VOT/VOR studies, the MnPASS toll tag database includes a large set of information about drivers’ choice of HOT lanes. The data, similar to RP survey data, allow us to estimate individuals’ preferences under actual circumstances.

In this study, we apply the simulated maximum likelihood estimation (SMLE) to estimate the parameters in the mixed logit model. The basic concept of SMLE is as follows. Denote $y_{np} = 1$
if driver $n$ chooses route $p$ and zero otherwise. Then the probability of driver $n$ choosing a route the she was observed can be expressed as $\prod_p (P_{np})^{y_{np}}$. Assume that drivers’ route choice is independent with each other. The probability of observing the drivers’ actual choices in the sample is expressed as the following likelihood function:

$$L(\beta) = \prod_{n=1}^{N} \prod_p (P_{np})^{y_{np}},$$

(6)

The log-likelihood function, which transforms the products into summations, is then expressed as:

$$LL(\beta) = \sum_{n=1}^{N} \sum_p y_{np} \ln P_{np}.$$  

(7)

We need to identify an estimator of $\beta$ that maximizes the log-likelihood function and therefore maximizes the probability of observing drivers’ actual choices. Since the probability $P_{np}$ is a function of $\theta$ in the mixed logit model, we need to estimate the parameters $\theta$ that defines the distribution of $\beta$. Therefore, the parameter estimation problem is mathematically expressed as:

$$\max_{\theta} LL(\beta|\theta) = \sum_{n=1}^{N} \sum_p y_{np} \ln\left(\int MNL_{np}(\beta) \cdot f(\beta|\theta) d\beta\right).$$

(8)

Based on the first-order condition, this unconstrained optimization problem is equivalent to finding a zero point of the objective function’s derivative, i.e.:

$$\frac{dLL(\beta|\theta)}{d\theta} = 0.$$  

(9)

The objective function (8) does not have a close form because of the existence of integral. The value of objective function and its derivative are generally approximated by the Monte Carlo or Quasi-Monte Carlo (QMC) simulation. The estimated probability is computed by:

$$\hat{P}_{np} = \frac{1}{K} \sum_{k=1}^{K} MNL_{np}(\beta_k),$$

(10)

where the values of $\beta_k$ are given by $k = 1, \ldots, K$ Halton draws from the density function $f(\beta|\theta)$. The estimated probability $\hat{P}_{np}$ is then inserted into the log-likelihood function for computing the value of the objective function and its derivative.

In transportation research, many efficient approaches have been used for SMLE of mixed logit models, such as the classic Broyden-Fletcher-Goldfarb-Shanno (BFGS) optimization algorithm (Train 2009), Genetic Algorithm (Liu, He et al. 2007), and trust region methods (Bastin, Cirillo et al. 2005). The software used for SMLE in this study was developed by Kenneth E. Train and downloaded from his website (http://elsa.berkeley.edu/~train/software.html). The software solves the unconstrained maximization problem by calling the solver ‘fminunc’ in MATLAB which applies the interior-reflective Newton method (Coleman and Li 1994) to solve large scale maximization problems. Other software packages (e.g., BIOGEME employed in (Carrion-Madera and Levinson 2011) can solve the SMLE for evaluating VOT/VOR.
3.4 Data Preparation

3.4.1 Assumptions on Toll Tag Database

In this study, drivers’ route choice data are from the toll tag database, which provides the trip information only when they used the MnPASS system. In other words, we do not know the traffic condition when MnPASS users traveled on the GPLs. If the parameter estimation is solely based on the data when drivers were using the MnPASS system, the coefficients would tend to be infinity. It indicates that using the MnPASS system will bring drivers the utility as large as possible. To enable parameter estimation using the toll tag database, we make the following assumptions:

- MnPASS users are regular commuters who travel on the I-394 every workday;
- MnPASS users have stable departure times in the morning.

These two assumptions allow us to apply the SMLE (8) to estimate VOT and VOR of I-394 MnPASS users, even if they were not observed in the toll tag data when they used the GPLs. Given the first assumption, a MnPASS user would travel on the GPLs if we did not observe her on the HOT lanes on a specific workday. Given the second assumption, we can use the average entrance time, based on all of her records in the database, to identify the traffic condition when she did not travel on the HOT lanes but used the GPLs.

It is worth noting that the two assumptions may deviate from drivers’ actual choice and hence result in biased estimates. First, MnPASS users may not travel on the I-394 on every workday. They may travel on other routes or choose other modes for their trips. They may not go to work on some workdays for certain reasons. This assumption would underestimate the utility brought by the HOT lanes, since the usage of GPLs are overestimated. The second assumption may bias drivers’ actual departure times, especially when the number of observations associated with a user is too small. To mitigate the biases, we removed from the data the users who rarely traveled on HOT lanes. Further, because morning commute tends to be less complex and more consistent than evening commute, we used eastbound trips to Downtown Minneapolis between 6 am and 10 am for estimation, to reduce departure time heterogeneity.

We applied our model on the toll tag data in year 2006. Originally, the database contains 438,044 toll records of 8,979 MnPASS users during the 254 workdays in year 2006. The distribution of these records, with respect to weekdays, is shown by Figure 3. The numbers of HOT trips on Mondays and Fridays are less than those on Tuesdays, Wednesdays, and Thursdays. Since the HOT lane users are not consistent across different weekdays, we decided to perform parameter estimations separately for different weekdays. For each of the five sets of toll tag data, we removed the toll records of drivers who traveled on the HOT lanes less than five times during weekday mornings in year 2006. The criterion of traveling on HOT lanes at least five times is arbitrary; however, we must notice that those infrequent HOT users may have reasons that are difficult to identify, e.g., they may have moved and changed their daily commute routes. Table 2 summarizes the HOT lane usage frequency distributions for different workdays. As indicated by Table 2, about 40 percent of drivers were removed from the data set when HOT lane usage frequency is considered in the estimation.
Table 2. HOT Lane Usage Distribution

<table>
<thead>
<tr>
<th>HOT Lane Usage</th>
<th>Number of Drivers (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Monday</td>
</tr>
<tr>
<td>1,2</td>
<td>1904 (27.7)</td>
</tr>
<tr>
<td>3,4</td>
<td>914 (13.3)</td>
</tr>
<tr>
<td>[5,10]</td>
<td>1388 (20.2)</td>
</tr>
<tr>
<td>[10,25]</td>
<td>1609 (23.4)</td>
</tr>
<tr>
<td>&gt;25</td>
<td>1062 (15.4)</td>
</tr>
<tr>
<td>Total</td>
<td>6877 (100)</td>
</tr>
</tbody>
</table>

3.4.2 Travel Time Estimation

Two methods can be used to estimate travel time: instantaneous travel time and actual travel time. Instantaneous travel time sums up the estimated travel times of all segments at the same moment when a vehicle enters the system at time $t_0$. Actual travel time is computed by summing up the actual travel times on all segments of the trip. The actual travel time for each segment is computed by using the traffic condition at the moment when the vehicle enters into the segment. The arrival time for each segment of trip is estimated recursively after travel times on upstream segments are updated (Liu, He et al. 2007).

Because the posted toll on the I-394 is dynamically calculated based on the worst traffic condition at the instant of time (more rigorously, updated every three minutes), we adopted the instantaneous travel time to estimate the travel time cost in the utility function. Therefore, when a driver enters the I-394 MnPASS system, her decision is based on the traffic condition at that moment instead of what will happen later on the trip. Mathematically, equation (11) illustrates the computation of instantaneous travel time from toll zone 1001 to toll zone 1005 (i.e. the whole I-394 MnPASS system):

$$TT_{int}(t_0) = \frac{0.5L_1}{V_1(t_0)} + \frac{0.5L_1 + 0.5L_2}{V_2(t_0)} + \frac{0.5L_3}{V_3(t_0)} + \frac{0.5L_4 + 0.5L_5}{V_4(t_0)} + \frac{0.5L_3}{V_5(t_0)},$$  (11)
where $L_i$ denotes the distance between detector $i$ and detector $i+1$ provided by the All Detector Report; $V_i$ denotes the velocity at detector $i$ provided by Data Extractor; and $t_0$ denotes the time that a vehicle enters the system, archived in the toll tag database. For trips using parts of the MnPASS system, Equation (11) should be adapted accordingly.

Instantaneous travel time was estimated for both GPLs and HOT lanes. The variables for travel time computation include zone lengths, detector locations, speed at every detector every 30 seconds, user time and date of entry, and user zone entrance and exit. Because GPLs include multiple lanes, the speed on the GPLs at a detector location was the simple average speed of all GPLs at the location. Figure 4 illustrates instantaneous travel times from toll zone 1 to toll zone 5 on Sept. 13, 2006, an example day with large variation.

### 3.4.3 Travel Time Variability Estimation

The travel-time variability, which is considered only for the GPLs, can be captured by a number of traditional measures, such as the standard deviation of the travel time on congested lanes, the difference between 80th percentile and the median travel time, and the difference between 90th percentile and the median travel time.

In this study, we employ an alternative measure to capture the variability. It is defined by the difference between 90th percentile and the instantaneous travel time on the GPLs. The 90th percentile travel time represents the “near-worst” traffic condition on the GPLs possibly experienced by drivers. For every 30 seconds of a weekday, we computed the 90th percentile travel time based on 52 weeks’ instantaneous travel times in year 2006. Then the travel-time variability that a driver can avoid by traveling on HOT lanes is the difference between the worst travel time (i.e., 90th percentile) and the instantaneous travel time on the GPLs at that moment when the driver enters the system. Figure 5 illustrates travel-time variability from toll zone 1001 to toll zone 1005 on Wednesdays.

![Figure 4. Travel Time between Toll Zones 1 and 5 on Sept. 13, 2006](image)
The rationale underlying the alternative measure is that the saving in reliability faced by a traveler who knows that the GPLs are already slower than average is correspondingly smaller, because the “worst possible” (e.g., 90th percentile used here) is not as far away from the already known condition. With the dynamic toll information, drivers can infer current traffic condition along the freeway. High values of toll essentially indicate high level of traffic congestion on downstream segments and drivers have a high probability to encounter longer travel times on the GPLs.

Traditional measures assign the same value of travel-time variability to different trips. Thus, even when the traffic condition is the worst on the GPLs, traditional measures state drivers can avoid a fixed value of unreliable travel-time by using the HOT lanes. This may be true when drivers do not have information about current traffic condition. However, when drivers observe high toll values, they recognize the travel time on the GPLs is less reliable (i.e., less value of variability), and thus they would expect a smaller travel time reliability on the GPLs.

3.4.4 Data Smoothening

As shown in Figure 4 and Figure 5, travel time and its variability estimated from loop detectors are sawtooth-like; a smooth curve is more reasonable to describe the change in temporal space. Therefore, we adopted locally weighted regressions to smooth the estimated travel time and its variability. In particular, all data in a small band will add weights into a predetermined linear function. The estimate can be obtained from the local linear quantile regression optimization process.

Figure 6 demonstrates the smoothed curves of travel time and its variability based on the data shown in Figure 4 and Figure 5, respectively. Note that, as shown in Figure 6 (a), traveling on HOT lanes may take longer time than on GPLs, especially in the early morning. Drivers on the GPLs were presumably speeding. For this case, we set the travel time on HOT lanes to be the same as on GPLs, implying no travel time difference between the HOT lanes and GPLs.
When smoothing the data, we also aggregated the estimated travel time and its variability into a three-minute time interval. The aggregation further removes the frequent fluctuations. More importantly, the three-minute interval is consistent with the update frequency of dynamic toll. Therefore, in the VOT/VOR estimation, all information about the system (i.e., travel time, travel-time variability, and toll) is updated in a synchronous three-minute interval.

**Figure 6. Smoothed Curves**

3.4.5 **Estimation Settings**

The convergence criterion in the SMLE was set to be the maximum change in parameters. If all the parameters change by less than 1e-6 from one iteration to the next, the (local) optimal
solution has been found. For each set of observed data for a specific weekday, we ran ten estimation processes using different seeds in random value generator. In each run of SMLE, 400 Modified Latin Hypercube Sampling (MLHS) draws (Hess, Train et al. 2006) from the parameter density function were used in evaluating the mixed logit model. The initial values of means were set as \([b^T, b^R, b^C] = [-40, -40, -2]\), and the initial values of standard deviations were set as \([W^T, W^R, W^C] = [10, 10, 1]\).

According to Table 2, more than 70,000 route choice records from about 7,000 MnPASS users were used in the estimation. It is difficult for a personal computer to handle such a heavy computational burden in a short time. We sent our estimation program to a super computer hosted by Minnesota Supercomputing Institute (MSI) at the University of Minnesota. The high-performance computing system used for our estimation, named ‘Elmo’, is a Sun Fire X4600 Linux cluster. It has 192 cores and 768 GB of memory spread across six nodes and an eight-core interactive node. The nodes are interconnected with a Gigabit network. For more details, see https://www.msi.umn.edu. The estimation jobs were executed by calling MATLAB under Linux. Each run of SMLE took about 16 to 20 minutes.

3.5 Estimation Results and Analysis

3.5.1 Estimation Results

The average estimates of parameters \(\theta = [b^T, W^T, b^R, W^R, b^C, W^C]\), based on the ten runs of SMLE for each weekday, are summarized in Table 3. Since travel time, travel-time variability and toll are considered as a disutility to drivers when choosing a route, the mean values of these parameters have negative sign, as expected. All the estimates are statistically significant at the 0.05 level. However, the standard deviations of all three parameters are relatively large compared to their estimates. Therefore, there is much variation among different HOT lane users.

Table 4 summarizes VOT and VOR distributions based on the estimated coefficients in Table 3, as well as the Reliability Ratio (RR) defined by \(RR = \frac{VOR}{VOT}\). On average, the VOR of MnPASS users is $25.45 per hour and the VOT is $11.63 per hour. They are higher than the estimates in (Carrion-Madera and Levinson 2011), where the mean VOT ranges from $3.40 to $5.76 per hour, and the mean VOR ranges from $0.78 to $4.76 per hour.

The RR estimated in this study has a high value ranging from 1.81 to 3.41. Such a high RR has been found in our previous study (Liu, He et al. 2007) where the RR is up to 3.36 when the traffic congestion level is low. However, this RR is much higher than that in other studies. For example, the RR in (Small, Winston et al. 2005) varies from 0.45 to 1.04 and the RR in (Carrion-Madera and Levinson 2011) varies from 0.20 to 0.83 depending on different models used. The RR reported in (Small, Noland et al. 1999), with a value of 1.31, is close to our estimate.
### Table 3. Parameter Estimation Results

<table>
<thead>
<tr>
<th>Weekday</th>
<th>Mean (b)</th>
<th>Standard Dev. (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimate</td>
<td>S.E.</td>
</tr>
<tr>
<td>Monday</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (T)</td>
<td>-14.04</td>
<td>0.37</td>
</tr>
<tr>
<td>Variability (R)</td>
<td>-26.36</td>
<td>0.38</td>
</tr>
<tr>
<td>Toll (C)</td>
<td>-1.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Tuesday</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (T)</td>
<td>-4.06</td>
<td>0.20</td>
</tr>
<tr>
<td>Variability (R)</td>
<td>-13.81</td>
<td>0.23</td>
</tr>
<tr>
<td>Toll (C)</td>
<td>-0.77</td>
<td>0.02</td>
</tr>
<tr>
<td>Wednesday</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (T)</td>
<td>-7.99</td>
<td>0.28</td>
</tr>
<tr>
<td>Variability (R)</td>
<td>-16.71</td>
<td>0.26</td>
</tr>
<tr>
<td>Toll (C)</td>
<td>-0.67</td>
<td>0.02</td>
</tr>
<tr>
<td>Thursday</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (T)</td>
<td>-5.82</td>
<td>0.32</td>
</tr>
<tr>
<td>Variability (R)</td>
<td>-17.30</td>
<td>0.31</td>
</tr>
<tr>
<td>Toll (C)</td>
<td>-0.73</td>
<td>0.02</td>
</tr>
<tr>
<td>Friday</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (T)</td>
<td>-20.12</td>
<td>0.57</td>
</tr>
<tr>
<td>Variability (R)</td>
<td>-36.50</td>
<td>0.59</td>
</tr>
<tr>
<td>Toll (C)</td>
<td>-1.05</td>
<td>0.02</td>
</tr>
</tbody>
</table>

### Table 4. Estimated VOT and VOR Distribution

<table>
<thead>
<tr>
<th>Weekday</th>
<th>Mean VOT ($/hr) [25%tile, 75%tile]</th>
<th>Mean VOR ($/hr) [25%tile, 75%tile]</th>
<th>Reliability Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monday</td>
<td>13.86 [-5.69, 12.74]</td>
<td>25.99 [-8.11, 25.21]</td>
<td>1.88</td>
</tr>
<tr>
<td>Tuesday</td>
<td>5.27 [-5.05, 8.03]</td>
<td>17.95 [-6.36, 18.94]</td>
<td>3.41</td>
</tr>
<tr>
<td>Wednesday</td>
<td>11.98 [-8.95, 10.92]</td>
<td>25.06 [-10.19, 17.69]</td>
<td>2.09</td>
</tr>
<tr>
<td>Thursday</td>
<td>7.96 [-8.87, 14.83]</td>
<td>23.64 [-11.64, 19.50]</td>
<td>2.97</td>
</tr>
<tr>
<td>Friday</td>
<td>19.08 [-9.79, 21.46]</td>
<td>34.61 [-13.41, 31.68]</td>
<td>1.81</td>
</tr>
<tr>
<td>Average</td>
<td>11.63 [-7.67, 13.59]</td>
<td>25.45 [-9.94, 22.60]</td>
<td>2.19</td>
</tr>
</tbody>
</table>
To illustrate drivers’ heterogeneity, we also computed the 25 to 75 percentile interval for each VOT and VOR. On average, the 25 to 75 percentile interval of VOT is [-$7.67, $13.59] per hour, and the 25 to 75 percentile interval of VOR is [-$9.94, $22.60] per hour. The wide ranges of VOT and VOR illustrate heterogeneous preferences to the HOT lanes. As we can see, the 75 percentiles of VOT and VOR are very close to their respective mean values. (Zmud, Bradley et al. 2007) estimated drivers’ willingness to pay using a stated preference survey of I-394 drivers. They found that the 25 percentile of VOT is close to zero whereas the 75 percentile is $11 per hour that is similar to the 75 percentile found in this study.

Table 4 shows that over 25 percent of drivers have negative values of VOT/VOR. A negative VOT/VOR of a driver indicates that the driver pursues a route with longer travel time or more unreliable travel time. (Small, Winston et al. 2005) suggested replacing the normal distribution with lognormal, truncated normal or triangular distribution to address this unreasonable result. However, the solver we used cannot identify an optimal solution when applying any one of these distributions, probably due to the large sample size in this study.

3.5.2 Implications and Explanations

The negative values of VOT/VOR suggest that other factors impact drivers’ choice between GPL and HOT lane, in addition to travel time and travel-time reliability. The model used in this study does not include drivers’ socio-demographic characteristics such as gender, income, household size, and number of children. All these factors may impact drivers’ preference to travel time and travel-time reliability when choosing routes. In addition, 14.2 percent (59,464 out of 419,062) of tolled trips were generated between 6 a.m. to 7 a.m. During this time interval, the mean travel time on HOT lanes is longer than that of GPLs while the travel-time variability on GPLs is close to zero, as shown in Figure 6. These may result in negative values of VOT/VOR as well.

Interestingly, the mean values of VOT and VOR for Friday are much higher than those for other weekdays. This result may be due to the low percentage of trips completed on Fridays, as shown in Figure 3. In general, fewer trips are associated with less congestion on the road. The drivers who kept using the HOT lanes under a mild congestion level are more sensitive to the travel time and its reliability. Further, the ownership of MnPASS transponder or route choice inertia may be the incentives of using the HOT lanes for those drivers traveling on Fridays.

In this study, the mean VOR is larger than the mean VOT for all weekdays. This is different from the finding of (Carrion-Madera and Levinson 2011) – drivers’ VOT is larger than their VOR. This difference may result from different sample subjects and variables used. The subjects in this study are all leasers of MnPASS transponders. They may prefer travel-time reliability to travel-time savings because they use the HOT lanes every day. In contrast, the subjects in Carrion-Madera’s study were not MnPASS transponder leasers, but occasional users of I-394. When they were hired for the experiment, they got the transponders for free to gain some experience on HOT lanes. Travel time may be more important for them than travel-time reliability, because they did not have enough experience of the travel time variation on the GPLs. In addition, Carrion-Madera’s model included socio-demographic variables whereas our model did not.
3.6 Summary

This chapter presents an alternative methodology for estimating VOT and VOR using dynamic toll records. Comparing with traditional data sources, dynamic toll data is a reliable, low-cost, well-organized source for travel choice information. The study site, the I-394 MnPASS system in Minneapolis, offers a natural testing bed for evaluating our proposed approach. MnPASS users’ preferences to travel time, travel-time variability, and out-of-pocket cost have been modeled in a mixed logit model. Differing from other studies, the travel time variability in this chapter is defined as the difference between 90th percentile and the instantaneous travel time, in order to account for drivers’ perception of congestion at the moment when they enter HOT lanes. The methodology could be applied to other study sites with dynamic toll strategy deployed.

The results show that drivers traveling on Fridays have higher VOT and VOR than other weekdays. In addition, MnPASS users’ mean VOR is higher than the mean VOT, when reliability is defined as the difference between 90th percentile and instantaneous travel time. It indicates that MnPASS users are willing to pay the toll more for travel time reliability than for travel time savings. Finally, as shown by the 25 to 75 percentile intervals of VOT and VOR, the heterogeneous values suggest that drivers’ willingness to pay the toll varies a lot.

This study has several limitations. First, we considered only travel time, its reliability, and toll in the model specification. Other factors may impact drivers’ choices. Unfortunately, we do not have demographic attributes of MnPASS users. Second, because the toll database does not contain trip information when MnPASS users travel on the GPLs, the estimates rely on the two assumptions: (1) MnPASS users are regular commuters and (2) their daily departure times are consistent. These two assumptions may bias the estimation results. However, we adopted some strategies to mitigate potential biases. Third, drivers’ departure time choice has not been modeled in this study. If drivers’ departure time choice is captured by the model, time-dependent VOT and VOR can be estimated. We leave these issues for future research.
4 Safety Benefits

4.1 Introduction

Safety benefit is a major component of benefit-cost analysis of transportation projects. Although previous studies have documented various benefits of converting HOV lanes to HOT lanes, few studies have considered safety benefits. One reason is that researchers did not observe apparent safety improvements before and after the conversion (Burris and Sullivan 2006; Sullivan and Burris 2006). Conceptually, the conversion of HOV lanes to HOT lanes should offer safety benefits. First, the underused HOV lanes may irritate solo drivers on general purpose lanes, and hence motivate them to “cheat”. Illegal users of HOV lanes may be more likely to make a sudden entry when they are frustrated by the large speed differential between HOT lane and general purpose lanes. Illegal users may make sudden exits when they realize the presence of polices. It is evident that intermediate access and lane changes by illegal users on the concurrent flow HOV lanes increased crash rates, while crash rates on barrier-separated HOV lanes were kept constant in the Dallas area (Skowronek, Ranft et al. 2002). Accordingly, illegal uses create a safety hazard. HOT lanes reduce violation rate by giving solo drivers a choice to opt in. After the conversion, the violation rate decreased from 20\% to 9\% on the concurrent flow section of the I-394 MnPASS whereas the violation rate on the I-35W HOV lanes increased from 23\% to 33\% during the same period (Munnich 2008). Therefore, the decreased violation rate may reduce crashes. Second, HOT lanes improve traffic conditions on general purpose lanes by attracting solo drivers to HOT lanes. The improvements of traffic flow during congested periods tend to reduce the number of crashes, since the number of crashes decreases (and then increases) as the volume/capacity ratio increases (Zhou and Sisiopiku 1997).

Moreover, for I-394, the designated access points on the MnPASS may help legal drivers avoid sudden entries and exits. This design improvement has the potential to reduce crashes due to the sudden behavior. When drivers get on I-394 at an interchange, they now know that they cannot enter the MnPASS lanes for at least one quarter mile downstream. The design improvement helps drivers avoid dangerous weaving maneuvers. After the conversion, we observed a large reduction in the number of crashes on the I-394.

Previous studies have explored the safety impacts of adding HOV lanes, compared crash rates for the concurrent flow HOV lanes and barrier-separated HOV lanes, and compared crash rates for HOV lanes with continuous and limited access points (Golob, Recker et al. 1989; Skowronek, Ranft et al. 2002; Cooner and Ranft 2006; Jang, Chung et al. 2009). However, we have yet to find studies that have investigated the safety impacts of HOT lanes. For example, it is found that the length of the access and the access to the neighboring ramps impact the collision rates in HOV lanes (Jang, Chung et al. 2008). According to Federal Transit Administration (FTA 1992), depending on the design of facilities, HOV lanes may have more or fewer crashes than the adjacent lanes. For I-10 in Los Angeles, the accident rate for HOV lanes was twice as high as the general purpose lanes. However, the crash rate of barrier-separated HOV lanes for I-10 in Houston was 50\% lower than that in the general purpose lanes. Also, some studies have focused on safety issues related to pricing. For example, (Noland, Quddus et al. 2008) studied safety impacts of London cordon pricing; (Abdelwahab and Abdel-Aty 2002) and (Mohamed, Abdel-Aty et al. 2001) investigated safety of toll plazas. However, few researchers have studied safety benefits of converting HOV lanes to HOT lanes.
This chapter used a before-after analysis to investigate safety benefits of converting the I-394 HOV lanes to HOT lanes. In particular, we applied Empirical Bayes method to test the alternative hypothesis: converting a HOV lane to a HOT lane reduces the number of crashes. As far as we know, we are the first in the United States to study the safety impacts of the HOV-to-HOT conversion. The results have important implications for justifying the conversion.

4.2 Methodology

We applied Empirical Bayes approach to investigate safety benefits of converting a HOV lane to a HOT lane. The Empirical Bayes method is well known for effectively addressing two long-standing issues in safety research: the regression-to-mean bias and imprecision due to limited accident history (refer to (Hauer, Harwood et al. 2002) for illustration of the issues). After twenty years’ applications, the Empirical Bayes method has become a classic approach in “conducting statistically defendable before–after studies of the safety effect of treatments applied to roadway sites” (Persaud and Lyon 2007) (p. 546).

Following Persaud and Lyon’s notation, safety benefits of converting a HOV roadway segment to a HOT segment are given by

\[ A - B \]

where \( A \) is the number of crashes that occurred after the conversion and \( B \) is the number of crashes that would have occurred in the after period without converting the HOV segment. For a given segment, \( B \) is estimated using the following steps (Persaud and Lyon 2007) (pp. 547-548):

1. Develop a safety performance function (SPF in the form of negative binomial model) using the crash data with traffic volumes and other characteristics of roadway segments similar to treatment roadway segments, or adapt an existing SPF.
2. Retro-predict/estimate the number of crashes that would be expected in each year of the “before” period by plugging corresponding traffic volumes and other characteristics of the treatment segment into the SPF. \( P \) is denoted as the sum of the annual SPF estimates in the before period.
3. Combine \( P \) with the actual count of crashes (\( x \)) at the treatment segment in the before period to obtain an estimate of the expected number of crashes (\( m \)) before the conversion. The following equation estimates the expected number of crashes (\( m \))

\[ m = wP + (1 - w)x \]

where the weight \( w \) is estimated as \( w = \frac{1}{1 + kP} \), where \( k \) is the dispersion parameter estimated from the negative binomial model of the SPF.
4. Compute an estimate of \( B \) by multiplying \( m \) with a factor \( f \) (\( B = mf \)), which is used to correct the length of the after period and changeable characteristics of the treatment in the before-after period such as traffic volumes. The factor \( f \) is the quotient of the sum of the annual SPF predictions in the after period and the sum of the annual SPF estimates in the before period \( P \).

Finally, we obtain the Empirical Bayes estimate (\( B_{sum} \)) of the whole roadway by summing \( B \)’s for all treatment roadway segments and compare it with the actual crash counts of these...
segments \(A_{\text{sum}}\) in the after period. The difference between \(A_{\text{sum}}\) and \(B_{\text{sum}}\) is the estimated safety benefits for treatment segments.

It is worth noting that the dispersion parameter in many studies (Hauer, Harwood et al. 2002; Monsere and Fischer 2008) may be specified as its inverse, but it was still called the dispersion parameter (Personal communication with Dr. Persaud on 4/15/2010 and Dr. Monsere on 4/20/2010).

### 4.3 Results

This section covers three elements: the development of a SPF, computation of safety benefits using the Empirical Bayes approach, and comparison with other before-after approaches.

#### 4.3.1 SPF Development

Previous research has demonstrated that the number of crashes per year at a roadway segment is correlated to the length and traffic volumes of the segment and variation may also be shown over years. To account for the differences in traffic volumes and other characteristics of roadway segments in the before-after period, we should first develop a prediction model – the SPF. Consistent with previous research (Kiattikomol, Chatterjee et al. 2008), the SPF is specified as follows:

\[
N = \beta_0 (L)^{\beta_1} (A\text{ADT})^{\beta_2} \exp(\alpha_1 X_1 + \alpha_2 X_2 + \cdots)
\]

where \(N\) is the expected number of crashes of a roadway segment per year; \(L\) is the length of the segment; AADT is annual average daily traffic of the segment; \(X_i\)'s are other characteristics of the segment; \(\alpha_i\) and \(\beta_i\) are parameters. We used the mainline crash data of interstate highways in the Minneapolis-St Paul seven-county metropolitan area to calibrate the SPF. The conversion of HOV lanes to HOT lanes attracted SOV drivers to use HOT lanes. This changed flow patterns on both HOT lanes and general purpose lanes. As a result, the conversion is likely to impact crashes on general purpose lanes. Therefore, we used crash data on both HOV lanes and general purpose lanes when calibrating the SPF.

MnDOT measures AADT every other year. We obtained the AADT data in 1998, 2000, 2002, 2004, 2006, and 2008, and respective mainline crash data (in ArcGIS format) from Mn/DOT. Because the HOT lane conversion happened in 2005, we have four-year observations before the conversion and two-year observation after the conversion. The AADT is measured on 250 roadway segments, which constitute the interstate highway network in the Twin Cities. We aggregated crashes onto the 250 segments using ArcGIS. The SPF was developed based on six-year data of 239 segments (for all interstate highways except I-394), totaling 1,434 observations. The model was fitted using the GENMOD procedure in SAS; we specified a log link and negative binomial distribution of the error term. We included number of ramps and year dummies (to capture variation over years) in the model in addition to segment length and AADT. As shown in Table 5, the length, AADT, and number of ramps of a segment are significantly and positively associated with the number of crashes at the segment. Compared to 2004, there were significantly fewer crashes in the system in 2006. Other year dummies are insignificant at the 0.10 level. We tried to include number of lanes in the model because it is evident that it impacts the number of crashes (Milton and Mannering 1998). However, the number of lanes was insignificant and hence removed from the final model. Design characteristics such as shoulder
lengths and the presence of median were not included in the model because interstate highways in the metro have few variations in the design characteristics.

Table 5. Safety Performance Function

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>Chi-Square-statistic</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-14.3934</td>
<td>197.6</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Log(AADT)</td>
<td>1.5094</td>
<td>289.98</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Log(Segment Length)</td>
<td>0.6043</td>
<td>168.09</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Number of Ramps</td>
<td>0.0670</td>
<td>19.74</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Year 1998 (dummy)</td>
<td>-0.1539</td>
<td>2.13</td>
<td>0.1449</td>
</tr>
<tr>
<td>Year 2000 (dummy)</td>
<td>0.1059</td>
<td>1.01</td>
<td>0.3140</td>
</tr>
<tr>
<td>Year 2002 (dummy)</td>
<td>-0.0310</td>
<td>0.09</td>
<td>0.7680</td>
</tr>
<tr>
<td>Year 2006 (dummy)</td>
<td>-0.2781</td>
<td>6.96</td>
<td>0.0083</td>
</tr>
<tr>
<td>Year 2008 (dummy)</td>
<td>-0.1243</td>
<td>1.39</td>
<td>0.2377</td>
</tr>
<tr>
<td>Dispersion parameter</td>
<td>1.2765</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>1434</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>1425</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deviance</td>
<td>1744.9422</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pearson Chi-square</td>
<td>998.2917</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Log Likelihood</td>
<td>114992.0815</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3.2 Safety Benefits of Conversion

Following Steps 2–4 in Section 3.2, we computed the number of crashes that would have happened in the “after” period without converting HOV lanes to HOT lanes. The Empirical Bayes estimates for the whole roadway are 828.3 crashes whereas the actual count for 2006 and 2008 was 785 crashes. Therefore, using the Empirical Bayes approach, we concluded a reduction of 43.3 crashes for the two years.

The effectiveness of HOT lanes in reducing crashes is measured by the index of effectiveness. It is estimated as (Persaud and Lyon 2007):

$$\theta = \frac{A_{sum}}{1 + \frac{Var(B_{sum})}{B_{sum}^2}}$$

and the standard deviation of $\theta$ is estimated as

$$SD(\theta) = \left[\theta^2 \left[\frac{Var(A_{sum})}{A_{sum}^2} + \frac{Var(B_{sum})}{B_{sum}^2}\right]^{0.5} \left[1 + \frac{Var(B_{sum})}{B_{sum}^2}\right]^2\right]$$

where $Var(A_{sum}) = A_{sum}$ and $Var(B_{sum}) = (1 - w)fB_{sum}$ (Harwood, Bauer et al. 2002).
After plugging the estimates into Equations 4 and 5, we found that the index of effectiveness is 94.7% and its standard deviation is 3.99%. Therefore, the number of crashes was reduced by an estimated 5.3%, with p-value being 0.093 for one-sided test. The percentage accident reduction is insignificant at the 0.05 level. Although the critical value of 0.05 is the rule of thumb in statistics, it is in fact an arbitrary number (Freedman, Pisani et al. 2007). Scholars also contend that the magnitude of an effect is at least as important as the statistical significance of the effect, especially since statistical significance is influenced by sample size (Ziliak and McCloskey 2004).

To determine the size of the effect, we estimated the predicted number of crashes (that would have happened) by severity (Fatal, Injury A, Injury B, Injury C, and Property damage), as shown in Table 6. Similar to Numerical Example 5 in (Hauer, Harwood et al. 2002), we multiplied the predicted number of crashes $B_{sum}$ by the proportion of crashes for each severity level in the Twin Cities highway network. This yields the predicted number of crashes by severity (the third column of Table 6). The safety benefits are the difference between the predicted number of crashes and the actual number of crashes for each severity level. The benefits were then converted into economic values using standard values for FY 2010 recommended by MnDOT. Overall, the average safety benefits for the two years are estimated to be about $4.66 million per year. The benefits are substantial given that MnPASS collected about $1.2 million tolls per year. Therefore, the safety benefits of converting HOV lanes to HOT lanes are practically important.

<table>
<thead>
<tr>
<th>Severity</th>
<th>Proportion on similar segments</th>
<th>Predicted number of crashes</th>
<th>Actual number of crashes</th>
<th>Benefits</th>
<th>Standard value</th>
<th>Economic benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Property damage</td>
<td>73.75%</td>
<td>610.9</td>
<td>569</td>
<td>41.9</td>
<td>$ 12,000</td>
<td>$ 502,800</td>
</tr>
<tr>
<td>Injury C</td>
<td>20.62%</td>
<td>170.8</td>
<td>168</td>
<td>2.8</td>
<td>$ 91,000</td>
<td>$ 254,800</td>
</tr>
<tr>
<td>Injury B</td>
<td>4.38%</td>
<td>36.3</td>
<td>43</td>
<td>-6.7</td>
<td>$ 124,000</td>
<td>(911,200)</td>
</tr>
<tr>
<td>Injury A</td>
<td>1.13%</td>
<td>9.3</td>
<td>5</td>
<td>4.3</td>
<td>$ 412,000</td>
<td>$ 1,771,600</td>
</tr>
<tr>
<td>Fatal</td>
<td>0.13%</td>
<td>1.1</td>
<td>0</td>
<td>1.1</td>
<td>$ 7,000,000</td>
<td>$ 7,700,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100.00%</strong></td>
<td><strong>828.3</strong></td>
<td><strong>785.0</strong></td>
<td><strong>43.3</strong></td>
<td></td>
<td><strong>9,318,000</strong></td>
</tr>
</tbody>
</table>

Note: standard values were recommended by MnDOT, for use in economic analysis in FY 2010.

### 4.3.3 Comparison with Other Approaches

There are many ways to predict the number of crashes that would have happened in the “after” period if the HOV-to-HOT conversion had not occurred. (Hauer 1997) offered four “simple-minded” approaches that are commonly used by transportation engineers. He discussed the underlying assumptions and shortcomings of these approaches (p.53). Here, we applied two to see how the estimate of safety benefits differed from the Empirical Bayes estimate (Table 7). In the first approach, we assumed that factors influencing the number of crashes showed little variation during the before and after periods. Thus, the expected average number of crashes after the conversion (2005) was the same as that before the conversion, had the conversion not been implemented. The last row of Table 3 showed that the average number of crashes was reduced by about 21%, which was about four times as large as the Empirical Bayes estimate. In the
second approach, we used the I-394 as a treatment group and other highways in the Twin Cities as a comparison group. If the HOV-to-HOT conversion had no impacts on safety, the proportional change in the number of crashes on the I-394 before and after 2005 should be the same as that on other highways during the same period. For example, because the average number of all types of crashes on all other highways after 2005 was 87.7 % (=6259.5/7137.8) of that before 2005, the expected average number of all types of crashes on the I-394 after 2005 should be 87.7% of that before 2005. Specifically, the expected number was 87.7% X 496 = 435.0 and the reduction was 42.5 (=435.0-392.5). Thus the number of crashes was reduced by 9.8% (=42.5/435.0), which was almost two times as large as the Empirical Bayes estimate. The second approach appeared to be similar to an experiment because of the treatment and control. However, it was not due to nonrandom assignment of the treatment. Because these approaches did not control for variation over years and the changes in roadway attributes (such as AADT) that affect safety before and after the conversion, they tended to overestimate the safety benefits of the HOV-to-HOT conversion in this study.

4.4 Summary

This chapter investigated whether the conversion of the I-394 HOV lanes to HOT lanes reduces the number of crashes on the mainline of I-394. Applying the Empirical Bayes method in the before-after data, we found that the number of crashes was reduced by 5.3%. Using standard crash values recommended by MnDOT, we found that the average economic benefit of reduced crashes for 2006 and 2008 was about $4.66 million per year. This is substantial given that the tolls collected total about $1.2 million per year. After comparing the estimates derived from simple before-after approaches, we found that these approaches tend to overstate the number of reduced crashes. However, more research is needed to confirm whether the overestimation is consistent across different HOT lanes.

Although we concluded safety benefits of the HOV-to-HOT conversion, Burris and Sullivan (Burris and Sullivan 2006) stated that the accident rates are similar for QuickRide in Houston. Without the information on changeable attributes such as AADT and variation over years in the crash rates, the safety benefits of QuickRide are still unclear. Further, for the I-394 MnPASS, the HOV-to-HOT conversion was accompanied by designating access points. Therefore, we are unable to differentiate to what extent the safety benefits are attributable to the conversion. Due to very limited studies on this issue, we are not confident to generalize our results to other HOT lanes. We speculate that the design and layout of the HOT lanes could play an important role. More research is needed to draw consistent conclusions on the safety benefits of HOT lanes and the de facto reasons for the benefits.
## Table 7. Crashes per Year before and after Conversion

<table>
<thead>
<tr>
<th>Severity</th>
<th>MnPASS Average number of crashes before 2005</th>
<th>MnPASS Average number of crashes after 2005</th>
<th>Reduction</th>
<th>Percent Reduction</th>
<th>Other Highways Average number of crashes before 2005</th>
<th>Other Highways Average number of crashes after 2005</th>
<th>Expected number of crashes after 2005</th>
<th>Reduction</th>
<th>Percent Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatal</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>100.0%</td>
<td>23</td>
<td>17</td>
<td>0.74</td>
<td>0.74</td>
<td>100.0%</td>
</tr>
<tr>
<td>Injury A</td>
<td>6.5</td>
<td>2.5</td>
<td>4</td>
<td>61.5%</td>
<td>34</td>
<td>33.5</td>
<td>6.40</td>
<td>3.90</td>
<td>61.0%</td>
</tr>
<tr>
<td>Injury B</td>
<td>25.25</td>
<td>21.5</td>
<td>3.75</td>
<td>14.9%</td>
<td>414.25</td>
<td>333.5</td>
<td>20.33</td>
<td>-1.17</td>
<td>-5.8%</td>
</tr>
<tr>
<td>Injury C</td>
<td>87.25</td>
<td>84</td>
<td>3.25</td>
<td>3.7%</td>
<td>1272.75</td>
<td>1272</td>
<td>87.20</td>
<td>3.20</td>
<td>3.7%</td>
</tr>
<tr>
<td>Property damage</td>
<td>376</td>
<td>284.5</td>
<td>91.5</td>
<td>24.3%</td>
<td>5393.75</td>
<td>4603.5</td>
<td>320.91</td>
<td>36.41</td>
<td>11.3%</td>
</tr>
<tr>
<td>Total</td>
<td>496</td>
<td>392.5</td>
<td>103.5</td>
<td>20.9%</td>
<td>7137.75</td>
<td>6259.5</td>
<td>434.97</td>
<td>42.47</td>
<td>9.8%</td>
</tr>
</tbody>
</table>
5 Other Benefits and Costs

5.1 Operating Cost Savings

As stated earlier, we consider only the reduction in fuel consumption for operating cost savings. As shown in Figure 7, previous research has illustrated that fuel economy is associated with travel speed (West, McGill et al. 1999). Since the MnPASS program enables slow-moving vehicles on the GPLs to move faster in the HOT lane, the increase in mobility is likely to lead to a decrease in fuel consumption.

![Figure 7. Fuel Economy by Speed](image)

Source: (West, McGill et al. 1999)

**Figure 7. Fuel Economy by Speed**

The process to calculate changes in fuel consumption for a particular MnPASS trip is as follows:

1. Use toll tag data to compute travel speed and find its associated fuel economy based on Figure 7;
2. Calculate fuel consumption of the MnPASS trip based on trip distance and fuel economy;
3. Use loop detector data to compute travel time for a trip which took place on the GPLs and at the same time as the MnPASS trip;
4. Calculate travel speed based on trip distance and travel time, then find its associated fuel economy;
5. Compute fuel consumption of the GPL trip based on trip distance and fuel economy;
6. Calculate the difference between the two fuel consumptions.

Repeat the steps above for all MnPASS trips in a year. The sum of all differences is the changes in fuel consumption of that year. Surprisingly, we found that fuel consumption consistently increased from 2006 to 2010. In particular, the increases were 394, 791, 2075, 2354, and 3709
gallons, respectively. Thus, the benefit of operating cost savings is in fact a cost. After checking the speed data of MnPASS trips and GPL trips, we found that although the speed limit was 55 miles per hour, many MnPASS users travelled at a speed higher than the limit, and that many MnPASS users drove faster than GPL users. According to the relationship between fuel economy and speed, fuel economy peaks at 55 miles per hour and decreases dramatically after the peak. Therefore, the improvements in mobility led to additional consumption of gasoline.

The increase in fuel consumption was converted to dollar values based on the historical and projected gasoline prices in Minnesota. Fuel taxes were removed from gasoline taxes. Overall, from 2006 to 2015, the present value for the increase in operating costs totals $62,142. Compared to other benefits and costs, this cost is negligible.

5.2 Costs

Capital costs of the MnPASS program were $8,716,000 (in 2005 nominal dollars). Operating costs include enforcement, postage, operation contract, verifone, and MnDOT maintenance cost, as shown in Table 8.

**Table 8. Detailed Operating Costs of the MnPASS**

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enforcement</td>
<td>$121,126</td>
<td>$135,468</td>
<td>$113,347</td>
<td>$152,126</td>
</tr>
<tr>
<td>Postage</td>
<td>$5,000</td>
<td>$5,000</td>
<td>$6,500</td>
<td>$6,500</td>
</tr>
<tr>
<td>Operation contract</td>
<td>$927,151</td>
<td>$959,582</td>
<td>$970,993</td>
<td>$1,015,747</td>
</tr>
<tr>
<td>Verifone</td>
<td>$1,645</td>
<td>$1,649</td>
<td>$1,649</td>
<td>$1,979</td>
</tr>
<tr>
<td>MnDOT costs</td>
<td>$240,000</td>
<td>$230,000</td>
<td>$230,000</td>
<td>$250,000</td>
</tr>
<tr>
<td><strong>Total costs</strong></td>
<td><strong>$1,294,922</strong></td>
<td><strong>$1,331,699</strong></td>
<td><strong>$1,322,489</strong></td>
<td><strong>$1,426,352</strong></td>
</tr>
</tbody>
</table>

Source: MnDOT

In year 2015, after 10 years of initial construction, all capital costs will be used up with zero remaining values. According to Julie Johnson from MnDOT, the MnPASS overhead signs need to be replaced in 10 years.
6 Benefit Cost Analysis and Sensitivity Analysis

In this study, the benefits of the I-394 MnPASS program include travel time savings, vehicle operating cost savings, safety benefits and remaining capital values; the costs consist of initial capital costs and annual operating costs. Again, vehicle operating cost savings are in fact costs because MnPASS users were more likely to operate vehicles at speeds associated with relatively low fuel economy than GPL users. The MnPASS has no remaining values after 10 years of operations. After the past and future streams of benefits and costs are discounted, we computed benefit-cost ratios (called ratio for simplicity) for the MnPASS. As shown in Table 9, we calculated two ratios: one ratio considers travel time savings and the other considers both travel time savings and travel time reliability savings. Because both ratios are larger than 1, the MnPASS program is economically justified.

Table 9. Summary of Benefit Cost Analysis

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Travel Time Savings and Reliability Savings</th>
<th>Travel Time Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel time savings</td>
<td>$7,449,560</td>
<td>$1,720,909</td>
</tr>
<tr>
<td>Vehicle operating cost savings</td>
<td>$(-62,142)</td>
<td>$(-62,142)</td>
</tr>
<tr>
<td>Safety Benefits</td>
<td>$45,845,651</td>
<td>$45,845,651</td>
</tr>
<tr>
<td>Remaining capital value</td>
<td>$-</td>
<td>$-</td>
</tr>
<tr>
<td>Total Benefits</td>
<td>$53,233,069</td>
<td>$47,504,417</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Costs</th>
<th>Travel Time Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>MnPass Capital Cost</td>
<td>$10,055,278</td>
</tr>
<tr>
<td>MnPass operating costs</td>
<td>$14,305,023</td>
</tr>
<tr>
<td>Total costs</td>
<td>$24,360,301</td>
</tr>
</tbody>
</table>

| Net Present Value            | $28,872,768                                 | $23,144,116         |
| Benefit-cost ratio           | 2.19                                       | 1.95                |

MnPASS users choose the HOT lanes not just for travel time savings, but also for reliable travel time (Cho, Goel et al. 2011). Table 9 shows the importance of travel time reliability. The valuation of travel time reliability savings ($5.73 million = $7.45 million - $1.72 million) is more than three times as large as that of travel time savings ($1.72 million), and it accounts for 23% of total costs ($24.4 million). That is, if we do not consider reliability benefits, the ratio will decrease by 0.23. Thus, travel time reliability savings are considerable and ignoring it will substantially understate the benefits of the MnPASS program. Overall, travel time savings and reliability savings collectively contribute about 0.30 (= $7.45 million / $24.4 million) to the ratio. Unless indicated, the ratio for the remainder of the section considers both travel time savings and travel time reliability savings. When calculating travel time-related benefits, we assume that the total durations of travel time savings and reliability savings after 2010 are the same as those in 2010. If we extrapolate the two durations using a linear regression based on the data from 2006 to 2010, the present values will be about $8.11 million, compared to $7.45 million in Table 9. This difference represents a 0.027 increase in the ratio. Alternatively, if we assume that both durations increase at annual rates of 5%, 10%, 15%, and 20%, the increases in the ratio will be 0.025, 0.053, 0.084, and 0.120, respectively. Note that the average increases for travel time savings and reliability savings from 2005 to 2010 were at 1.3% and 9.0%, respectively. Because of the limited overall contribution of travel time savings and reliability savings to the ratio (0.30),
the variations in the forecasts have a marginal impact on benefit-cost ratio. That is, the benefits from travel time and reliability savings are inadequate to justify total costs of the MnPASS program.

Safety benefits are estimated at about $45.8 million, which account for more than 85% of the total benefits. Safety benefits alone contribute about 1.88 ($45.8 million / $24.4 million) to the ratio. If safety benefits are not considered, the ratio (0.30) is much smaller than 1 and hence the MnPASS becomes not justified. The valuation of safety benefits depends on economic values used in the BCA. For FY2010, MnDOT recommended $7,000,000, $412,000, $136,000, $91,000, and $12,000 for fatal, injury A, injury B, injury C, and property damage crashes, respectively. For FY2006, the standardized values were $3,600,000, $286,000, $61,000, $30,000, and $4,400, respectively. As shown in Table 10, the ratio decreases dramatically when we use FY 2006 values rather than FY 2010 values. However, the MnPASS is still justified since the ratio of 1.32 is larger than 1. Since there were no fatal mainline crashes on the I-394 in 2006 and 2008, the benefits from fatal crash reductions account for a significant share of the overall safety benefits. If we do not consider fatal crash reductions, the MnPASS program becomes unjustified.

Table 10. Variation of Safety Benefits

<table>
<thead>
<tr>
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<th>With fatal crashes</th>
<th>Without fatal crashes</th>
</tr>
</thead>
<tbody>
<tr>
<td>FY 2010 crash values</td>
<td>2.19</td>
<td>0.72</td>
</tr>
<tr>
<td>FY 2006 crash values</td>
<td>1.32</td>
<td>0.59</td>
</tr>
</tbody>
</table>

From 2006 to 2010, there was only one fatal crash associated with a motorcycle on the ramp to the HOT reversible section. This crash does not qualify a mainline crash as defined in Chapter 4 because it happened on the ramp. Thus, there were virtually no fatal mainline crashes since the conversion of HOV lanes to HOT lanes. Even if we count the crash, the ratio reduces to 1.52 and 1.00, respectively. The MnPASS is still economically justified.
7 Conclusions

In this study, we conducted a benefit cost analysis to evaluate the net societal benefits and costs that were brought about by the I-394 MnPASS program. Where applicable, the implementation of this study followed the BCA guidance of MnDOT. The study focused on I-394, with a 10-year timeframe from 2006 to 2015. The benefits considered included travel time savings, safety benefits, and vehicle operating cost savings and the costs consisted of capital costs and annual operating costs. This study has the following strengths and weaknesses.

7.1 Advantages and Limitations

To our knowledge, this study has the following unique characteristics. First, travel time savings were estimated using each individual driver's behavior at the disaggregate level. Previous studies relied on either the simulation from a regional travel demand forecasting model or temporal aggregations (say, 7:00-7:15 and 7:15-8:00) of individual drivers’ behavior (Burris and Sullivan 2006). These outcomes obscure the differences of individual behavior. Second, this study considered the benefits of both travel time savings and travel time reliability, and the valuations of travel time savings and reliability were derived from econometric models for individual driver’s behavior. HOT lane users chose lanes because of travel time savings and/or the reliability of the lanes. However, previous studies considered only travel time savings and exclusively relied on standardized economic value of travel time. Last but not least, this study estimated safety benefits from crash reduction using the Empirical Bayes method. Previous studies scarcely considered the benefits resulting from the conversion of HOV lanes to HOT lanes. This study also showed that “naïve” approaches tended to overstate safety benefits, which highlighted the importance of using a sound methodology.

This study also has a few limitations. First, the valuations of travel time savings and reliability were derived using the 2006 data and then were adjusted for inflation from 2006 on. Although the valuation can vary because of congestion level over time, onerous computing burdens under a limited project timeframe precluded us from developing models for years 2007-2010. Second, similar to previous studies (Burris and Sullivan 2006), this study considered only benefits for MnPASS users (except safety benefits). The MnPASS program might bring about benefits to GPL users: (Arnebeck 2006) stated that travel speed on the GPLs increased by 2%-15%. However, the mobility improvements on the GPLs were likely to be confounded by many factors. For example, if congestion level across the region decreases, we expect the increase in travel speed on I-394 GPLs. If there is construction along the I-394 corridor (including both freeway and local arterials), travel speed on I-394 GPLs is likely to decrease. Given the difficulty in addressing these confounding factors, we followed the practice of previous studies. Nevertheless, this evaluation offers some insights on the benefits and costs associated with the I-394 MnPASS program.

7.2 Summary

Overall, the BCA concludes that the I-394 MnPASS program is economically justified. Specifically, travel time savings (not including reliability savings) can compensate only a very small share (about 7%) of total costs, and travel time reliability savings contribute to an additional 23%. Different variations on these two savings do not materially change their
contribution. Thus, travel time savings and travel time reliability savings are important sources of the benefits, but they are not the dominant sources. One potential reason is that congestion along the I-394 corridor is not as severe compared to many corridors in Los Angeles and Washington, D.C.

Safety benefits dominate the total benefits of the MnPASS, especially those from fatal crash reductions. The specific contribution of safety benefits to cost compensation also depends on the standard economic values used. It is worth noting that the safety benefits of the I-394 MnPASS program are associated with converting underused HOV lanes to HOT lanes, accompanied by designating access points. Therefore, the safety benefits have limited generalizability for scenarios in which HOT lanes are added to existing freeways.

Finally, future BCA of HOT lane projects should consider travel time reliability savings and safety benefits. Ignoring the two benefits may substantially skew the outcome.
References


