THE IMPACT OF THE I-35 HOT LANE TOLL CAP ON CONGESTION AND REVENUE

A Thesis

by

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ABSTRACT

The Minnesota Department of Transportation has deployed a dynamic toll pricing algorithm that charged tolls to single-occupant vehicles for using the MnPASS lanes during the operational hours. The toll algorithm was set to vary tolls from $0.25 up to $8 i.e., the toll cap, based on the traffic conditions on the MnPASS lanes. This research analyzed the pattern of occurrence of toll caps on I-35W MnPASS lanes using two years (2016 and 2017) of toll transaction data. Toll caps were most frequently charged to morning hour trips that began near Burnsville and Highway 13 tolling locations and ended near Downtown Minneapolis in the northernmost section of the I-35W MnPASS lanes. Many SOV travelers continued to pay to use the MnPASS lanes when the toll was $8 which resulted in the level of service C conditions and below near Cliff road. Speed and Flow readings near Cliff road became worse when trips were charged the maximum toll. Additionally 65-70% of MnPASS trips where users paid $8 tolls, had an average trip speed below 50 mph. Hence, the toll algorithm was unable to raise tolls during peak demand and maintain least LOS C traffic conditions during the toll cap. This research estimated speed and flow on the MnPASS lanes at tolls greater than the toll cap. MnPASS customers were assumed to choose MnPASS lanes over GP lanes only if the increased toll was worth their travel time savings. Moreover, customers who paid $8 toll may be willing to pay a greater toll than $8. It was found that MnPASS lanes could maintain least LOS C conditions along with better throughput and increased revenue if the toll could exceed $8.

DEDICATION

I dedicate this thesis to my parents Smt. Annapurna Gupta and Shri Rajendra Gupta. I cannot imagine and expect any success in my life without your blessings.

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This thesis is an outcome of many individuals who have contributed their part through their support. It is impossible to list everyone here; however, I want to acknowledge some major contributions to express my gratitude to some very special people.

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Contributors

This work was supervised by a thesis committee consisting of Professor Mark Burris and Professor Bruce Wang of the Zachry Department of Civil & Environmental Engineering and Professor Katherine Turnbull of the Department of Landscape Architecture and Urban Planning.

The data analyzed for this thesis was provided by the Minnesota Department of Transportation. All other work conducted for the thesis (or) dissertation was completed by the student independently.

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NOMENCLATURE

DOT	Department of Transportation
FHWA	Federal Highway Administration
GPL	General Purpose Lane
HOT	High Occupancy Toll
HOV	High Occupancy Vehicle
HPMS	Highway Performance Monitoring System
ML	Managed Lane
MnDOT	Minnesota Department of Transportation
MnPASS	Minnesota's system of priced managed lanes
MPH	Miles Per Hour
TL	Tolling Location
VOT	Value of Travel Time
VPH	Vehicles per Hour
VPM	Vehicles Per Mile

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1. INTRODUCTION

1.1. Overview

Investment and expansion of road infrastructure have often failed to address the problem of peak demand. Reducing peak demand requires more innovative solutions. One solution is the concept of High Occupancy Toll(HOT) lanes where the traffic demand can be managed through pricing and vehicle occupancy requirements.

High Occupancy Toll lanes use pricing as a tool to manage traffic demand. The Minnesota Department of Transportation (MnDOT) introduced the HOT lanes on I-394 in 2005. These HOT lanes are commonly known as MnPASS lanes in Minnesota. In 2009 MnDOT extended these lanes to I-35W and is planning to expand the network in the upcoming years (Figure 1).

I-35W is a twenty mile north-south facility connecting the city of Burnsville in the south to Downtown Minneapolis(MnDOT,2020). The MnPASS lane began near Crystal lake road going northbound before ending at 42^{nd} Street. A priced dynamic shoulder lane on I-35W northbound from 42^{nd} St. to 26^{th} St was also operated by MnDOT. Another MnPASS lane is operated in the southbound direction from 42^{nd} St. to McAndrews road.

MnPASS lanes are separated from the GPLs by a double-white strip buffer. Travelers can enter and exit at locations marked as open access, as shown in Figure 2.

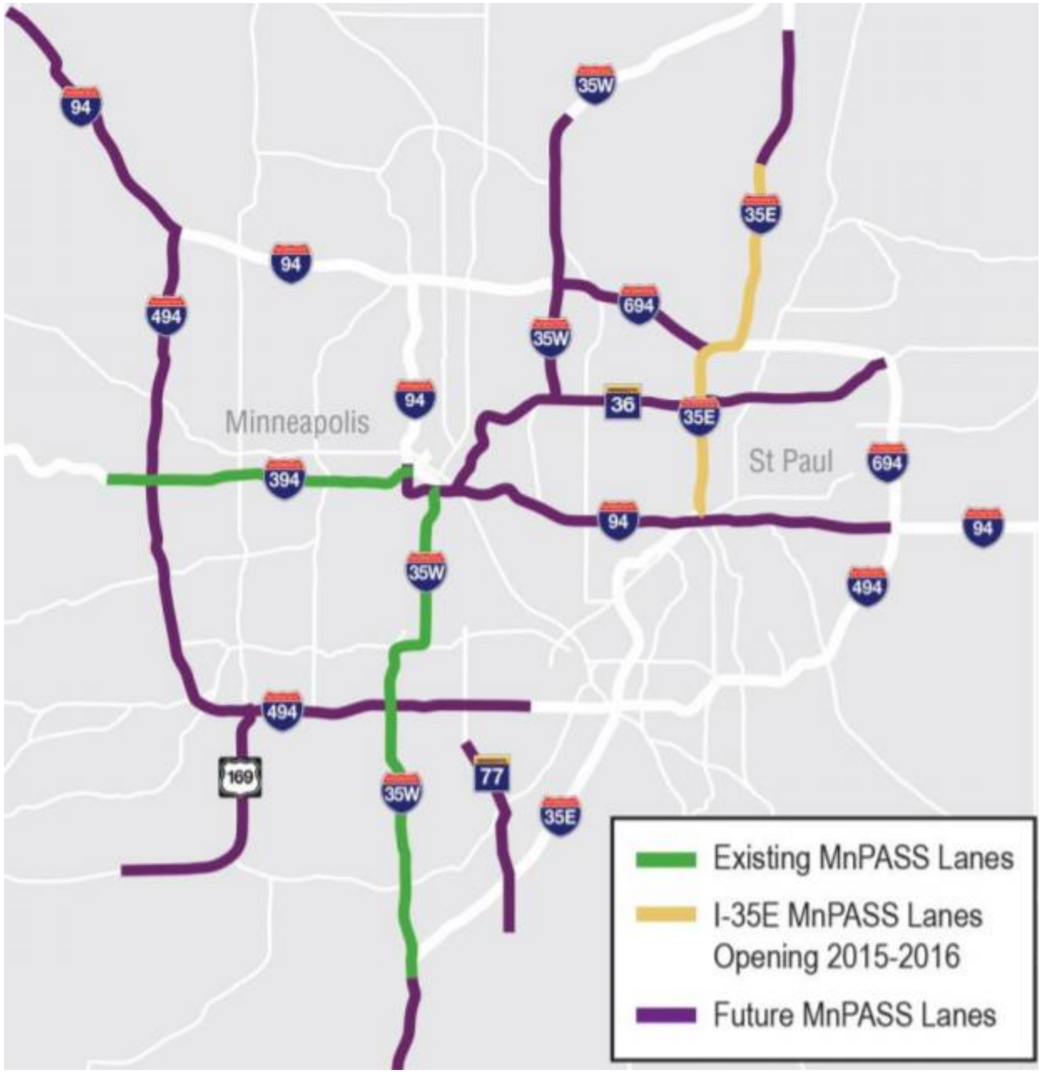

Figure 1 A network of MnPASS lanes in Minnesota

Source: www.Mnpass.org, 2020

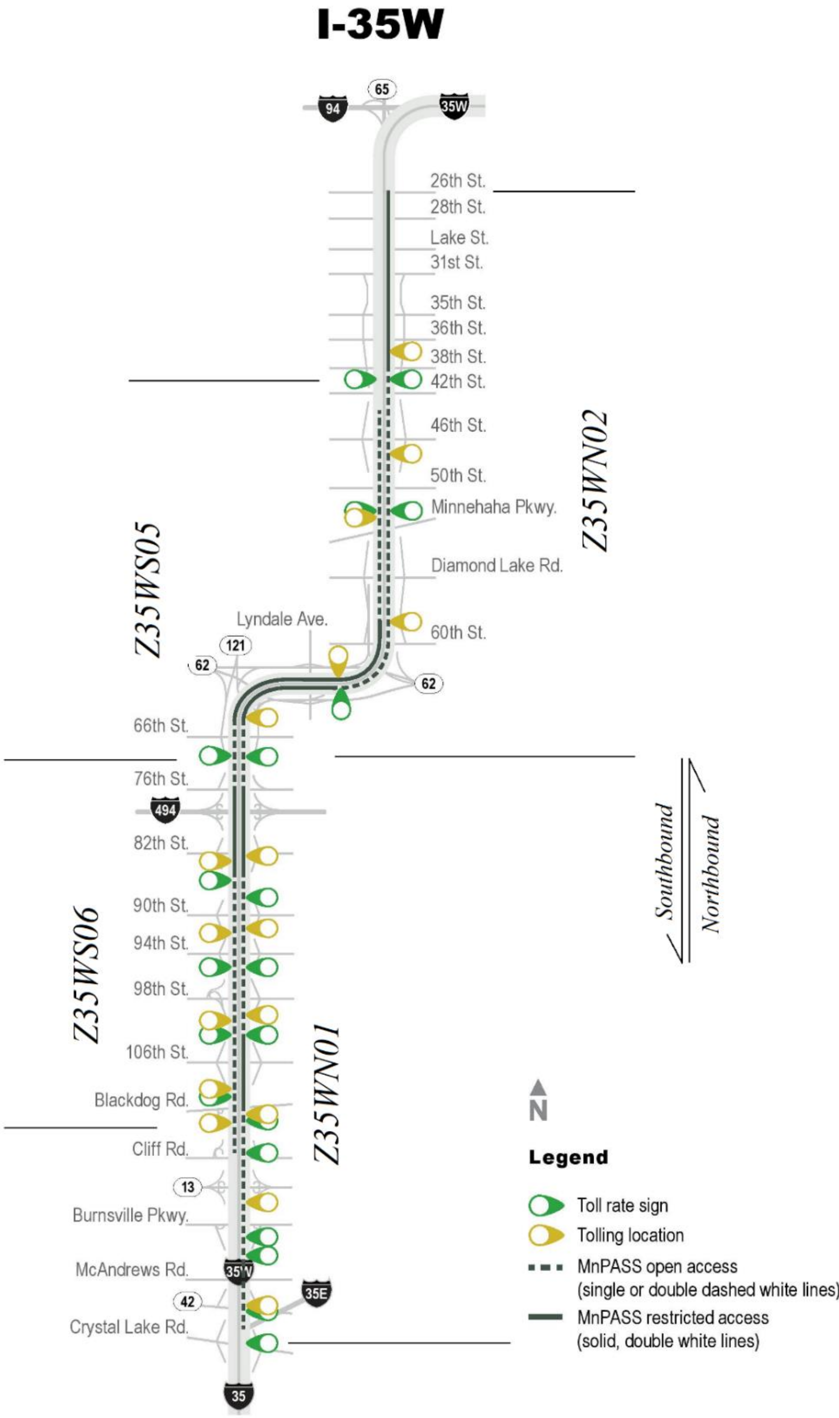

Figure 2 Map of I-35W HOT lane facility

Source: www.mnpass.org, 2020

1.2. Hours of Operation

The tolls are charged on the MnPASS lane during the operational hours, as shown in Table 1. Only single-occupant vehicles (SOVs) are charged a toll, while transit, vanpools, HOV2+, and motorcycles may drive for free. The operational hours are only for weekdays, as during weekends, the lanes are open to all and not tolled. When the price signs read "open", all vehicles can use the MnPASS lanes for free.

Table 1 Operational hours of the I-35W MnPASS lanes facility

Direction	Zone	Location	Morning Tolled Travel Times	Afternoon Tolled Travel Times
NB	Z35WN01	Crystal Lake Rd to Hwy 62	6am-10am	None (open)
NB	Z35WN02	Hwy 62 to 42nd St.	6am-10am	3pm-7pm
SB	Z35WS05	42nd St. to I-494	6am-10am	3pm-7pm
SB	Z35WS06	I-494 to Hwy 13	None (open)	3pm-7pm

Source: www.mnpass.org, 2020

The dynamic shoulder lane (from 42nd St. to 26th St.) was tolled whenever it was open and its hours of operation were from 6 am to 7 pm.

1.3. Pricing Schedule on the MnPASS Lanes

Toll rates vary from \$0.25 to \$8 depending upon the traffic conditions on the MnPASS lanes. \$8 is the maximum toll and will be referred to as a toll cap in this study. Figure 3 shows an example of a price message sign(PMS) board present on the MnPASS lanes. It shows two prices for trips based on the traveler's exit.

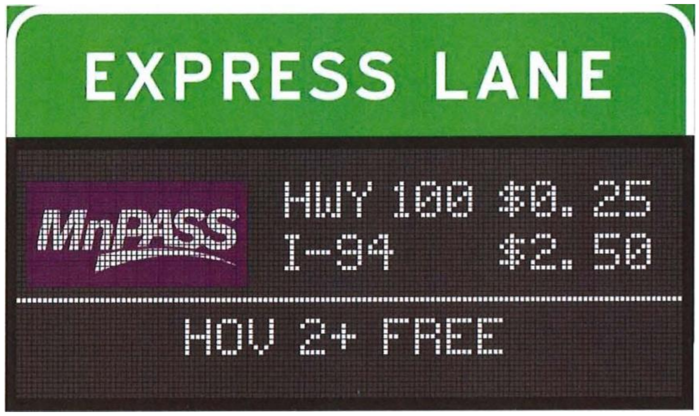

Figure 3 Price message signboard on MnPASS lanes

Source: www.mnpass.org, 2020

1.4. Problem Statement

The pricing has been set to increase the toll during high demand to ensure LOS C conditions on the MnPASS lanes (approximately 50-55 mph). However, the present pricing plan sometimes fails to discourage users from entering the MnPASS lanes, especially when the toll reached the maximum price. Some travelers see the toll cap as an indicator of congestion on the GPLs and chose to use the MnPASS lanes. Therefore, the demand for the toll lanes sometimes increases beyond the capacity. In such situations, toll agencies were unable to maintain the serviceability of the HOT lanes as the algorithm was unable to raise the toll prices due to the toll cap. The toll cap could have affected the speeds on MnPASS lanes and could result in low serviceability or a complete breakdown of the facility if too many travelers are willing to pay the $8 toll.

This study examined the effect of the toll cap on speeds on both MnPASS and GP lanes by analyzing two years of toll transactions. Additionally, this research explored the potential traffic and revenue impacts had the toll price algorithm did not have a toll cap.

1.5. Objectives

The main objective of this research was to examine the effects of having a toll cap and the potential change if the cap did not exist. Secondary objectives included:

1. Analyze the occurrence of toll caps for any potential patterns by:

a. Time of the day
b. Day of the week
c. The month of the year
d. Location

2. Examine the price sensitivity of MnPASS lane users to evaluate the efficiency of the tolls.
3. Observe and report the effect of a price cap on the MnPASS and GPL speed parameters
4. Analyze the relationship between toll pricing and travel time savings to recommend changes in pricing strategy that maximizes traffic throughput as well as maintain the required LOS.
5. Examine the potential impact of raising the toll prices above the current toll cap on congestion and revenue.

1.6. Research Benefits

The research findings will be useful to agencies and policymakers in developing HOT lane policies. The research study will help toll agencies better understand the implications of a toll cap. As the issue affects the general public, detailed research about the pros and cons of a toll cap helps decision-makers as they make policies for priced lanes. The analysis will also help researchers and practitioners in designing toll rate strategies and improve pricing as a tool to manage traffic demand.

2. LITERATURE REVIEW

2.1. Overview

This chapter describes the existing literature on managed lanes with a focus on HOT lane pricing strategies. Also, regression techniques that explain the relationship between traffic parameters are examined.

2.2. Managed Lanes

Transportation agencies across the country are facing challenges with increasing travel demand, especially during peak hours. With limited resources, transport officials and researchers have looked for strategies that manage this increasing demand with the existing infrastructure. One option is a facility commonly known as a Managed Lane(ML). The Federal Highway Administration(FHWA) defines these managed lanes as "designated lanes or roadways within highway rights-of-way where the flow of traffic is managed by restricting vehicle eligibility, limiting facility access, or and in some cases collecting variably priced tolls" (FHWA, 2012). High Occupancy Vehicle(HOV) lanes incentivize carpooling by offering discounted tolls or free usage to carpools. The purpose is to promote higher throughput during peak hour usage, but the eligibility conditions have drawn many critics over time(Poole and Oraski, 1999; Kwon and Varaiya, 2007). Researchers and practitioners suggested opening the HOV facility to everyone and charge Single Occupant Vehicles(SOV) with a toll to use the facility in addition to the eligibility conditions. Also, studies have found that commuters traveling on the managed lanes received better time savings and offered travel time reliability in comparison to general-purpose lanes (Burris et al.,2011; Supernak et al.,2003; Sullivan, 2000). This concept of managed lanes ensures fast travel and increased reliability, besides becoming another revenue source for meeting transportation needs.

Many practitioners and researchers support the idea of value pricing in providing transport services. This concept involves pricing transport facilities to improve and efficiently use the existing transportation system. HOT lanes implement the concept of value pricing by supplying a higher level of service for an additional user fee(Lee, 2008).

Variable pricing came under the concept of value pricing and regarded as the only strategy which can manage demand on a real-time basis(Goodin at al., 2011; Burris et al., 2011; Supernak et al., 2003). Tolling provides an option for the operators to adjust the demand by changing the tolls to encourage or discourage travelers from entering on the facility(Wood et al., 2014).

The tolls are charged to the HOT lane users based on the pricing set by the operator. Tolls could be either a fixed toll or a variable toll. Generally, a fixed toll pricing is opted by agencies for toll roads and bridges. But this method often fails to manage the traffic demand during peak hours of operation. In this regard, variable pricing was found as an alternative to fixed toll pricing.

Almost all the toll algorithms of HOT lanes deploy variable pricing as a strategic measure to manage the traffic demand on their lanes. One of the important goals of the variable pricing is to maximize the utilization of toll lanes as well as try to maintain free-flow speeds(Palma and Lindsey, 2011). Variable pricing shifts the commuters to other modes or to off-peak period based on the fact that a majority of rush-hour drivers are not commuters (Pricing C., 2008). Variable pricing is further divided into time-of-day pricing and dynamic pricing. In time-of-day pricing, the tolls are set according to the time of day and day of the week. A time-based schedule is prepared where tolls are adjusted to correlate the times of day with the level of congestion. Examples of facilities that adopted time-of-day pricing are IH 10 Katy Freeway in Texas and SR-91 Express lanes in Los Angeles. Another type of variable pricing which is more complex and involves a greater level of complexity is dynamic pricing. In dynamic pricing, the tolls are based on the congestion present at that time, on managed lanes or general-purpose lanes or both. Tolls change in increments based on parameters like speed, density or flow detected during the elapsed time interval. Some facilities restrict the tolls to be raised above a certain price level, also known as the price ceiling or the toll cap.

In pricing facilities and services, estimating traveler’s capability and willingness to pay is one of the essential steps during project planning. Many studies have examined traveler’s value of time and incorporate the heterogeneity in Value of Travel Time(VOT) values while evaluating the toll rates(Jang et al., 2014; Patil et al., 2011; Burris et al., 2012). It is reasonable to say that the SOVs who pay to use the ML will have the highest VOT among travelers. A revealed preference value of time showed the VOT of the I-394 ML users as $73/hour in the morning and $49/ hour in the afternoon(Burris et al., 2012). Even though the overall travel time savings (TTS) was very small, the MnPASS users appeared to be paying for more than just TTS and gave importance to other factors like safety and travel time reliability. The study also found a higher variation in the toll rates during the morning(7:30 to 8:30 a.m.) and evening peak hours(5:00 to 6:00 p.m.) compared to off-peak hours, which had little or no variation.

Various studies have been done on the responsiveness of the users to use managed lanes. Stated preference surveys and revealed preference surveys have been conducted to understand the travel behavior of commuters. In the stated preference survey, travelers are asked about their preferences or hypothetical questions for a specific mode of travel. Users' background information is collected to build choice models and predict their preferred mode of toll. There is another way to understand the user characteristics which is completely different from the stated preference survey which is the revealed preference(RP) method. The data for RP is obtained from the traveler's real-world choices, for example, toll transaction data which is used in the calculation of value of travel time (VOT) analysis(Burris and Brady, 2018). Similarly, this study has used transaction data to perform VOT analysis and understand the usage pattern of travelers who paid the maximum toll. More general trends about such users have been researched based on the stated and revealed preference surveys. Patil et al. (2011) analyzed variation in travel time savings for managed lane (ML) users when taking unusual trips rather than ordinary trips. For example, a traveler running late for an appointment has VOT approximately 300% higher than an ordinary trip.

The Minnesota DOT implemented the concept of HOT lanes to allow Single Occupant Vehicles (SOV) in addition to carpools, motorcycles, and buses to use the MnPASS lanes. By using MnPASS, travelers save travel time and improve their reliability over the general-purpose lanes(GPL). SOVs are required to pay the dynamic toll while other eligible vehicles are exempted from paying any toll. This pricing strategy tends to maximize passenger throughput by incentivizing carpools and transit vehicles. The toll rates increased with increased in vehicle density on the MnPASS lane until the price hits the ceiling, known as the toll cap.

These toll caps have been set up so that the toll-paying users find the rates reasonable and become familiar with their use(Wood et al., 2014). However, Toth and Guensler (2014) had a different experience with their findings of the toll cap. They analyzed tag reads from the I-85 HOT lane facility in Georgia and found that the full-corridor speeds decreased during the maximum toll which led to frequent breakdown of the facility. The authors also mentioned that the toll amount was not high enough to limit the number of HOT lane paying users and these users did not experience average speeds over the FHWA recommended speed of 45mph.

Over time, many toll-paying users might not hesitate to pay high toll rates, which may lead to excess demand during peak operational times. Understanding the choice behavior of travelers is necessary to predict traffic demand on managed lanes. Janson and Levinson (2014) used data from field experiments and two years of toll and traffic data to measure traffic driver responses to pricing changes. They found that both SOVs and HOVs had increased their usage of MnPASS lanes at higher tolls. Another study evaluated the travel behavior before and after a toll increase and concluded that the ML usage increased after the toll was raised (Burris and Ashraf, 2019).

Some sources have suggested that raising toll prices do not always have the intended action of lessening the traffic(Dickson, 2019). Motorists feel higher toll prices act a signal that gridlock ahead is really bad and paying a higher toll price is better than getting stuck in bad traffic(Malone, 2014). A similar situation occurred in 95 Express lanes in Florida, where the system is similar to the MnPASS express lanes. Both the express lanes in Florida and Minnesota have a toll cap, which may be the cause of this problem. But, 95Express operators revised the toll cap from $7 to $10.5 in March 2014 after the express lanes were launched in 2008. Also, the concerned authorities have come up with a rule to extend the cap by another $3.5 if the toll hits the ceiling price on 45 different days during any six months starting the first day of the initial month(Malone, 2014).

Previously, studies have been performed to maximize revenue from the toll users through theoretical approaches. Cheng and Ishak (2013) developed and simulated a pricing strategy that aimed at maximizing revenue while maintaining a minimum desired level of service. The strategy was developed using simulation and its performance was compared with the pricing strategy adopted on the 95 express lanes in Florida. The proposed strategy showed a steadier toll rate profile stating that high-income groups exhibit a higher probability of choosing the managed lane despite an increase in toll. Another study by Lou et al. (2011) recommended an optimal toll pricing strategy based on a self-learning approach. The methodology will try to learn about the user's willingness to pay by analyzing the loop detector data and specify tolls that maximized the throughput and ensured superior LOS. Another study by Jang et al. (2014) tried to compare the dynamic pricing strategy with a fixed toll strategy based on revenue maximization and total traffic delay. The study used an underutilized HOV as an example to recommend a pricing strategy based on parameters like expected delays, available capacity for toll-paying customers, and travelers' value of time. All these studies suggested pricing improvements and recommended revenue maximization based on the theoretical approaches. However, this study used real-world data to recommend price changes that will maximize the revenue as well as maintain least LOS C conditions on the MnPASS lanes.

2.3. Speed-Density-Flow Relationships

Traffic parameters can be useful for describing the traffic behavior and are used for defining and calibrating models that run the MnPASS toll pricing algorithm. These parameters are obtained directly from detectors or through models where these parameters are inter-related. It is essential to define relationships for a better understanding of how traffic may change due to hypothetical changes assumed in the toll rate as done in this research.

Greenshield proposed one of the simplest relationships between speed and density. He assumed a linear speed-density model between speed and density and formulated an equation (see Equation 1) for this relationship (May, 1990)

$$u = u_f - \left[\frac{u_f}{k_j}\right] k \qquad (1)$$

Where u is the speed at density k, u_f is free speed and k_j is the jam density. Another equation established a relationship between flow and density. Flow is one of the most commonly used traffic parameters and is the rate at which vehicles cross a given point on the lane. It is normally described in terms of vehicles per hour. Speed and density will be described in terms of miles per hour(mph) and the number of vehicles per mile, respectively in this study.

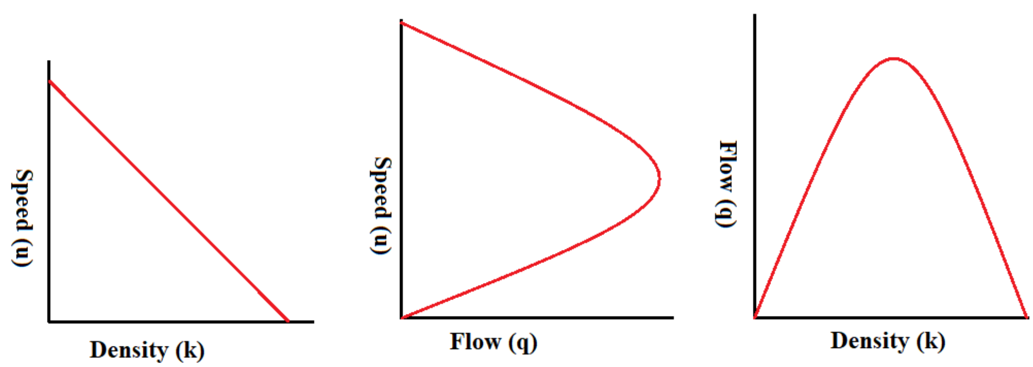

Figure 4 Traffic Flow Models

Source: May (1990)

As seen in figure 4, all the figures have taken two variables at a time to explain the relationship between the parameters. All three figures have related two variables at a time even though these are ideal relationships. These ideal relationships will guide the regression models and see if the derived relationship models closely match them. More discussion about the type of regression models to be used is discussed in the next section.

2.4. Polynomial Regression Models

Regression analysis is a kind of predictive modeling technique that relates dependent and independent variables. Here the technique is used to relate two traffic parameters at a time to create a regression model. Using this model, the research will try to predict the dependent traffic parameter based on the given parameter.

A linear model is one of the simplest models which describes a relationship between the dependent variable(x) and independent variable(y), generally represented by equation 2. It relates a predictor variable with the response model.

$$y = \beta(x) + c \qquad (2)$$

β = regression coefficient or estimators

c = constant or error

Sometimes linear models fail to depict the relationship between the dependent variable(x) and independent variable(y), especially where the relationship is curvilinear. In such situations, polynomial models are in a better position to explain those relationships. Polynomial regression models can extend up to nth order polynomial, as shown in the equation below.

$$y^{pred} = \beta_0 + \beta_1 x + \beta_2 x^2 \dots\dots\dots + \beta_n x^n + c \qquad (3)$$

y = observed value

y^{mean}= mean of all n number of observations

y^{pred} = predicted value

A residual is a difference between an observation and the predicted value as defined in equation 4.

$$\text{Residual} = y - y^{pred} \qquad (4)$$

As seen in equation 3, an independent parameter can be related to a dependent parameter based on the polynomial regression model. These are useful in developing curvilinear relationships as well. For example, the ideal relationship between flow and density is quadratic in nature. A polynomial regression model of second order could be used to relate flow and density collected from the detectors. The accuracy of the models is determined by the statistical tests as explained below.

2.5. Statistical Tests

Two tests will be performed to check the accuracy of the prediction models.

R-Squared test- It is one of the necessary tests used in a regression model to explain the strength of the relationship between variables. The higher the score, the better is the predicting power of the model. It is defined as per the equation 5.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y^{pred} - y)^2}{\sum_{i=1}^{n}(y - y^{mean})^2} \quad \text{for n number of observations} \qquad (5)$$

Root Mean Square Error (RMSE)- It measures the standard deviation of residuals and how spread these residuals are. If the scores are lower, it means that the predicted values are closer to the observed values and hence, better-predicting power. It is defined as per the formula given in equation 6.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y^{pred} - y^{mean})^2}{n}} \qquad (6)$$

As seen in Figure 4, ideal relationships between flow-speed and flow-density are curvilinear. Polynomial regression will be used to fit those curves as well as provide a numerical expression to predict the dependent variables.In this study, the dependent variables flow and speed were regressed separately with the independent variable density. Then, the order of the polynomial regression was decided and checked based on the accuracy scores, given by R-squared and RMSE tests.

2.6. Chapter Summary

As per the review of existing literature, various studies were available to understand how pricing has been used in the design of MLs. Most studies have tried to analyze the factors behind the selection of MLs over GPLs and estimated traveler's capability and willingness to pay. Various studies attempted to evaluate toll pricing algorithms theoretically, but very few studies have performed empirical studies on relating tolls with traffic parameters(Friesz et al., 2007; Lou et al. ,2011; Jang et al., 2014; Phan et al., 2016). This thesis will try to fill this gap by exploring the toll transaction dataset and traffic information obtained from the Minnesota Department of Transportation (MnDOT). Several sources have mentioned the toll cap could be the cause of traffic congestion(Toth and Guensler, 2014), but no study has inspected this issue in detail. This study examined the issue and analyzed the pattern of occurrence of the toll cap transactions and how a toll cap can affect the level of service on the MnPASS lanes. More information about the data used in this analysis will be explained in the next chapter.

3. DATA COLLECTION

3.1. Overview

In this study, the I-35W MnPASS lanes toll dataset was obtained from MnDOT. Traffic parameters like speed, density, and flow were also needed to describe the traffic characteristics at the time of toll transactions. The traffic dataset was extracted from software called as Dataextract developed by MnDOT. In addition, information about the detectors and the price message signs was also needed to identify and locate the ones used in the analysis.

3.2. Toll Transaction Data

A request was submitted to the Data Practices office of MnDOT to provide toll transaction and toll pricing data. This request was sent through the department website (https://www.dot.state.mn.us/information/datapractices/index.html). Both datasets consisted of all the toll transactions and toll prices that occurred on I-35W from Jan 1st, 2016 to Dec 31st, 2017. The dates were chosen to get the recent and complete data for two whole years.

The toll transaction dataset was sent in the form of a Comma Separated Value (CSV) file. Each row is a trip and had an entry time when a vehicle was detected at the first tolling location. The first and the last tolling location of a MnPASS trip are recorded as EntryLoc and ExitLoc respectively. Also, each row included the direction of travel, whether it was a northbound or Southbound trip. A toll is charged to each trip based on the vehicle eligibility conditions and depending upon where the user traveled on the MnPASS lanes.

A toll amount of $0 indicated that either the user had a transponder set to HOV(free) mode or they drove the lane outside of tolling hours. Table 3 shows a sample taken from the transaction dataset to explain the trip details. For example, the first row is a northbound trip and was first detected at Burnsville tolling location and last detected at 36th St. It was a SOV trip where the user paid a $4 toll to use the MnPASS lanes.

In this study, a long toll and short toll describe the type of toll paid for a trip. For example, a trip was charged a short toll if the first and last detected tolling locations were located in the same zone(Figure 2), otherwise a long toll is charged.

Table 2 Sample Toll Transaction dataset

S.No.	EntryTime	Road	Direction	EntryLoc	ExitLoc	TollAmt($)
1	10-02-2016 08:06:58	I-35W	NB	Burnsville	36th St	4
2	10-02-2016 08:06:58	I-35W	SB	82nd St	82nd St	0
3	10-02-2016 08:07:00	I-35W	NB	Burnsville	82nd St	2.5
4	10-02-2016 08:07:05	I-35W	NB	60th St	36th St	2.5

The transaction data consisted of 1,448,885 trips in the year 2016 and 1,887,818 trips in the year 2017. There were 10 tolling locations in the northbound direction of I-35W MnPASS lanes and 6 tolling locations in the southbound direction of I-35W MnPASS lanes(Figure 2).

3.3. Toll Pricing Data

The analysis required the share of SOV and HOV in the total flow at each toll amount to predict the share of HOVs at higher tolls in the case if tolls could exceed $8. For this it was also required to know the toll posted on the signs at the time when a HOV trip began. Since HOV trips are not charged any toll and their toll amount was $0 in the toll transactions dataset. Pricing data will be used to know the prevailing rate when the HOV trip was first detected at a tolling location.

The toll pricing dataset had a mix of both file types- Comma Separated Value (CSV) and Structured Query Language (SQL) forms. As Python can read CSV format easily, the SQL data was transformed into the required CSV format. Each toll data file had the following attributes detailing the event_id, event_date, device id, toll zone, and toll price (Table 3).

Table 3 Sample toll pricing data

event ID	event date	description	device id	toll zone	price($)
4055404	2016-01-04 06:46:41	Price DEPLOYED	MP35WN09_2	Z35WN02	2
4055405	2016-01-04 06:46:41	Price DEPLOYED	MP35WS01_2	Z35WS05	0.5
4055406	2016-01-04 06:46:41	Price DEPLOYED	MP35WS03_1	Z35WS06	0

The date and time when the toll was posted are given in the event_date column. Here "Price DEPLOYED" in the description indicated the MnPASS algorithm's intent to display the price to the sign. By "Price VERIFIED', it meant that the software asked the sign if it displayed to the user as it was intended. If the answer was yes or VERIFIED, the price was charged to the user. If the system charged a fee, unlike the displayed price and verification failed, the user was charged with the minimum toll of $0.25. Therefore, Price VERIFIED will be used as the source of the pricing information.

Additionally, details about the construction projects which might affect the frequency of toll cap transactions were collected. There were no major construction updates found for I-35W during the two year period (2016-17) which might have affected the frequency of occurrence of toll cap transactions.

Various price message signs present along the corridor displayed the toll price for SOVs. If there were two device IDs at the same price message signboard(location), one device id indicated tolls for short trips, whereas the other one indicated the toll for long trips. Table 4 and Table 5 show the locations of price message signs boards present along the I-35W MnPASS lanes in the Northbound and Southbound direction respectively.

Table 4 Price message sign and device ids along I-35W northbound direction

Northbound I-35W MnPASS lane	
Device ID	**Physical location**
MN35WN01_1	I-35 NB @ Crystal Lake Rd
MN35WN01_2	I-35 NB @ Crystal Lake Rd
MN35WN02_1	I-35W NB @ Co Rd 42
MN35WN02_2	I-35W NB @ Co Rd 42
MN35WN03_1	I-35W NB @ Timberland Dr
MN35WN03_2	I-35W NB @ Timberland Dr
MN35WN04_1	I-35W NB @ Burnsville Pkwy
MN35WN04_2	I-35W NB @ Burnsville Pkwy
MN35WN05_1	I-35W NB @ Cliff Rd
MN35WN05_2	I-35W NB @ Cliff Rd
MN35WN06_1	I-35W NB @ Black Dog Rd
MN35WN06_2	I-35W NB @ Black Dog Rd
MN35WN07_1	I-35W NB N of 106th St
MN35WN07_2	I-35W NB N of 106th St
MN35WN08_1	I-35W NB @ 94th St
MN35WN08_2	I-35W NB @ 94th St
MN35WN09_1	I-35W NB N of 90th St
MN35WN09_2	I-35W NB N of 90th St
MN35WN10_1	I-35W NB S of 66th St
MN35WN11_1	I-35W NB @ Nicollet Ave
MN35WN12_1	I-35W NB S of 50th St
MN35WN13_1	I-35W NB @ 41st St

Table 5 Price message sign and device ids along I-35W southbound direction

Southbound I-35W MnPASS lane	
Device ID	**Physical Location**
MN35WS01_1	I-35W SB at 41st St
MN35WS01_2	I-35W SB at 41st St
MN35WS02_1	I-35W SB S of 50th St
MN35WS02_2	I-35W SB S of 50th St
MN35WS03_1	I-35W SB S of 66th St
MN35WS04_1	I-35W SB at 85th St
MN35WS05_1	I-35W SB @ 94th St
MN35WS06_1	I-35W SB N of 106th St
MN35WS07_1	I-35W SB N of Minnesota River

In this study, information about the PMS boards present in the northbound direction was used as the majority of toll cap transactions occurred in the northbound direction.

3.4. Pricing plan of I-35W MnPASS lanes

MnDOT adjusts the toll prices based on the traffic density levels on the MnPASS lanes measured every three minutes. Traffic conditions on the general-purpose lanes did not directly affect the toll prices. Table 6 shows the pricing plan of the MnPASS lanes. Toll prices were proportional to the traffic density and the traffic density level for the toll to hit the maximum rate was 50 vehicles per mile (vpm).

Table 6 Pricing plan for normal operation of MnPASS lanes

Level of Service	Min Density (vpm)	Max Density (vpm)	Min Rate ($)	Default Rate ($)	Max Rate ($)
A	0	11	0.25	0.25	0.5
B	12	18	0.5	0.5	1.5
C	19	31	1.5	1.5	2.5
D	32	42	2.5	3	3.5
E	43	49	3.5	5	5
F	50	50	5	8	8

Source: Janson and Levinson, 2014

The default toll rate increased and decreased depending upon the change in traffic density levels on the MnPASS lanes. Table 7 shows the change in prices prompted by a change in density on the MnPASS lanes. The tolling algorithm stored traffic density from the previous three minutes and adjusted the toll based on the difference in density levels**.** The change in density levels is represented by the Greek letter Δ (delta).

Table 7 Price Changes based on changes in Density – Used for all the pricing plans

	Change (Δ) in density in vpm					
Density (vpm)	**Δ 1**	**Δ 2**	**Δ 3**	**Δ 4**	**Δ 5**	**Δ 6**
0 -18	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
19+	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50

Source: Janson and Levinson, 2014

The toll increments for the same change in density level were higher if the density was above 19 vpm. The tolling algorithm was set to charge higher during the peak demand for MnPASS lanes.

3.5. Traffic Data

Loop Detectors were embedded below the pavement surface throughout the MnPASS and GP lanes. A detector sensed the vehicular traffic flowing on the lane, and the software calibrated the responses to provide the chosen traffic parameters as output. These systems usually record traffic volume. Traffic volume is the actual number of vehicles that arrived during an interval of time (say 60 seconds). Flow is obtained by multiplying the volume by the number of time intervals in an hour. Speed is retrieved by the average speed of the vehicles that pass between a pair of detectors in a time interval while density (vehicles per mile) is measured by dividing flow readings(vehicles per hour) by speed readings (miles per hour).

Information about the detector location was available online on the website (http://www.dot.state.mn.us/rtmc/reports/ADR_2014.pdf). For this study, density, speed, and flow were obtained using the DataExtract tool developed by MnDOT. This tool is available on MnDOT's website (http://data.dot.state.mn.us/datatools/dataextract.html). This tool generated output in the form of a comma-separated value(CSV) file. Table 8 shows the output where density, flow, and speed were extracted from the MnPASS detector 259. The traffic parameters were extracted at a minute interval. It can be seen that the last row did not have any reading under density, flow, and speed columns as the detector 259 had not detected any vehicle during that minute interval.

Table 8 Sample output generated from the Dataextract tool

Detector No.	Date	Time	Density(vpm)	Flow(vph)	Speed(mph)
259	1/3/2017	9:49:00	14.7	780	53.0
259	1/3/2017	9:50:00	23.0	1500	65.2
259	1/3/2017	9:51:00	9.7	660	68.3
259	1/3/2017	9:52:00	9.8	600	61.5
259	1/1/2017	6:05:00	0.0	0	-1.0

Traffic parameters can be used to describe the traffic characteristics of the MnPASS and GP lanes when the trip began and when the trip was first detected at a tolling location. The study related tolls with the traffic density levels at different locations to determine the critical detectors which detect traffic densities that had triggered the tolls.

The transaction dataset did not have information about the trip speed or duration. Few assumptions were made to estimate the average speed during each trip. A group of MnPASS detectors will be selected to find the average speed on the corridor (see section 4.7 for more details). This speed will be used to represent the corridor speed of the lane as well as the average trip speed.

3.6. Chapter Summary

This chapter presented a brief overview of the data that was needed to meet the project objectives. The chapter discussed the following:

1. Toll transactions on I-35W MnPASS lanes collected during 2016 and 2017
2. Dataextract tool which will be used to extract speed, density, and flow parameters from detectors present along the MnPASS as well as GP lanes.

4. DATA ANALYSIS

4.1. Preliminary Analysis

Each row in the toll transaction dataset represents a trip. Each trip is charged once and is recorded as a toll transaction in the dataset. The dataset consisted of trips that occurred during the tolling as well as non-tolling hours of operation. A preliminary analysis of the toll transaction data is checked for obvious errors. As seen from Table 9, the number of toll transactions was higher in the northbound direction than the southbound direction for both the years, 2016 and 2017. Also, the total number of transactions increased in 2017 compared to 2016 and the monthly totals (Figure 5) appeared reasonable.

Table 9 Frequency of toll transactions

Direction	2016	2017	Total
NB	855836	1107817	1963653
SB	593049	780001	1373050
Total	1448885	1887818	

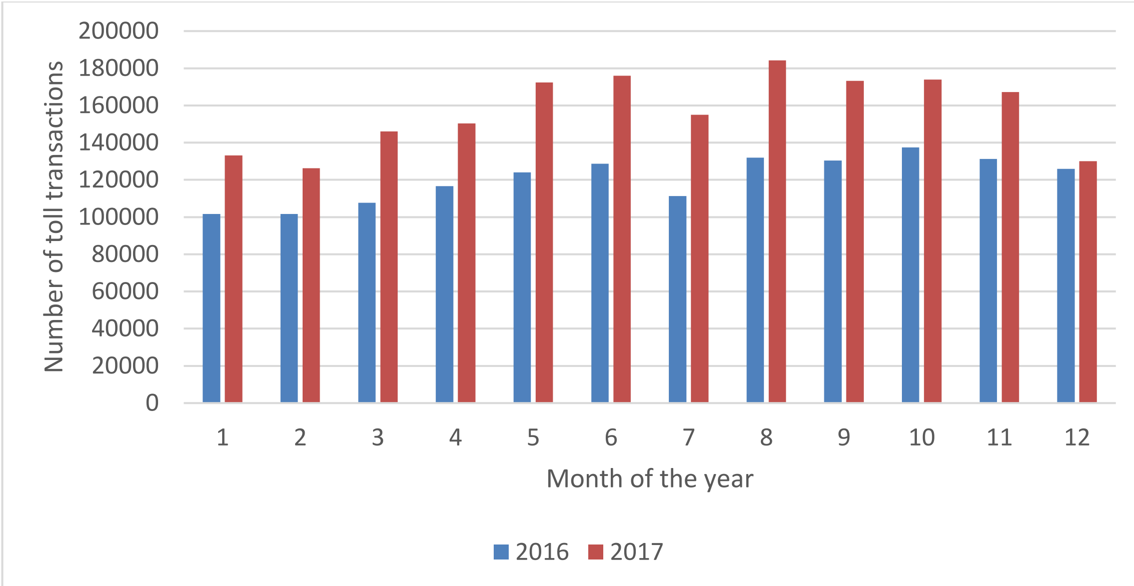

Figure 5 Frequency of toll transactions by the month of the year

Another check was done to see if the dataset had enough transactions at the toll cap to conduct this research. As seen in Table 10, a total of 32,966 toll cap transactions occurred on I-35W MnPASS lanes during 2016 and 2017.

Table 10 Frequency of toll cap transactions by direction

Direction	2016	2017	Total	%
NB	13431	16618	30049	91.2
SB	1521	1396	2917	8.8
Total	14952	18014	32966	100

Around 91% of the total toll cap transactions happened on the northbound I-35W MnPASS lanes. Hence, this research will focus on northbound trips in detail in the following sections.

Table 11 highlights the frequency of toll cap transactions between each pair of tolling locations. A majority of toll cap transactions originated at Highway 13 and Burnsville tolling locations. Figure 6 shows the tolling locations arranged in the order along I-35W northbound direction.

Table 11 Frequency of toll cap transactions happened in the northbound direction

First detected Tolling Location	**Last detected Tolling Location**										
	36thSt	46thSt	60thSt	66thSt	82ndSt	90thSt	98thSt	Cliff Rd	Highway13	Burnsville	Grand Total
36thSt	150										150
46thSt	369	85									454
60thSt	544	56	75								675
66thSt	355	49	37	42							483
82ndSt	82	9	7	5							103
90thSt	140	26	11	10		4					191
98thSt	83	15	15	8	3	2	9				135
Cliff Rd	876	138	73	44	51	41	26	28			1277
Highway13	7785	828	436	285	630	650	654	656	482		12406
Burnsville	8410	763	484	280	834	902	841	986	448	227	14175
Grand Total	18794	1969	1138	674	1518	1599	1530	1670	930	227	30049

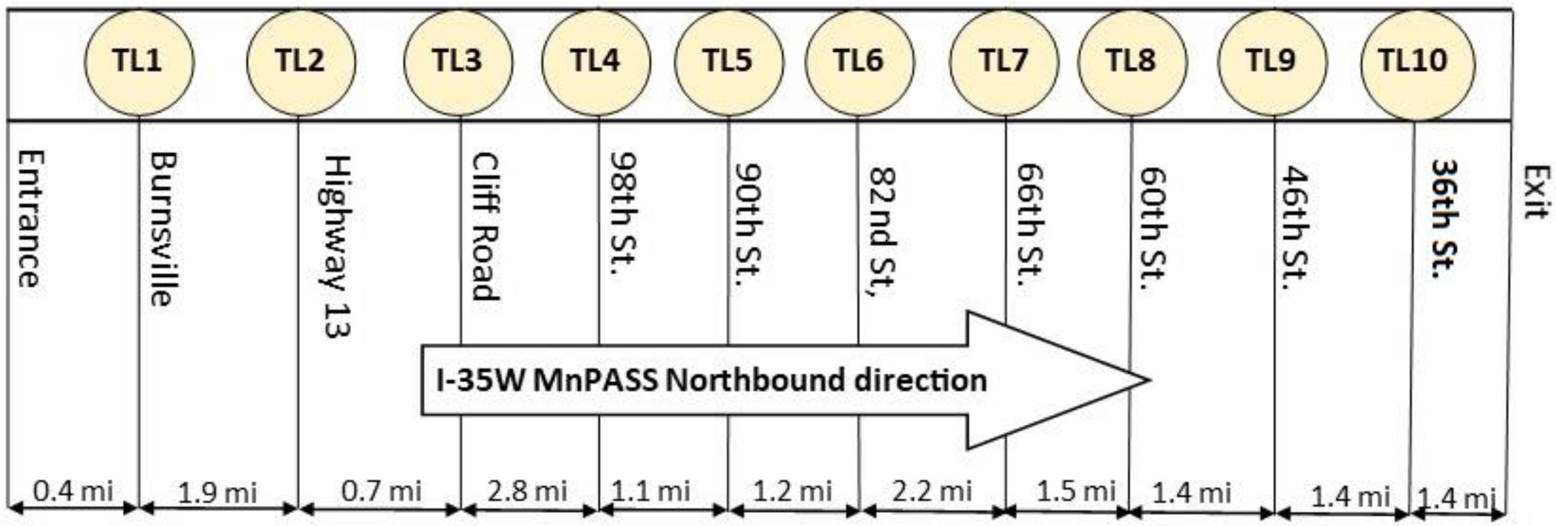

Figure 6 Tolling locations(TL) along I-35W Northbound MnPASS lanes

The trips from Burnsville and Highway 13 tolling locations which were charged the maximum toll comprised nearly 88% of all the northbound toll cap transactions and 80% of all the toll cap transactions on I-35W MnPASS lanes. Nearly 5% of all trips (see Table 12) from these two tolling locations were charged the $8 toll. It can be safely assumed that the toll cap transactions at these two locations were enough for conducting research.

Table 12 Toll cap transactions originated at Highway 13 and Burnsville tolling locations

	Toll cap trips	Tolled trips	Percent of transactions at the toll cap
Highway13	12406	255482	4.86
Burnsville	14175	286272	4.95

From the dataset of these two locations, HOV and SOV trips were identified and summarized in Table 13 below. HOV trips refer to those transactions which had a $0 toll amount, whereas SOV trips were identified by trips charged with a non-zero toll amount. Another condition for a trip to be identified as a HOV trip is that the transaction must have occurred within the operational hours. It would be impossible to identify an HOV or SOV trip from the dataset if the transaction happened outside the hours of operation. The lanes were open to all the vehicles and transactions which occurred outside the hours of operation were already assigned a $0 toll.

Table 13 Summary of trips which were first detected at Burnsville and Highway 13 tolling locations

Tolling Locations	HOV trips	SOV(tolled) trips	Total trips
Highway13	51765	255482	307247
Burnsville	62690	286272	348962

For our research, the analysis of the transactions corresponding to both tolling locations was done separately. The behavior of the MnPASS users towards the tolls might be different at each location.

The toll is charged to the user depending upon where the user traveled on the MnPASS lane. If a user is first detected at either of those two tolling locations and is last detected at or before the 82^{nd} St. tolling location, that trip was charged a short toll and will be called as a short toll trip in this study. If the trip was last detected at 66^{th} St. tolling location or further downstream tolling locations, that trip was charged a long toll and will be called as a long toll trip.

4.2. Price Sensitivity to Tolls

In this section, the price sensitivity of the MnPASS lane users was examined to evaluate the efficiency of the toll algorithm. As observed in Table 14, short trips were approximately 74% of all the MnPASS tolled trips that began at Burnsville or Highway 13 tolling locations.

Table 14 Short and long toll trips initiated at both tolling locations

	Burnsville TL			Highway 13 TL		
Type of toll	Short toll	Long toll	Total	Short toll	Long toll	Total
Frequency	209174	76558	286272	189499	65983	255482
Percentage of total (%)	73.06	26.74	100	74.17	25.82	100

The opposite was found for transactions at the toll cap. Users paid the maximum toll more often for long trips compared to short trips(Table 15). Approximately 14% of long toll trips and 2% of short toll trips were charged the maximum toll (Figure 7). Also, the long toll-paying users were most likely to pay a $8 toll for long trips from Burnsville or Highway 13 tolling locations.

Table 15 Frequency of trips at each toll amount

Toll Amount ($)	Frequency of Short Tolls		Frequency of Long Tolls	
	Trips from Burnsville	**Trips from Highway 13**	**Trips from Burnsville**	**Trips from Highway 13**
0.25	3770	3270	2099	438
0.5	19035	16393	1154	794
0.75	19560	15261	4887	3534
1	19223	14556	3919	3348
1.25	20505	17264	3208	2486
1.5	22819	20530	3641	2551
1.75	21988	20933	3713	2618
2	17816	16733	3525	2619

Table 15 Frequency of trips at each toll amount (Continued)

Toll Amount ($)	Frequency of Short Tolls		Frequency of Long Tolls	
	Trips from Burnsville	**Trips from Highway 13**	**Trips from Burnsville**	**Trips from Highway 13**
2.25	12601	12358	3639	2700
2.5	9086	9101	3814	2920
2.75	5645	5470	3508	2842
3	3822	3875	3072	2544
3.25	3244	3334	2818	2452
3.5	2087	2117	2575	2275
3.75	1958	2223	2428	2247
4	1402	1512	2101	2018
4.25	1520	1635	1898	1862
4.5	1521	1678	1666	1821
4.75	1286	1405	1537	1586
5	1233	1488	1501	1522
5.25	1495	1508	1038	1286
5.5	1427	1595	1190	1376
5.75	1384	1501	1056	1118
6	1669	1718	852	1012
6.25	1458	1625	912	1003
6.5	1362	1413	938	1211
6.75	1555	1562	913	968
7	1361	1203	902	1054
7.25	1280	1054	781	903
7.5	1255	1202	737	903
7.75	1109	910	599	638
8	**4238**	**3072**	**9937**	**9334**
Total	209714	189499	76558	65983

From Figure 7, it can be seen that the percentage of long toll transactions decreased at higher tolls except at the toll cap. Another important interpretation was made from a lower frequency of transactions observed for tolls between $3 to $ 7.75. The toll algorithm would have detected a big change in density when the tolls were nearing $3. This might have led the toll algorithm to skip the higher tolls and charge customers traveling towards downtown with the toll cap more frequently. It can be seen that a majority of travelers going on long trips which began at Burnsville and Highway 13 tolling locations still used the MnPASS lanes when the toll was $8. Another study had a similar observation that SOVs increased their MnPASS usage, seeing the high toll rates as a sign of congestion on the GP lanes (Janson and Levinson, 2014).

A much smaller percentage of short toll-paying users paid $8. However, the short tolls also rarely were between $3.75 to $7.75. This behavior was seen with long tolls as well which suggested that the density levels on the MnPASS lanes rose quickly as the tolls approached higher tolls.

Travelers continued to use the MnPASS lanes despite the maximum tolls. The toll algorithm most likely failed to regulate the demand as per the capacity using pricing as a tool. This situation may have led to a lower level of service conditions on the MnPASS lanes. In section 4.7, this study investigated the speed characteristics at the time when the toll hits the cap.

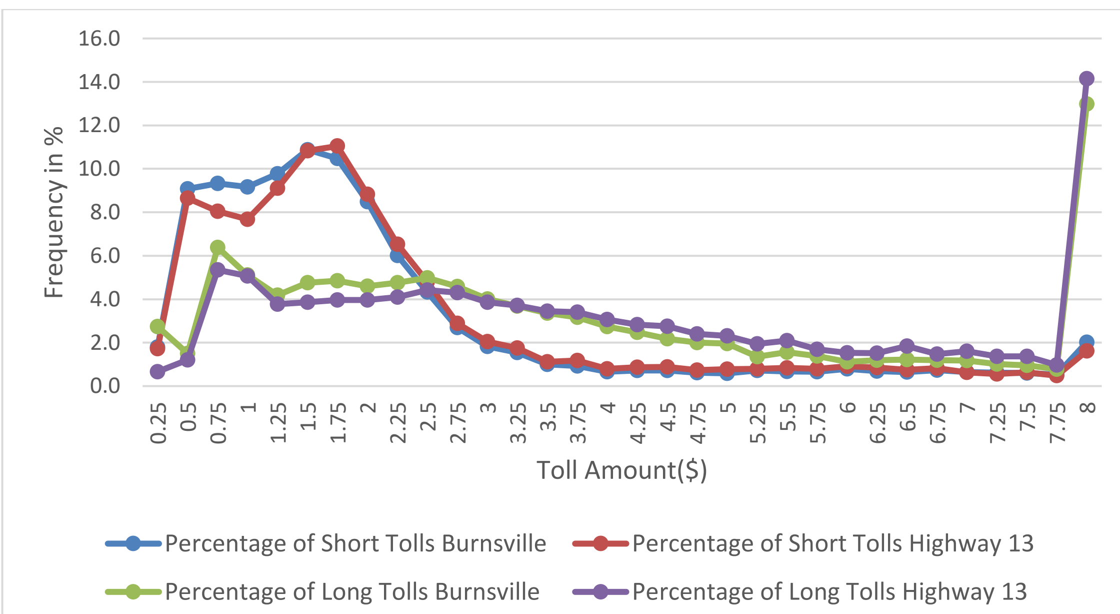

Figure 7 Percentage frequency at each toll amount

4.3. Share of HOV Trips to Total Trips

This section highlights the share of HOV trips at each toll price interval, especially during the toll cap period. For this study, a good estimate of SOVs and HOVs in the traffic flow at each toll amount is required. This proportion is later used to predict the share of SOVs and HOVs in the flow at toll rates greater than $8.

Since HOV trips don't pay any toll, the toll amount recorded in the dataset was $0. Hence, pricing data was used to find the posted toll price. The pricing data was merged with the transaction data based on the datetime column. Now, the merged dataset included HOV trips and the toll price posted on signs at that time.

The number of HOV and SOV trips at each toll price interval was used to calculate the share of SOV to total trips. As seen in Table 16, the share of SOV to total trips decreases at higher tolls. The HOV/SOV distribution was found almost similar for transactions initiated at both tolling locations. The share of SOV to total trips decreases for both long as well as short tolls at both locations. However, for short tolls, the decrease in the share of SOV trips to total trips was higher at the maximum toll. One of the possible reasons could be that users paying for long trips benefitted from better travel time savings and it was worth paying the maximum toll. The TTS for both short and long trips has been calculated and is discussed in detail in section 4.8.

Table 16 Share of SOV trips to Total trips

	Trips from Burnsville TL		**Trips from Highway 13 TL**		
	Share of SOV to total trips in percent				
Toll Amount($)	**Long toll**	**Short toll**	**Long toll**	**Short toll**	**Overall**
0.25	99.3	92.7	95.8	91.6	94.9
0.5	93	84.8	94.1	85.5	89.4
0.75	87.8	82.4	91.2	82.8	86.1
1	84.2	85.2	88.2	84.7	85.6
1.25	84.2	85.2	86.3	86.1	85.5

Table 16 Share of SOV trips to Total trips (Continued)

	Trips from Burnsville TL		Trips from Highway 13 TL		
	Share of SOV to total trips in percent				
Toll Amount($)	Long toll	Short toll	Long toll	Short toll	Overall
1.5	83.5	85.6	84.4	86.2	84.9
1.75	84.3	83.6	84.3	85.2	84.4
2	84	82.2	85.7	82.8	83.7
2.25	83.1	80.2	84.9	82.3	82.6
2.5	84.1	79.6	85.8	81.9	82.9
2.75	83.3	78.1	84.9	80.4	81.7
3	82.5	78	83.9	79.4	81
3.25	82.8	78.1	82.3	82.3	81.4
3.5	83.4	78.2	83.1	80.8	81.4
3.75	83.3	73.8	83	79.4	79.9
4	83.6	76.7	84.1	79.5	81
4.25	80.4	77.9	84	81.1	80.9
4.5	82.3	77.7	85.7	81.9	81.9
4.75	81.4	76.7	83.4	80.1	80.4
5	82.9	77.4	84	79.3	80.9
5.25	80.6	76.1	86.3	77.7	80.2
5.5	84.3	78.5	85.6	81.4	82.5
5.75	84.7	76	84.5	80.5	81.4
6	81.3	76.9	83.3	77.1	79.7
6.25	81	75.5	83.9	75.9	79.1
6.5	81.2	71.2	86.3	71.2	77.5
6.75	82	75.9	83.2	75.3	79.1
7	80.2	74	82.3	74.3	77.7
7.25	77.9	72.8	83.5	73.1	76.8
7.5	79.6	67.3	84.9	70.6	75.6
7.75	79.1	68.8	82.2	68.8	74.7
8	78.6	61	80.5	60.9	70.3

4.4. Frequency of Occurrence of Toll Cap Transactions

This section will discuss the frequency of occurrence of toll cap transactions initiated at Burnsville and Highway 13 tolling locations based on various periods.

4.4.1. Month of the year

Figure 8 highlights the frequency of toll cap transactions by month of the year. Users were more likely to pay the maximum toll during the fall months compared to spring and summer months.

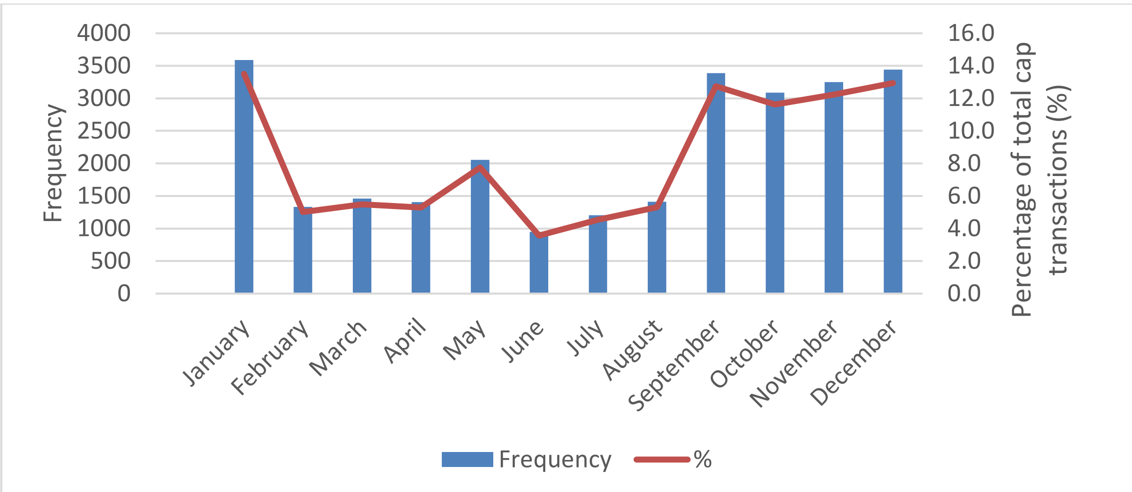

Figure 8 Frequency of toll cap transactions by month of the year

4.4.2. Day of the week

The frequency of occurrence of a toll cap transaction varied by day of the week (see Figure 9). The frequency of toll cap transaction was lowest on Friday and was highest on Tuesday.

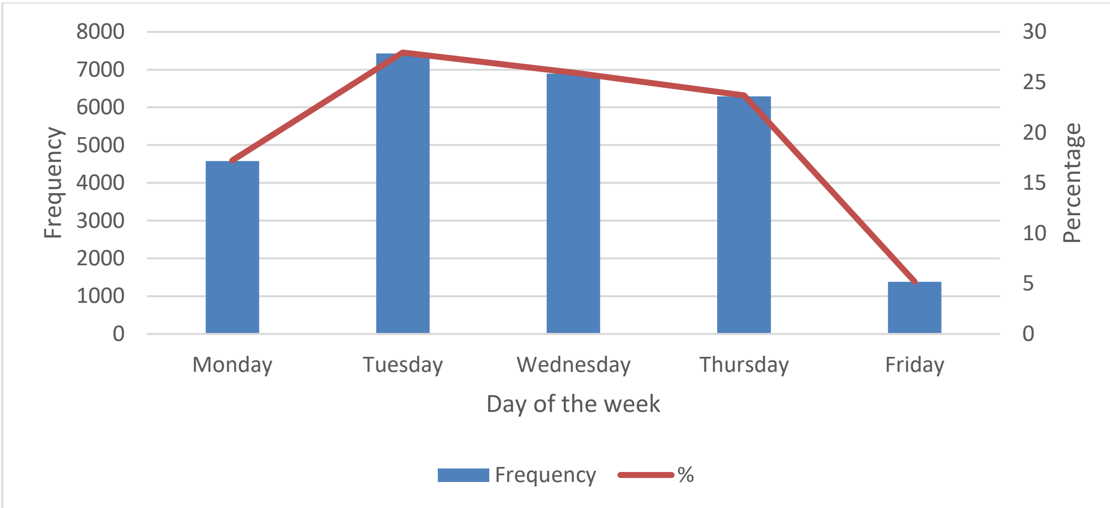

Figure 9 Frequency of occurrence of toll cap transactions by day of the week

4.4.3. Time of the day

The frequency of occurrence of a toll cap transaction also varied by the time of the day(see Figure 10). Approximately 70% of all the toll cap transactions from both locations occurred between 7:30 AM to 8:15 AM. This time has also been the busiest hour of the day as daily commuters use the MnPASS lanes to drive to downtown Minneapolis.

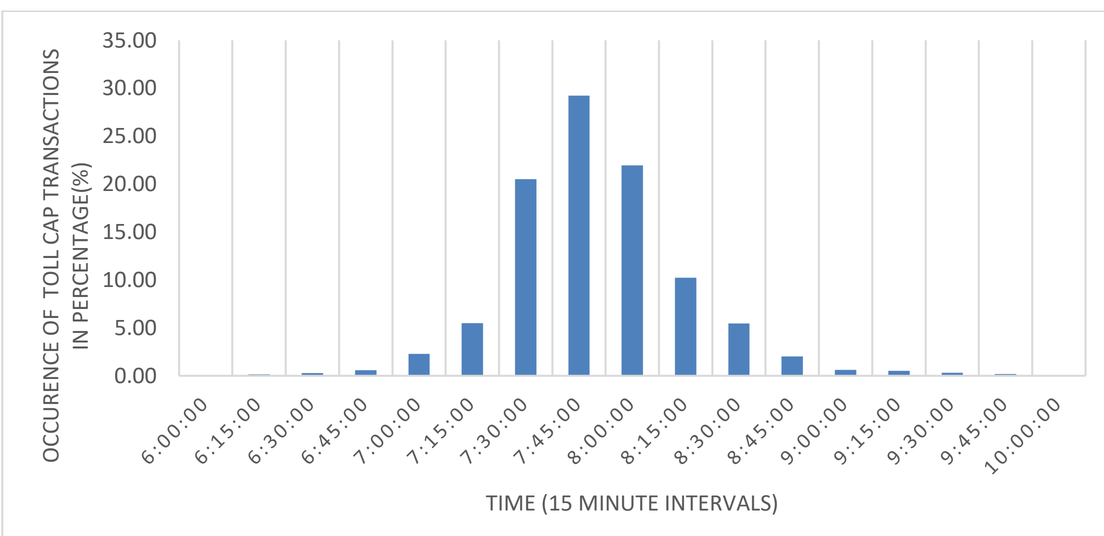

Figure 10 Frequency of occurrence of toll cap by the time of day

4.5. Determining Critical Detectors

As detailed in the literature review, managed lane tolls are set to keep the traffic flowing at free-flow speeds. The tolls must be set to keep the traffic demand below capacity and try to maintain at least LOS C conditions or above on the MnPASS lanes. The tolls were charged based on the worst(maximum) density detected on the MnPASS lanes downstream of a user's entry point. Both short and long tolls were adjusted based on the worst downstream density levels detected on the MnPASS lanes. The short toll for MnPASS trips from Burnsville and Highway 13 tolling locations was based upon the worst downstream density detected on the MnPASS lanes in the zone Z35WN01(See Figure 2 for zone boundaries). The long toll for trips from those two locations was based upon the worst downstream density detected anywhere on the northbound I-35W MnPASS lanes.

There could have be some critical detectors at locations downstream where the traffic density readings might be highest and thus determine the toll rate for most of the time. The purpose of finding those critical locations was to establish and study the relationship between density levels and the toll amount. The relationship will be used to evaluate the pricing plan and analyze the effect of the current pricing strategy on the traffic flow and speed parameters near the critical detector(location).

Each set of transactions was merged with the density levels from a downstream MnPASS detector at a time. Sets of transactions are distinguished by the first detected location and the trip type. There were 4 such sets of transactions, long and short trips which originated at Burnsville and Highway 13 tolling locations.

Ten detectors were chosen such that they were situated throughout the I-35W northbound MnPASS lanes. Table 17 shows the selected MnPASS detectors on the northbound corridor of I-35W MnPASS lanes. The density readings from each sensor was merged with a set of transactions and the average density at each toll price was calculated.

Table 17 Selected detectors along I-35W MnPASS lanes northbound direction

Set No.	Cross Street	MnPASS Detector (#)	chainage (miles)
	Crystal lake /Entrance		0
1	County Road 42	7040	0.4
2	Burnsville Parkway	461	2.3
3	Cliff Road	500	3
4	102nd St.	541	5.8
5	89th St.	579	6.9
6	80th St.	729	8.1
7	66th St.	3938	10.3
8	60th St.	5935	11.8
9	46th St.	5969	13.2
10	35th St.	6794	14.6
	Exit		16

As noted earlier, the traffic density present downstream affected the tolls. Burnsville and highway 13 tolling locations were located just upstream of the MnPASS detectors on County Road 42 (detector # 7040) and Burnsville Parkway(detector #461) respectively. The tolls for trips originated from Burnsville Parkway were not affected by the density readings from the County road 42 MnPASS detector since the detector was present upstream of the tolling location.

Long tolled and short tolled transactions were merged with the traffic density readings from each detector separately based on the datetime column. A row in the merged dataset indicated the traffic density readings at the time when the trip was first detected and when the transaction was initiated at the tolling location.

The average traffic density at each toll price interval was calculated for each combination of transaction dataset(long or short) and all detectors. Also, the default price was calculated based on the average traffic density at each toll price interval, taking the current pricing plan as a reference. If the average traffic density was found proportional to the toll price intervals and the default price was close enough to the toll price intervals, that detector may be one of the critical detectors for the transaction dataset.

A total of 30 combinations were tried to find the critical detectors for both short tolled trips and long tolled trips from Burnsville and Highway 13 tolling locations. As per the pricing plan(See Table 6), the average density for the maximum toll is 50 vpm. Only two detectors situated on the MnPASS lanes had average density readings at $8(highlighted by the red text font) above 50 vpm (See Table 18 and Table 19). These were the detectors near Cliff road(detector 500) and Burnsville parkway(detector 461). This indicated that the density readings from either of the two detectors was responsible for setting up the toll cap transactions most of the time.

A detector is said to be critical if the traffic density at the detctor location often dictated the toll rate. Only two MnPASS detectors were found to satisfy the conditions for being a critical detector. From Table 20 and Table 21 it can be seen that the density levels were found to be proportional at tolls for long tolled and short tolled trips from Burnsville and Highway 13 tolling locations for detectors 461 and 500.

Table 18 Average density at each toll price charged to Burnsville trips

Detector No.	**7040**		**461**		**500**		**541**		**579**		**729**		**3938**	**5935**	**5969**	**6794**
Trip type	**S**	**L**	**S**	**L**	**S**	**L**	**S**	**L**	**S**	**L**	**S**	**L**	**L**	**L**	**L**	**L**
Toll ($)	**Average Density (vpm)**															
0.25	6	9	10	20	13	28	9	20	7	17	5	13	9	12	24	20
0.5	5	5	7	8	10	10	9	9	8	7	6	5	5	5	6	5
0.75	6	6	10	9	14	12	13	10	11	8	9	6	5	5	6	5
1	7	6	13	9	17	12	16	11	14	9	10	7	6	6	7	6
1.25	8	7	15	11	21	14	18	13	15	11	12	9	7	7	9	7

S- Short trip L-Long trip

Table 18 Average density at each toll price charged to Burnsville trips (Continued)

Detector No.	7040		461		500		541		579		729		3938	5935	5969	6794
Trip type	S	L	S	L	S	L	S	L	S	L	S	L	L	L	L	L
Toll ($)	Average Density (vpm)															
1.5	9	7	18	12	26	16	20	15	17	12	13	10	8	8	10	9
1.75	10	8	21	14	29	19	22	17	19	14	14	11	8	9	11	10
2	11	8	24	15	33	21	23	17	20	15	15	11	8	9	13	12
2.25	12	9	26	16	36	23	25	19	22	16	16	12	9	10	14	14
2.5	12	9	28	18	40	25	26	20	23	17	17	13	9	10	15	16
2.75	13	10	30	20	43	27	27	21	24	18	17	13	9	11	17	17
3	12	10	30	20	44	29	27	21	23	18	17	14	10	12	18	19
3.25	14	10	33	21	46	29	28	22	24	19	17	14	10	12	20	21
3.5	13	10	33	21	46	31	26	23	23	20	17	15	11	13	23	23
3.75	12	10	32	21	47	32	27	22	24	20	17	15	10	13	24	25
4	13	10	32	22	45	33	28	24	23	20	17	15	11	14	26	26
4.25	13	10	34	23	52	35	28	23	23	20	17	15	11	14	27	27
4.5	13	10	42	24	51	35	27	24	23	20	17	15	11	16	30	29
4.75	12	10	33	24	52	35	27	24	22	21	16	15	11	16	31	30
5	13	11	39	27	52	37	25	24	22	21	17	16	12	16	32	31
5.25	15	10	43	24	53	36	28	24	22	21	16	16	11	16	34	34
5.5	13	11	48	25	53	39	27	24	23	21	17	16	11	17	36	32
5.75	15	10	48	26	54	36	26	23	22	20	17	15	11	16	39	34
6	18	10	56	23	54	36	26	23	22	21	17	15	11	17	41	34
6.25	16	9	53	24	53	37	26	23	22	20	17	15	12	16	39	34
6.5	20	10	56	25	53	37	28	25	22	21	17	15	11	19	45	36
6.75	19	10	59	28	54	39	25	24	22	21	16	15	11	19	44	36
7	29	10	64	26	53	37	26	24	22	21	16	15	11	19	46	38
7.25	28	10	69	30	55	39	24	24	20	22	16	15	12	21	48	37
7.5	28	10	67	31	53	39	26	23	21	21	16	15	11	22	50	37
7.75	35	11	67	33	53	42	26	24	21	25	16	16	11	21	47	38
8	45	22	80	54	52	50	21	25	18	21	14	16	12	23	48	38

S- Short trip L-Long trip

Table 19 Average density at each toll price charged to Highway 13 trips

Detector No.	461		500		541		579		729		3938	5935	5969	6794
Trip type	S	L	S	L	S	L	S	L	S	L	L	L	L	L
Toll($)	Average Density (vpm)													
0.25	10	17	14	23	10	15	9	14	7	11	8	10	15	17
0.5	7	9	10	10	9	9	8	6	6	5	5	5	6	6
0.75	10	9	14	12	13	10	11	8	8	6	5	5	7	6
1	12	8	17	11	15	10	13	8	10	7	6	6	7	6
1.25	14	10	21	13	17	12	15	10	11	8	7	7	8	7
1.5	18	12	25	16	19	14	17	12	12	9	7	8	10	9
1.75	21	13	29	18	22	16	19	13	14	10	8	8	11	11
2	24	15	32	20	23	17	20	14	15	11	8	9	12	12
2.25	26	16	36	22	25	18	22	15	16	12	9	10	14	14
2.5	28	17	39	24	26	19	23	16	17	12	9	10	16	16
2.75	30	19	42	26	27	20	24	17	17	13	9	11	17	17
3	29	20	43	28	27	21	23	19	17	14	10	12	19	19
3.25	31	20	44	28	28	21	23	18	17	14	10	12	20	21
3.5	33	21	44	30	27	22	23	19	17	14	10	13	23	23
3.75	32	21	47	32	27	22	24	19	17	14	10	14	24	25
4	32	21	44	31	27	23	22	19	16	15	11	14	26	27
4.25	33	23	52	33	27	23	23	20	17	15	11	14	28	28
4.5	38	24	51	34	27	24	23	20	16	15	11	16	30	30
4.75	36	23	52	34	27	23	22	20	17	15	11	16	32	31
5	40	26	51	37	25	24	22	21	16	16	12	16	33	32
5.25	44	24	54	35	28	24	22	21	16	15	11	16	35	33
5.5	50	25	52	39	27	24	23	21	16	15	11	17	37	32
5.75	51	24	54	34	26	23	22	20	17	15	11	16	39	34
6	55	23	55	35	26	23	23	20	17	15	11	18	42	35
6.25	54	24	53	36	26	23	23	20	16	15	12	17	41	34
6.5	58	25	53	36	27	24	22	21	16	15	11	19	46	35
6.75	58	26	54	37	26	24	22	21	16	15	11	18	45	37
7	62	25	54	36	26	23	21	20	16	15	11	17	45	38
7.25	63	27	55	37	24	23	21	22	16	15	11	22	48	38
7.5	65	32	54	38	26	24	21	22	17	15	11	24	52	39
7.75	64	31	55	42	26	25	22	22	16	16	11	21	49	39
8	73	51	55	49	22	25	18	22	14	16	12	24	49	39

S- Short trip L-Long trip

But, the average density as seen in Table 21 at other high tolls($4+) of detector# 461 was comparatively less than as seen for the detector#500 in Table 20 . Also, the default price at each toll price interval was found close to the pricing plan for the average density readings from the detector no. 500 (Table 22 and Table 23) than compared to the detector no. 461. Hence, the MnPASS detector 500 was selected to be a critical detector for long and short tolled trips from both locations.

Before starting the analysis on the merged datasets, few data quality control steps were applied to the dataset. All the extracted readings less than zero were removed. Speed readings greater than or equal to 100 mph, and flow readings greater than or equal to 2400 vph were removed from the traffic dataset. Only 0.24% of tolled transactions from Burnsville tolling location and 0.23% of tolled transactions from Highway 13 tolling location were filtered out from the merged dataset with the MnPASS detector 500.
There is unusual deviation observed in the traffic parameters at the $0.25 toll (See Table 18-23). The reason for that when there was any discrepancy between the toll shown and the toll charged to the user, a trip was charged the minimum toll of $0.25. This is likely the reason why the traffic parameters at a $0.25 toll did not follow the trend shown by the parameters observed at other tolls.

Table 20 Average density readings at the MnPASS detector 500 located near Cliff road on I-35W northbound MnPASS lanes

	Trips from Burnsville TL		**Trips from Highway 13 TL**	
Toll Amount ($)	**Average density at long toll (vpm)**	**Average density at short toll (vpm)**	**Average density at long toll (vpm)**	**Average density at long toll (vpm)**
0.25	28	13	23	14
0.5	10	10	10	10
0.75	12	14	12	14
1	12	17	11	17
1.25	14	21	13	21
1.5	16	26	16	25
1.75	19	29	18	29
2	21	33	20	32

Table 20 Average density readings at the MnPASS detector 500 located near Cliff road on I-35W northbound MnPASS lanes (Continued)

	Trips from Burnsville TL		Trips from Highway 13 TL	
Toll Amount ($)	Average density at long toll (vpm)	Average density at short toll (vpm)	Average density at long toll (vpm)	Average density at long toll (vpm)
2.25	23	36	22	36
2.5	25	40	24	39
2.75	27	43	26	42
3	29	44	28	43
3.25	29	46	28	44
3.5	31	46	30	44
3.75	32	47	32	47
4	33	45	31	44
4.25	35	52	33	52
4.5	35	51	34	51
4.75	35	52	34	52
5	37	52	37	51
5.25	36	53	35	54
5.5	39	53	39	52
5.75	36	54	34	54
6	36	54	35	55
6.25	37	53	36	53
6.5	37	53	36	53
6.75	39	54	37	54
7	37	53	36	54
7.25	39	55	37	55
7.5	39	53	38	54
7.75	42	53	42	55
8	50	52	49	55

Table 21 Average density readings at the MnPASS detector 461 located near Cliff road on I-35W northbound MnPASS lanes.

	Trips from Burnsville TL		Trips from Highway 13 TL	
Toll Amount ($)	**Average density at long toll (vpm)**	**Average density at short toll (vpm)**	**Average density at long toll (vpm)**	**Average density at long toll (vpm)**
0.25	20	10	10	17
0.5	8	7	7	9
0.75	9	10	10	9
1	9	13	12	8
1.25	11	15	14	10
1.5	12	18	18	12
1.75	14	21	21	13
2	15	24	24	15
2.25	16	26	26	16
2.5	18	28	28	17
2.75	20	30	30	19
3	20	30	29	20
3.25	21	33	31	20
3.5	21	33	33	21
3.75	21	32	32	21
4	22	32	32	21
4.25	23	34	33	23
4.5	24	42	38	24
4.75	24	33	36	23
5	27	39	40	26
5.25	24	43	44	24
5.5	25	48	50	25
5.75	26	48	51	24

Table 21 Average density readings at the MnPASS detector 461 located near Cliff road on I-35W northbound MnPASS lanes. (Continued)

	Trips from Burnsville TL		Trips from Highway 13 TL	
Toll Amount ($)	**Average density at long toll (vpm)**	**Average density at short toll (vpm)**	**Average density at long toll (vpm)**	**Average density at long toll (vpm)**
6.25	24	53	54	24
6.5	25	56	58	25
6.75	28	59	58	26
7	26	64	62	25
7.25	30	69	63	27
7.5	31	67	65	32
7.75	33	67	64	31
8	54	80	73	51

Table 22 Density and default price based on trips from Highway 13 tolling location

Toll Amount ($)	Average density at long toll (vpm)	Default price ($)	Average density at short toll (vpm)	Default price ($)
0.25	23	-	14	-
0.5	10	0.25	10	0.25
0.75	12	0.5	14	0.5
1	12	0.5	17	0.5
1.25	13	0.5	21	1.5
1.5	16	0.5	25	1.5
1.75	18	0.5	29	1.5
2	20	1.5	32	3
2.25	22	1.5	36	3
2.5	24	1.5	39	3
2.75	26	1.5	42	3

Table 22 Density and default price based on trips from Highway 13 tolling location (Continued)

Toll Amount ($)	Average density at long toll (vpm)	Default price ($)	Average density at short toll (vpm)	Default price ($)
3	28	1.5	43	5
3.25	28	1.5	44	5
3.5	30	1.5	44	5
3.75	32	3	47	5
4	32	3	44	5
4.25	33	3	52	8
4.5	34	3	51	8
4.75	34	3	52	8
5	37	3	51	8
5.25	35	3	54	8
5.5	39	3	52	8
5.75	34	3	54	8
6	35	3	55	8
6.25	36	3	53	8
6.5	36	3	53	8
6.75	37	3	54	8
7	36	3	54	8
7.25	37	3	55	8
7.5	38	3	54	8
7.75	42	3	55	8
8	49	5	55	8

Table 23 Density and default price based on trips from Burnsville tolling location

Toll Amount ($)	Average density at long toll (vpm)	Default price ($)	Average density at short toll (vpm)	Default price ($)
0.25	13	-	28	-
0.5	10	0.25	10	0.25
0.75	14	0.5	12	0.5
1	17	0.5	12	0.5

Table 23 Density and default price based on trips from Burnsville tolling location (Continued)

Toll Amount ($)	Average density at long toll (vpm)	Default price ($)	Average density at short toll (vpm)	Default price ($)
1.25	21	1.5	14	0.5
1.5	26	1.5	16	0.5
1.75	29	1.5	19	1.5
2	33	3	21	1.5
2.25	36	3	23	1.5
2.5	40	3	25	1.5
2.75	43	5	27	1.5
3	44	5	29	1.5
3.25	46	5	29	1.5
3.5	46	5	31	1.5
3.75	47	5	32	3
4	45	5	33	3
4.25	52	8	35	3
4.5	51	8	35	3
4.75	52	8	35	3
5	52	8	37	3
5.25	53	8	36	3
5.5	53	8	39	3
5.75	54	8	36	3
6	54	8	36	3
6.25	53	8	37	3
6.5	53	8	37	3
6.75	54	8	39	3
7	53	8	37	3
7.25	55	8	39	3
7.5	53	8	39	3
7.75	53	8	42	3
8	52	8	50	8

It was seen that the average density was proportional to tolls. It can be interpreted that the demand (i.e. density) for the MnPASS lanes increased at higher tolls. But this relationship cannot be used to predict the demand for MnPASS lanes at tolls greater than the current toll cap. There could be a limitation on how much a user is willing to pay a toll for using the MnPASS lanes. In the upcoming sections, more analysis has been done to predict the demand at tolls greater than $8 without using the density-toll relationship. In the next section the effect of tolls on flow and speed near the Cliff road (critical location) has been analyzed.

4.6. Average Traffic Parameters on I-35W Northbound Direction near Cliff Road

It can be seen from Figure 11 and Figure 12 that the traffic flow remained at equilibrium close to 1700 vph and average speeds slowly dropped below 45 mph on when the short toll rose from $3 to $7.75. Flow readings near the Cliff road on I-35W MnPASS lanes dropped when the short toll was $8. Similar observations were noted for short toll trips from Burnsville(Figure 12). Due to the toll cap, the toll algorithm was unable to raise the tolls causing the congestion to continue and flow to deteriorate near the critical location.

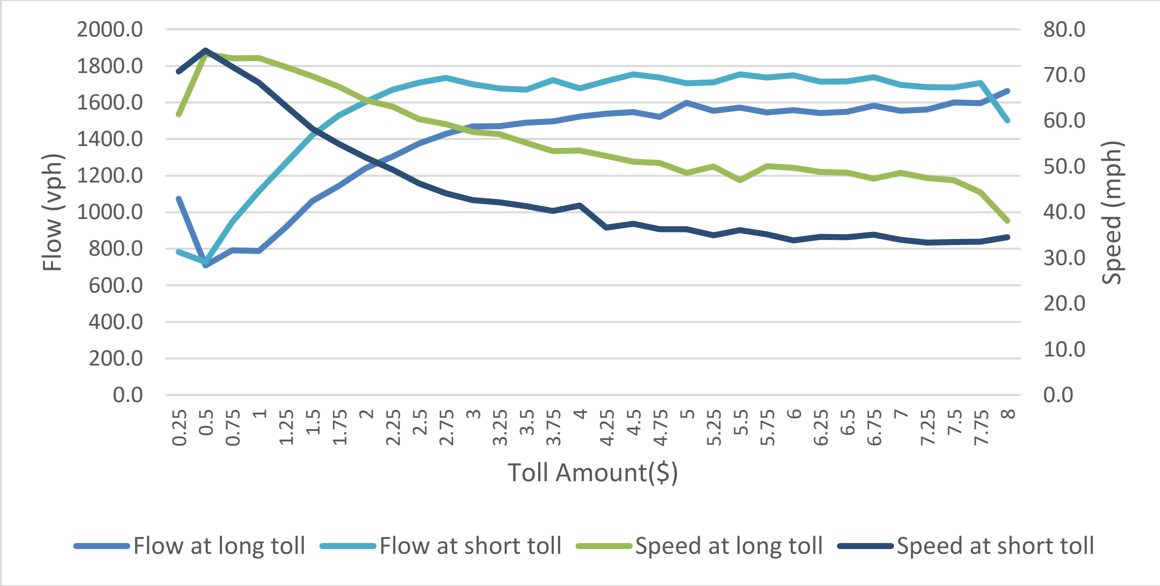

Figure 11 Average flow and speed parameters on I -35W MnPASS lanes near Cliff Road at short and long tolls charged by Highway 13 TL

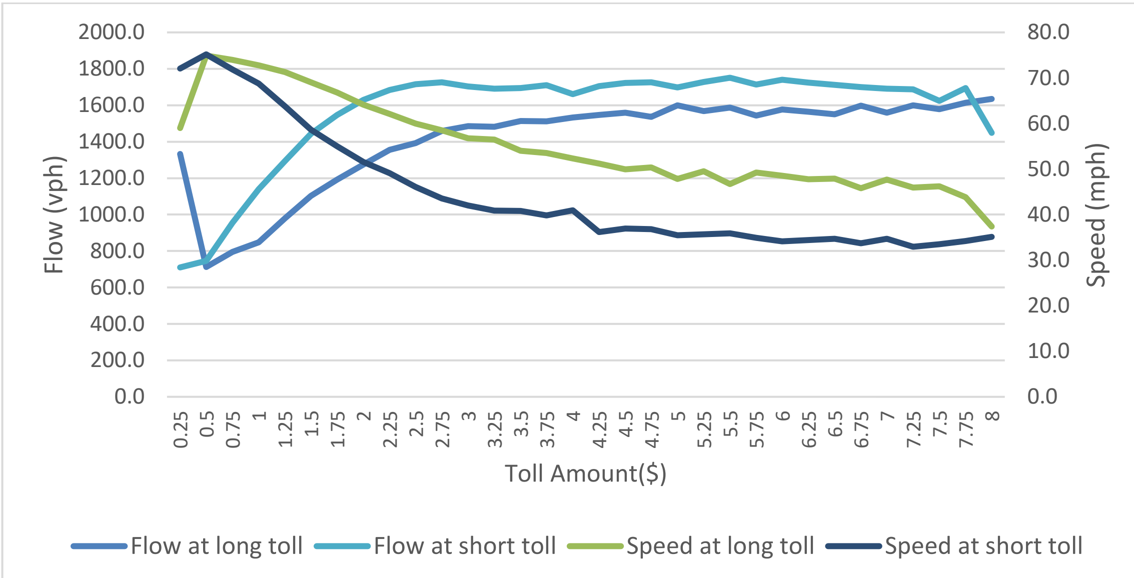

Figure 12 Average flow and speed parameters on I -35W MnPASS lanes near Cliff Road at short and long tolls charged by Burnsville TL

One of the objectives was to see the impact of a toll cap on GP lane speeds as well. Figure 13 shows the speed on I-35W northbound GP lanes near Cliff road. It can be seen that the speeds were below 30 mph at higher tolls($4+). On an average, the traffic conditions on the GP lanes start becoming worse near Cliff road when the short tolls were higher than $1.5. There was no major change in speeds observed at the toll cap compared to speeds at other higher tolls. The speed on the GP lanes near Cliff road averaged approximately 20-25 mph during the toll cap. It was concluded that the speed on MnPASS lanes was still better than the GP lanes at higher tolls and it could be one of the reasons that compelled commuters to choose the MnPASS lanes.

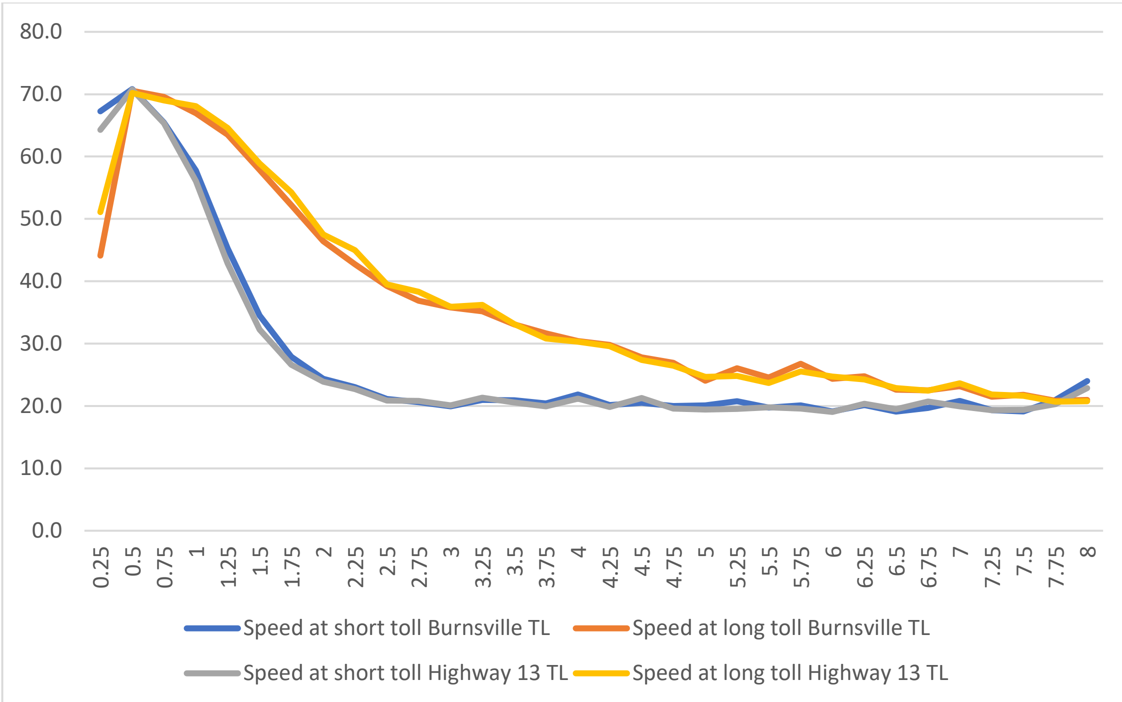

Figure 13 Average speed on I-35W GP lanes near Cliff Road at short and long tolls by both Tolling Locations

4.7. Speed at the Time of Toll Cap Transactions

One of the research objectives was to examine the effect of the toll cap on the traffic speed of MnPASS lanes. Figure 14 and Figure 15 show the speed distribution on I-35W MnPASS lanes near the Cliff road (critical detector) at the time when $8 was charged for short trips from Highway 13 and Burnsville tolling locations. MnPASS speeds were below 50 mph near Cliff road in about 83% of the transactions when the short toll was $8. The critical location was congested whenever the MnPASS trips began from either of these two locations and when the toll was $8.

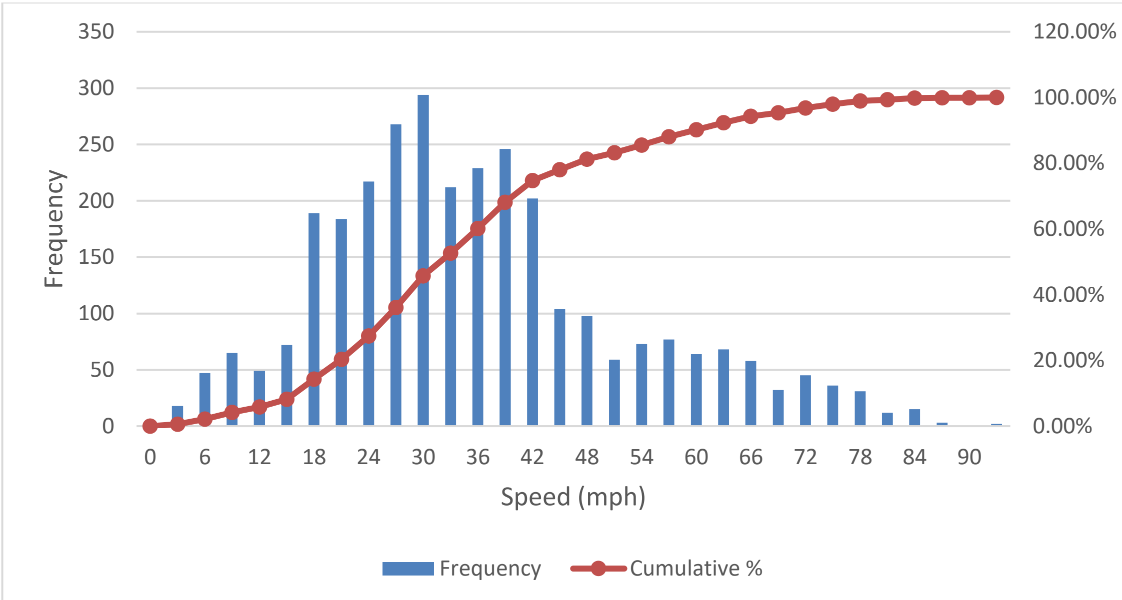

Figure 14 I-35W MnPASS lanes speed distribution near Cliff road short tolls were charged $8 by Highway 13 tolling location

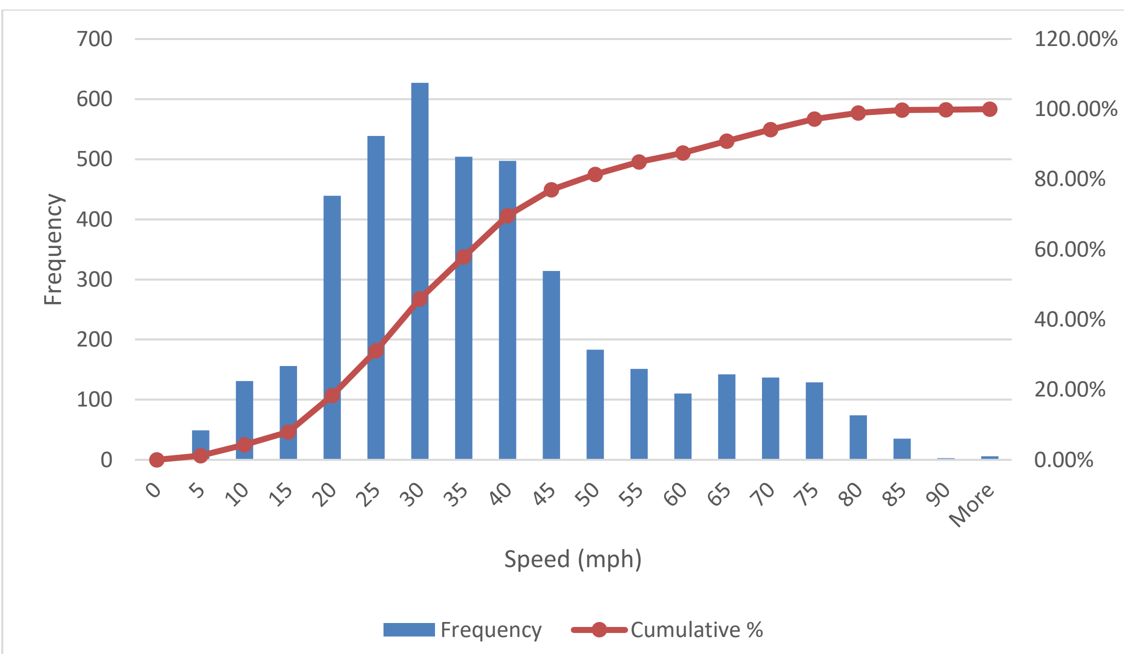

Figure 15 I-35W MnPASS lanes speed distribution near Cliff road when short tolls charged $8 by Burnsville tolling location

Similarly, Figure 16 and Figure 17 show that speed on the MnPASS lanes near Cliff Road remained low when the long toll was $8. The speed at the critical location was below 50 mph for nearly 84% of long tolled transactions. In this section, it was seen that the speed on the MnPASS lanes near Cliff road was most likely to be below 45 mph when the toll was $8 for the MnPASS trips from Burnsville and Highway 13 tolling locations.

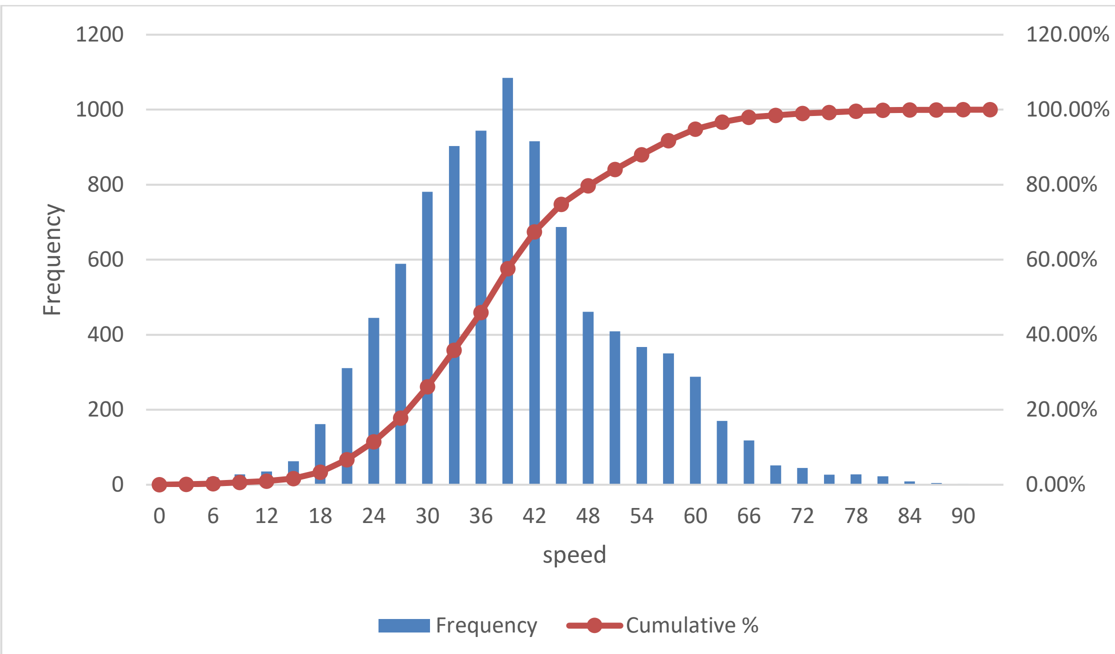

Figure 16 I-35W MnPASS lanes speed distribution near Cliff road when long tolls were charged $8 by Highway 13 tolling location

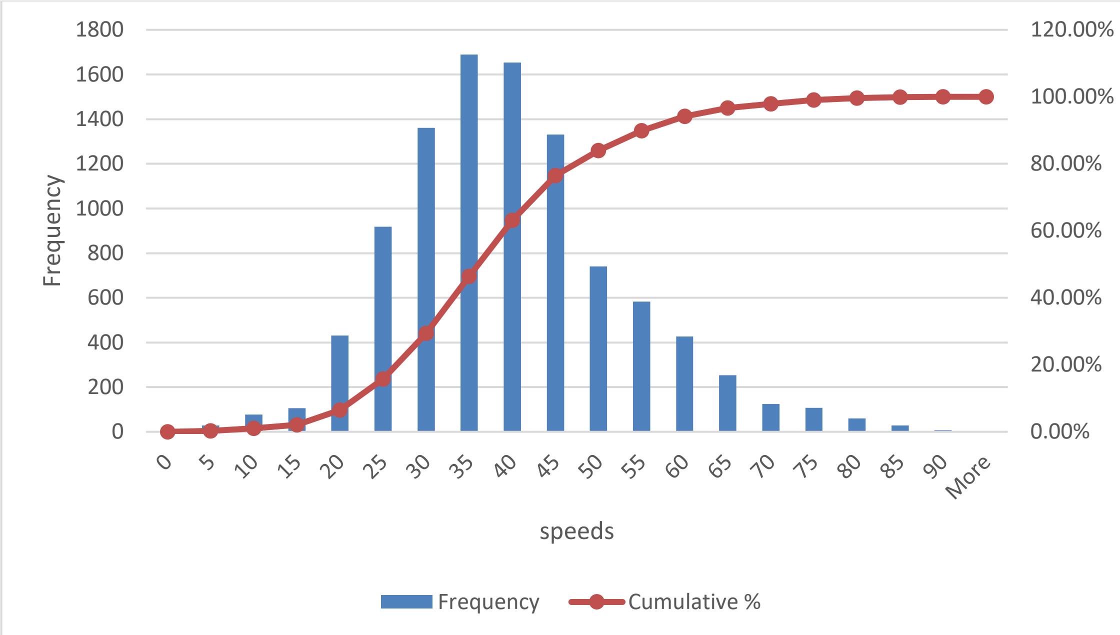

Figure 17 I-35W MnPASS lanes speed distribution near Cliff road when long tolls were charged $8 by Burnsville tolling location

This finding suggested that current toll cap could not prevent the traffic from causing low speeds near Cliff Road on I-35W northbound MnPASS lanes.

4.8. Corridor Speeds During the Toll Cap

Figures 11-17 in the previous section highlight the speed near Cliff road but not the condition of overall northbound MnPASS lanes when the toll was $8. In this section more analysis has been done to explore the corridor speed during the maximum toll. The corridor speed of the MnPASS lane is calculated using various MnPASS detectors present throughout the I-35 northbound direction. Ten MnPASS detectors (Figure 19) were used to calculate the corridor speed.

The entire I-35W northbound corridor was divided into segments where each segment length was equal to half the distance between the adjacent set of detectors. Figure 18 is an example of calculating segment length for detector 461.

Segment length for detector no. 461 = (D1+D2)/2 = (1.9+0.7)/2 = 1.3 mi

Figure 18 Example of a detector set up to calculate the segment length for detector no. 461

The segment length for detectors near the entrance and exit to the MnPASS lanes was calculated differently. The segment length for those detectors was the sum of the length at the end to the MnPASS lanes and half the distance between the adjacent set of detectors.

For example, the segment length for detector 7040 was calculated as 1.65 miles Segment length for detector 7040 = 1.1+(1.1)/2 = 1.65 mi. Table 24 shows the segment length and the selected detectors along I-35W northbound direction. The total length of the I-35W northbound MnPASS lanes was 16 miles.

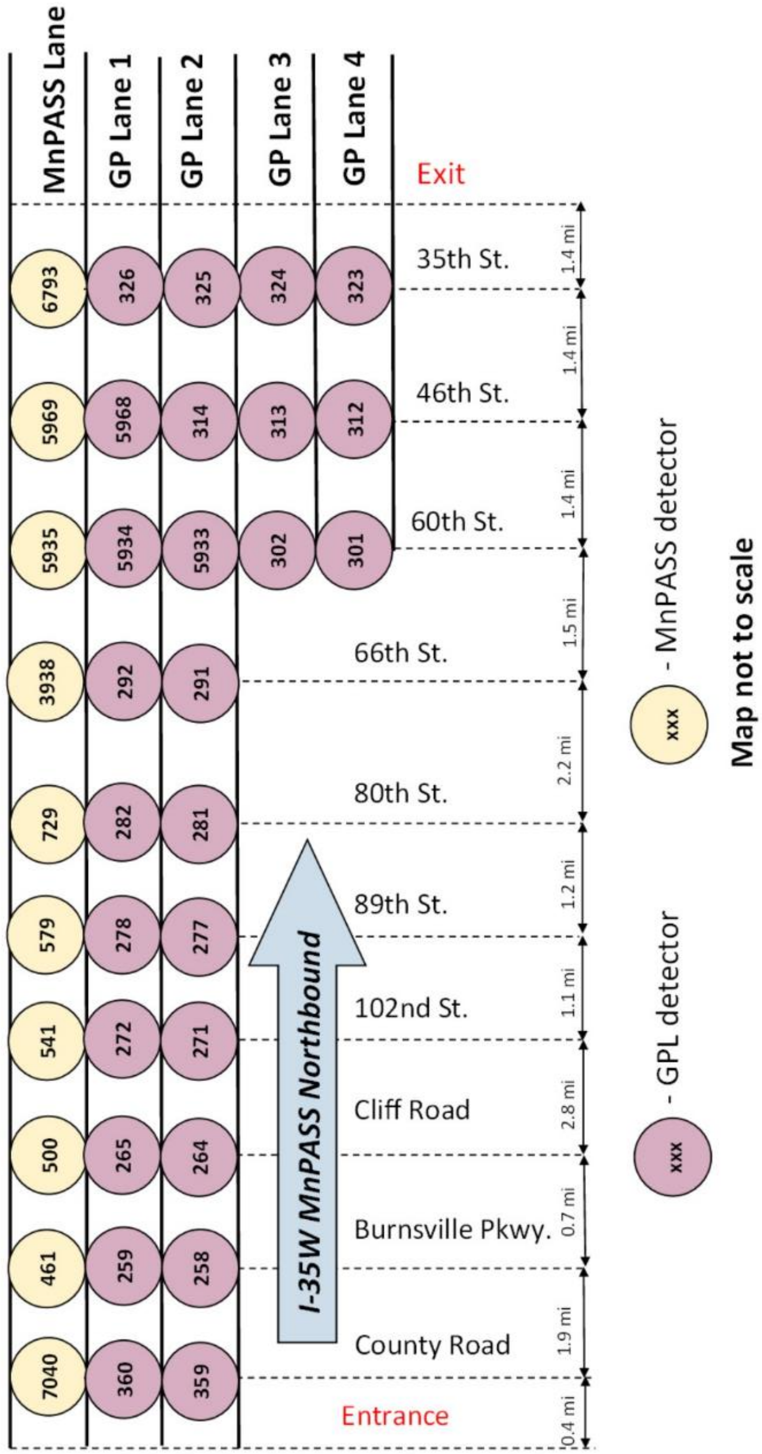

Figure 19 Detectors along MnPASS and GP lanes on I-35W MnPASS lanes

Table 24 Selected detectors and segment length

S No.	Cross Street	MnPASS Detector(#)	chainage (miles)	Distance between the cross streets (mi)	Segment (mi)
	Crystal lake/ Entrance		**0**		**-**
1	County Road 42	7040	0.4	0.4	1.35
2	Burnsville Parkway	461	2.3	1.9	1.3
3	Cliff Road	500	3	0.7	1.75
4	102nd St.	541	5.8	2.8	1.95
5	89th St.	579	6.9	1.1	1.15
6	80th St.	729	8.1	1.2	1.7
7	66th St.	3938	10.3	2.2	1.85
8	60th St.	5935	11.8	1.5	1.45
9	46th St.	5969	13.2	1.4	1.4
10	35th St.	6793	14.6	1.4	2.1
	Exit		16	1.4	-

If there was a missing speed reading in the detector output file, then that reading was replaced by the free flow speed. The free flow speed was taken as 70 mph for the MnPASS lanes and GP lanes. Speed readings during the night(12 AM-3 AM) were extracted from the detectors over a complete one-month period of August 2016. The average speed was approximately 70 mph and was taken as the free flow speed on MnPASS lanes as well as GP lanes.

The corridor speed on the MnPASS lane was calculated using speeds collected from all the 10 selected MnPASS detectors. Speeds were weighted based on the flow and the segment length to incorporate the effect of traffic conditions at that time. The corridor speed was used to observe the speed throughout the corridor with respect to tolls especially at the time of toll cap. The average speed dataset was merged with the toll dataset based on the datetime column. Now the attributes of the merged dataset were: Time of transaction (rounded off to nearest minute), toll amount and average trip speeds on the MnPASS lane.

From Figure 20, it was seen that the corridor speed on the MnPASS lanes decreased as the tolls increased. Average corridor speeds during short tolls were lower than the average corridor speeds during long tolls.

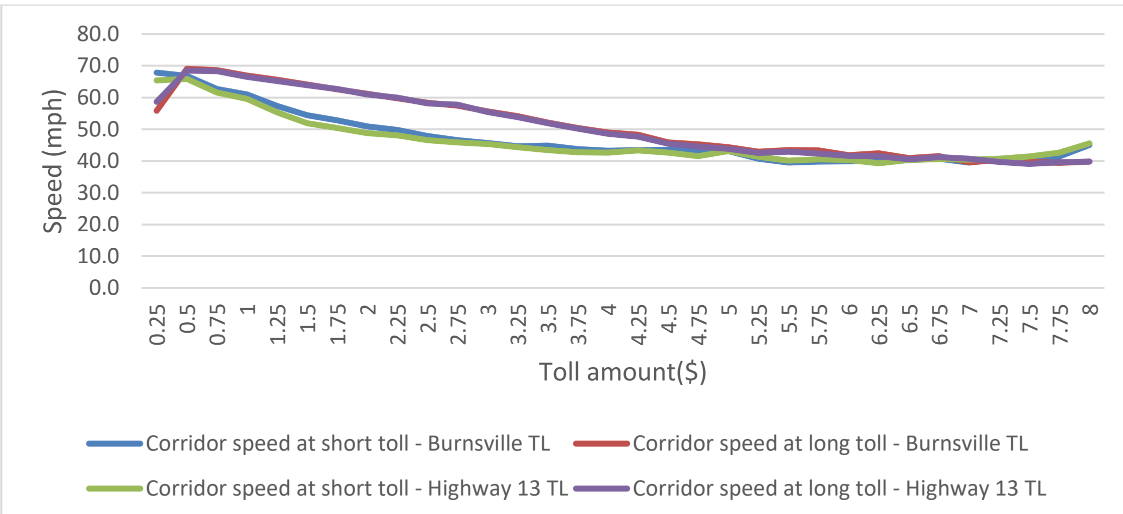

Figure 20 Average corridor speed on the MnPASS lanes at toll price intervals

Figures 21-24 display the MnPASS corridor speed distribution curves during the time of toll cap. Almost 25% of short MnPASS trips which began from highway 13 (Figure 21) and 36% of short trips which began from Burnsville (Figure 22) had corridor (average speed) below 45 mph during the toll cap period. Whereas 22% of long trips beginning from highway 13(Figure 24) and 26% of long trips from Burnsville(Figure 23) had corridor (average speed) below 45 mph during the toll cap period. It can be seen that the average speed remained below 45 mph for a higher percentage of trips when the short toll was the maximum toll. This indicates that whenever the toll for short trips which began near Burnsville and Highway 13 tolling locations was $8, the MnPASS trips were likely to experience trip speeds less than 45 mph. From figures 21-24, it can be seen that around 65-70% of MnPASS trips which were charged the maximum toll had an average speed below 50 mph. Thus the MnPASS lanes were unable to maintain at least LOS C conditions when the toll was $8.

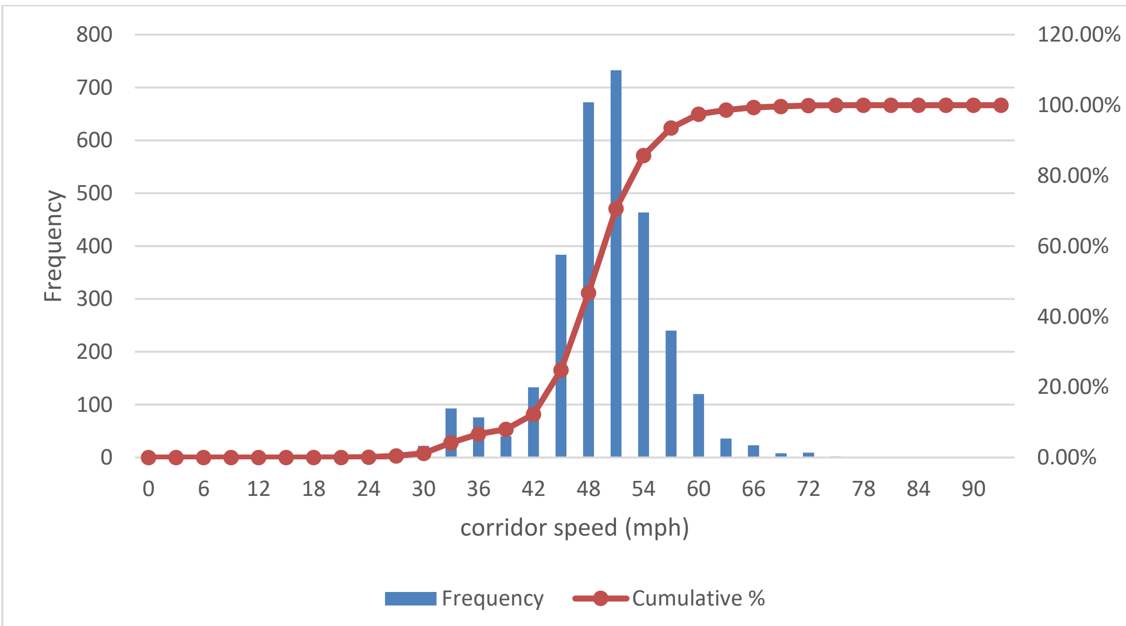

Figure 21 Corridor speed distribution of I-35W MnPASS when short tolls were charged $8 by Highway 13 tolling location

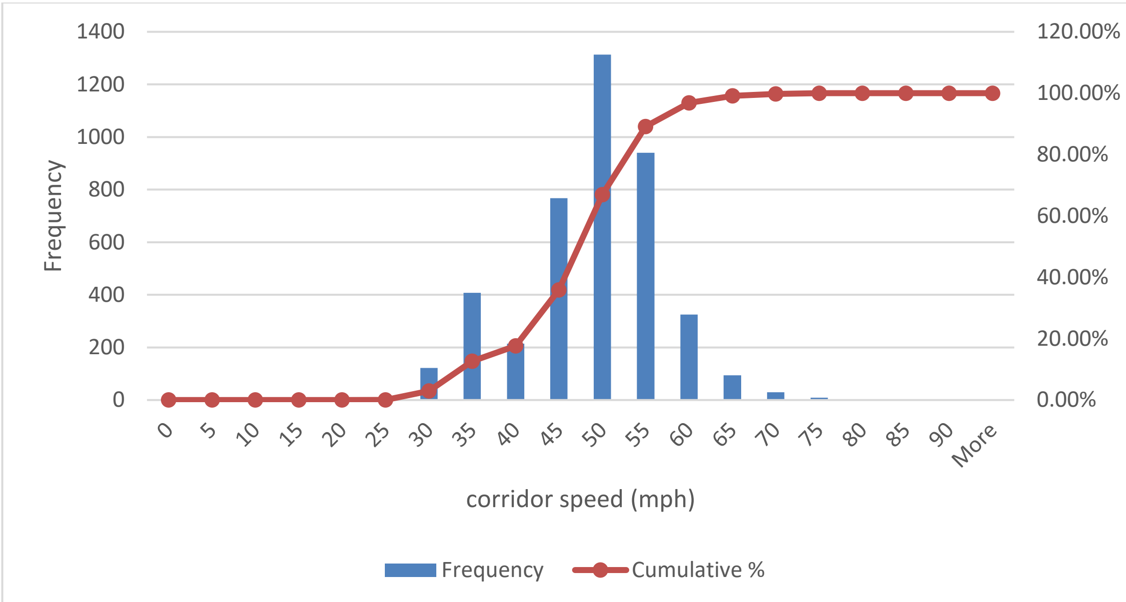

Figure 22 Corridor speed distribution of I-35W MnPASS when short tolls were charged $8 by Highway 13 tolling location

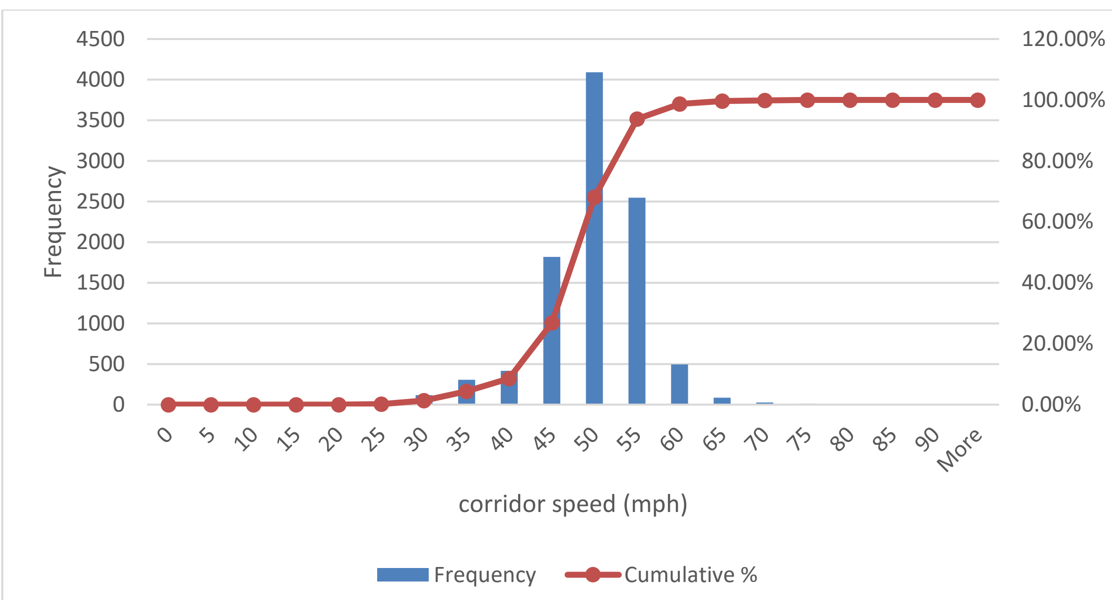

Figure 23 Corridor speed distribution of I-35W MnPASS when long tolls were charged $8 by Highway 13 tolling location

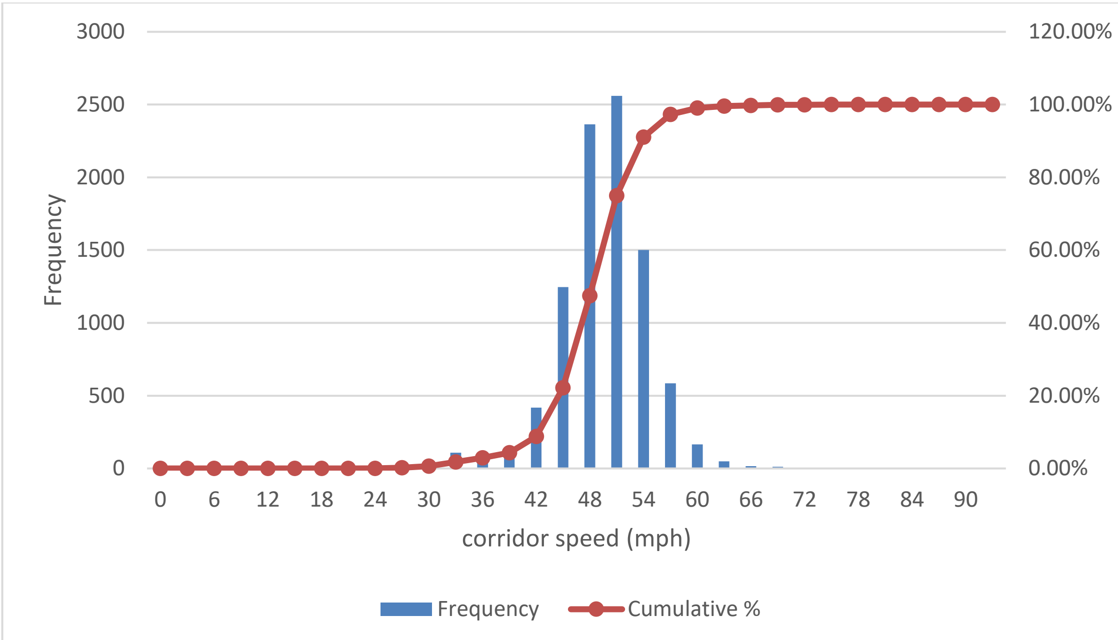

Figure 24 Corridor speed distribution of I-35W MnPASS when long tolls were charged $8 by Burnsville tolling location

Figure 25 shows the GP lane speeds at various toll prices. It can be seen that the corridor speeds continued to decrease at higher short tolls. But the average corridor of the GP lanes was close to 40 mph at tolls greater than $5 and no considerable difference in speeds was observed at the maximum toll.

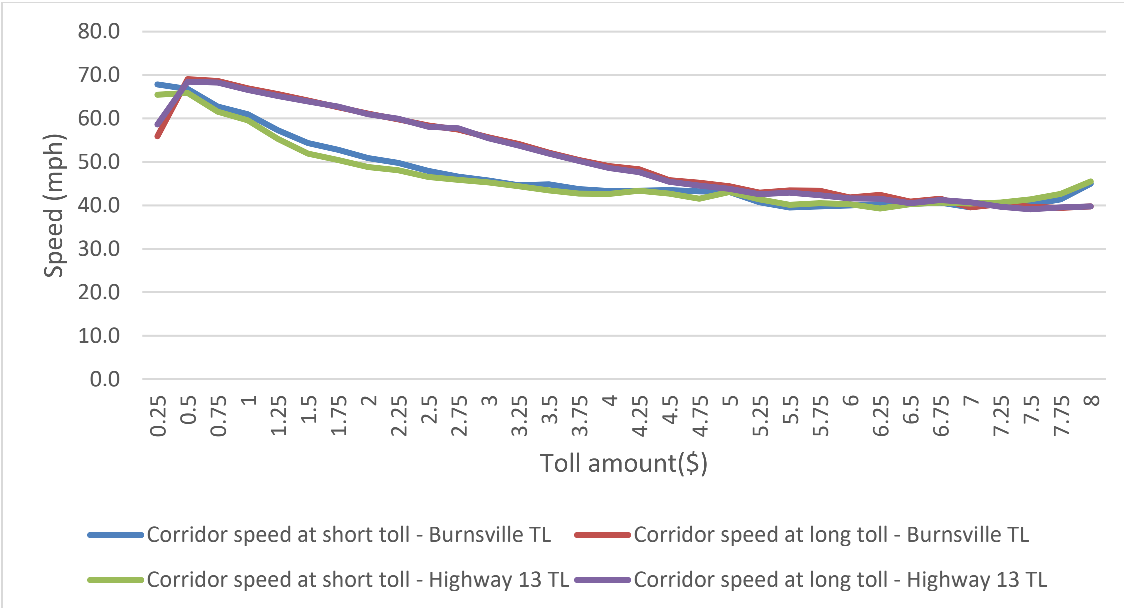

Figure 25 Average corridor speeds on the GP lanes at toll price intervals

Despite low speeds, users continued to use the MnPASS lanes during the toll cap period. The next section will examine the travel time savings offered to MnPASS users and if this could be reason why users opted to use the MnPASS lanes during toll cap.

4.9. Travel Time Savings

For each trip on the MnPASS lane, an alternate GPL trip was needed to calculate the TTS for each MnPASS trip. This procedure assumed that the alternate trip would start at the same time on the GPL. Trip length and average speed were two basic requirements for calculating the travel time in each lane. Since there was no information available about the trip except the time of the toll transaction, some assumptions were needed to calculate trip length and average speed on MnPASS and GP lanes.

First, the trip length was estimated using the first and last tolling locations. Since transactions corresponding to only two locations have been taken for analysis, there were only two possible options for a transaction to have the first tolling location- Burnsville and Highway 13. Basically, the distance between the first and last tolling locations was taken as trip length. However, some trips had the same first and last tolling locations. If the first tolling location was Burnsville, then the trip was assumed to start from the entrance and end just before the first exit from the I-35W lanes. Whereas if the first tolling location was Highway 13, then the trip was assumed to start near the first entrance after the Burnsville tolling location and end near the first exit after the highway 13 tolling location. Additionally, if the last tolling location was present at the beginning of the restricted access (See Figure 2 for MnPASS restricted access), the MnPASS trip was assumed to end with restricted access. There were four tolling locations in the I-35W northbound direction which were located just at the entrance of the restricted access. If the trip was last detected at those locations, the trip was assumed to continue along with the restricted access and end as soon as the open access began. The trip length for the alternate trip was the same as the MnPASS trip. Table 25 details the calculated trip length between each pair of tolling locations.

Table 25 Trip length associated with each set of tolling locations

			Trip Length (miles)	
Tolling Location No.	**Name**	**Chainage (miles)**	**Burnsville Pkwy TL**	**Highway 13 TL**
	Entrance	0	-	-
TL1	Burnsville Pkwy	0.4	1.4	-
TL2	Highway13	2.3	2.3	1.9
TL3	Cliff Road	3	3	3
TL4	98th St.	5.8	5.8	5.8
TL5	90th St.	6.9	6.9	6.9
TL6	82nd St.	8.1	8.8	8.8
TL7	66th St.	10.3	11.1	11.1
TL8	60th St.	11.8	11.8	11.8
TL9	46th St.	13.2	13.2	13.2
TL10	38th St.	14.6	16	16
	Exit	16	-	-

Average speeds of MnPASS trips and its alternate GPL trips were needed to calculate the travel time on the MnPASS lane and GP lanes respectively. As per equation 7, the difference between the travel time taken by the alternate trip and the MnPASS trip was the travel time savings for the MnPASS user.

Travel Time Savings (TTS) = GPL Travel time – MnPASS lane Travel time (7)

The travel time for the MnPASS trip was calculated using the corridor speed calculated in the section 4.8. Similarly, the travel time for the alternate trip on the GP lane was calculated from the corridor speed on the GP lanes in a similar way. Ten sets of GP lane detectors(Table 26) placed parallel to the MnPASS detectors were selected for calculating the corridor speed at a one minute interval. An additional condition for calculating the speed on GP lanes was to take the average speed of all the GP lanes. A representative speed of the GP lanes was calculated using the flow-based weighted average of all the GP lanes.

Table 26 Selected GPL detectors along I-35W northbound direction

Set No.	Cross Street	GPL Lane 1 Detector (#)	GPL Lane 2 Detector (#)	GPL Lane 3 Detector (#)	GPL Lane 4 Detector (#)	Segment (mi)
	Crystal lake/ Entrance					-
1	County Road 42	360	359	-	-	1.35
2	Burnsville Parkway	259	258	-	-	1.3
3	Cliff Road	265	264	-	-	1.75
4	102nd St.	272	271	-	-	1.95

Table 26 Selected GPL detectors along I-35W northbound direction (Continued)

Set No.	Cross Street	GPL Lane 1 Detector (#)	GPL Lane 2 Detector (#)	GPL Lane 3 Detector (#)	GPL Lane 4 Detector (#)	Segment (mi)
	Crystal lake/ Entrance					-
5	89th St.	278	277	-	-	1.15
6	80th St.	282	281	-	-	1.7
7	66th St.	292	291	-	-	1.85
8	60th St.	5934	5933	302	301	1.45
9	46th St.	5968	314	313	312	1.4
10	35th St.	326	325	324	323	2.1
	Exit					-

In Figure 26, the average TTS is calculated at each toll amount. It can be seen that the average TTS at the maximum toll was 3.53 minutes. In Figure 27, the TTS offered to the long toll-paying users increased with tolls whereas the short toll-paying users were offered a modest TTS. An interesting observation was that the TTS of long toll-paying users decreased at the maximum toll. Due to increased congestion, the average MnPASS lane speed decreased during the toll cap which led to less travel time savings for these users.

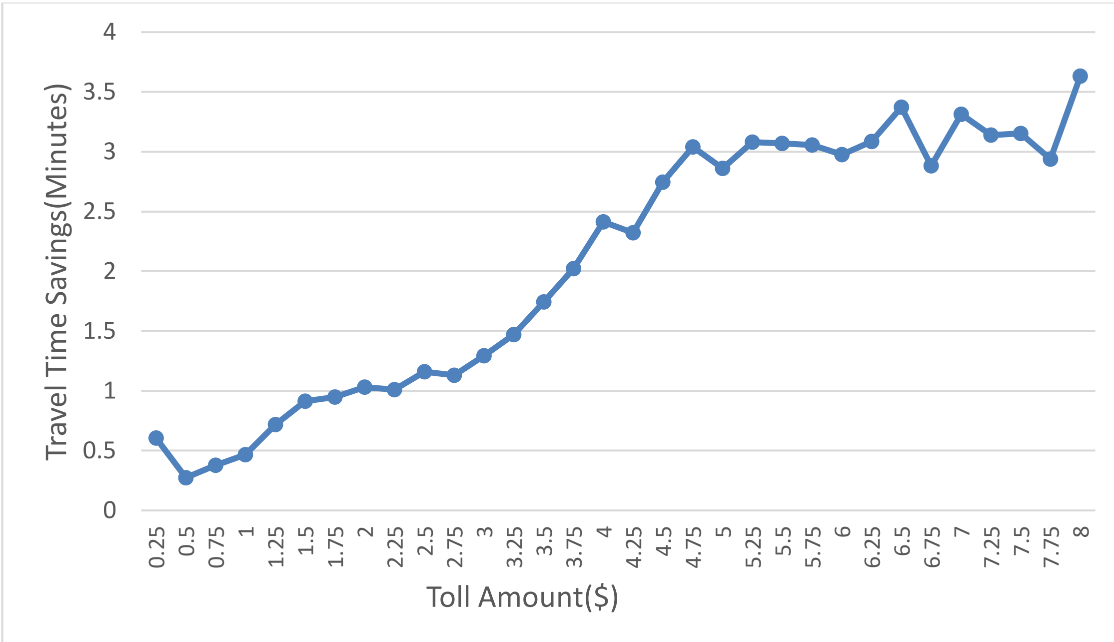

Figure 26 Average travel time savings at each toll amount($)

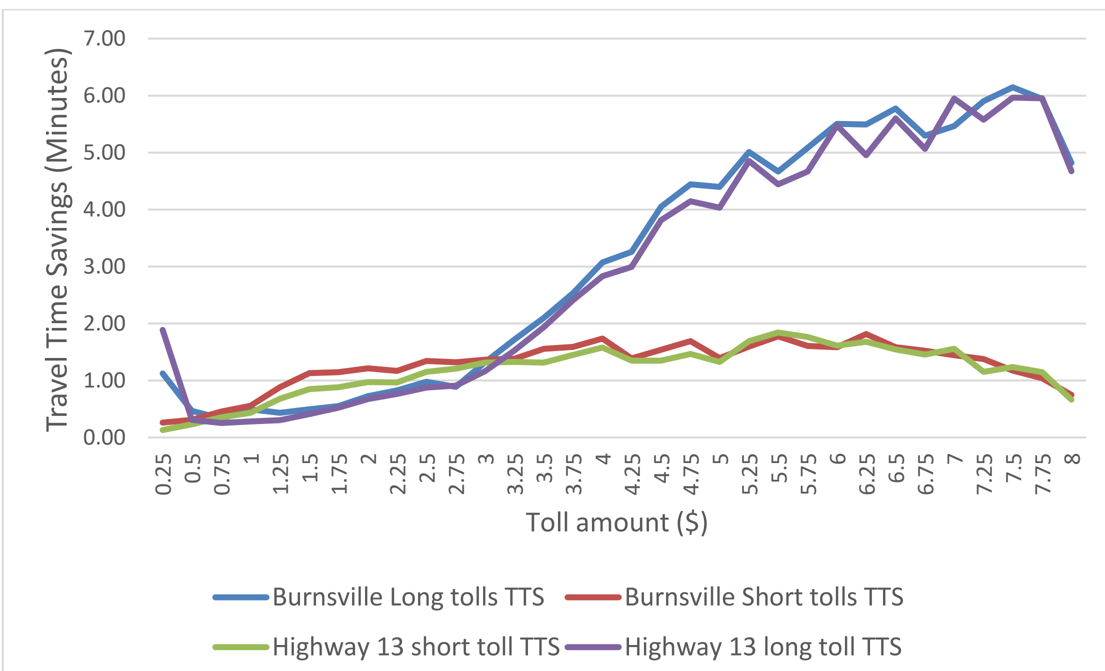

Figure 27 Travel time savings at each toll price interval by trip type and location

Next section will explore the value placed by MnPASS customers on their TTS. The value put on the travel time will be used to estimate the willingness to pay of MnPASS users for tolls greater than $8.

4.10. Value of Travel Time Savings

The value a MnPASS customer placed on their travel time savings was examined. As noted in the literature review the value of travel time(VOT) is the amount that a traveler is willing to pay for travel time savings. Since negative values are not logical, only those trips which had a positive TTS were included.

$$\boldsymbol{VOT}\left(\frac{\$}{\boldsymbol{hr}}\right) = \frac{\boldsymbol{Toll}\ (\$) * \boldsymbol{60}}{\boldsymbol{TTS}\ (\boldsymbol{Minutes})} \qquad (\mathbf{8})$$

An interesting finding was that around 15% of toll-paying users had VOT greater than $400 per hour. Those users were offered very small travel time savings. Practically, these users prefer MnPASS lanes over GP lanes for reasons other than travel time savings. These VOT values were excessively large and not used in estimating the true value of travel time savings. As per the distribution (Figure 28), the median value of TTS placed by the MnPASS users who paid for northbound trips was $88 per hour. The average travel time savings was 1.27 minutes. It can be seen that the toll paying users were willing to pay a higher toll for less travel time savings.

As seen earlier, the demand for MnPASS lanes increased at higher tolls. However, this finding cannot be used to predict MnPASS demand at higher tolls using the positive relationship between density and tolls. Users have a limit to pay the maximum toll worth their travel time savings. Figure 28 will be used to find the percentage of users who were willing to pay a higher toll based on their value of travel time savings. The VOT was found to be very high but this study used the change in frequency distribution at different VOT for the purpose of prediction of flow at tolls over $8. The distribution suggests that users have a limitation to pay the maximum toll for their travel time savings. The number of users who were willing to pay for their travel time savings decreases with an increase in toll. Based on this finding, this research tried to predict the number of users who were willing to pay a toll higher than the toll cap.

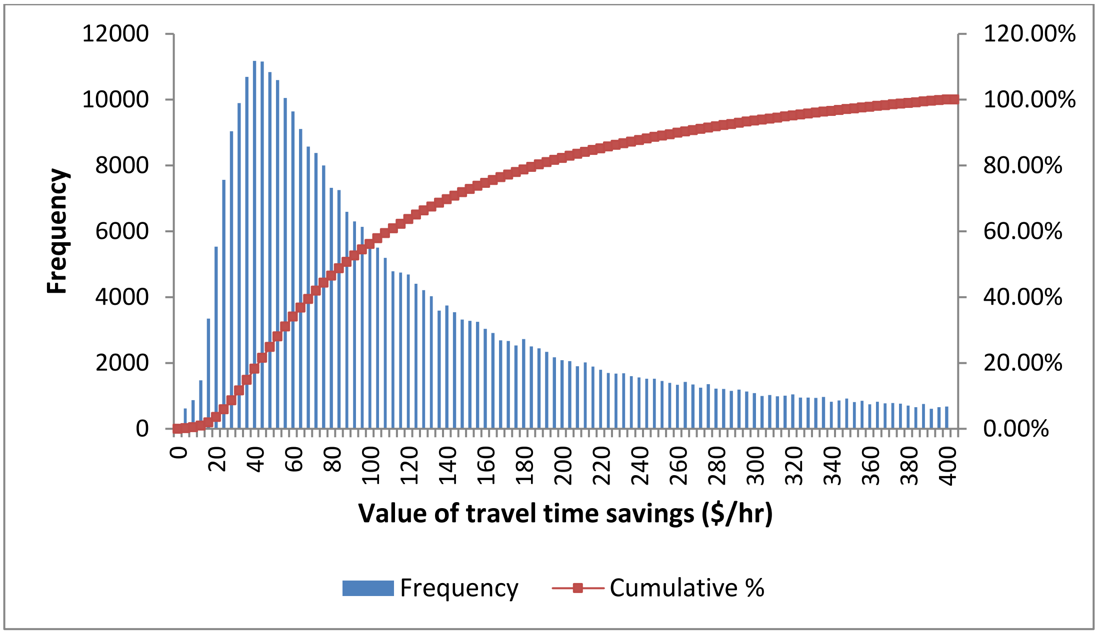

Figure 28 Willingness to pay for toll paying users

In the next section, speed-density-flow relationships were developed using regression models. These relationships explained their interdependency, which was used for predicting a missing traffic parameter. It was then possible to predict traffic parameters at tolls higher than $8 using the polynomial regression models. The predicted traffic parameters were examined to see if the LOS conditions improved at higher tolls.

4.11. Speed Density Flow Relationships

In this section, the relationship between traffic parameters was modeled and compared to ideal relationships discussed in the literature review. Three fundamental traffic parameters- Speed, Density, and Flow were used to model the relationships.

As shown in Figure 29 and Figure 30, scatterplots were used to relate speed, density, and flow parameters extracted from the detector 500 on the MnPASS lane (near Cliff road). Scatterplot curves were fitted with the line of best fit using the polynomial regression technique and the order of the polynomial regression was decided based on R-Squared and RMSE statistical tests.

A first-order polynomial was checked if it fits the speed and density relationship. It successfully fits the speed-density curve as shown in Figure 29. The accuracy scores (see Table 27) suggested that the first order suitably fits for predicting speeds on the MnPASS lanes. There was not much difference seen with RMSE and squared R accuracy scores. Second-order and third-order polynomial equations seemed to overfit the models. Therefore, the first-order polynomial regression was selected for the prediction of speeds given the density parameter.

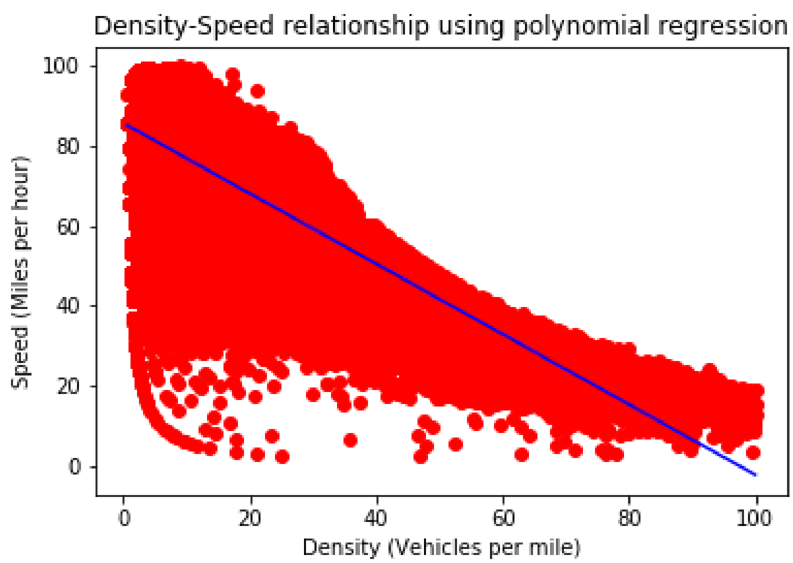

Figure 29 First-order polynomial regression between speed and density

The coefficients of the polynomial which described the first-order expression were as follows:

$$\beta_0 = 0, \beta_1 = -0.88, \qquad c = 85.806$$

The coefficients were put in the general form (Equation 3) to get a specific equation for finding the speed given a density reading.

$$Speed\ (mph) = -0.88 * (Density) + 85.806 \tag{9}$$

A negative slope indicated that speed is inversely proportional to the density. This observation was similar as seen in the ideal relationships discussed in the literature review.

Table 27 Accuracy scores for polynomial regression between Speed and Density

	Order = 1	Order = 2	Order =3
R Squared	0.587	0.589	0.614
Root Mean Square Error	7.47	7.45	7.22

Another regression model was estimated between flow and density parameters using the polynomial regression technique. In this case, the second-order polynomial fits the curve better than the first-order polynomial.

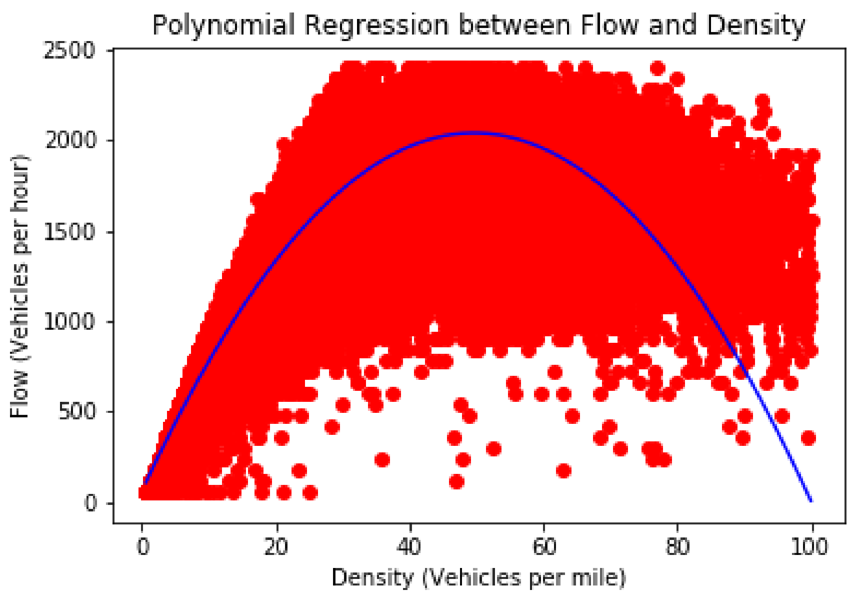

Figure 30 Second-order polynomial regression between flow and density

There was a significant difference between the squared R score of the first order and second-order polynomial equations(Table 28). Also, the RMSE decreased significantly when the order was changed from the first order to the second-order polynomial. A lower RMSE score meant that the predicted flows were closer to the observed flows. Hence, the second-order polynomial was found to be better in predicting the flow on the MnPASS lanes given the density parameter.

Table 28 Accuracy scores for polynomial regression between Flow and Density

	Order = 1	**Order = 2**	**Order =3**
R Squared	0.668	0.91	0.93
Root Mean Square	240.04	122.08	107.42

The coefficients of the polynomial describing the second-order expression were put in the general form of the polynomial equation(Equation 3) to get a specific equation for relating flow and density parameters. The second-order equation was used to predict flow given the density parameter.

$$\boldsymbol{\beta_0 = 0, \beta_1 = 79.99, \quad \beta_2 = -0.805, \quad c = 54.408}$$

$$\textbf{Flow in vph} = \mathbf{79.99 * Density - 0.805 * (Density)^2 + 54.408} \quad (\mathbf{10})$$

$$\textbf{Maximum flow} = \mathbf{2042\ vph} \quad (\mathbf{11})$$

It can be seen from the line of best fit drawn in Figure 30 that the flow peaked around 2000 vph at density levels near 40 vpm. Hence, the tolls should be adjusted in order to keep the flow between 1500 to 2000 vph and maintain at least 45 mph speed on MnPASS lanes during the peak demand.

One of the objectives of this research is to estimate a toll that would maintain high throughput for most of the time and at least LOS C condition on the MnPASS lanes. The tolls should be raised to achieve maximum flow if needed. In the next section, the research explored the potential speed and flow parameters on the MnPASS lanes at tolls greater than $8.

4.12. Prediction of Traffic Parameters at Higher Tolls

From Figure 26, it can be seen that users did get an average of 3-4 minutes of travel time savings at high toll levels. Some travelers might have viewed the high toll as a sign of higher travel time savings and increased their use of MnPASS lanes. Speeds on the MnPASS lanes frequently dropped below 45 mph during the toll cap period. One of the objectives of this research was to examine possible changes in pricing to maintain the recommended LOS on the MnPASS lanes. In this section, traffic parameters were predicted at tolls greater than $8.

In Figure 11 and Figure 12, it can be seen that the maximum equilibrium flow at $6 toll reached more than 1700 vph. This will serve as the starting point to adjust the tolls to maintain the maximum throughput and keep it near 1700 vph for a longer time. Although the equilibrium flow near Cliff road was higher when the short toll was $6 compared to the case when the long toll was $6. This methodology aims to set the tolls such that the flow remains around 1700 for a longer time. The tolls were raised by $0.5 and flow was predicted at the raised price. Speed was predicted using the models developed in the previous section.

Travelers who paid a $6 toll got an average TTS of 3 minutes. These travelers valued their travel time least $121.2 per hour which was calculated based on the toll and TTS. The calculated VOT is clearly higher than the median VOT. But the methodology works because it incorporates a change in VOT rather than using absolute value of time. When the toll was increased to $6.5, those travelers who valued their TTS atleast $131.3 per hour were assumed to continue using the MnPASS lanes and who had their VOT below it were assumed to stop using the MnPASS lanes at the increased price. This assumption caused the number of toll-paying travelers to decrease and the percent decrease was obtained from the value of travel time distribution (Figure 28). The increase in cumulative percentage when the VOT increased from $121.2 per hour to $131.3 per hour was taken as the percentage users who would stop using the MnPASS lanes at the higher toll. The following example explains the process.

Initial (Step 0) – As seen in Figure 11 and Figure 26 the average flow and TTS at $6 is 1748 vph and 3 minutes respectively. The percentage share of SOV trips of the total flow at $6 was approximately 79.7%. The share of HOV vehicles is assumed to remain constant at higher tolls. In this methodology, the percentage decrease due to the increased toll is applied to the share of SOV vehicles only. After deduction of SOV vehicles, an updated flow value is predicted at the increased toll.

Another traffic parameter, speed was also predicted at the increased toll. The prediction of speed parameter used two already developed equations 9 and 10. First, traffic density was found out using flow-density relationship (See equation 10). Then, the density parameter was put in the equation 9 to get the speed on the MnPASS lanes. A stepwise methodology to predict speed and flow on the MnPASS lanes at tolls greater than $8 has been discussed in the following paragraphs.

Step No. 1 – The toll is increased by $0.5, and the VOT increased with same TTS. As per equation 8, the calculated VOT was $131.3 per hour at $6.5 toll and 3 minutes of TTS. It is initially assumed that the users enjoyed the same TTS at the increased toll. From the cumulative distribution (See Figure 28), around 36% of MnPASS users value their TTS at least $120 per hour, and 33% of users value their TTS at least $130 per hour. More precise percentages for a specific VOT were calculated using linear extrapolation. The users who valued their TTS at least $120 per hour but less than $130 per hour were assumed to stop using the MnPASS lanes at the increased price. These users who were not willing to pay $6.5 to save 3 minutes led to a decrease in flow of SOV in the MnPASS lanes. Approximately 2.5% of MnPASS customers were assumed to switch to GPLs when the toll was increased to a $6.5 toll.

Step No. 2 – The updated MnPASS lane flow at the increased toll price was obtained by reducing the flow of SOV vehicles by 2.2%. The reduction in SOVs resulted in higher speed and an increase in TTS for the travelers who were paying for the increased toll and using the MnPASS lanes. The increased speed resulted in increased TTS, which is denoted as induced TTS. Due to the increased TTS at the same price, it led to the return of some MnPASS customers who valued their TTS worth the $6.5 toll. The above three steps were repeated until equilibrium was found at that toll price. Then the tolls were repeatedly increased by $0.5 until the flow on the MnPASS lanes near the Cliff road dropped below 1500 vph.

Table 29 Stepwise explanation of proposed method

Step	Toll Amount ($)	Flow (vph)	Decrease in flow of SOV(%)	%SOV in total flow	Flow of HOV vehicles (vph)	Flow of SOV vehicles (vph)	Density (vpm)	Speed (mph)	TTS (Mins.)	Induced TTS (Mins.)	VOT ($/hr)
0	6	1748		79.7	356	1392	30.6	58.9	3		121.2
1	6.5		2.5						3		131.3
2	6.5	1713		79.2	356	1357	29.5	59.8	3.2	0.3	120.6
1	7		2.2						3.2		129.9

As seen in Table 30, it was possible to raise tolls up to $12.5 and still maintain the flow close to 1500 vph. The percentage share of SOV vehicles in the flow decreased at higher tolls as the methodology assumed reduction in SOV users who would not be willing to pay a higher toll worth their travel time savings. The number of HOV vehicles in the total flow was kept constant. Since, the total flow decreased at higher tolls, the percentage share of SOV in the total flow decreased as well.

Table 30 Prediction of parameters based on the proposed methodology

Toll Amount ($)	Flow (vph)	Decrease in flow of SOV(%)	%SOV of total flow	Flow of HOV vehicles (vph)	Flow of SOV vehicles (vph)	Density (vpm)	Speed (mph)	TTS (Mins.)	Induced TTS (Mins.)	VOT ($/hr)
6	1748		79.7	356	1392	30.6	58.9	3		121.2
6.5		2.5						3		131.3
6.5	1713		79.2	356	1357	29.5	59.8	3.2	0.3	120.6
7		2.2						3.2		129.9
7	1683		78.9	356	1328	28.6	60.6	3.4	0.2	122.0
7.5		2						3.4		130.7
7.5	1657		78.5	356	1301	27.8	61.3	3.6	0.2	124.1
8		1.8						3.6		132.4
8	1633		78.2	356	1278	27.1	62	3.8	0.2	127.0
8.5		1.6						3.8		134.9
8.5	1613		77.9	356	1257	26.6	62.4	3.9	0.1	131.1
9		1.5						3.9		138.8
9	1594		77.7	356	1238	26.2	62.7	4	0.1	135.8
9.5		1.4						4		143.3
9.5	1577		77.4	356	1221	25.6	63.3	4.1	0.1	138.9
10		1.3						4.1		146.2
10	1561		77.2	356	1205	25.25	63.6	4.2	0.1	143.6
10.5		1.2						4.2		150.8
10.5	1546		77	356	1191	24.8	64	4.3	0.1	147.5
11		1.1						4.3		154.5
11	1533		76.8	356	1178	24.6	64.2	4.3	0	153.1
11.5		1.1						4.3		160.0
11.5	1520		76.6	356	1165	24.25	64.5	4.4	0.1	157.4
12		1						4.4		164.2
12	1509		76.4	356	1153	24	64.7	4.4	0.1	162.4
12.5		1						4.4		169.1
12.5	1497		76.2	356	1141	23.6	65	4.5	0.1	166.1

Another important observation was that the speed on the MnPASS lanes remained at least LOS C conditions and above. Thus, it might be possible for the toll operator to keep the tolls greater than $8 and can still maintain least LOS C on the MnPASS lanes. In the next section, revenue is estimated based on the customer's willingness to pay a toll greater than $8.

4.13. Revenue

As seen in the previous section, a MnPASS user may be willing to pay a higher toll based on their value of travel time. It was assumed that the customers who paid a $8 may be willing to pay a higher toll for MnPASS trips begining from Burnsville and Highway 13 tolling locations. The conditions were set based on the assumption that the user paid a higher toll only if it was worth their TTS. For example, if a user valued its TTS at least $127 per hour but less than $131 per hour, they can be expected to pay at least $8.5 for saving 3.8 minutes.

A total of 26,581 transactions were charged the maximum toll to trips which began from Burnsville and Highway 13 tolling locations (See Table 15). Only 0.09% of the toll cap transactions were removed due to the conditions applied to the merged dataset. So, a total of 26,555 toll cap transactions initiated at Burnsville and Highway 13 tolling locations were used to estimate the predicted revenue. Table 31 shows the revenue collected from such users who paid the maximum toll possibly due to TTS. Also in the same table, revenue based on the user's value of travel time savings has also been aggregated. The frequency of transactions at tolls over $8 was distributed based on the assumption that the users have a limit to pay a higher toll. The cumulative frequency distribution curve in Figure 28 suggested that the distribution flattened at higher tolls and justified that the freuqnecy of users having higher VOT decreased. The cumulative frequency distribution between two VOT gave the percentage of users who fall in the range. A higher percentage indicated that more number of users were in this range and it could be used as a weightage factor. The weightage factor was applied to the 26,555 transactions and then the frequency at each toll was obtained.

Table 31 Comparison of revenue based on current pricing scheme and at increased tolls over $8

Toll ($)	Number of toll cap transactions	Revenue based on current pricing plan($)	VOT ($/hr)	Cumulative frequency% (from Figure 28)	difference in CDF %	Frequency of transactions at tolls over $8	Estimated Revenue ($)
8	26,555	212,440	127	66.03%	1.26	3092	24740
8.5			131.1	67.29%	1.39	3416	29033
9			135.8	68.68%	0.72	1762	15856
9.5			138.9	69.40%	1.36	3349	31818
10			143.6	70.76%	0.99	2427	24266
10.5			147.5	71.75%	1.33	3268	34312
11			153.1	73.08%	1.06	2594	28533
11.5			157.4	74.13%	1.12	2759	31734
12			162.4	75.26%	0.79	1947	23370
12.5			166.1	76.05%	0.79	1941	24257
Total	**26555**	**212,440**				**26555**	**267,919**

If tolls had been allowed to rise above $8, the predicted revenue was found to be higher than the revenue collected if there was a $8 toll cap. The predicted revenue was found to be 26.11% higher if the tolls could raise above $8 compared to the revenue collected from toll cap transactions initiated at Burnsville and Highway 13 tolling locations based on the current pricing plan.

4.14. Chapter Summary

In this chapter, the frequency of occurrence of toll cap transactions was analyzed by location, direction, day of the week, time of the day, and month of the year. The northbound trips from Burnsville and Highway 13 for which the user paid the maximum toll comprised 80% of all toll cap transactions that occurred on I-35W MnPASS lanes during 2016 and 2017. In most of the transactions, the toll algorithm was unable to raise the toll due to the toll cap which caused congestion to continue on the MnPASS lanes and continued to choose MnPASS over GP lanes during toll cap. This research analyzed that if the tolls had been allowed to increase above $8, it could have been possible to maintain at least LOS C condition on the MnPASS lanes as well as generate extra revenue for the toll operator.

5. SUMMARY AND CONCLUSIONS

A toll cap is a maximum toll that the MnPASS system charged from its customers. A toll cap of $8 had been in the pricing plan since the MnPASS lanes were first introduced in 2005. The primary objective of this study was to analyze the effects of the toll cap on the MnPASS lanes. Two-year toll transaction data and toll pricing data were obtained from the Minnesota Department of Transportation for conducting the research. Additionally, traffic parameters- speed, density, and flow on the MnPASS as well as GP lanes were extracted from the detectors through the DataExtract tool developed by MnDOT.

In the preliminary analysis, it was observed that approximately 91% of toll cap transactions on the I-35W MnPASS lanes occurred during the northbound commute towards downtown Minneapolis. Nearly 88% of those toll cap transactions were MnPASS trips which began near Burnsville and Highway 13 tolling locations. Around 5% of trips which began at either of the two tolling locations were toll cap transactions and were charged the maximum toll. The toll cap transactions that originated from these two locations were used for the analysis in this study.

A toll is charged to a user based on the zone where the user took an exit. If the user entered and traveled in the same zone, the trip is charged with a short toll, and a long toll if the user traveled to a different zone. All the toll cap transactions analyzed in this study originated (first detected) at Burnsville or Highway 13 tolling locations and were northbound trips. In this study, a trip was called as a short trip if it was last detected before or at 82nd St tolling locations, and a long trip if the trip was last detected at 66th St. or downstream tolling locations. Long trips were charged the maximum toll more often than short trips.Users paid the maximum toll for almost 13% of long trips and only 1.6% for short trips from Burnsville or Highway 13 tolling locations. These findings suggest that the users were more likely to pay the maximum toll for long trips and continued to use the MnPASS lanes if they have to travel longer to downtown Minneapolis. One of the reasons behind this observation could be that the long toll-paying users got average TTS of 4.6 minutes whereas the short toll-paying users got average TTS less than a minute.

The study tried to analyze the frequency of occurrence of a toll cap transaction by time of the day, day of the week and month of the year. Approximately 70 % of the toll cap transactions at Burnsville and Highway 13 tolling locations occurred more frequently between 7:30 A.M. to 8:15 A.M. and the frequency peaked around 8 a.m. Users paid the maximum toll more frequently on weekdays other than Friday. Toll cap transactions were more recurring during the fall season compared to the spring and summer season and were least frequent during June. These findings indicated that users were most likely to pay the maximum toll for work bound trips travelling towards downtown Minneapolis.

Additionally, this research examined the price sensitivity of the MnPASS lane users to evaluate the efficiency of the tolling algorithm. The tolls are adjusted based on the highest MnPASS traffic density downstream of the user's entry point detected in the last 3 minutes. A detector was said to be critical if its traffic density levels dictated the tolls for most of the time. One such critical detector was located on the I-35W MnPASS northbound lane near Cliff road. The traffic density levels near the critical location were proportional to tolls from which it can be interpreted that the demand(density) for MnPASS lanes increased at higher tolls even during the toll cap. Also the speed and traffic flow parameters at the location of the critical detector was analysed. Traffic speed on the MnPASS lanes near Cliff road was below 50 mph for most of the time when the toll was $8. Apart from analyzing the speed at one location, the study also analyzed the corridor speed on both MnPASS as well as GP lanes. The corridor speed was calculated using speeds extracted from ten sets of detectors present along the I-35W northbound lanes. Each set of detectors comprised of a MnPASS as well as GP lane detectors. The corridor speed represented the average speed across the MnPASS or GP lanes and has also been used to estimate the average trip speed. Approximately 50% of MnPASS trips from Burnsville and Highway 13 tolling locations which were charged the maximum toll had an average trip speed (corridor speed) below 50 mph. The toll algorithm was unable to maintain at least LOS C traffic conditions on the MnPASS lanes when it charged $8 toll. Due to the toll cap, the toll algorithm was unable to raise the tolls causing congestion to continue on the MnPASS lanes near Cliff road during the toll cap period.

Additionally, this study examined the relationship between toll pricing and travel time savings to examine the potential impact of raising the toll prices above $8. The value of travel time distribution suggested that users have a limitation to pay the maximum toll for their travel time savings. The number of users who were willing to pay higher for their travel time savings decreased at higher value of time. Based on this finding, this research tried to predict the number of users who were willing to pay a toll higher than the toll cap. This observation was used to predict the percentage of users who might be willing to a toll greater than $8 based on their value of travel time. A methodology was proposed to explore traffic speed and flow on the MnPASS lanes at tolls greater than $8 based on user's value of time. The results indicated that it might be possible to maintain a high throughput close to the equilibrium flow for a longer duration and still maintain a high traffic throughput upto $12.5 toll.

In this study, revenue was also predicted in the case when tolls were allowed to be raised more than the current cap. The predicted revenue was compared with revenue collected from trips where users paid $8 based on the current pricing plan. A user who paid the maximum toll was assumed to pay a toll greater than $8 based on their VOT. The estimate revenue was found to be 26.11% higher if the tolls could raise above $8. This study analyzed toll cap transactions for trips which began from only two locations. But the toll cap transactions at these locations comprised a majority of all the toll cap transactions that occurred on the MnPASS lanes. Thus, it can be concluded that a better revenue collection and least LOS C traffic conditions could have been possible if the tolls were allowed to raise above $8.

5.1. Limitations

This research has some limitations due to insufficient trip information and data constraints. First, each trip or a toll transaction does not include information about the time of entry and exit on the MnPASS lanes. Therefore, the travel time and average speed in each trip had to be assumed based on the corridor speed parameters obtained from detector readings.

While the research used VOT as a measure for a user to opt for MnPASS lane over GPL for prediction of flow and speed at tolls greater than $8. But there could be other reasons other than TTS which might compel toll-paying users to pay a toll greater than $8. Twenty one percent of toll cap transactions from Burnsville and Highway 13 tolling location had negative TTS which indicated that users paid the maximum toll for using MnPASS lanes for reasons other than TTS like trip reliability and safety. Additionally, there were 15% of transactions where users paid the maximum toll and had VOT greater than $400 per hour. This VOT was clearly high as it was determined only from toll paying users and did not include those users which chose GP lanes. The VOT calculated in this study cannot be a representative of all the I-35W MnPASS and GP lane users.

Basically, the change in VOT was used to estimate the frequency of users who would not be willing to pay a higher toll. The study tried its best estimate to predict the frequency at tolls over $8 and is just a hypothetical scenario in the case if tolls were allowed to raise.

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