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MnPASS Modeling and Pricing Algorithm Enhancement

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May 2015

Research Project
Final Report 2015-22

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Technical Report Documentation Page

1. Report No. MN/RC 2015-22	2.	3. Recipients Accession No.
4. Title and Subtitle MnPASS Modeling and Pricing Algorithm Enhancement		5. Report Date May 2015 6.
7. Author(s) John Hourdos, Michael Janson, David Levinson, and Gordon Parikh		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Minnesota Minnesota Traffic Observatory Department of Civil Engineering 500 Pillsbury Drive SE Minneapolis, MN 55455		10. Project/Task/Work Unit No. CTS # 2013020 11. Contract (C) or Grant (G) No. (c) 99008 (wo) 43
12. Sponsoring Organization Name and Address Minnesota Department of Transportation Research Services & Library 395 John Ireland Boulevard, MS 330 St. Paul, Minnesota 55155-1899		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code
15. Supplementary Notes http://www.lrrb.org/pdf/201522.pdf		

16. Abstract (Limit: 250 words)

While High Occupancy Vehicle (HOV) lanes have been used for decades as a strategy for mitigating congestion, research has shown that they are not always effective. A 2001 study of the I-394 and I-35W HOV lanes in Minnesota found that the HOV lanes were on average underutilized, moving fewer people than the General-Purpose Lanes (GPL) even with the increased number of passengers per vehicle. To address the issue of underuse, in 2003 the Minnesota Legislature authorized the conversion of the I-394 HOV lanes into High-Occupancy Toll (HOT) lanes, named the MnPASS Express Lanes. The MnPASS lanes operate using a fully dynamic pricing schedule, where pricing is dictated by the level of congestion in the HOT lane. To better understand the nature of HOT lanes and the decisions of their users, this study explored the possibilities for a microscopic traffic simulation-based model of HOT lanes. Based on a series of field studies where the price of the toll was changed while observing changes in demand in the HOT lane, models describing the lane choice behavior of MnPASS users were developed and calibrated. These models interfaced with the traffic simulation software Aimsun through a number of extension modules and tested on the two MnPASS corridors of I-394 and I35W corridors in the west and south suburbs of Minneapolis, Minnesota. The integrated HOT simulation tool was also used to develop and test a number of alternative pricing strategies including a more efficient version of the current strategy.

17. Document Analysis/Descriptors Traffic simulation, High occupancy toll lanes, Aimsun, Congestion pricing, Tolls		18. Availability Statement No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 87	22. Price

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Final Report

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May 2015

Published by:

Minnesota Department of Transportation
Research Services & Library
395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155-1899

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Acknowledgments

We would like to thank the Minnesota Department of Transportation for supporting this project. We would like to acknowledge the help, support, and cooperation of Brian Kary, Farideh Amiri, and Alan Rindels with MnDOT, as well as all the current and past researchers at the Minnesota Traffic Observatory, Andrew Owen, Bala Subrahmanyam Kambala, and Stephen Zitzow whose hard work made this project a success.

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Executive Summary

While High Occupancy Vehicle (HOV) lanes have been used for decades as a strategy for mitigating congestion, research has shown that they are not always effective. A 2001 study of the I-394 and I-35W HOV lanes in Minnesota found that the HOV lanes were on average underutilized, moving fewer people than the General-Purpose Lanes (GPL) even with the increased number of passengers per vehicle. Regardless, the political support for HOV lanes as a means of encouraging carpool and transit use was fairly high. To address the issue of underuse, in 2003, the Minnesota Legislature authorized the conversion of the I-394 HOV lanes into High-Occupancy Toll (HOT) lanes, named the MnPASS Express Lanes. HOT lanes are an alternative to traditional HOV lanes that allow vehicles that don't meet the occupancy requirement to use the HOV lane for a toll, encouraging transit and carpooling while providing those driving alone with another option for increased travel time reliability. This gives communities with underutilized HOV lanes a third option for increasing throughput on the road without discouraging carpool and transit use. In Minneapolis, the conversion of the I-394 HOV lanes to HOT lanes increased the number of vehicles using the lanes by 33% without decreasing HOV and transit use and maintaining speeds of 50-55 mph 95% of the time.

The MnPASS lanes operate using a fully dynamic pricing schedule, where pricing is dictated by the level of congestion in the HOT lane. This allows the system to maintain near free-flow speeds the majority of the time. While performance of these lanes is generally considered to be good, due to the service they provide to vehicles, as one of the few instances of dynamically priced HOT lanes in existence, there is little to compare them against. Whether the pricing algorithm in operation is the optimal for the system, or if there are other pricing algorithms that could perform better or optimize different goals, requires both theoretical development and empirical testing, first via simulation, and subsequently in the field.

To better understand the nature of HOT lanes, the decisions of their users, as well as the potential of the pricing algorithms for revenue and demand balance, this study explored the possibilities for a microscopic traffic simulation-based model of HOT lanes. Based on a series of field studies where the price of the toll was changed while observing changes in demand in the HOT lane, models describing the lane choice behavior of MnPASS users were developed and calibrated. As a side product, these field studies also produced valuable insights in the interpretation of the price mechanism by the MnPASS users. For example, both SOVs and HOVs increased usage of the MnPASS lanes as prices increased. The increased demand resulting from higher prices (and decreased demand from lower prices) is likely a result of driver perception of the posted price. Although in reality the price only reflects the conditions on the MnPASS lane, drivers' likely view the price as an indication of time savings and congestion on the regular lanes, suggesting higher prices provide greater time savings. No travel times or congestion level information is made available to drivers entering MnPASS corridors, therefore, the MnPASS price may be perceived as a signal of downstream congestion.

The developed subscription and lane choice models interfaced with the traffic simulation software Aimsun, developed by Transport Simulation Systems (TSS), through a number of extension modules and implemented on the simulations of the two MnPASS corridors of I-394

and I35W corridors in the west and south suburbs of Minneapolis, Minnesota. The integrated HOT simulation application is capable of simulating the operation of the MnPASS Dynamic Pricing Algorithm as well as the choices of individual drivers to subscribe to and use the MnPASS system. Regarding the latter, the HOT simulation application is capable of emulating lane use under either MnPASS lane access designs, the Closed Access design of I-394, or the Open Access design of I-35W. The modular nature of the application also allows easy exchange of pricing strategies without affecting the main core of the program.

The lane choice model, currently incorporated into the HOT simulation application, implements a value-of-time mechanism that takes into account the price of the HOT lane, the average travel time experienced during past trips over each of the two alternatives (HOT and GPL), as well as the travel time reliability of the two alternatives as is formulated over all past trips. For the purposes of the simulation application, this perception of travel time and travel time reliability is built through successive simulation runs. With each simulation run, the drivers improve their knowledge of expected traffic conditions on each alternative, and given the prevailing HOT price, decide if they will use the facility or not. The system converges to an equilibrium beyond which the simulated drivers always choose the same alternative. Although the learning mechanism is general and can be used on any facility, the value-of-time coefficients of the lane choice model were calibrated based on real data from I-394 eastbound and specifically for the full trip to downtown Minneapolis. This was required by the project schedule. Resources did not allow the development of a more general value-of-time formulation. This resulted in very good performance of the tool on I-394 eastbound and not so good performance on the three other facilities of I-394 WB, I-35 NB, and I-35W SB. Regardless, now that the HOT simulation application is available and proven, investigating and implementing a more general value-of-time formulation is a feasible next step.

The HOT simulation application was designed to facilitate the testing of different pricing strategies. As part of this study, four new pricing strategies were developed as alternatives to the current system used on the MnPASS HOT lanes. The first is similar to the current pricing algorithm in that it relies strictly on HOT density for determining price, but calculating it from an equation as opposed to a set of tables. The other three pricing strategies incorporate the density of the GPLs into the equations, using the difference between the densities to determine price. Although not specifically explored, it was shown that the development of usage or revenue maximizing strategies is feasible through the use of the simulation tool. Finally, the quicker price response afforded by the continuous pricing function, as opposed to the density and level of service tables used by the current MnPASS algorithm, would provide drivers with a more accurate picture of the conditions on the HOT lane and reduce the likelihood of breakdown in the HOT lane due to the delay in price increase. Equation-based price algorithms would also be more easily integrated into MnDOT's current traffic management software than the current MnPASS system, allowing greater control over the system and its calculations. Given these encouraging simulation-based results, a field implementation experiment may be the next step.

1 Introduction

While High Occupancy Vehicle (HOV) lanes have been used for decades as a strategy for mitigating congestion, research has shown that they are not always effective. A 2001 study of the I-394 and I-35W HOV lanes in Minnesota found that the HOV lanes were on average underutilized, moving less people than the General-Purpose Lanes (GPL) even with the increased number of passengers per vehicle. During congested periods, however, the HOV lanes carried more people than the GPLs. In addition to this, the political support for HOV lanes as a means for encouraging carpool and transit use was fairly high (Cambridge Systematics, 2002). To address the issue of underuse, in 2003 the Minnesota Legislature authorized the conversion of the I-394 HOV lanes into High-Occupancy Toll (HOT) lanes, named the MnPASS Express Lanes (MnDOT, 2013).

HOT lanes are an alternative to traditional HOV lanes that allow vehicles that don't meet the occupancy requirement to use the HOV lane for a toll, encouraging transit and carpooling while providing those driving alone with another option for increased travel time reliability. This gives communities with underutilized HOV lanes a third option for increasing throughput on the road without discouraging carpool and transit use. In Minneapolis, the conversion of the I-394 HOV lanes to HOT lanes increased the number of vehicles using the lanes by 33% without decreasing HOV and transit use and maintaining speeds of 50-55 mph 95% of the time (FHWA, 2013).

The MnPASS lanes operate using a fully dynamic pricing schedule, where pricing is dictated by the level of congestion in the HOT lane. This allows the system to maintain near free-flow speeds the majority of the time, providing some guarantee of travel time to users who decide to pay the toll, as well as to transit users and HOVs. While performance of these lanes is generally considered to be good, due to the service they provide to vehicles, as one of the few instances of dynamically priced HOT lanes in existence, there is little to compare them against. Whether the pricing algorithm in operation is the best for the system, and how well it or any other pricing algorithm would perform in a different environment with different users, requires both theoretical development and empirical testing, first via simulation, and subsequently in the field.

In order to better understand the nature of HOT lanes and the decisions of their users, this study explores the possibilities for a microscopic traffic simulation-based model of HOT lanes. Based on a series of field studies where the price of the toll was changed while observing the changes in the demand on the HOT lane, models describing the lane choice behavior of MnPASS users were developed and calibrated. As a side product, these field studies produced valuable insights on the interpretation of the price mechanism by the MnPASS users.

Using the traffic simulation software Aimsun developed by Transport Simulation Systems (TSS), a number of extension modules were developed to interface with a simulation of the I-394 and I35W corridors in the west and south suburbs of Minneapolis, Minnesota. Together with these extension modules, the simulation model is capable of simulating the operation of the MnPASS Dynamic Pricing Algorithm as well as the choices of individual drivers to subscribe to and use the MnPASS system. This report describes the methodology used in developing these models and presents the results of their application on the I-394 and I-35W corridor HOT lanes,

including a comparison of the results of the simulation with real measurements. The simulation framework was designed to facilitate the testing of alternate pricing strategies in the MnPASS lanes in an environment where travel times are influenced by the choices of the users, the results for which are also presented. Finally, some recommendations for future research and improvements to the models are provided.

1.1 MnPASS Dynamic Pricing Algorithm

This section presents a summary description of the existing MnPASS dynamic pricing algorithm. The MnPASS dynamic pricing algorithm is based on the concept of maintaining Level of Service (LOS) "C" or better in the High Occupancy Toll (HOT) lanes. On both MnPASS corridors (I-394 and I-35W) the toll is calculated based on fixed destinations (figure 1.2). For example on eastbound 394 one toll section is from the start of the HOT lane on I-494 to the junction with TH-100 and the second toll section is from TH-100 to downtown Minneapolis or I-94. Each section has its own price and travelers who traverse both are charged the sum of the two tolls up to a maximum of $8.00. I-394 has two destinations (toll sections) while I-35W has three. The freeway corridor is divided into several toll zones. The toll zones are defined as the sections between successive toll tag detectors. The location of a toll tag detector is also referred to as toll plaza (Figure 1.1). Each trip is defined as the distance from the plaza at which the vehicle's toll tag is first detected to the plaza that it is detected last. As explained later, the customer locks on a toll price at the time it is first detected but is actually charged upon exiting the toll section.

Figure 1-1 A toll plaza on I-394 Eastbound

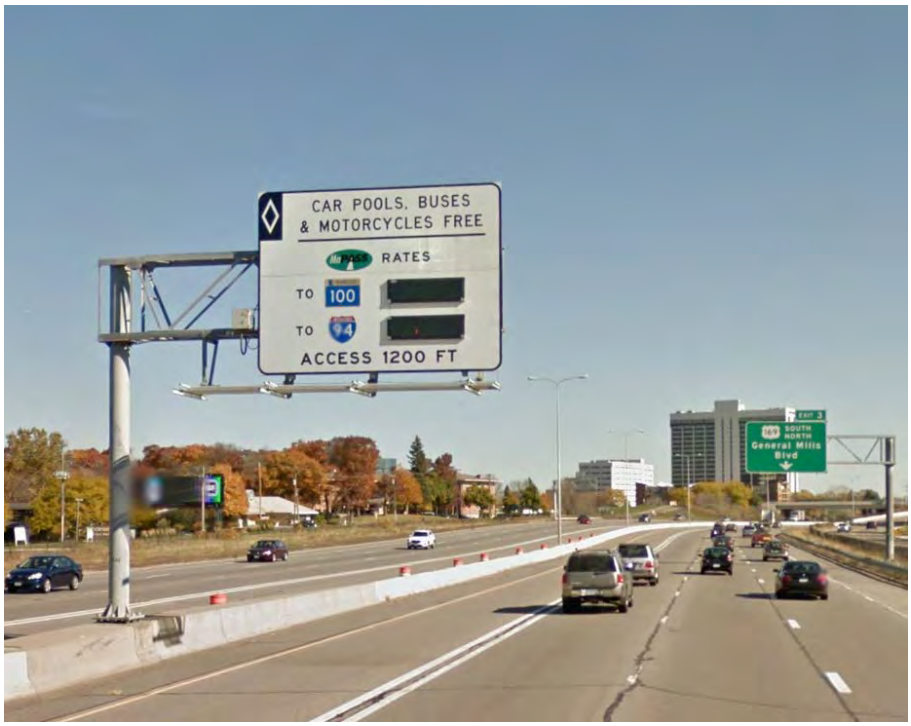

Figure 1-2 MnPASS price sign showing the two destination in I-394 EB

1.1.1 Data Collection

Traffic data is collected by MnDOT from the HOT lanes only. Each toll zone has a given set of magnetic loops counting traffic for that zone. Every 30 seconds the traffic count is converted to traffic density. MnDOT collects the data and reports it to the public every 30 seconds, so finer data is not generally available. Prior to calculating the density, obvious erroneous data is eliminated. For various reasons, erroneous data for a 30 second period can be either 0, negative or a very high number (impossibly high). It is felt that the data records on either side of the erroneous data are also erroneous (due to timing problems) and all three are deleted.

1.1.2 Traffic Density Calculation

The Traffic Density (K) is then calculated for each valid 30 second interval using the following formula:

$$\text{Traffic Density} = ((C/P)*3600)/(S*N)$$

Where: C = The total vehicle count over the period.

P = Length of the measurement period in seconds.

S = Average measured vehicle speed over the period in MPH.

N = The number of lanes in operation at this tolling zone in this traffic direction.

The traffic density calculations are averaged over a six minute time period. The calculated traffic density is then truncated to a whole number.

1.1.3 Rate Calculation

The MnPASS lanes on each corridor are organized into a series of overlapping zones, each with its own entry point but sharing the same end point (destination). The maximum TK (averaged density over a six minute interval) downstream from each HOT lane entry point is used to calculate the rate for that entry point. Each entry point's rate is calculated separately, and users are charged only the rate for their entry point. This allows the system to charge drivers only for the worst traffic they would experience, avoiding situations where they might be charged for the traffic state on a segment of the road they will not drive on.

In cases where vehicles traverse multiple pricing zones, for instance vehicles taking both the reversible and non-reversible portions of the I-394 MnPASS lanes, there is also a maximum price of $8.00 that can be charged to an individual vehicle. This is determined separately for each vehicle by reducing the price of the less expensive zone when the total price exceeds $8.00. This feature allows MnDOT to declare a maximum price payable and protect drivers from paying excessive amounts during unusual congestion.

The Level of Service of the HOT lane can be found using the maximum K from a traffic table as shown below.

Table 1-1 Traffic LOS Table

Level Of Service	Traffic Density (K) **(Vehicles/Lane/Mile)**
A	**0–11**
B	**>11–18**
C	**>18–29**
D	**>29–35**
E	**>35–45**
F	**>45**

For example: If the maximum K downstream from a HOT lane is 21, then LOS is C. The algorithm also uses an LOS delta settings configuration to smoothly increase or decrease the rate proportionally to increases or decreases in K.

Table 1-2 Price change Delta Settings Table (partial)

K	Δ1	Δ2	Δ3	Δ4	Δ5	Δ6
20	0.00	0.25	0.50	0.75	1.00	1.25
21	0.00	0.25	0.50	0.75	1.00	1.25
22	0.00	0.25	0.50	0.75	1.00	1.25
23	0.00	0.25	0.50	0.75	1.00	1.25
24	0.00	0.25	0.50	0.75	1.00	1.25
25	0.00	0.25	0.50	0.75	1.00	1.25
26	0.00	0.25	0.50	0.75	1.00	1.25

The current rate for each HOT entry point would be adjusted based on the change in K since the last 3 minute rate calculation, using the current K to look up the rate change. If the K at the last rate calculation was 23, subtracting 23 from 21 will give us a delta of -2. Reading across the K line 23 to a delta of 2 would cause a current rate reduction of $ .25. If the previous K had been 19, it would cause the rate to increase by $ .25. This method allows rates to change in proportion to the change in K but avoid large fluctuations.

It was recognized early on that rates do not decrease in the same manner as they increase. Thus, a minimum and maximum value was established for each LOS range allowing rates to adjust at each LOS level.

Table 1-3 LOS Boundarie Algorithm Settings

Level of Service	Min K	Max K	Minimum Rate	Default Rate	Maximum Rate
A	0	11	0.25	0.25	0.50
B	12	18	0.50	0.25	1.50
C	19	29	1.50	1.50	2.50
D	30	35	2.50	3.00	3.50
E	36	45	3.50	5.00	6.00
F	46	50	6.00	8.00	8.00

In the table above, the Default Rate is only used at system start-up when there is no previous data to create a delta. At each Level of service, a rate table is used to ensure that the rate does not lie outside of a preset range for that level of service. For example if the density changes from 19 with a price of $1.75 to 18, changing from LOS C to B, the delta rate would be $0.00 leaving the price at $1.75. Since the level of service changed, the rate would default to the maximum for LOS B of $1.50.

Suppose the maximum K is suddenly increased by more than 6 and the state is still in the previous LOS, then the algorithm takes this difference as 6 and considers the corresponding delta rate.

In the rate table, if the range of K overlaps between two levels of services, algorithm considers the first LOS for a Traffic Density. For example, if the rate table is defined as follows

A (min K is 0, max K is 11)

B (min K is 11, max K is 18)

Traffic Density 11 falls in A and B level of services. In this case, algorithm considers LOS for the K 11 as A.

2 Measuring Demand Response to Pricing Parameter Changes

Developing an understanding of people's value of time as well as their understanding of the system's operation can happen in two ways, carefully crafted surveys, or direct experimentation. Rarely in transportation research is the latter an option but fortunately in this project MnDOT was flexible enough to allow it. With the help of the RTMC and the private contractor managing daily operation of MnPASS we were able to organize experiments were we changed the pricing levels of the system and observed changes in the lane utilization. The following sections describe these experiments and discuss the insights gained from them.

2.1 Methodology

Several field experiments were conducted between October 2012 and January 2013. Drivers were never made aware of any changes to the pricing plan. The first field experiment took place on I-394 between October 8, 2012 and November 2, 2012. During this period, prices for all MnPASS lanes on I-394 were altered according to the revised pricing schedules displayed below. No changes were made to the delta value table. This same delta table was used for all field experiments. Prices during the first week were altered by raising the density threshold at each level of service by 2 points (Table 2.3). Prices during the remaining three weeks were altered by raising the density thresholds by 20% instead of a fixed 2 point increase (Table 2.4). The intent was to lower the average price to MnPASS users. The altered pricing plans for this field experiment, however, were based on a pricing plan dating back to 2005 (Table 2.2). The actual pricing plan in place on I-394 before beginning the field experiment is displayed in Table 2.1. The structure of the 2005 plan includes an additional C- level of service (LOS) and the prices for the various LOS are different than the current pricing plan. The intent was to keep the minimum, maximum and default pricing values the same. However, because of this different pricing structure, pricing changes were not consistent across different density levels. Prices at lower densities were decreased as intended, but prices at higher densities were actually increased. This difference can be seen in figures discussed in the results section. The error in implementing this different pricing structure was later discovered and repaired. The second I-394 field experiment did not experience this same problem.

Table 2-1 Pricing Plan for Normal Operation of MnPASS Lanes (both I-35W and I-394)

Level of Service	Min K	Max K	Min Rate ($)	Default Rate ($)	Max Rate ($)
A	0	11	0.25	0.25	0.50
B	12	18	0.50	0.50	1.50
C	19	31	1.50	1.50	2.50
D	32	42	2.50	3.00	3.50
E	43	49	3.50	5.00	5.00
F	50	50	5.00	8.00	8.00

Density in veh/mi/ln; Prices in $

Table 2-2 Original Pricing Plan from 2005 for I-394

Level of Service	Min K	Max K	Min Rate ($)	Default Rate ($)	Max Rate ($)
A	0	11	0.25	0.25	0.25
B	11	18	0.25	0.25	0.50
C	18	26	0.50	1.50	2.50
C-	26	29	2.50	3.50	4.00
D	29	35	4.00	5.00	6.00
E	35	45	6.00	7.00	8.00
F	45	50	8.00	8.00	8.00

Density in veh/mi/ln; Prices in $

Table 2-3 Modified pricing plan for first week of first field experiment on I-394, 2012-10-8 to 2012-10-12

Level of Service	Min K	Max K	Min Rate ($)	Default Rate ($)	Max Rate ($)
A	0	13	0.25	0.25	0.25
B	14	20	0.25	0.25	0.50
C	21	28	0.50	1.50	2.50
C-	29	31	2.50	3.50	4.00
D	32	37	4.00	5.00	6.00
E	38	50	6.00	7.00	8.00

Density in veh/mi/ln; Prices in $

Table 2-4 Modified pricing plan for weeks 2-4 of first field experiment on I-394, 2012-10-15 to 2012-11-2

Level of Service	Min K	Max K	Min Rate ($)	Default Rate ($)	Max Rate ($)
A	0	13	0.25	0.25	0.25
B	14	22	0.25	0.25	0.50
C	23	31	0.50	1.50	2.50
C-	32	35	2.50	3.50	4.00
D	36	42	4.00	5.00	6.00
E	43	50	6.00	7.00	8.00

Density in veh/mi/ln; Prices in $

The second field experiment took place on I-35W between October 29, 2012 and November 23, 2012. During this period, prices were altered according to Table 2.5. Again, no changes were made to the delta values. By raising the density thresholds by 20% at each level of service, the price was effectively lowered. The same pricing plan was used for the entire field experiment. Several days were excluded from the analysis due to incomplete loop detector data for those dates. The corresponding dates from the baseline period were also excluded in order to stay consistent.

Table 2-5 Modified pricing plan for I-35W field experiment, 2012-10-29 to 2012-11-23

Level of Service	Min K	Max K	Min Rate ($)	Default Rate ($)	Max Rate ($)
A	0	13	0.25	0.25	0.50
B	14	22	0.50	0.50	1.50
C	23	37	1.50	1.50	2.50
D	38	50	2.50	3.00	8.00

Density in veh/mi/ln; Prices in $

The third field experiment was conducted on I-394 lasting five weeks. The experiment consisted of changes to the pricing plan displayed in Table 2.6 and took place in December 7-21, 2012 and January 7-25, 2013. No changes were made to Table 2.5, displayed above. The holiday season at the end of December and beginning of January was excluded. The density thresholds at which prices changed were lowered during this experiment, effectively increasing price. The change was estimated to increase the average price by around 15%. All other operations of the pricing algorithm were left the same. After the experiment, prices were reverted to their previous levels.

Table 2-6 Modified pricing plan for second field experiment on I-394

2012-12-10 to 2012-12-21 & 2012-1-7 to 2013-1-25

Level of Service	Min K	Max K	Min Rate ($)	Default Rate ($)	Max Rate ($)
A	0	9	0.25	0.25	0.50
B	10	15	0.50	0.50	1.50
C	16	25	1.50	1.50	2.50
D	26	34	2.50	3.00	3.50
E	35	39	3.50	5.00	5.00
F	40	50	5.00	8.00	8.00

Density in veh/mi/ln; Prices in $

The field experiments were analyzed by comparing to the same days one-year prior. For example, if the experiment began on the first Monday in October, that same Monday the year before was used as the start date. In order to account for changes occurring between 2011 and 2012, a control period was analyzed. The control period usually consisted of one month prior to the field experiment. The changes in the control period between 2011 and 2012 were compared to the changes between the baseline period and the field experiment. The control periods and baseline period all contained the same pricing plan. This helps determine which changes are caused by the changes to the pricing plan and helps eliminate other confounds such as fuel prices and employment. MinnesotaGasPrices.com (2013) reveals, however, that average fuel prices in Minnesota between 2011 and 2012 were within $0.50. Anomalies such as holidays and poor weather days were removed from analysis. In addition, no changes to express transit service on the corridors were made during the analysis period (Metropolitan Council, 2013)

Price and demand data from the field experiments were taken from specific plazas along the corridor. The selected points represent plazas which typically have the maximum density compared to upstream plazas. Therefore, the density at these critical plazas (as they will be referred to) is often responsible for the posted prices upstream. Data for I-394 used price and demand measurements from plaza 1003 in the eastbound direction and plaza 2003 westbound. These plazas include the section of I-394 between Hwy 169 and Louisiana Ave. The corresponding HOT loop detectors used for the analysis include 5453 for eastbound and 5460 for westbound. These loop detectors are located within the respective plazas near Winnetka Ave S.

On I-35W, both plazas 3006 and 3013 in the northbound direction, along with 4009 and 4011 southbound were analyzed. Plaza 3006 includes the area around Black Dog Road and 3013 includes the section of south Minneapolis between 42nd Street and 26th Street. Plazas 4009 and 4011 are located near 98th Street S and Cliff Road respectively. The corresponding HOT loop detectors used were 525 (106th Street) and 6792 (38th Street) in the northbound direction and 1000 (98th Street) and 1008 (Black Dog Rd) in the southbound direction. The general purpose loop detectors used correspond to those listed on the MnDOT All Detector Report in parallel with the listed HOT detectors. The results discussed come from these critical points.

In economics, elasticity is the measurement of how responsive an economic variable is to a change in another. Price elasticity of demand (PED or $\boldsymbol{\varepsilon}$) is a measure used in economics to show the responsiveness, or elasticity, of the quantity demanded of a good or service to a change in its price. More precisely, it gives the percentage change in quantity demanded in response to a one percent change in. Price elasticities are almost always negative, although analysts tend to ignore the sign even though this can lead to ambiguity. Only goods that do not conform to the law of demand, such as Veblen and Giffen goods, have a positive PED. In general, the demand for a good is said to be inelastic (or relatively inelastic) when the PED is less than one (in absolute value): that is, changes in price have a relatively small effect on the quantity of the good demanded. The demand for a good is said to be elastic (or relatively elastic) when its PED is greater than one (in absolute value): that is, changes in price have a relatively large effect on the quantity of a good demanded (Wikipedia, 2015). For the purposes of the discussion of the MnPASS experiments, demand can be either the density or flow in the HOT lane and price is the

prevailing toll. Our initial hypothesis, and that of those who designed the system, was that the MnPASS system would follow the regular law of demand and have negative elasticities, meaning as the price increases the demand decreases.

Driver elasticity for the field experiments was calculated by comparing price and demand to a baseline period. Average price and demand every three minutes throughout the peak period was calculated as well as the overall weighted average price and density. This was done for each week of the field experiments as well as same period one-year prior. Data corresponds to the critical plazas discussed earlier. Prices and densities for this analysis come from the MnPASS system logs. MnPASS lane share (S_{MnPASS}) is calculated from loop detector data. Elasticity was calculated using two different methods. First, by looking at the changes in price and demand between the two periods for every three-minute period, the elasticity for each 3 minute period was calculated and averaged to yield an average of elasticities. The other method compared the overall weighted prices and densities for the two periods. This yielded an *elasticity of averages* measurement. This same procedure was done for a control period, comparing 2011 and 2012 one month before each field experiment. The control periods utilized the same pricing plan as the baseline period. The final elasticity for the field experiments was the net change occurring between the baseline and field experiment, subtracting out any changes between 2011 and 2012 in the control.

Average of Elasticities

For Field Experiment

$$\varepsilon_E = \frac{\dfrac{D_{E,2012,t} - D_{B,2011,t}}{D_{B,2011,t}}}{\dfrac{P_{E,2012,t} - P_{B,2011,t}}{P_{B,2011,t}}} \tag{2.1}$$

For Control

$$\varepsilon_C = \frac{\dfrac{D_{C,2012,t} - D_{C,2011,t}}{D_{C,2011,t}}}{\dfrac{P_{C,2012,t} - P_{C,2011,t}}{P_{C,2011,t}}} \tag{2.2}$$

Elasticity of Averages

$$\varepsilon_E = \frac{\dfrac{\bar{D}_{E,2012} - \bar{D}_{B,2011}}{\bar{D}_{B,2011}} - \dfrac{\bar{D}_{C,2012} - \bar{D}_{C,2011}}{\bar{D}_{C,2011}}}{\dfrac{\bar{P}_{E,2012} - \bar{P}_{B,2011}}{\bar{P}_{B,2011}} - \dfrac{\bar{P}_{C,2012} - \bar{P}_{C,2011}}{\bar{P}_{C,2011}}} \tag{2.3}$$

In these equations, the subscript E denotes the field experiment and the subscript B denotes the baseline period. The control period is noted by subscript C and each period is marked with its

respective year. D represents demand (density or S_{MnPASS}), P represents price, and ε the resulting elasticity.

2.2 Results and Discussion

The following figures display changes in price and density for the third field experiment and its control. Twelve minute moving averages were used to smooth the data. The error bars represent one standard deviation in each direction.

Figure 2.1 shows the changes in price and density during the morning peak period for the first field experiment on I-394 occurring from 2012-10-8 to 2012-11-2. As discussed earlier the pricing plan during the field experiment followed a different structure than the baseline, leading to a lower price at lower densities and a higher price at higher densities. The elasticity analysis focuses on the time period between 7:00 AM - 9:00 AM. Over this time period, price during the field experiment experienced an increase on average when compared to the baseline. Density during the field experiment was higher than the baseline across the entire morning peak period, including the 7:00 AM - 9:00 AM elasticity analysis period.

Figure 2.2 represents the control period for the first experiment. September 2011 (2011-9-5 to 2011-10-7) is compared to September 2012 (2012-9-3 to 2012-10-5). This period represents five weeks leading up to the field experiment. In the shoulder peak, the two periods follow a fairly similar pattern, but 2012 has a much longer lasting peak. This led to an overall average price and density increase between 2011 and 2012 in the control.

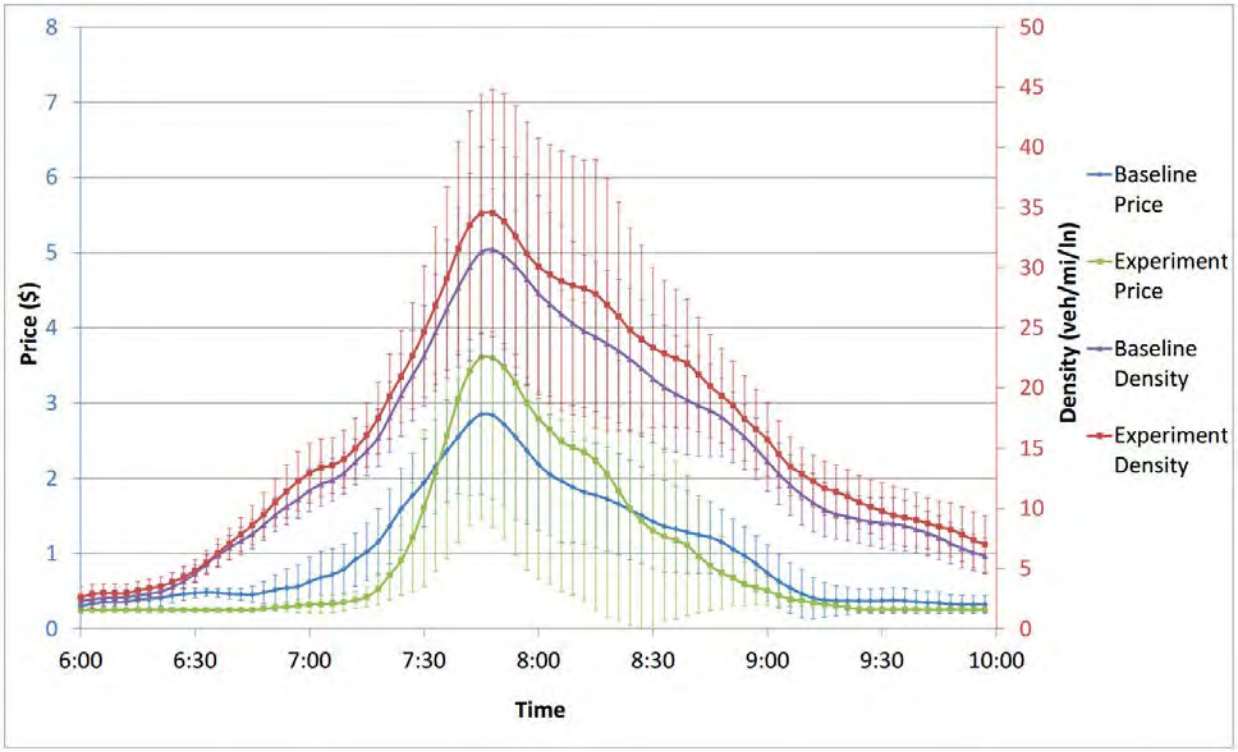

Figure 2-1 Price and Density vs. Time - I-394 Field Experiment: 2012-10-8 to 2012-11-2

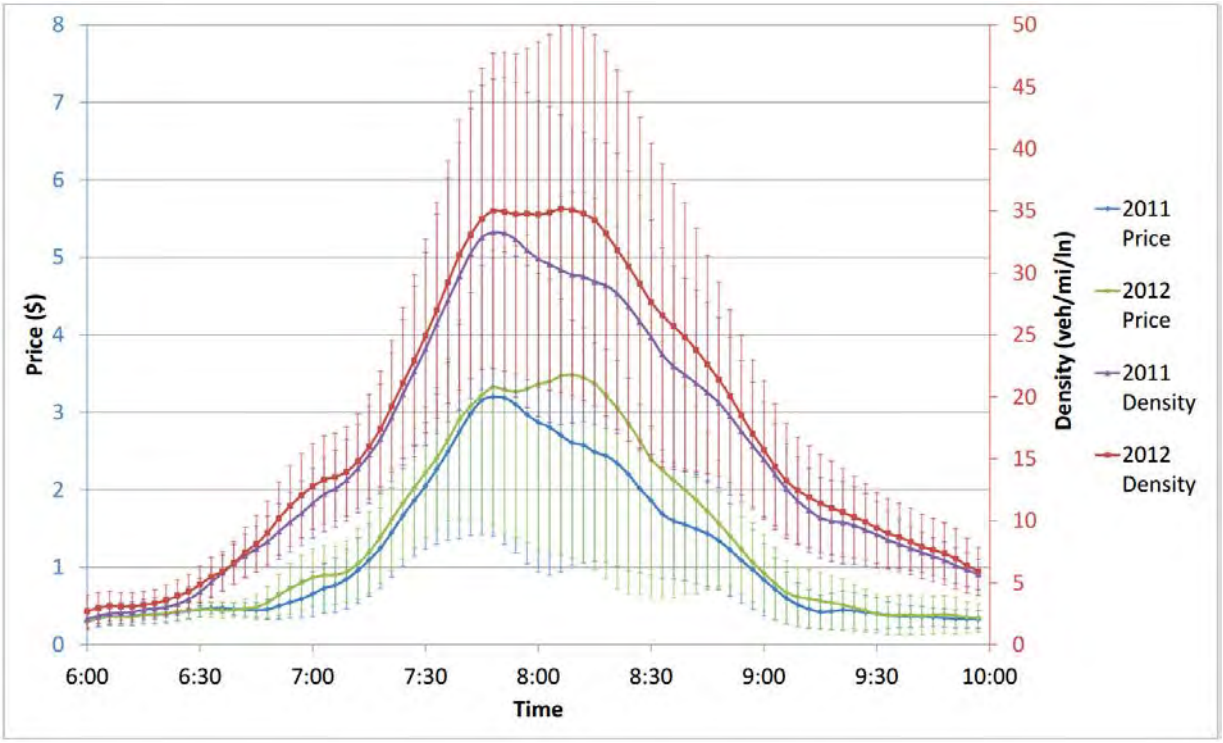

Figure 2-2 Price and Density vs. Time - I-394 Control: September 2011 & 2012

Data in Figure 2.3 show the average price and density levels during the morning peak period on I-35W for the baseline and field experiment periods. The field experiment took place from 2012-10-29 to 2012-11-23. The baseline period includes the same days as the field experiment, but one-year prior.

The control period compared October 2011 (2012-10-3 to 2012-10-28) with October 2012 (2012-10-1 to 2012-10-26) to observe changes from one year to the next, shown in Figure 2.4. This period represents four weeks preceding the field experiment. The pricing plans during the control periods are the same, however, a significant increase demand can be seen in 2012. This increase in demand led to an increase in prices in October 2012.

During the field experiment, prices were decreased by raising density thresholds. Prices between the baseline and field experiment are displayed in Figure 2.4. Increases to price in the field experiment are due to an increase in demand similar to what can be seen in the control. Both graphs show a demand increase between the 2011 period and 2012, however, in Figure 2.3 the price increase between 2011 and 2012 is less dramatic than during the control in Figure 2.4. Therefore, the changes to the pricing plan had the expected effect of decreasing price compared to what it would have been if no change were made.

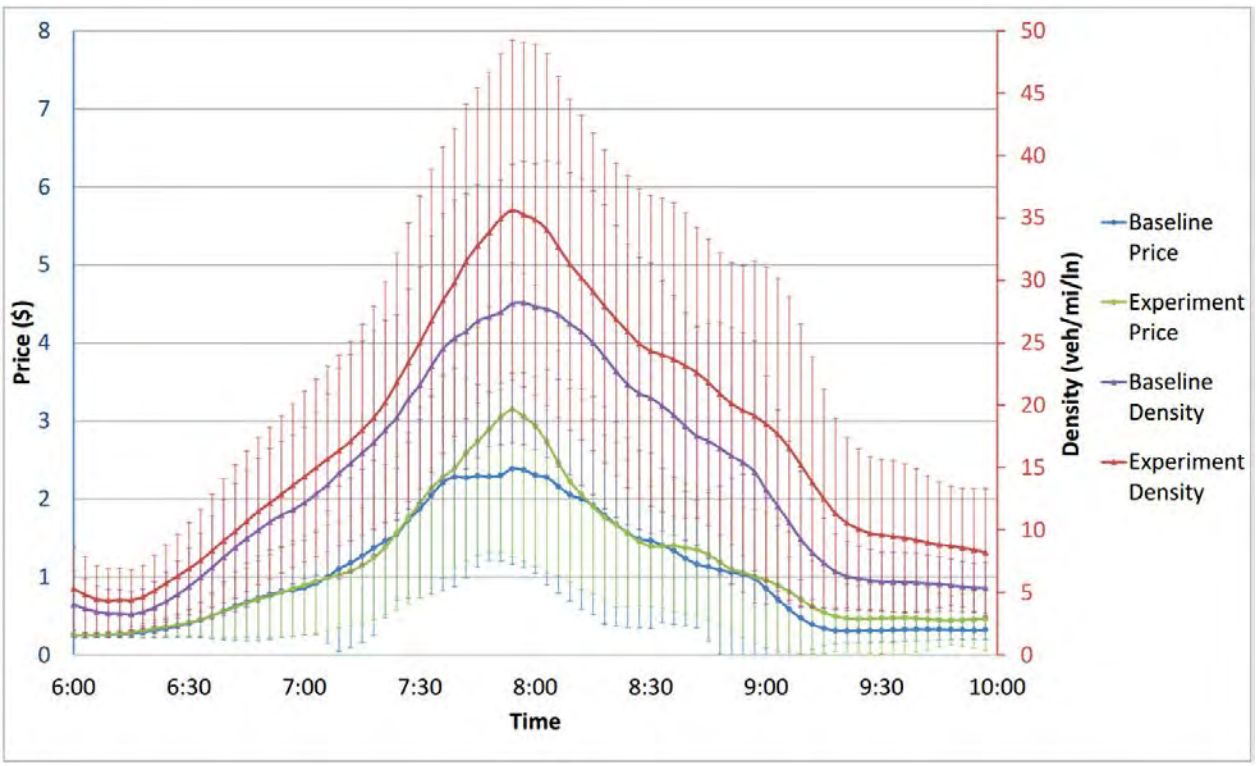

Figure 2-3 Price and Density vs. Time - I-35W Field Experiment: 2012-10-29 to 2012-11-23

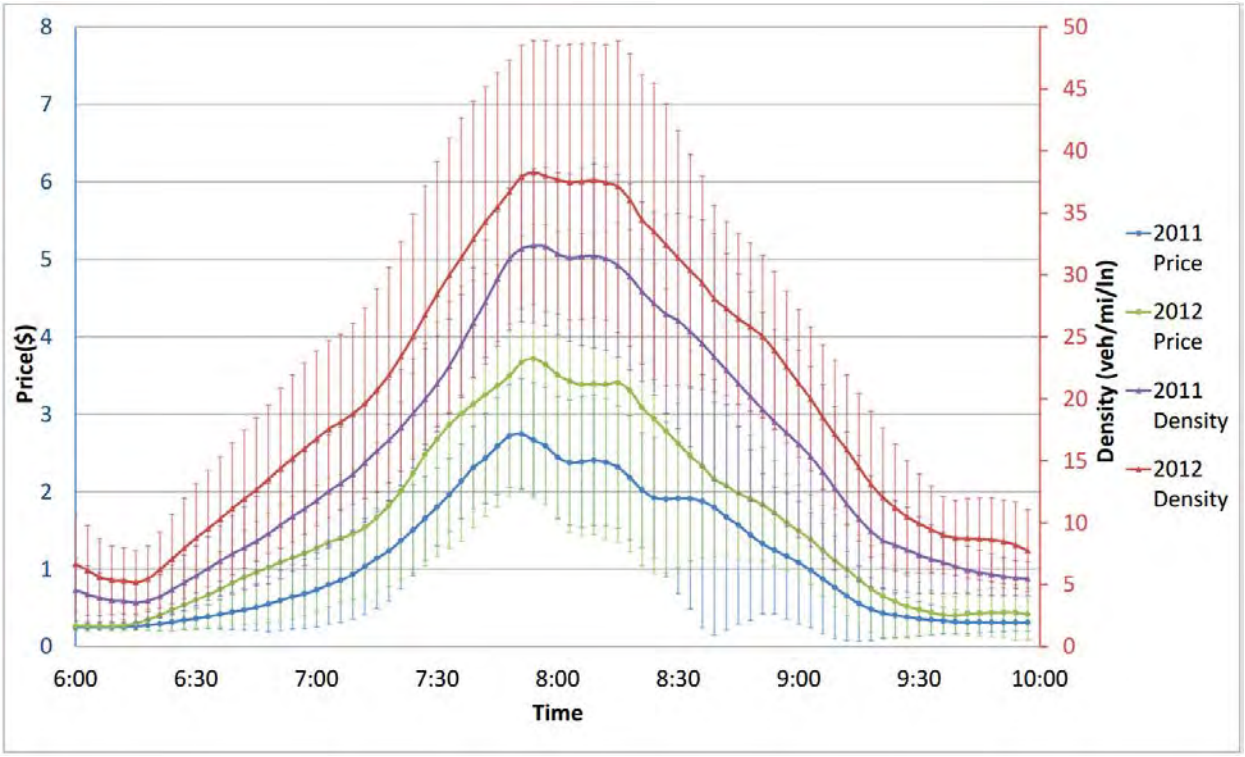

Figure 2-4 Price and Density vs. Time - I-35W Control: October 2011 & 2012

Data in Figure 2.5 show the average price and density levels during the morning peak period on I-394. The field experiment includes 2 weeks in December 2012 (12/7-12/21) and 3 weeks in January 2013 (1/7-1/25). The baseline period includes the same days as the field experiment, but one year prior. Prices were increased during the field experiment by lowering density thresholds. Average paid prices throughout the morning peak period were consistently higher during the 5 week experiment.

Figure 2.6 represents the control period which compares November 2011 (2011-11-18 to 2011-12-9) and November 2012 (2012-11-16 to 2012-12-7). This period represent 3 weeks preceding the field experiment. The first two weeks in November could not be used in the control because the pricing plan during these weeks in 2012 was set to match the plan from 2005 in Table 2.2 instead of the baseline plan in Table 2.1. The resulting changes in the control were relatively small compared to the changes seen in Figure 2.5 between the baseline and field experiment.

Figure 2.5 reveals that the MnPASS lanes saw a consistent increase in density throughout the peak period during the field experiment. Although less responsive than the price increase, density at nearly every time segment during the analyzed periods was higher. This led to the positive elasticity results displayed in Tables 2.8 and 2.9.

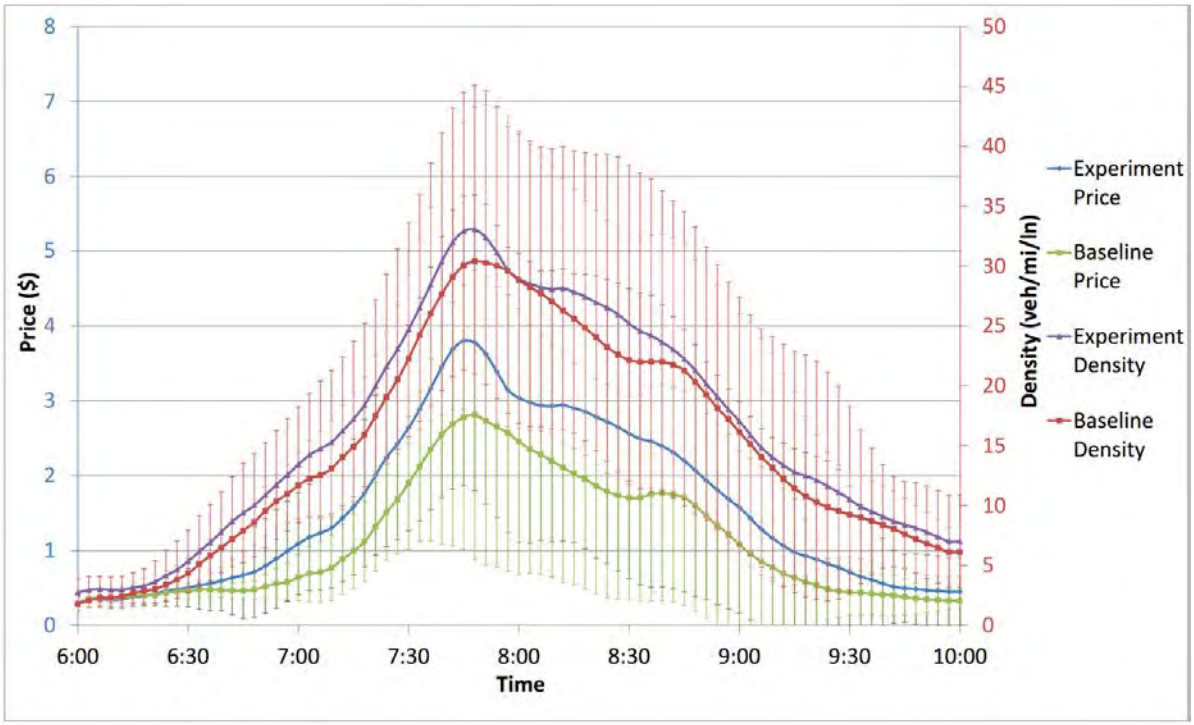

Figure 2-5 Price and Density vs. Time - I-394 Field Experiment: 2012-12-10 to 2012-12-21 & 2013-1-7 to 2013-1-25

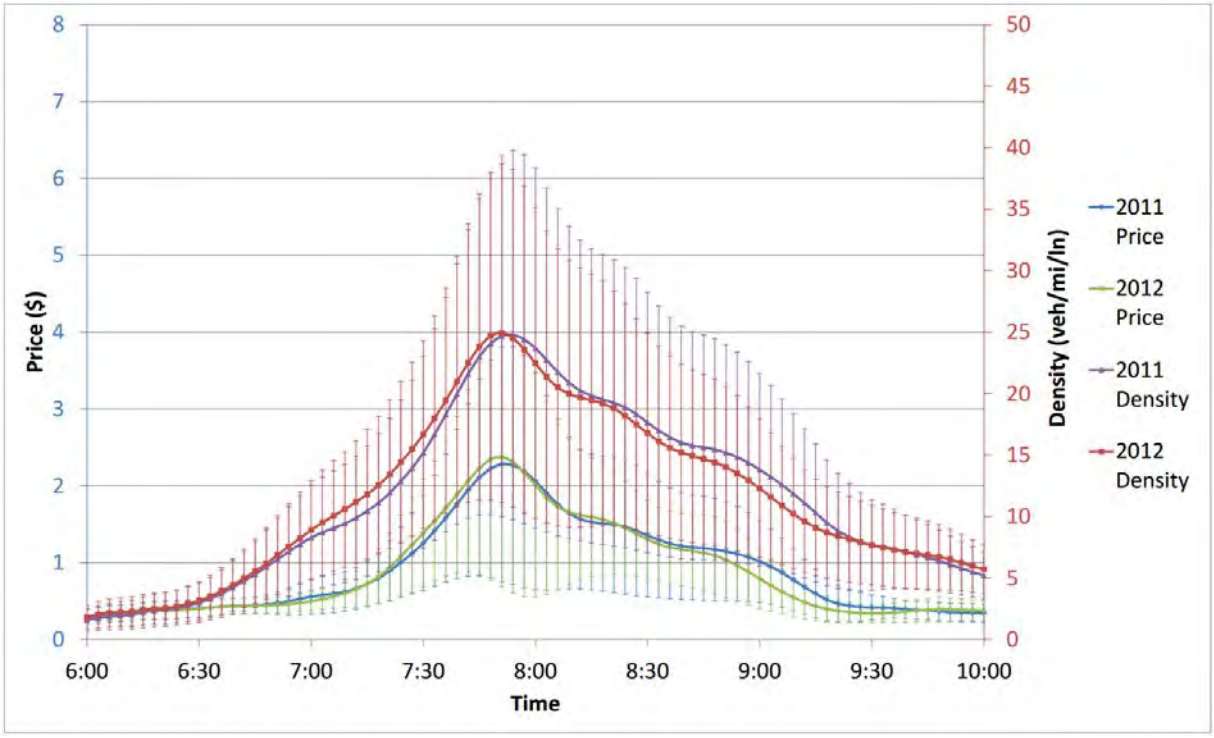

Figure 2-6 Price and Density vs. Time - I-394 Control: November 2011 & 2012

Table 2.7 displays weighted averages of price and density for the baseline, field experiment and control periods. A net change between the baseline and field experiment, including changes in the control, are also displayed. The number of lanes corresponding to the MnPASS lane share is displayed below the table. Average general purpose lane speeds are included as another measure of change between the periods. Elasticity was calculated using both density and MnPASS lane share as a measure of demand. Table 2.8 shows the elasticity values calculated from the weighted averages in Table 2.7. Results in Table 2.9 include the mean, median and standard deviation of elasticity values for every three minutes between 7:00 AM and 9:00 AM.

The first field experiment on I-394 resulted in statistically significant changes in price and density. The control period also resulted in significant changes in price and density between 2011 and 2012. There was no statistically significant change in the average GP speed. Overall, there was a net increase in price, density and S_{MnPASS}. Although the intention was to decrease the price, the varied structure of the pricing plan for this field experiment led to higher prices and higher densities. The averages were taken between 7:00 AM and 9:00 AM. Over this time period, price was primarily higher during the field experiment than the baseline. The increase in both price and demand led to positive elasticity of averages values for the first field experiment. The mean, median and standard deviation of individual elasticity measurements displayed in Table 9 reveal no statistically significant difference for the field experiment. There was a high standard deviation of the individual measurements. There was, however, a statistically significant positive elasticity measured in the control period between 2011 and 2012.

Values for the I-35W field experiment were separated into measurements from plaza 3005 and plaza 3012. At both plazas, there was a statistically significant increase in price, density and S_{MnPASS} between 2011 and 2012. There was no statistically significant change in the average GP speed. The price increases between the baseline and field experiment were less pronounced due to the “price decrease" caused by increasing the density thresholds. This led to a net price decrease in price in both plazas. In all cases except S_{MnPASS} on plaza 3012, demand also saw a net decrease when including the control period. This resulted in nearly all positive elasticity results in Table 8. Similarly to the first field experiment, high standard deviation values in Table 2.9 resulted in no statistically significant average elasticity measurements between the baseline and field experiment. The control, however, saw statistically significant increases between 2011 and 2012. There was no statistically significant change in the average GP speed.

The third field experiment saw statistically significant increases in price and density both between the baseline and field experiment. The control period only saw a significant change in S_{MnPASS} between 2011 and 2012. There was no statistically significant change in the average GP speed. The net values were all positive, resulting in positive elasticity values in Table 2.9. The average of individual elasticity measurements were also positive and statistically significant between the baseline and field experiment for both density and S_{MnPASS}. Unlike the other field experiments, price, density and S_{MnPASS} for this experiment saw consistent increases across all time periods and density levels, as can be seen in Figure 2.5. This consistency led to steady

Table 2-7 Weighted Averages of Descriptive Statistics

	Baseline	Field Experiment	% Change	Control % Change	Net % Change
(1) Plaza 1003					
Price	2.024	2.418	19.45*	16.09*	3.353
Density	25.31	27.50	10.54*	9.657*	0.885
S_{MnPASS}	20.76	21.50	3.566	1.627	1.939
GP_{speed}	91.5	93.8	2.5	0.9	1.6
(2) Plaza 3005					
Price	2.010	2.229	10.88*	68.75*	-57.87
Density	24.98	30.92	23.79*	37.41*	-13.62
S_{MnPASS}	22.36	24.13	7.871*	16.17*	-8.301
GP_{speed}	90.1	89.3	-0.9	2.2	-3.1
Plaza 3012					
Price	1.71	1.882	9.717	38.04*	-28.33
Density	21.74	25.78	18.61*	22.45*	-3.840
S_{MnPASS}	13.36	15.56	16.49*	12.02*	4.471
GP_{speed}	87.6	85.8	-2.1	-0.8	-1.3
(3) Plaza 1003					
Price	2.192	3.044	38.84*	-2.569	41.41
Density	26.03	28.07	7.830*	-6.381	14.21
S_{MnPASS}	20.9	20.99	2.980	-8.217*	11.20
GP_{speed}	91.9	88.0	-4.24	-4.04	0.20

** Significant at 0.05 significance level*
Time of Day: 7:00-9:00
Density in units veh/mi/ln
Speed in km/h

S_{MnPASS} *is percent of overall flow using the MnPASS lane*
(1) I394: FE: 2012-10-8 to 2012-11-2, Base: 2011-10-10 to 2011-11-4, Control: September 2011 and 2012
(2) I35W: FE: 2012-10-29 to 2012-11-23, Base: 2011-10-31 to 2011-11-25, Control: October 2011 and 2012
(3) I394: FE 2012-12-10 to 2012-12-21 & 2013-1-7 to 2013-1-25, Base: 2011-12-12 to 2011-12-23 & 2012-1-9 to 2012-1-27, Control: November 2011 and 2012
Plaza 1003 lanes: 1 HOT, 2 GP, 1 Auxiliary
Plaza 3005 lanes: 1 HOT, 2 GP
Plaza 3012 lanes: 1 HOT, 4 GP

Table 2-8 Field Experiment Elasticity of Averages

Demand Measure	Without Control	Net (with control)
(1) Plaza 1003		
Density	0.5421	.2641
S_{MnPASS}	0.1829	.5784
(2)		
Plaza 3005		
Density	2.186	0.2354
S_{MnPASS}	0.7234	0.1435
Plaza 3012		
Density	1.915	0.1356
S_{MnPASS}	1.697	-0.1578
(3) Plaza 1003		
Density	0.2016	0.3431
S_{MnPASS}	0.0767	0.2704

Time of Day: 7:00-9:00
(1) I394: FE: 2012-10-8 to 2012-11-2, Base: 2011-10-10 to 2011-11-4, Control: September 2011 and 2012
(2) I35W: FE: 2012-10-29 to 2012-11-23, Base: 2011-10-31 to 2011-11-25, Control: October 2011 and 2012
(3) I394: FE 2012-12-10 to 2012-12-21 & 2013-1-7 to 2013-1-25, Base: 2011-12-12 to 2011-12-23 & 2012-1-9 to 2012-1-27, Control: November 2011 and 2012

elasticity results and the small standard deviation values. Another indication of consistency are the similar mean and median values.

Loop detector data were used to determine the total number of MnPASS lanes users (HOV + SOV) along the two corridors. Counts were gathered for the critical plaza(s) on each corridor using loop detector 5453 for eastbound I-394 and 5460 for westbound. On I-35W, loop detectors 525 and 6792 in the northbound direction were used and 1000 and 1008 in the southbound direction. The transponder logs record the starting and ending plaza for paying SOVs, along with their starting time and paid toll. The assumption was made that drivers do not exit the MnPASS lane between their starting and ending plaza. Therefore, a paying SOV is counted at each plaza between their starting and ending plaza. If the critical plaza lies between the starting and ending plaza, the vehicle is counted as a paying SOV. Cross-referencing these two data sources, independent counts for SOV and HOV can be determined. SOV in this case excludes business accounts which are defined as those accounts with more than two transponders.

Table 2-9 Field Experiment Average of Elasticities

Demand Measure	Mean	Median	Std Dev
(1) Plaza 1003			
Density (FE)	-0.9719	0.1245	7.385
S_{MnPASS} (FE)	-1.192	-0.0719	7.920
Density (Control)	0.5058*	0.4613	0.8900
S_{MnPASS} (Control)	0.1377*	0.0495	0.3914
(2)			
Plaza 3005			
Density (FE)	-2.769	-0.2377	18.05
S_{MnPASS} (FE)	-1.624	-0.2695	9.520
Density (Control)	0.6654*	0.5440	0.0236
S_{MnPASS}(Control)	0.3131*	0.2836	0.1752
Plaza 3012			
Density (FE)	-2.581	0.7562	22.44
S_{MnPASS} (FE)	-2.8290	0.4052	22.29
Density (Control)	0.6925*	0.6035	0.2870
S_{MnPASS} (Control)	0.4522*	0.3965	0.3129
(3) Plaza 1003			
Density (FE)	0.2110*	0.2307	0.0874
S_{MnPASS} (FE)	0.0981*	0.1011	0.0755
Density (Control)	1.016	1.159	3.148
S_{MnPASS} (Control)	0.8144	0.9299	2.447

* Significant at 0.05 significance level
Time of Day: 7:00-9:00
(1) I394: FE: 2012-10-8 to 2012-11-2, Base: 2011-10-10 to 2011-11-4, Control: September 2011 and 2012
(2) I35W: FE: 2012-10-29 to 2012-11-23, Base: 2011-10-31 to 2011-11-25, Control: October 2011 and 2012
(3) I394: FE 2012-12-10 to 2012-12-21 & 2013-1-7 to 2013-1-25, Base: 2011-12-12 to 2011-12-23 & 2012-1-9 to 2012-1-27, Control: November 2011 and 2012

Vehicle counts from the field experiment as well as the baseline period were gathered. The tolls paid by SOVs were used to find the average price paid for each period. The changes in price and SOV vehicle counts were used to determine the elasticity to price of paying SOVs. Elasticity for HOVs as well as total elasticity were also calculated.

One month before each field experiment were compared to the same period in 2011. The pricing plan used during the two periods was the same and also matched the prices during the baseline period. Elasticity results were calculated using the net change in price and vehicle counts, subtracting any changes occurring between 2011 and 2012 in the control period.

Elasticity for SOVs and HOVs follows the same format as Equation 2.3 where demand is replaced with flow (veh/hour). HOV and SOV vehicle counts for the MnPASS lanes during the three field experiments were measured at the respective critical plazas. SOV counts are for individual accounts and exclude business accounts or those with more than two transponders tied to one account. The values are converted to flow (vehicles/hours) and are displayed in Table 10. Average prices can be found in Table 2.7.

Using the change in vehicle flow and the average price change between the two periods, elasticity values were calculated and are displayed below in Table 2.10.

Table 2-10 Field Experiment Elasticity of Average Vehicle Flow

	Flow in Vehicles/Hour (Q)					
	Baseline (B)	Field (E)	Δ (%)	Control Δ (%)	Net Δ (%)	Elasticity
(1) Plaza 1003						
Total HOT	1083	1111	2.581	1.211	1.370	0.4086
HOV	665	636	-4.458	-8.391	3.673	1.095
SOV	416	475	14.29	16.62	-2.333	-0.6958
(2) Plaza 3005						
Total HOT	1043	1167	11.96	16.75	-4.791	0.0828
HOV	738	808	9.606	11.09	-1.481	0.0256
SOV	305	359	17.66	32.64	-14.97	0.2587
Plaza 3012						
Total HOT	905	1071	18.30	19.33	-1.033	0.0365
HOV	678	789	16.40	16.19	0.2101	-0.0074
SOV	227	281	23.96	25.84	-1.882	0.0664
(3) Plaza 1003						
Total HOT	817	821	0.4092	-4.108	4.517	0.1091
HOV	442	412	-6.779	-9.412	2.633	0.0636
SOV	375	409	8.867	4.519	4.348	0.1071

Time of Day: 7:00-9:00
(1) I394: FE: 2012-10-8 to 2012-11-2, Base: 2011-10-10 to 2011-11-4, Control: September 2011 and 2012
(2) I35W: FE: 2012-10-29 to 2012-11-23, Base: 2011-10-31 to 2011-11-25, Control: October 2011 and 2012
(3) I394: FE 2012-12-10 to 2012-12-21 & 2013-1-7 to 2013-1-25, Base: 2011-12-12 to 2011-12-23 & 2012-1-9 to 2012-1-27, Control: November2011 and 2012

Results of vehicle flow for the three field experiments tend to validate earlier results, with a few exceptions. Both field experiments on I-394 saw a total net increase in flow. Previous results showed net increases in density and S_{MnPASS} during these experiments. The first field experiment saw net increases in total flow and HOV. Although there was a net decline in SOV flow, there was a large increase seen in both the field experiment and control period. The observed net price change during the first field experiment was positive. This is due to an increase in demand as well as the increase in price from the pricing plan at higher density levels as explained earlier. With the modified pricing structure, it was expected that prices would be lower at lower densities and higher at higher densities. This complexity makes analysis of the first field experiment more difficult to discern.

Results from the I-35W field experiment resulted primarily in net decreases in flow. This corresponds to a net decrease in price. Changes were greater and more consistent at plaza 3005, compared to plaza 3012. Plaza 3005 saw net decreases in both SOV and HOV flow, while plaza 3012 saw a net decrease in SOV flow, but a very small net increase in HOV flow. Total flow at plaza 3012, however, decreased. Elasticity results are displayed in Table 10. Results from the third field experiment were the most consistent with net increases in SOV and HOV flow. These increases corresponded with an increase in price. These led to the positive elasticity values in Table 10.

2.3 Conclusions

With the increasing interest in HOT lanes around the US, it is important to understand drivers' responses to varying toll prices. Specifically focusing on the MnPASS lanes on I-394 and I-35W in Minneapolis, this study found drivers paid between $60 and $124 per hour of travel time savings. Consistent with other studies, these values suggest drivers are paying for more than just travel time savings, but other factors such as reliability.

Analysis of driver elasticity using various methods yielded positive demand elasticity to price. Both SOVs and HOVs increased usage of the MnPASS lanes with higher prices. Statistically significant elasticities ranged between about +0.03 to +0.85. The increased demand resulting from higher prices (and decreased demand from lower prices) is likely a result of driver perception of the posted price. Although in reality the price only reflects the conditions on the MnPASS lane, drivers' likely view the price as an indication of time savings and congestion on the regular lanes, suggesting higher prices provide greater time savings. No travel times or congestion levels are made available to drivers entering MnPASS corridors, therefore, the MnPASS price may act as a signal of downstream congestion. Drivers must make a quick decision whether to use the MnPASS lanes and the posted price acts as one important factor. Other intangibles also influence a user's lane choice decision. In any case, drivers are consuming different goods when the toll varies, because time savings is not constant. These different goods represent different demand curves rather than movement along a single downward sloping demand curve (Beggs 2010). Therefore, although price is higher, quantity consumed is also higher.

3 Development of basic micro-simulation model

3.1 MnPASS Corridors

The MnPASS system is currently deployed in two freeway corridors. The original deployment was on I-394 which was also the developing ground for the dynamic pricing algorithm. I-35W was the second MnPASS corridor, which utilizes the same algorithm but introduced a different access design. Currently several other corridors are in various stages of MnPASS implementation.

3.1.1 Interstate 35W

Modeling I-35W and part of I-35 begins with establishing boundaries. The total road length is approximately 28 miles spanning from downtown Minneapolis to the southeast corner of Scott County near 260th St. Traversing north from the southern boundary, the MnPASS system begins at Burnsville Parkway and ends when downtown is reached. This 14 mile road section is slightly longer than the 11.5 mile southbound trip with the MnPASS system beginning at 42nd St. and ending at Burnsville Parkway. A map of the sections of highway used for modeling purposes is shown in Figure 3-1. The figure shows the particular sections starting at the north and moving to the south.

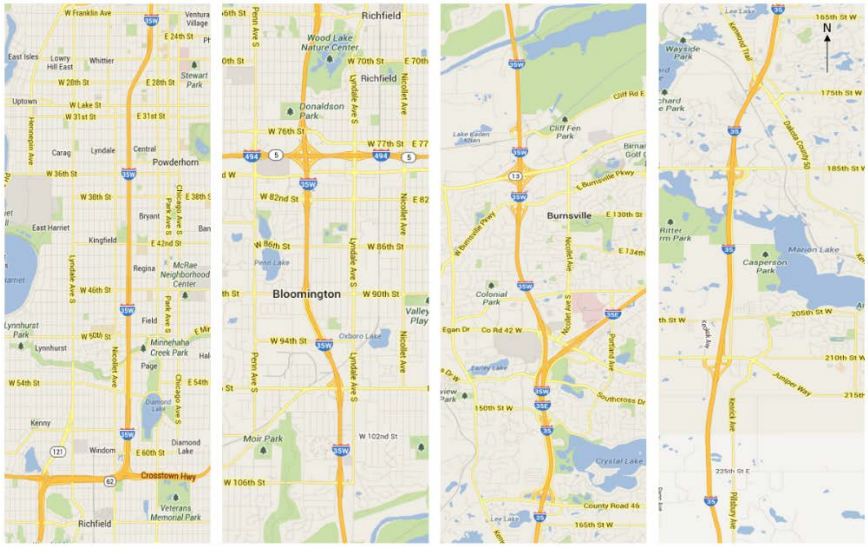

Figure 3-1 I-35W Road Sections of Interest

Starting from the southern side of downtown Minneapolis, I-35W has four general purpose (GP) lanes in both directions. The northbound direction has a fifth lane that is restricted to high occupancy vehicles (HOV), buses or single occupant vehicles (SOV) willing to pay a fee to use the high occupancy toll (HOT) lane. South of the Hwy 62 interchange, the southbound number of GP lanes reduces to three and sometimes bottlenecks to two while still maintaining access to the HOT lane.

At the start of the northbound commute from the southern end of the MnPASS system, there are two GP lanes accompanied by the HOT lane. The number of GP lanes increase to three just south

of I-494 and then reduces back to two near the Hwy 62 interchange. Four GP lanes and the HOT lane appear north of the Hwy 62 interchange and remain until exits for downtown Minneapolis and the I-94 interchange.

3.1.2 Interstate 394

Starting on the western end, Figure 3-2 shows I-394 beginning at Gleason Lake Dr. and ending at I-94 interchange. The I-394 corridor is 11 miles long and has three lanes in both directions, two of which are general purpose lanes and one of which is the HOT lane. Approximately 8 miles of the corridor from west to east are appropriately striped to contain the HOVs and SOVs willing to pay, but the remaining 3 miles contains a barrier separated reversible section of highway which funnels vehicles into downtown Minneapolis during the morning peak demand and funnels them out of the city during the afternoon peak demand.

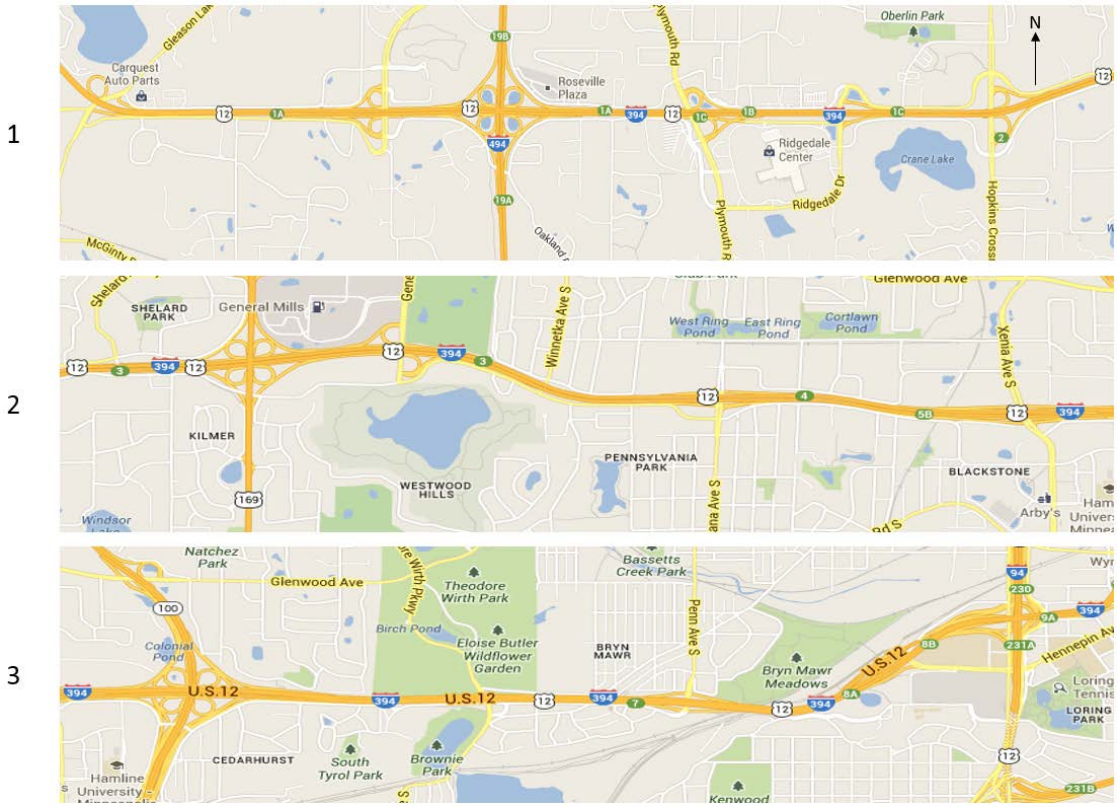

Figure 3-2 I-394 Sections of Interest

Table 3-1 I-35W and I-394 Roadway Information

Category	Highways	
	I-394 (WB & EB)	**I-35W (NB & SB)**
Number of exit/entrance ramps	23	44
Total Length of Managed Lanes [miles]	11	25.5
Length of Closed Access Points [miles][1]	12.8	6.4
Length of Open Access Points [miles][1]	4.5	20.7
Number of HOT Lanes	2*	2
Design Speed Limits [mph]	55	55**
Number of Open Access Points	9	16

*There are 2 HOT lanes west of Hwy 100. East of 100 is where the reversible section begins.

**Posted speed limit changes to 65mph south of I-494 and 70mph south of Co. Rd. 42

[1] Lengths found in Aimsun

Table 3-1 quickly allows one to view the differences between the two different interstate highways. The I-35W model in Aimsun is approximately double the length of the 394 model. Another big difference between the two networks is the length proportion of open access points to closed access points to the HOT lane. The I-394 network has much longer stretches of highway that restrict drivers from entering the facility, whereas the I-35W network has far fewer occasions of these.

3.2 Developing Geometry in AIMSUN

As described in the project work plan, the MTO capitalized on prior work to accelerate the process of modeling the two MnPASS corridors. Specifically, as part of an ITS Institute funded project, the entire Twin Cities freeway system was modeled in a microscopic simulation application. Although the results of that project were not exactly what was required in this case, it offered a considerable savings in effort. A figure of the existing freeway-wide model can be seen in Figure 3-3.

Two separate models were extracted and expanded to include the correct, functional geometry of the HOT lanes. This involved explicit modeling of the open and restricted access areas, controls for the reversible section of I-394, as well as additional information pertaining to the pricing algorithm structure. Finally, during the ongoing calibration of the models, a number of functional details had to be implemented to ensure correct operation. Figures 3-4 and 3-5 show the modeled geometry for the two MnPASS corridors.

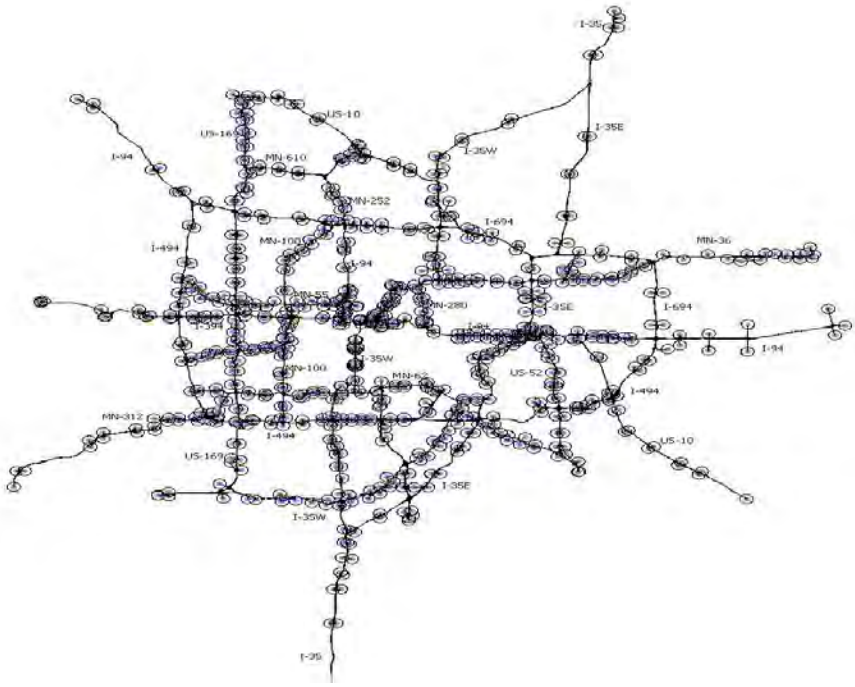

Figure 3-3 Twin Cities Freeway and Major Highway Network Model

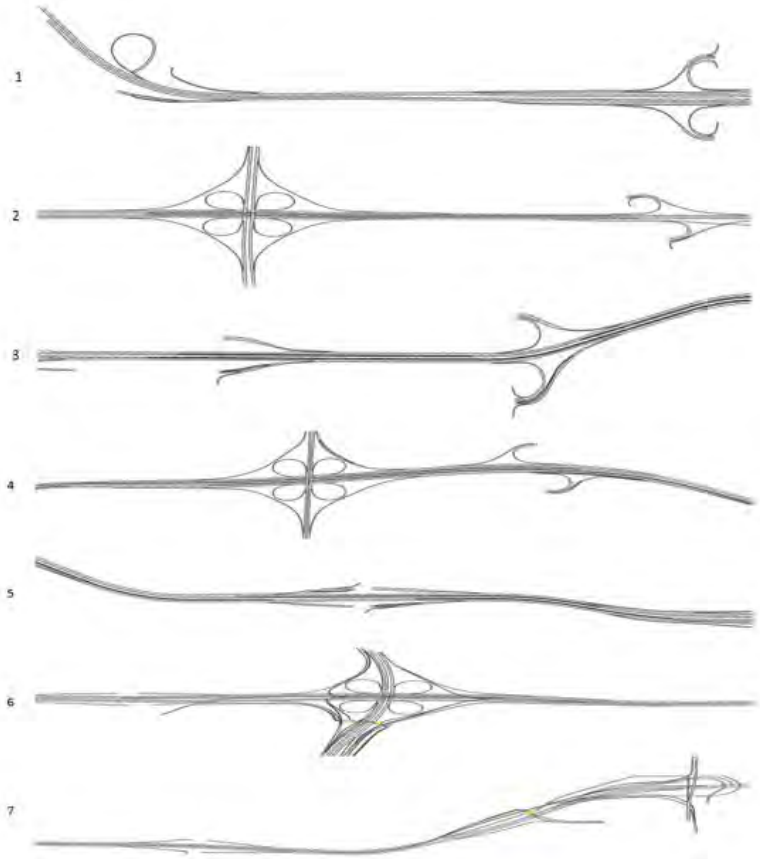

Figure 3-4 I-394 Microscopic Simulation Model Geometry

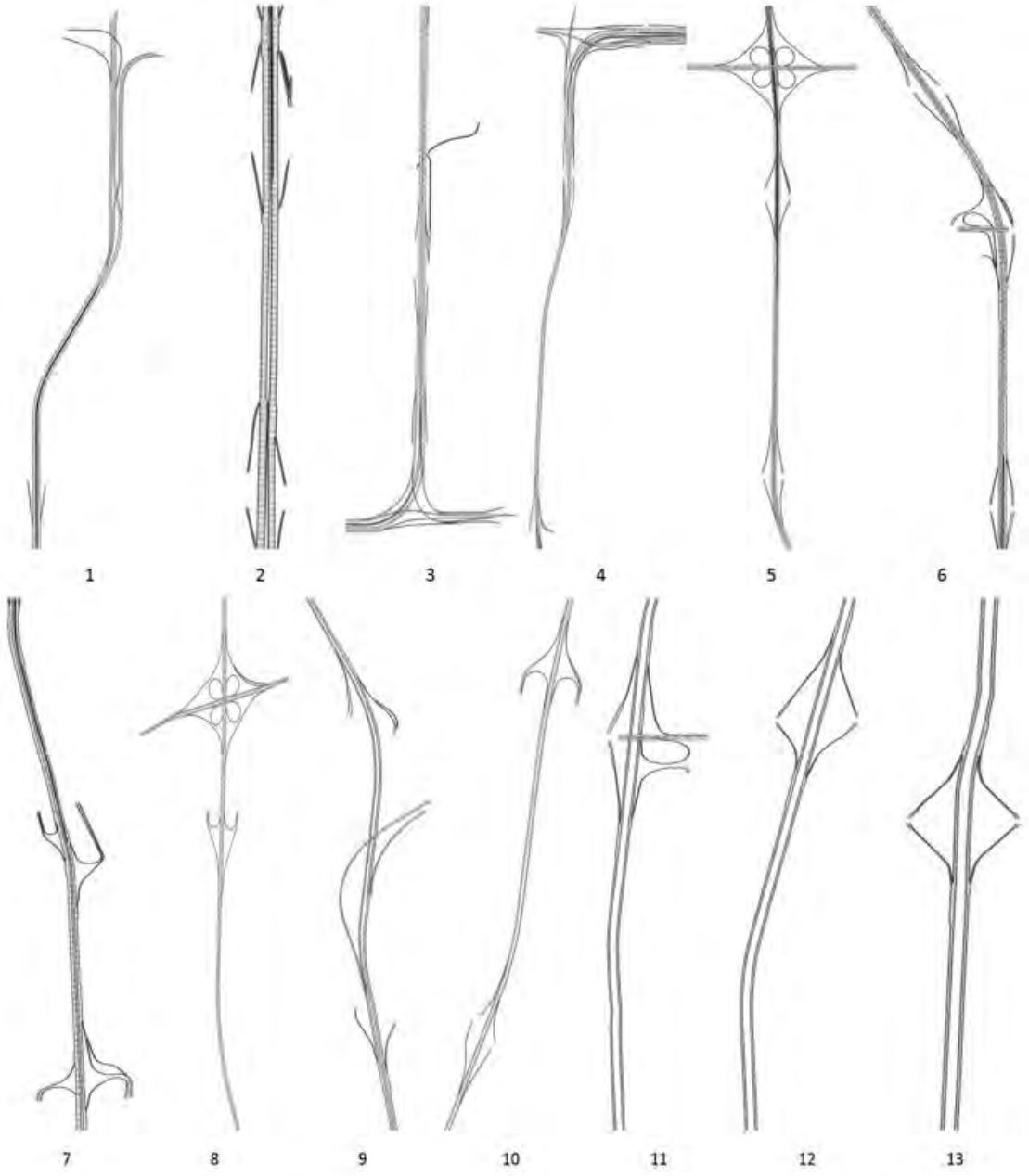

Figure 3-5 I-35W Microscopic Simulation Model Geometry

3.2.1 Refinement of geometry

In order to replicate traffic along the two corridors it was essential to have up-to-date geometry replicated in the models so traffic would move as intended. This was done using aerial imagery provided by Google and Bing and overlaying the geometry on the images. The HOV lanes along the corridor, when access is restricted, are modeled as separate roads that run parallel to the main line. The start and stopping points of the HOV lanes were chosen based on the actual locations of changes of access. Wherever there was open access the HOV was merged with the mainline to allow entry and exit. Figure 3.6 shows a section of 35W at W 76th St. where the restricted access

begins on the southbound lanes and the mainline and HOV lanes are separated. It also shows the northbound HOV lane being merged back in with the main line.

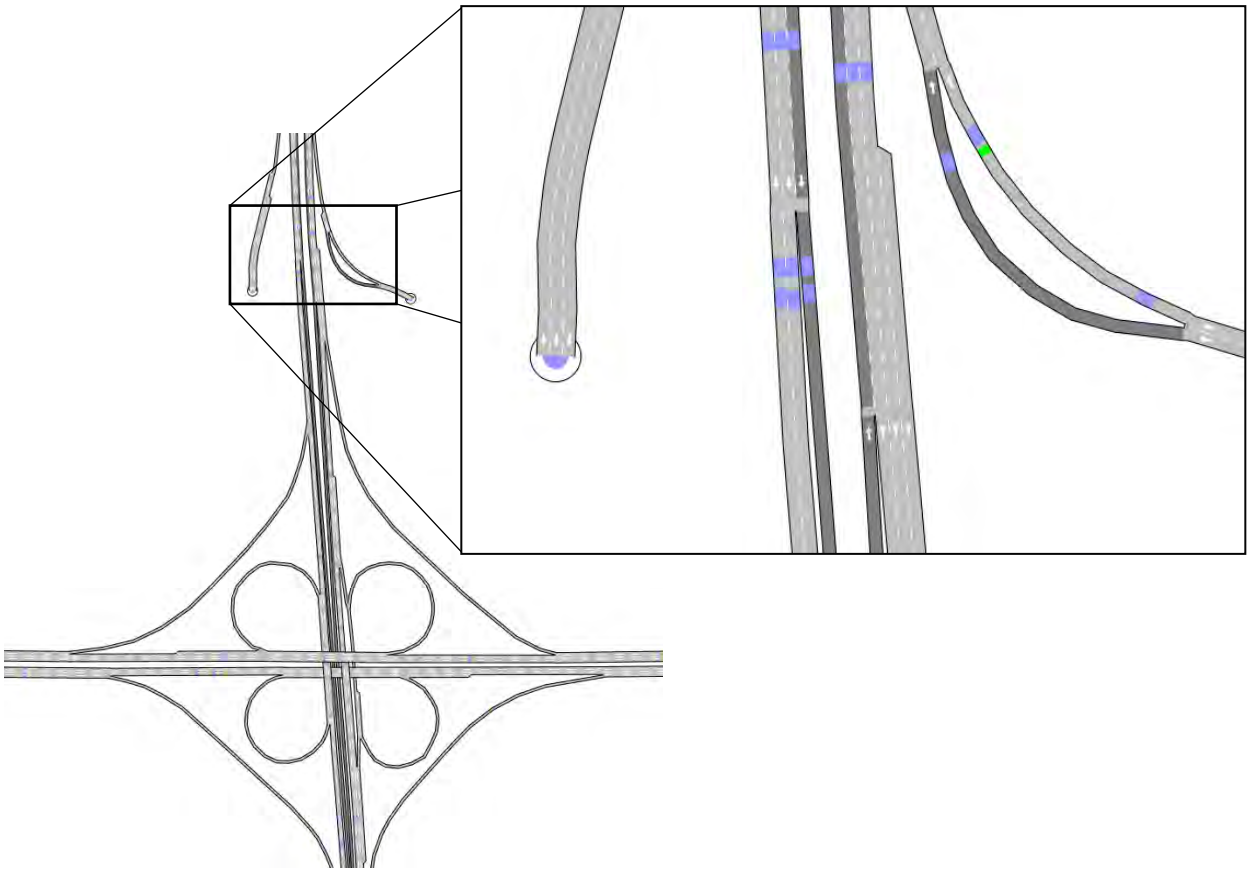

Figure 3-6 HOV Lanes at I-35W and W 76th St

Figure 3-7 I-35W and 76th St Aerial Imagery (Google Maps)

3.2.2 Simulation Run-Time Controls

3.2.2.1 Reversible Section

Since in the simulation environment there is no way for a single section to accommodate switching traffic directions, the I-394 reversible lane was modeled as two roads placed on top of each other: one heading east and the other heading west. Specific traffic strategies implemented based on the time of the simulation ensure that traffic is only travelling in a single direction at any time. This is accomplished using traffic management scenarios similar to those used on the real I-394. To stop all traffic flow in one direction of the reversible section, all sections that are entrances for that direction are closed off to traffic. The closures run at the same time as the corresponding gates that control the reversible portion. An example of this can be seen in the figure below.

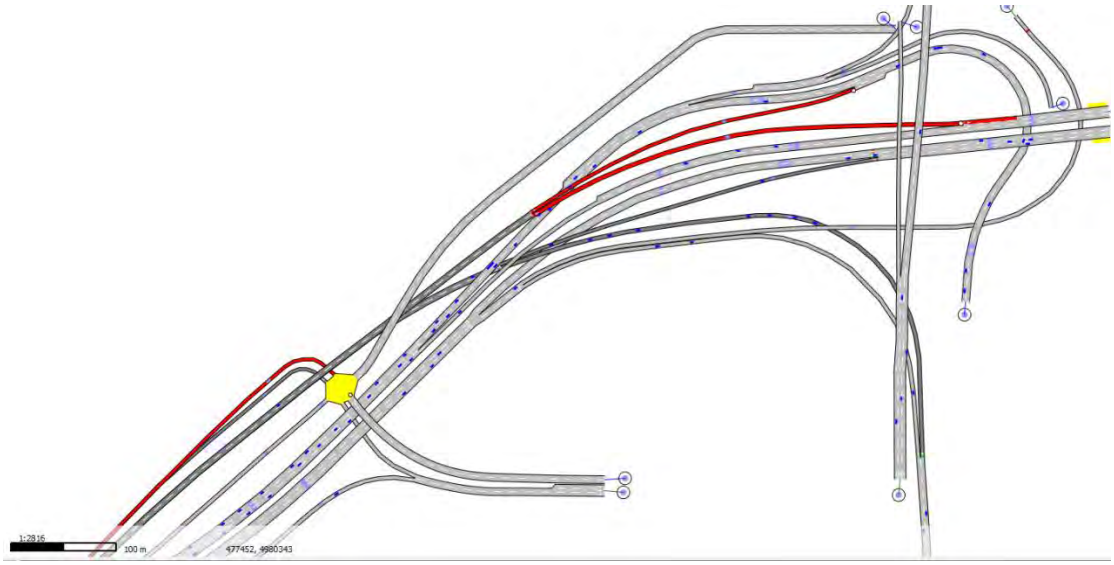

Figure 3-8 Westbound I-394 Reversible Closed

3.2.2.2 Cloverleaf Intersections

The simulated vehicles of Aimsun have difficulties using the cloverleaf interchanges with collector roads and distributor roads as intended. The first issue arises when vehicles attempt to use them as a bypass. For example, as in the figure below, vehicles travelling Eastbound on I-394 will leave the main line of I-394 and use the lanes intended for cars entering and exiting I-394 from a cloverleaf or otherwise, then rejoin I-394. Other than the occasional accidental turn, this is a rare vehicle behavior. This problem was solved by using Force Turnings, making all vehicles that would continue on I-394 maintain their course on the main line. This prevented unrealistic congestion levels in and around the cloverleaf intersections.

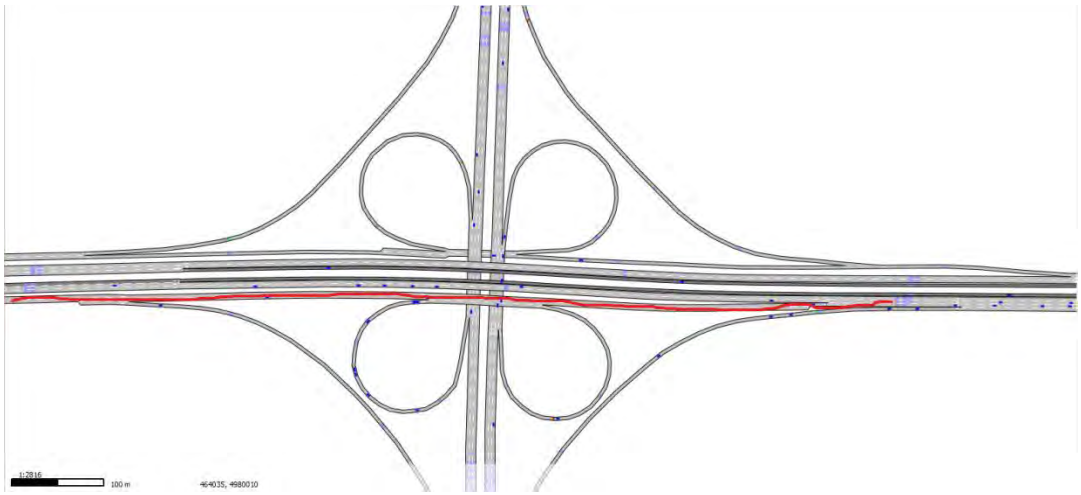

Figure 3-9 Red Line Showing Path Prohibited by the Simulation Controls

3.2.3 MnPASS Relevant Information

Several pieces of information are relevant to the functionality of the MnPASS Pricing Algorithm that are logical to define and save along with the simulation model. The AIMSUN simulator allows the user to extend the context of any of the model building blocks and enter information that is location specific. The current MnPASS Pricing Algorithm has a number of definitions and concepts in its structure and the ones that are location specific are saved with the model.

- **CorridorID:** This parameter is an attribute of a roadway section and all sections that are in the same group with respect to pricing all belong to the same corridor.
- **SectionOrder:** Section order could be derived at runtime through the Application-Programming Interface (API) but it is more efficient to store this information along with the network. Through this attribute the program knows the downstream sections and their detectors.
- **IsGate:** This attribute is also defined at the level of a section. Sections that have this attribute set indicate that they are on the locations of charging stations in the real world.
- **HOTDetector:** This attribute is defined at the detector level to designate detectors in the HOT lane. This reduces the error that is associated with the misidentification of detectors in the general purpose lanes as being located in the HOT lane in cases where not all lanes in a section extend to the full length.

All these attributes are custom additions to the section or detector objects of the simulation application and are set by the user during the implementation of the geometry. They do not participate with the traffic simulation but are used by the attached pricing algorithm.

3.3 Demand Changes to Simulation Model

3.3.1 Extraction of Geometries from the Regional Model

The extraction of the I-394 and I-35W Micro networks required the use of the macro model of the entire Twin Cities region. This was done by identifying a subarea to be included in each corridor. In order to reduce the errors that may arise from intersections at the ends of on/off ramps, the model was extracted in such a way that the intersections were cut out as seen in

Figure 3-10. Once a single polyline enclosed the desired roadway it was defined as a sub-network. This allowed Aimsun the ability, given a Macro demand run, to differentiate the smaller section of the network and not only create Centroids for it but Traversal Matrix Demand Tables for the smaller portion. From here all 24 demand intervals were run in order to create 24 Traversal matrices for the smaller portions of the network.

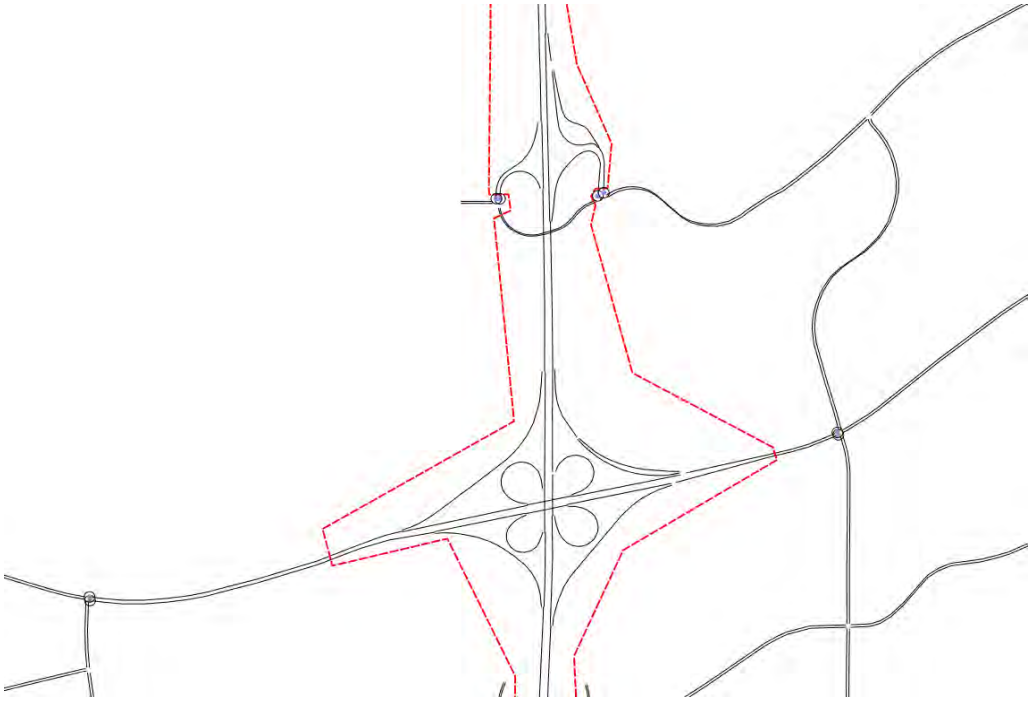

Figure 3-10 Example of the I-35W Subarea Around TH-13

Once all traversal matrices were created the network was cleaned up of all unnecessary information such as geometry outside the area of interest, Full Network demand, etc. This was done by saving the Full Network under a new file name and deleting unnecessary information. This was required due to the large size of the Full Network and the large lag time between opening, closing, saving, etc. In total the Full Network is roughly 800MB, compared to the size of each of the two corridors after cleanup of around 2MB. This was essential since many of the network tweaks needed to calibrate the model would need the simulation restarted before they could take effect.

3.3.2 Demand adjustments

3.3.2.1 Choosing a Date for a Real Data Set

For the purposes of both model calibration and to guarantee better realism of the demand than that described by the RPM, a date of typical traffic conditions was identified. For the purposes of this task and for the calibration of the model one day on each corridor was selected. Following the procedure described later in this section any other day can be selected and used for the experiments. Current days are:

- I-394 – November 29th 2011 (Figures 3.11 and 3.12)
- I-35W – November 8th 2012 (Figures 3.13 and 3.14)

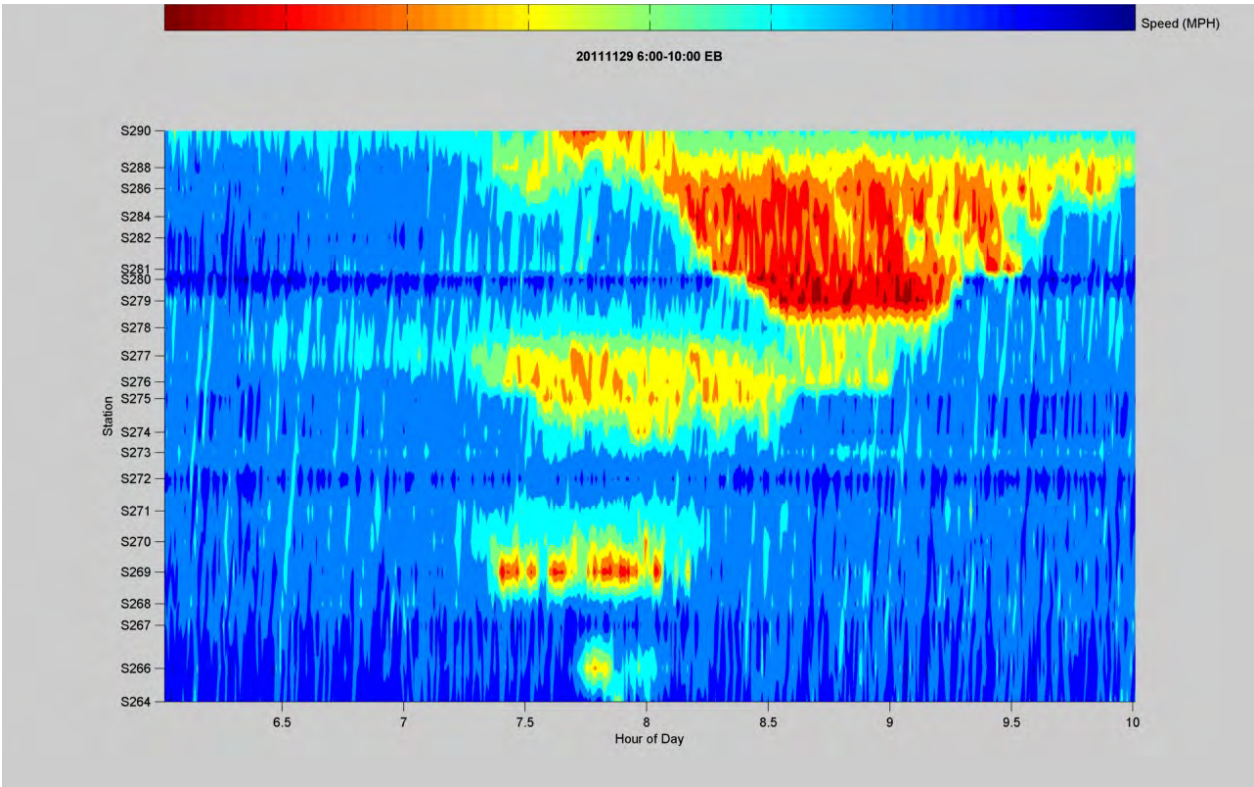

Figure 3-11 Speed Contour Plot for I-394 EB, AM Peak Period

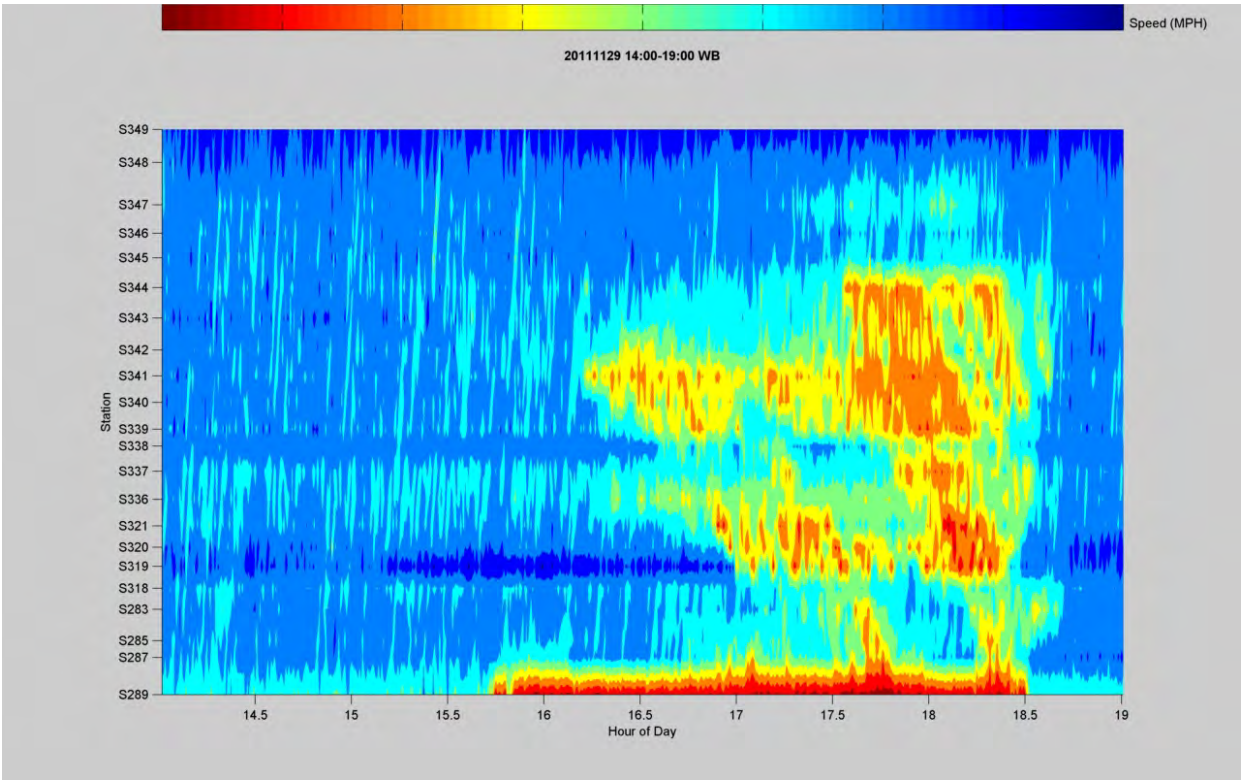

Figure 3-12 Speed Contour Plot for I-394 WB, PM Peak Period

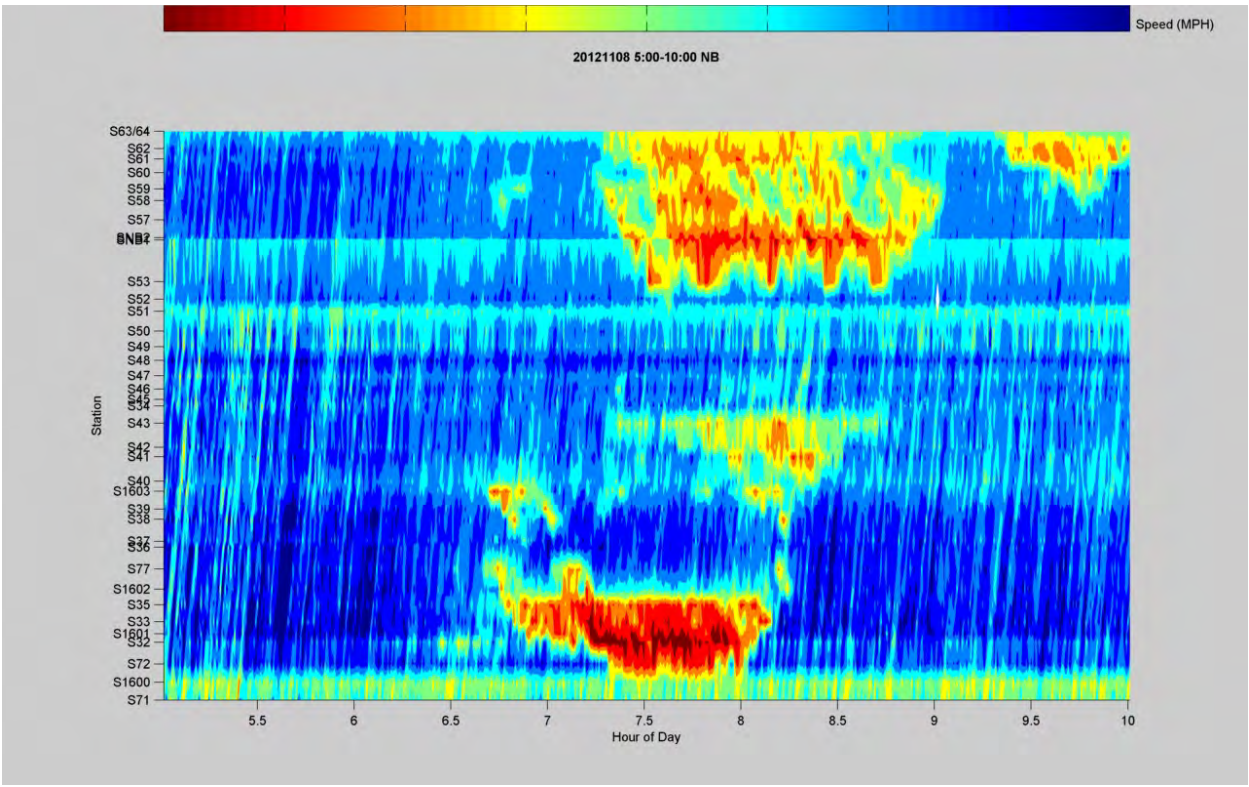

Figure 3-13 Speed Contour Plot for I-35W NB, AM Peak Period

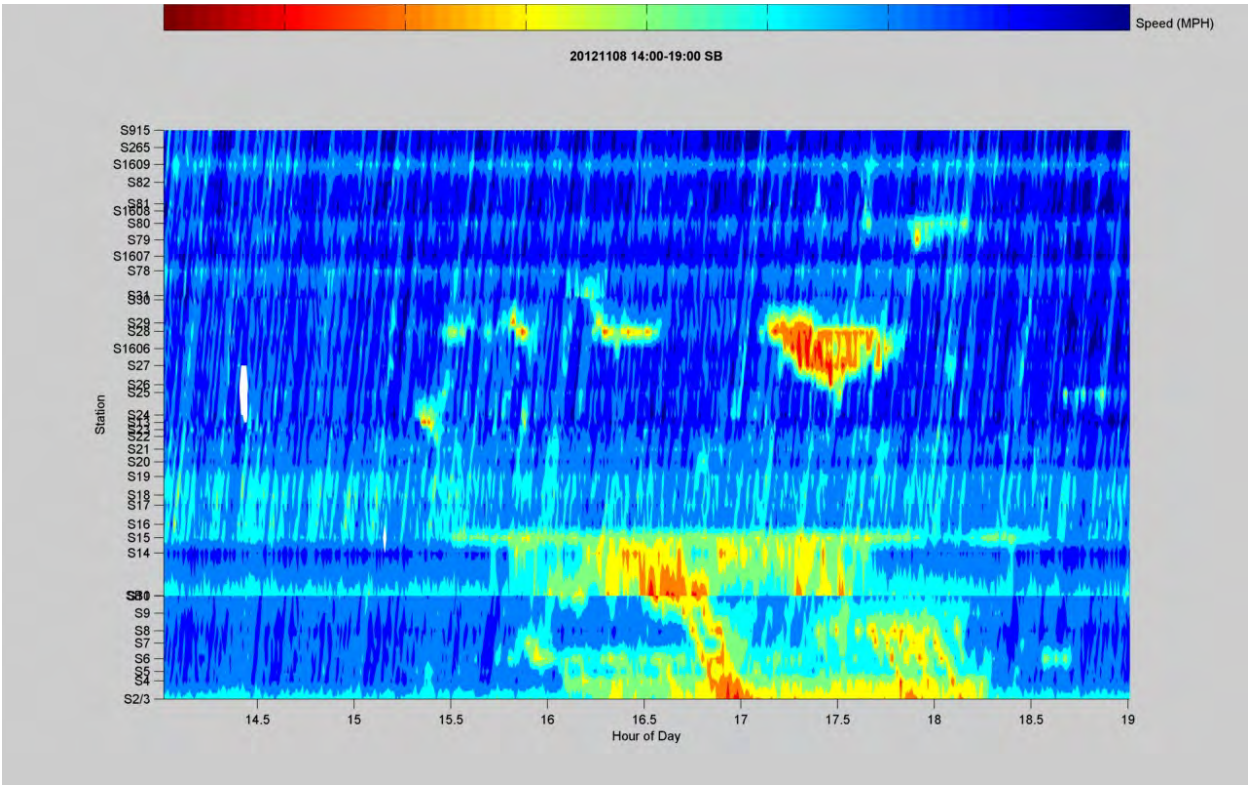

Figure 3-14 Speed Contour Plot for I-35W SB, PM Peak Period

The month of November was chosen each time for the pool of dates that would be examined. In November the roadways don't experience as much leisurely travel, and vehicles aren't yet affected by the poor driving conditions caused by ice and snow. Then, only Tuesdays, Wednesdays, and Thursdays were compared, as the roadways are less likely to experience vehicle traffic from vacationers or other occasional drivers on these days. Speed contour plots of the qualifying days were then compared to determine which date exemplified average traffic conditions.

Each of these days had the peak period demand calibrated based on actual detector measurements. For I-394 123 detectors in 59 stations are used to calibrate the demand and the model while I-35W requires 581 detectors in 120 stations.

3.3.2.2 Matrix Adjustments

The matrices created by the static traffic demand based on the Voyager data had to be adjusted to fit the detector data collected from MnDOT. For unknown reasons, Aimsun was unable to perform matrix adjustments that were acceptable for the purposes of this project. Therefore, adjustments had to be made by hand. Adjustments were made for all input centroids based on the adjacent detector(s) data. Given the total volume measured at an entrance ramp, the number of trips from this origin to all destinations was adjusted so the sum matches the detector measurements. For this method of matrix adjustment the Voyager demand model has to be assumed correct to an extent as the matrices are only adjusted line by line with multiplication.

For entrance ramps where there is an HOV bypass lane, the detector at that lane was used to adjust the HOV matrix demand. When there was no bypass lane the total between SOV, HOV, and trucks was used for the adjustment.

3.3.2.3 Correction of Demand Generated by the Macro Traffic Assignment

There have been cases where the demand had to be specifically adjusted since the error was great. An example of these few cases is the entrance ramp to I-394 from Lyndale Ave. When the transversal matrices were created for I-394, the input centroid for the Lyndale entrance ramp to I-394 was given zero vehicles. This was likely due to some geometric feature that made another entrance onto I-394 slightly shorter in distance. The macroscopic traffic assignment model will send all traffic to the shortest route until that route gets full, after which longer routes are considered. In this case the other route did not get full so the Lyndale Ave entrance remained empty. This is an artifact originating from the way the Regional Planning network is constructed. Specifically, vehicles originating on Hennepin Ave heading towards I-394 can access both the Dunwoody Blvd entrance and the Lyndale Ave ramp from the same point which is not true in reality. To correct this error, the volume data from the Dunwoody Blvd centroid was copied to the Lyndale Ave centroid. Both centroids were then adjusted as described in the previous section.

3.3.3 Scenarios for Calibration and Validation

During this task a number of demand scenarios were created for calibrating and validating the model. Through the matrix adjustment described above, the original traversal matrices were fixed to produce the right amount of traffic. The durations of these matrixes remained the same

as the one used in the RPM. These hour or 45 minute long matrixes do not generate correct transitions during the start and the end of the peak periods. To improve accuracy and realism the matrices for each vehicle type, SOV, HOV, and Truck, were split into 15 minute intervals and introduced in the model based on factors calibrated from real data. The following figure shows for example the loading of the I-394 morning peak period for SOVs. The original 5 matrixes generated 18 new ones to generate a more appropriate demand profile for each vehicle type.

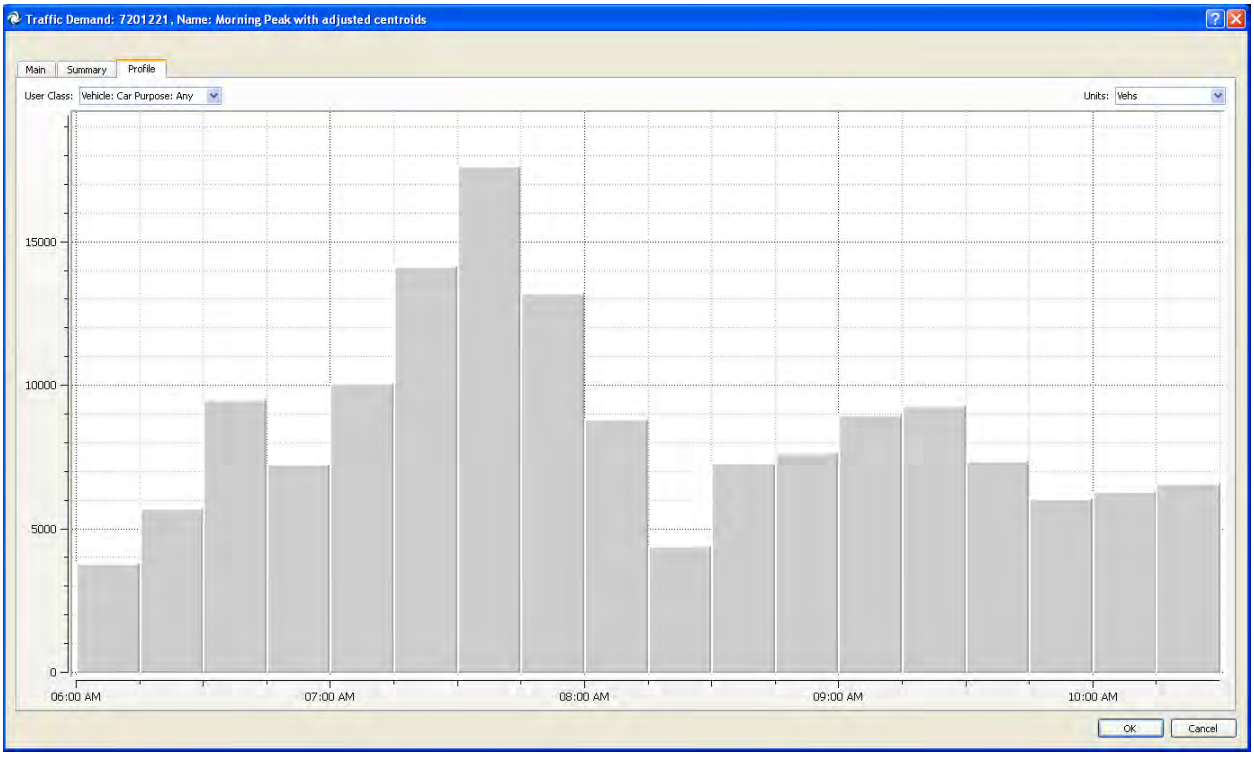

Figure 3-15 I-394 EB Morning Peak Demand Profile

4 MnPASS HOT pricing simulation

In order to test alternate pricing frameworks in a demand responsive environment, the Minnesota Traffic Observatory developed an extension routine for the Aimsun transport modeling software that mimics the behavior of the MnPASS Dynamic Pricing Algorithm. The Aimsun implementation of the MnPASS Pricing Algorithm is based on the operation of two routines, both run by the simulator inside Aimsun, communicating with the simulation with the Aimsun API. These two components each handle a separate aspect of the MnPASS Algorithm: one routine generates prices for the MnPASS network based on the traffic state, and another manages the subscriber vehicles, together forming a means of simulating the specific role of vehicles possessing MnPASS transponders inside the network. A detailed description of these components and how they can be integrated into an Aimsun network, is presented below.

4.1 MnPASS Pricing Algorithm Routine

The first routine required for simulating the MnPASS network is responsible for generating the price for each of a series of overlapping areas based on the current traffic state in the network. This routine uses geometric data from the Aimsun model to build a map of MnPASS pricing zones, referred to as Destinations, made up of plazas with the same end point. The price is calculated based on tables read from configuration files. The traffic state in each plaza is monitored throughout the simulation and a price is generated every 3 minutes. Data is communicated to the user and other processes through files on the disk.

4.1.1 Building the Pricing Corridors

The price paid by a vehicle using the HOT lane varies depending on where the vehicle entered the HOT lane, at one of several plazas each with the same Destination. Information describing how these plazas should be organized is specified using the custom attributes in the Aimsun model discussed in Section 3.2.3. This allows the MnPASS information to be closely related to the geometry of the roadway, both simplifying the process of creating the pricing corridors as well as the means of tracking vehicles during the simulation.

At the beginning of each simulation, the MnPASS Pricing Algorithm scans the sections in the network, reading the custom attributes. From these attributes the algorithm creates a key-value map of corridors and their sections, then sorts the sections into plazas. At this point, the tables used to determine the price are read from configuration files using the corridor identifier. Detectors are then associated with the sections to make traffic data available to the algorithm. Since the pricing algorithm only cares about the traffic in the HOT lane, only the detectors in this lane are used.

4.1.2 Generating Prices during the Simulation

Once the corridors have been created in the program, the simulation can begin and the MnPASS Algorithm begins generating a price. Whereas density must be calculated from loop detector data in the real MnPASS network, the Aimsun API provides this statistic with a simple function. In order to contain the values to calculate the 6-minute moving average of the detector density, the objects representing the detectors each maintain their own list of traffic density values. This list, and the average, is updated every thirty seconds and made available to the plaza (referred to as zones in the program) objects.

Every 3 minutes, the price is recalculated using the 6-minute moving average of the traffic density at each detector. For each zone, the downstream detector with the highest average density is chosen as the controlling detector. This detector's density is then used to calculate the price based on the rate tables from the configuration files. How this is done exactly is discussed in detail in the section on the *MnPASS Dynamic Pricing Algorithm* document (Section 1.1). In short, values in one table are used to translate the traffic density for a zone into a level of service. Prices are set to the default rate for the current level of service at the beginning of the simulation and increased incrementally with each integer change in traffic density, based on the values in the other table. Prices will default to either the minimum or maximum value for the current level of service if the computed price lies outside of this range. Each time the price is recalculated, the new price is shared with the routine managing the simulation vehicles. A description of this routine is presented below.

4.2 Methodology for Simulating MnPASS Pricing Operations

While modeling the MnPASS Dynamic Pricing Algorithm inside the simulation environment is relatively straightforward, given that the only input is detector data, integrating this routine alone into the simulation does not sufficiently capture the effects of the MnPASS system on the traffic network. Whereas in the real network individual drivers are responsible for observing the price of taking the HOT lane and acting on this information, the simulation engine that manages the vehicles in the model is not capable of this behavior. Therefore it was necessary to establish a methodology for emulating this behavior inside the computer.

4.2.1 MnPASS Subscription Assignment

Single-occupant vehicles using the MnPASS lanes are required to have transponders for electronic tolling purposes. Since not all vehicles are equipped with these transponders, a subscription choice model was developed to assign subscriptions to vehicles probabilistically based on their origin in the network. Transportation choice theory suggests that the decision to subscribe to MnPASS is based in part on the benefits that the MnPASS system provides to its subscribers. In the formulation of this model, this benefit is represented by the increase in accessibility to jobs that residents experience when they gain access to MnPASS lanes. For each origin, the number of jobs at all destinations reachable within 30 minutes is summed, using travel time matrices calculated from a shortest-path search based on the Metropolitan Council's 2009 RPM. This is done twice: once assuming the driver is not a MnPASS subscriber and once assuming they are. This provides the incremental accessibility benefit of having a MnPASS subscription which, along with origin demographics information, is used to model the choice of having a MnPASS subscription based on a given origin with a binomial logit model. Further details on the development of this algorithm are discussed in detail in "*Incremental Accessibility Benefits and HOT Lane Subscription Choice*" by Owen et al. (2014).

To generate subscription statuses for vehicles in simulation, for each vehicle that enters the network, the location of entrance is used to probabilistically determine an origin TAZ for that vehicle based on macroscopic path assignments generated using the 2009 RPM. The proportion of households with MnPASS accounts in the selected TAZ is then taken as the probability of the vehicle having a transponder. Because a vehicle's subscription status is unlikely to change on a

daily basis, this information is generated only once for each batch of simulations, during the first simulation, then saved and read for future simulations.

While this model represents well the residences of transponder owners (what share of an origins residents own transponders), those users need to be assigned to destinations. The initial model begins with the assumption that the probability that a vehicle is equipped with a transponder is equal to the percentage of the population in a given traffic analysis zone (TAZ) that report transponder ownership, based on billing address locations. During verification of the model, it was determined that this assumption underrepresented the number of transponder owners in the I-394 network (since transponder owners are probably more likely to use the MnPASS lanes than non-transponders owners in a zone). Therefore this model was adjusted to incorporate a modification factor to adjust the probability of transponder ownership based on their network origin. This is justified by the assumption that vehicles in this region of the traffic network, which contains a MnPASS lane, are more likely to be equipped with transponders than their origin TAZ might suggest because of the increased proximity of a MnPASS system. Further work is recommended to better match subscribers and non-subscribers to destinations, routes, and freeway entrances, which is particularly important for simulating proposed MnPASS corridors without existing usage data.

4.2.2 High-Occupancy Toll Lane Choice Model

To simulate the choice subscribers make of whether or not to use the MnPASS high-occupancy toll (HOT) lane, a lane choice model was developed extending previous work (Carrion, 2010). The binomial logit model determines the probability of a vehicle using the HOT lane based on estimated travel time and travel time variability for both the HOT and general-purpose lanes, as well as the posted toll price. Travel time variability is defined as the 90th percentile – 50th percentile travel time. Increases in expected travel time or travel time variability for a particular lane will decrease the probability that a subscriber will use that lane. Expected travel times and travel time variability are calculated for each subscriber from a travel history database. The coefficients of this model were calibrated using real data of vehicles traveling along I-394 eastbound to Downtown Minneapolis, provided by the Metropolitan council. Detailed results of the calibration process are described in "*HOT or Not: Driver Elasticity to Price and Alternative Pricing Strategies on the MnPASS HOT Lanes*" by Janson (2013).

In the simulation platform, vehicles require a training period to inform their choices, consisting of approximately 25 simulations with identical vehicle trip distribution run consecutively. During each simulation, vehicles that are eligible to use the HOT lane, as determined by trip eligibility tests and the MnPASS Subscription model, have their probability of using the HOT lane generated and a "choice" assigned. At the end of each simulation the vehicle's "choices" are recorded to a database, along with the associated travel times and tolls paid, and the next simulation is run. The choice to use 25 runs is based on an investigation of the model's convergence. More analysis on this point can be found in Section 6.4.

Although the methodologies described in Jansen (2013) describe a lane choice model based on the driver's choice of whether or not to use the HOT lane for their entire trip, after efforts to calibrate the simulation for the I-394 AM Peak period, it was found that this could not

demonstrate sufficient demand for the HOT reversible lane leading to downtown Minneapolis. Since the reversible lane is separated into a different pricing zone, it was suggested that some drivers may opt to break up these two choices and only use the reversible lane even if they were eligible to use the lane before this point.

To achieve this, the lane choice model was incorporated into the I-394 model twice: once for the non-reversible lanes west of TH 100, and once for the reversible lane east of TH 100. The travel times reported to the database are those for the individual trip segments, with the records for each trip entered into a separate database, one for each decision. Since making this change, the number of simulation vehicles observed in the reversible section over the course of the AM Peak period has more closely matched the real data used to verify results. The results from three different alternative implementations of the Lane Choice model are presented in Section 6.1.

4.2.3 Modeling the MnPASS Lanes

In order to model the functionality of the MnPASS lanes, it was necessary to be able to influence the path of a vehicle at the lane level. Aimsun provides this functionality by way of "Reserved Lanes." These are lanes in a section that only allow vehicles of a certain class, much like the MnPASS lanes but generalized for greater flexibility. To use these to implement a model of the MnPASS system, in each road segment containing an HOT lane, the left-most lane was designated as Reserved Compulsory for vehicles of type HOT. This designation triggers the simulator to send all vehicles of type HOT to that lane, unless their intended route prohibits it.

During each simulation, each vehicle that enters the network is looked up in a table of subscribers using the vehicle's Aimsun ID number, with the exception of the first simulation of a batch, during which the subscriber information is generated as discussed in Section 4.2.1. In order to ensure that vehicles are "the same" (i.e. have the same origin, destination, and departure time associated with the vehicle's ID number) from run to run, the same random seed is used for each simulation and all simulations in a batch are run on the same machine.

If the vehicle is recorded as a subscriber, its route is analyzed to determine where it would enter the MnPASS system and what prices it would pay if it did. This information is then fed to the LaneChoice algorithm so a choice can be made, as described in the "High-Occupancy Toll Lane Choice Model" section. If the vehicle "chooses" to take the general-purpose lanes, then the vehicle is released unchanged. If, however, the vehicle decides to take the HOT lane, its vehicle type is changed to HOT, and the simulator will direct it to take the reserved HOT lane. All subscribers have a number of their attributes saved during the length of their trip, including the lane they chose, the toll they paid, their origin, destination, and entrance time. When they exit from the network, this information is retrieved and used to calculate travel time and log the vehicle's experience to a file. At the end of the simulation, this file is read and its values added to the LaneChoice database to inform future travel time estimates, after which the next iteration can begin. A flow chart depicting this process is shown in Figure 4-1.

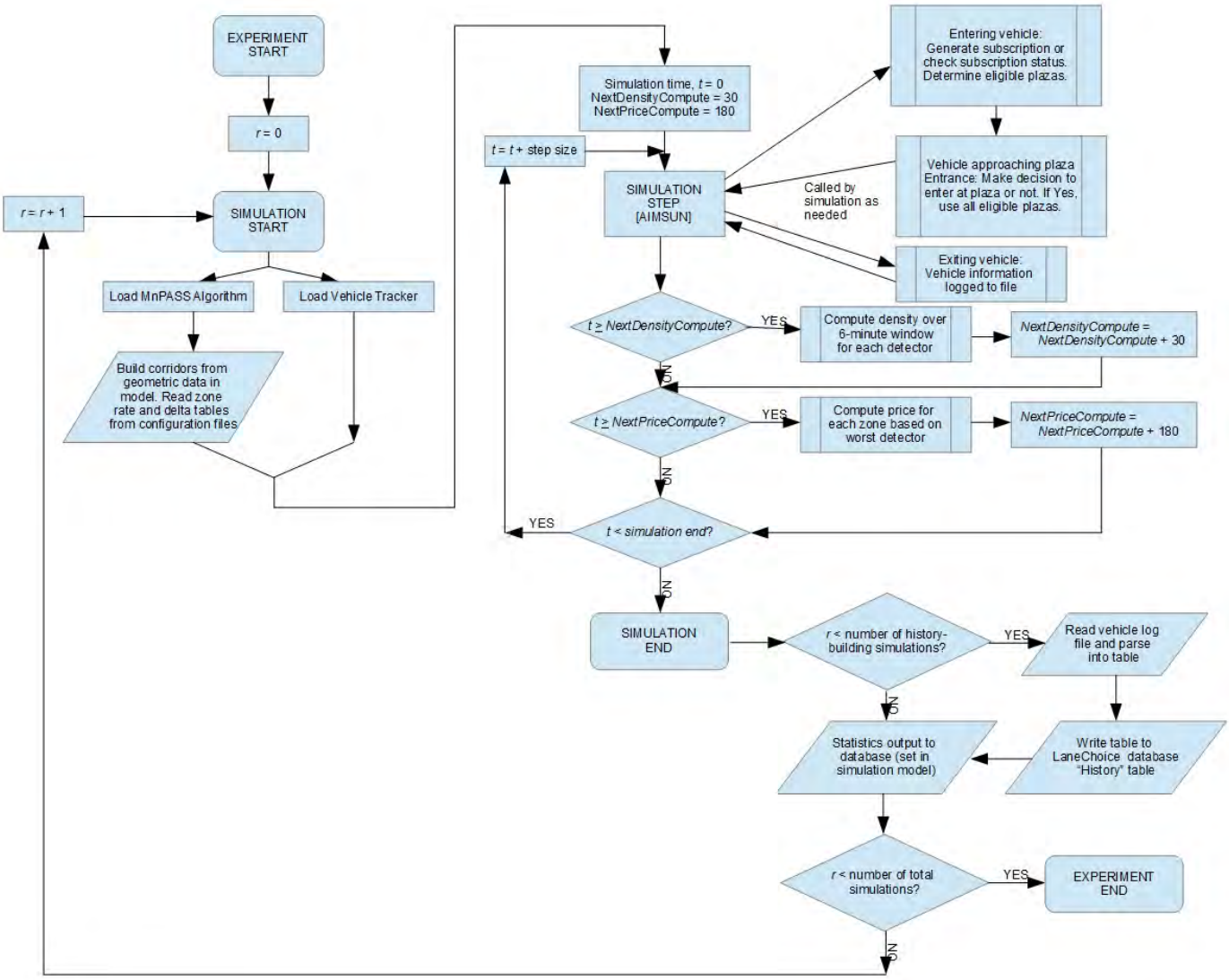

Figure 4-1 Flow chart of the simulation training period algorithm.

4.3 Setting up a MnPASS Test Network

The following section provides detailed instructions on how to install, configure, and run the suite of tools for testing the MnPASS Algorithm in a simulation environment. This will describe the process of installing the required programs, adding the necessary corridor information to the network, creating the necessary configuration files, running the program, and viewing the results. The examples and figures used are from the I-394 EB implementation of the MnPASS algorithm. All other corridors have similar configurations but possible different number of zones and pricing tables.

4.3.1 Installing Required Programs

In order to use the MnPASS Algorithm testing software, you must be using the Aimsun transport modeling software to simulate the traffic network. Due to some changes in the program functionality between versions, it is critical that Aimsun version 7 is used. Any other version will not be able to run the custom routines required to emulate the MnPASS system. It is also critical that the 64-bit version of Aimsun is used. Due to some bugs in the earlier releases of this version, it is advised that you use the latest possible release of this version. At the time of writing, the preferred version to be used is Aimsun 7.0.4 R25783 x64. Installing this program is outside the scope of this document, although it is a fairly simple process with considerable resources provided by the program developer, TSS - Transport Simulation Systems. Upgrading the HOT simulation application to a later version of Aimsun is possible but outside the scope of this project.

In addition to this, two other pieces must be installed in order for the programs to function. While Aimsun is installed with its own Python interpreter with all the standard Python modules, this leaves out many of the popular third-party modules that have been developed for Python. In order to use these modules, it is necessary to first install the exact same Python interpreter over the one installed by Aimsun, then to install the specific module that is required. For Aimsun 7.0.4 R25783 x64, the required Python version is 2.6.6 (r266:84297) 64-bit, the installer for which has been included with the additional files required for this project. The required module is the Numpy module, of which version 1.8.0 is the latest version for Python 2. Because the default installer for this module is not compatible with the 64-bit version of Python, an unofficial installer was obtained from a public repository hosted by the Laboratory for Fluorescence Dynamics at the University of California, Irvine. This installer is also included with the other files for this project.

For the sake of clarity, you must run the following provided installers in the following order:

1) Aimsun_7_0_4_R25783_W64_71d7.exe
2) python-2.6.6.amd64.msi
3) numpy-MKL-1.8.0.win-amd64-py2.6.exe

Once you have installed these programs, you must also modify your PATH environment variable so that you can execute the command-line script. To do this:

1) Open the Control Panel by going to *Start -> Control Panel*.
2) In *User Accounts and Family Safety*, click on *User Accounts*.

3) On the *User Accounts* page, in the left pane, select *Change my environment variables*.
4) In the *User Variables* group, either select the variable *PATH* and click *Edit…*, or if it's not there click *New…*.
5) If you created a new variable, set the name to *PATH*. If you did not change any of the installation directories when installing the programs above, you may simply add the following entries to the end of the Variable Value, separated by semicolons (see Figure 1). If you did change them, then these should be the installation directories you specified:
   - C:\Program Files\TSS-Transport Simulation Systems\Aimsun 7.0
   - C:\Python26

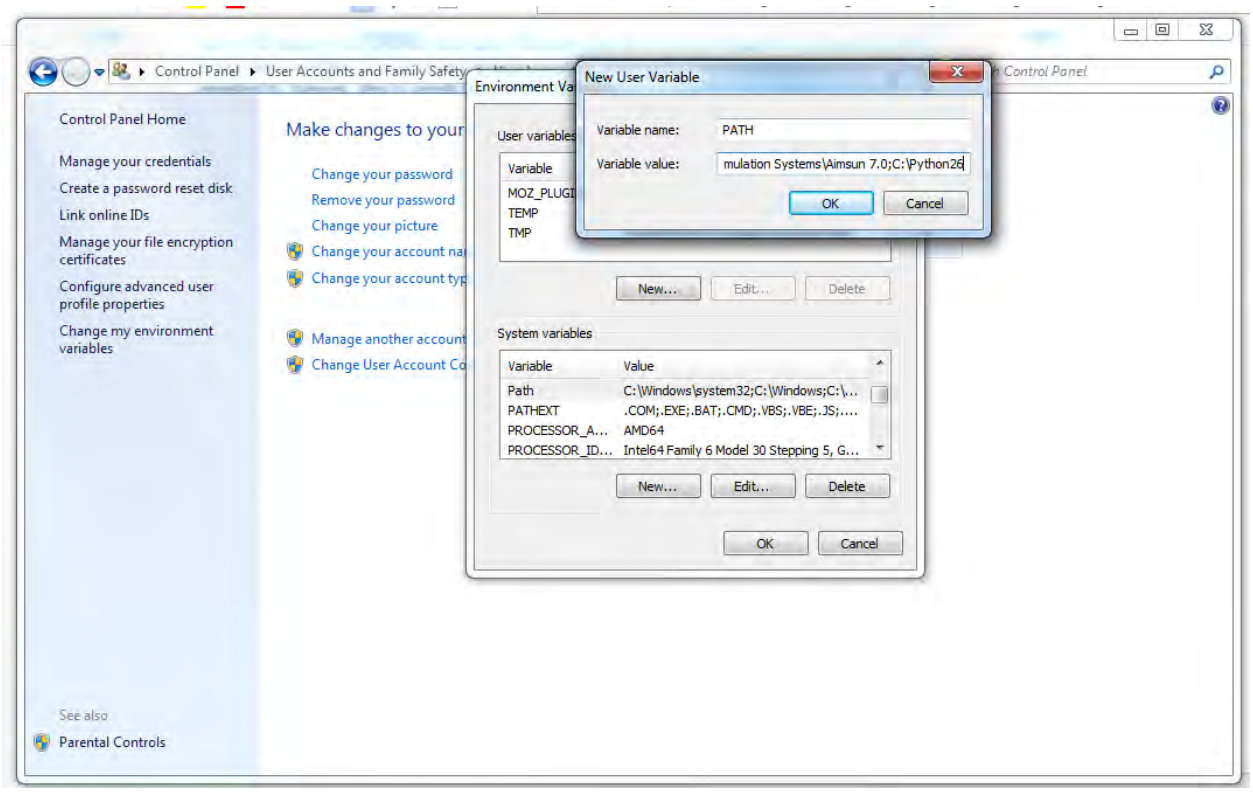

Figure 4-2 Creating or modifying the PATH environment variable

4.3.2 Setting up the Model

Depending on whether or not you already have a network to simulate, once all the required programs are installed, you must either create your network with the MnPASS system you would like to test, or reconfigure your network to include the MnPASS system. Creating a network for simulation is outside the scope of this document, however resources are provided by TSS to help users learn this process. Once the network has been created, it may be modified to include effects of a MnPASS system by following the steps below.

4.3.2.1 Creating a Reserved Lane

The first step to allow simulations of a MnPASS system is to designate one of the lanes on the road of interest as the HOT lane. Doing this in Aimsun involves three steps: creating a vehicle class and type to use the lane, creating the lane, and designating lanes in a number of sections as that lane. To create a vehicle class and type in an Aimsun network:

1) Navigate to the "Vehicles" section in the Project Explorer by unfolding "Demand Data" and selecting "Vehicles."
2) Create a new vehicle class by right-clicking "Vehicles" and selecting "New" -> "Vehicle Class."
3) Open the Properties menu of the new vehicle class and change the name to something meaningful. Press "OK" to save the changes (see Figure 4-3).

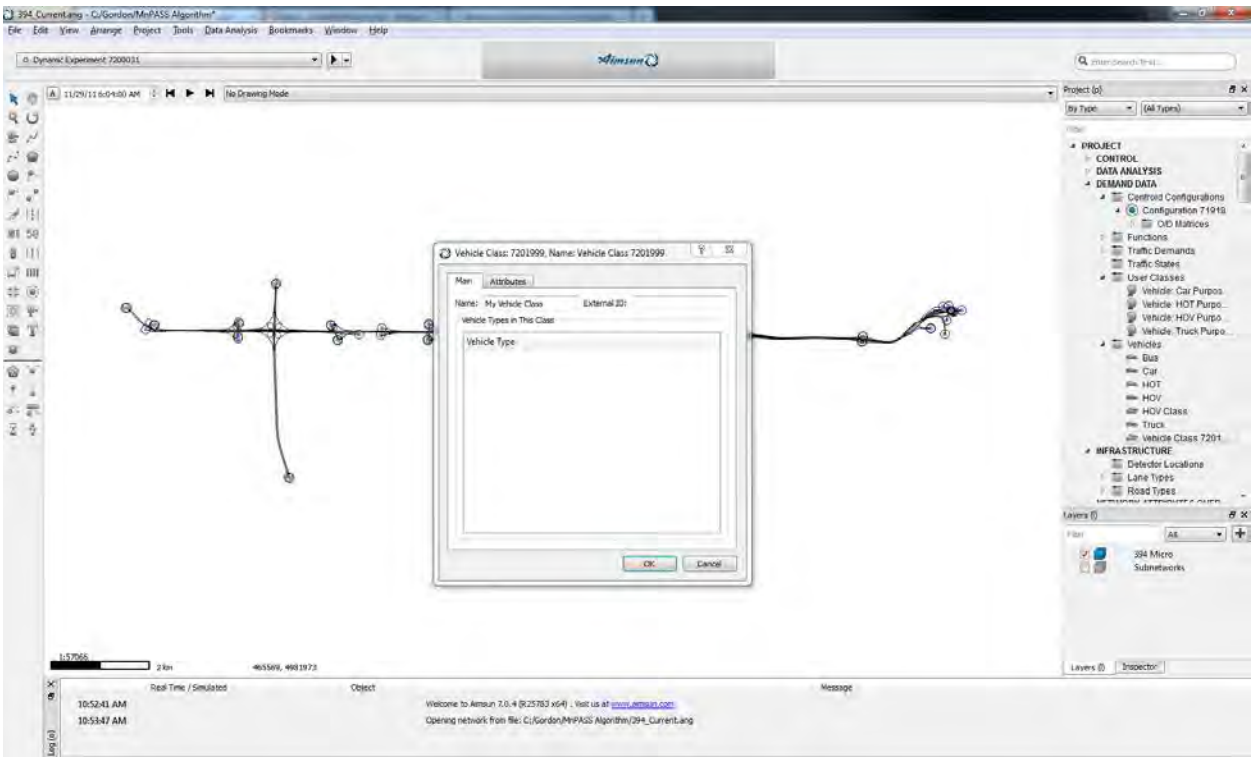

Figure 4-3 Creating a new vehicle class in Aimsun

4) Create a new vehicle type by right-clicking "Vehicles" and selecting "New" -> "Vehicle Type."
5) Open the Properties menu (Figures 4-4 and 4-5) of the new vehicle type and change the name and properties as needed. In the "Class" tab, check the box next to the class you just created to assign vehicles of this type to this class. Press "OK" to save the changes.

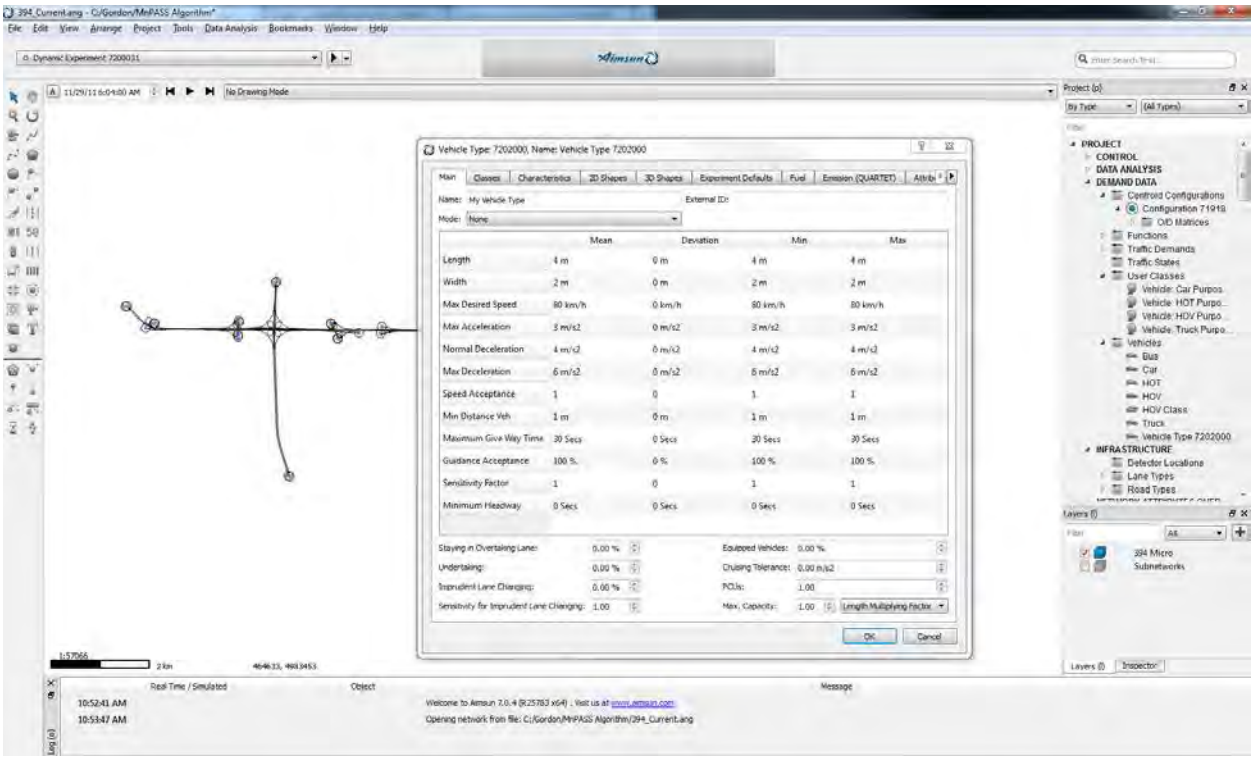

Figure 4-4 Creating a new vehicle type in Aimsun

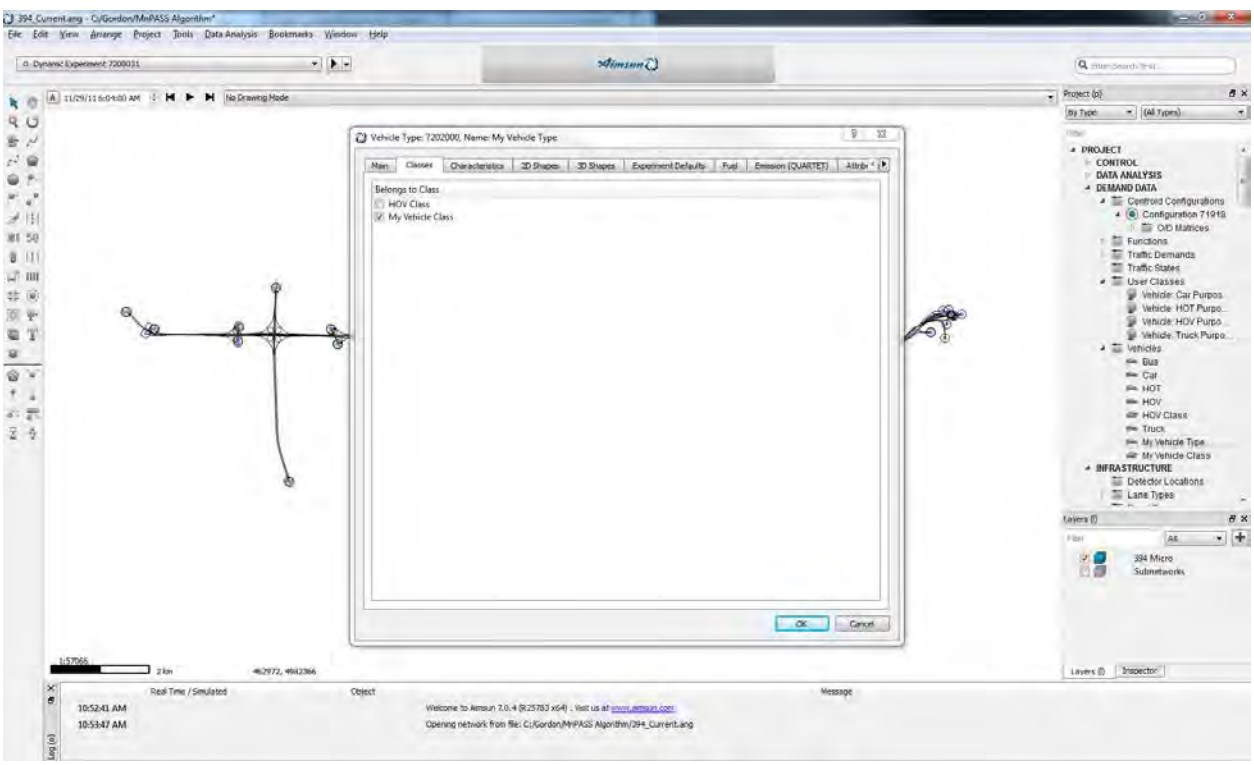

Figure 4-5 Defining the vehicle class of a vehicle type

It will also be necessary to create demand data for this vehicle type. Resources on how to do this can be found in the Aimsun Users' Manual and related documentation.

Once you have created the vehicle class and type, you may create the lane type that will be reserved for them. To do this:

1) Navigate to the "Lane Types" section in the Project Explorer by unfolding "Infrastructure" and selecting "Lane Types."
2) Create a new lane type by right-clicking "Lane Types" and selecting "New Lane Type."
3) Open the properties menu (Figure 4-6) of the Lane Type you just created and change the name to something meaningful. For the vehicle class you created earlier, select "Reserved Compulsory" from the drop down in the table. This will ensure that all vehicles of this type will use this lane when possible. Press "OK" to save the changes.

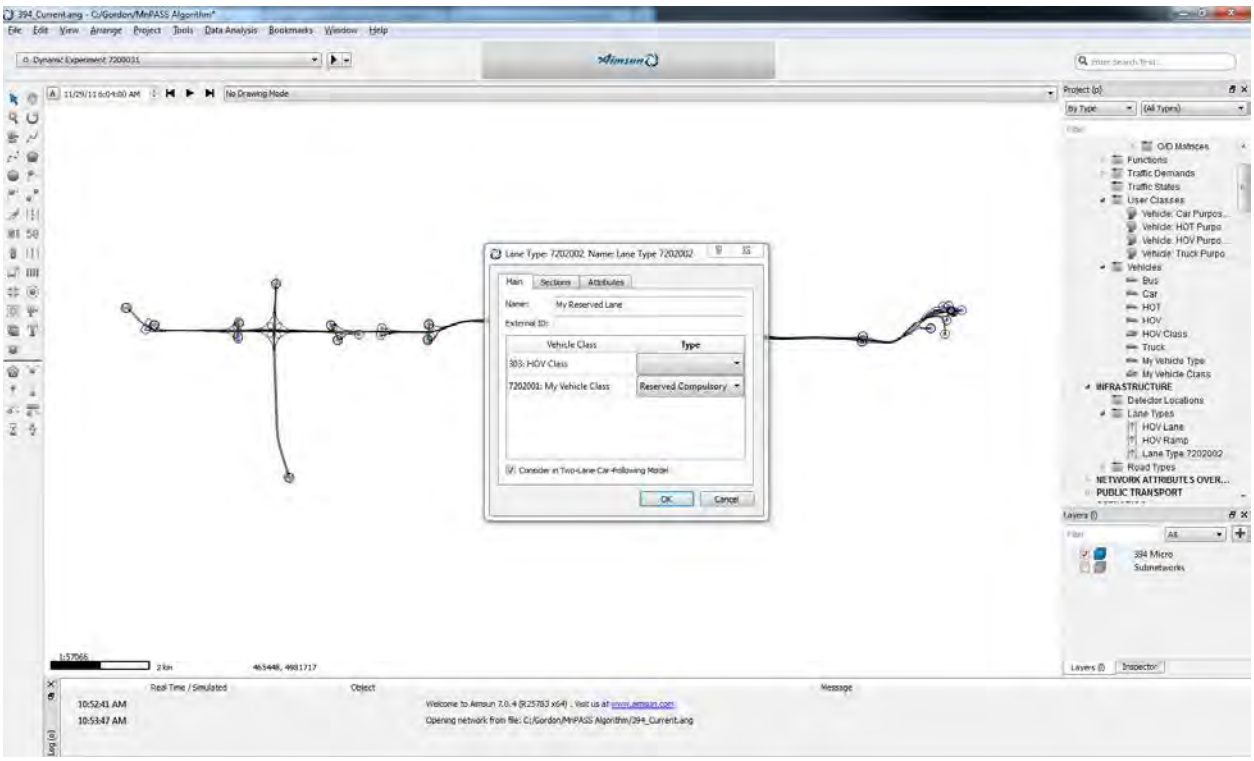

Figure 4-6 Creating a new Reserved Lane in Aimsun

Once you have a vehicle class and lane type reserved for them, you may begin defining lanes in your network as belonging to this type. In existing MnPASS systems, the HOT is either the leftmost lane, or a restricted-access section. You will have to consult the road design to know exactly how to model this for the road in question. The HOT lane must be defined for each section that includes this lane. Once you have determined all the sections that contain an HOT lane, you may define this lane in these sections by following this procedure:

1) For each section, open the section's Properties menu by double-clicking on the section in the model.

2) Click on the “Lanes” tab to edit the Lane Type of the lane(s) in the section.
3) For each lane that you would like to reserve, select the reserved lane type that you created earlier. Note that lanes are numbered from left to right, with the leftmost lane set as lane one. See Figure 4-7 for an example.

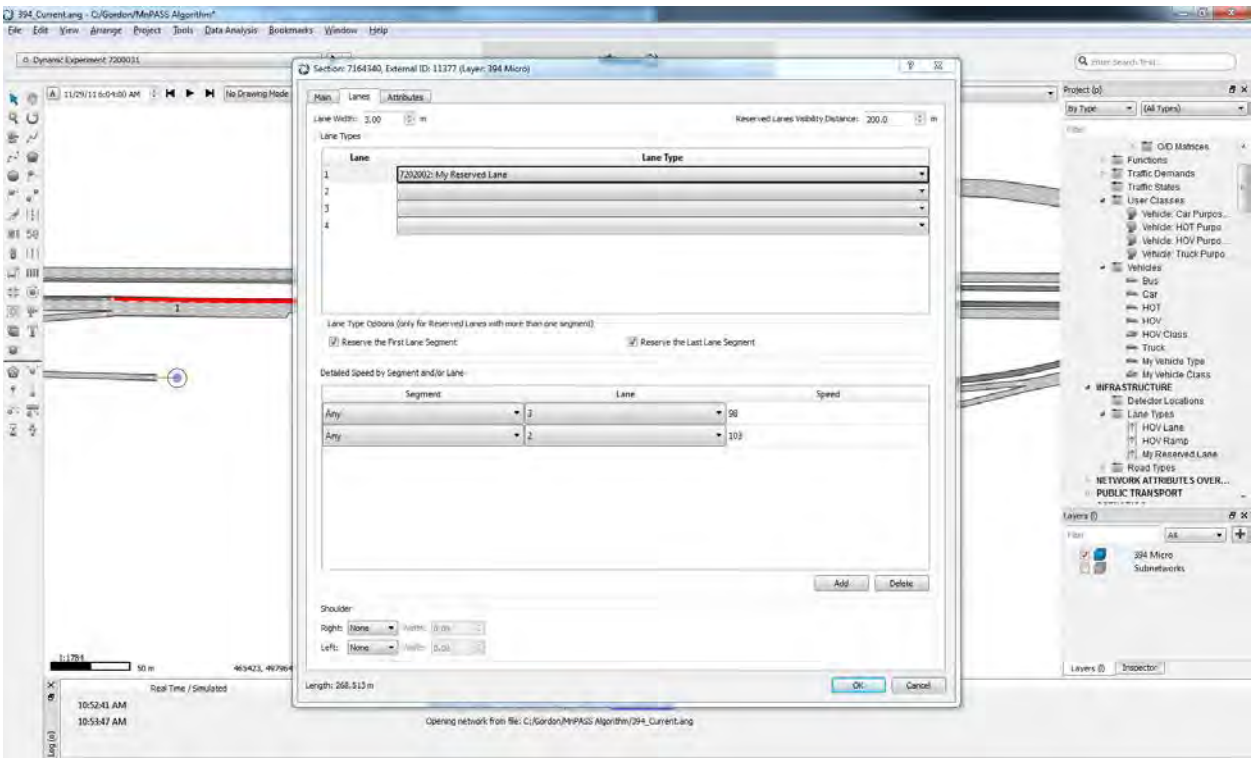

Figure 4-7 Specifying a reserved lane in a section

4) Press “OK” to save the new section properties and repeat for all applicable sections.

4.3.2.2 Defining Custom Section Attributes for MnPASS Algorithm

Once you have added the reserved lane to the model, you must create the custom section attributes that will be used by the MnPASS Algorithm to generate its corridor map by following the instructions below (see Figure 4-8 for reference):

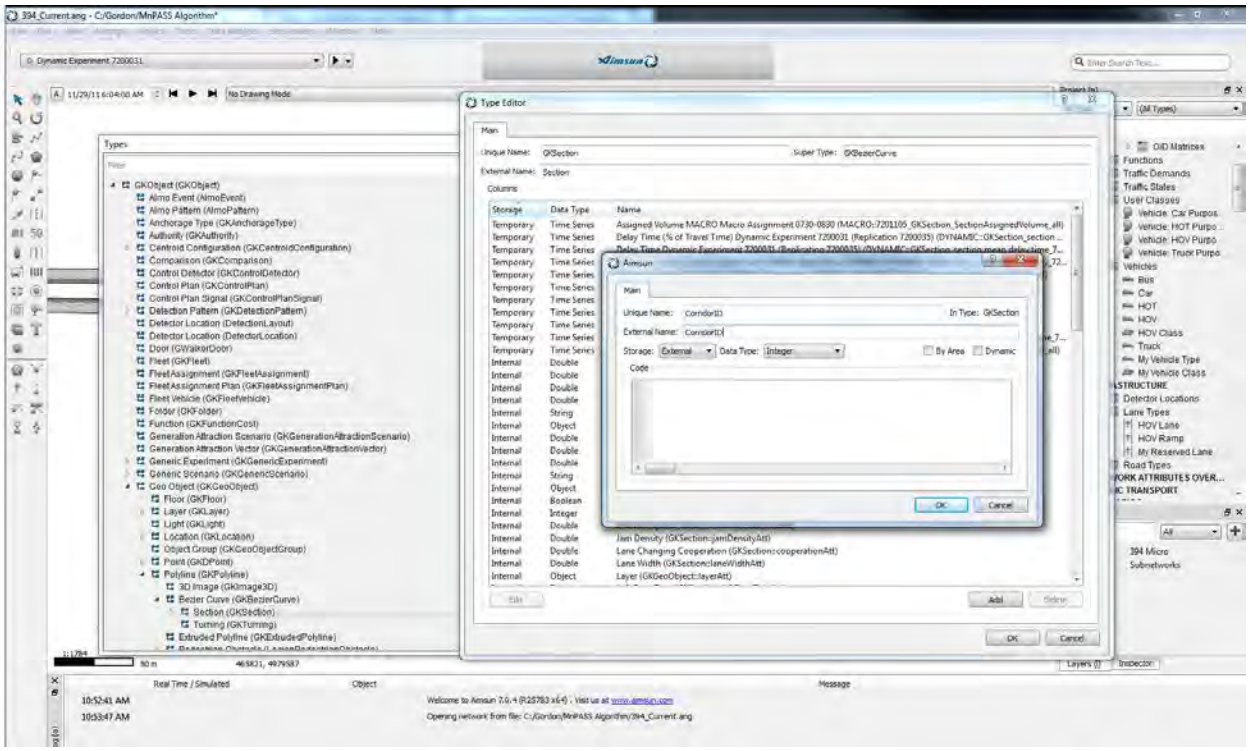

Figure 4-8 Creating a new attribute in Aimsun

1) Open the “Types” window in the Aimsun model by going to “Window” -> “Windows” -> “Types.”
2) Select the Section type by unfolding “GKObject” -> “Geo Object” -> “Polyline” -> “Bezier Curve” and clicking on “Section.”
3) Right click on “Section” and select “Properties.”
4) Click the “Add” button below the table of existing columns to create a new attribute.
5) Set the “Unique Name,” “External Name,” and “Data Type” for the new attribute based on the entries in the table below. Leave all other options as is (“Storage” should be “External,” no boxes should be checked). Click “OK” to save the attribute.

Table 4-1 Custom section attribute parameters

Unique Name	External Name	Data Type
CorridorID	CorridorID	Integer
SectionOrder	SectionOrder	Integer
IsGate	IsGate	Boolean

6) Once all three attributes have been created, click “OK” to exit the Type Editor and close the “Types” window.

Once you have created the custom attributes, you must define them in all of the relevant sections. This will be highly dependent on the actual configuration of the road you are modelling, but the general idea is fairly straightforward. It is important to be careful and check your work

continuously at this step, as a mistake here could lead to unpredictable behavior in the algorithm at runtime. The custom attributes are defined as follows:

Table 4-2 Custom section attribute descriptions

CorridorID	This is the identifier used to find the pricing table for each corridor in the configuration files. This must be unique for each corridor, but the same for each section in a particular corridor.
SectionOrder	This defines the order of sections in the corridor. The most upstream section of a corridor should have a *SectionOrder* of 1.
IsGate	This defines the actual location of a MnPASS tolling station where vehicles are charged. Since this is defined at the section level, a section that has a tolling station would have an *IsGate* value of *Yes*, while a section with no tolling station would have a value of *No*.

For information on how to define these attributes, you should reference the MnPASS location maps. Generally, you would specify the first section that contains a toll rate sign as the first section of that corridor (*SectionOrder* = 1), the section immediately downstream as the second section (*SectionOrder* = 2), and so on. Any sections that contain a tolling location should be given an *IsGate* value of *Yes*. The last section of the corridor will generally be the last section with a tolling location. Make sure to give any sections that are supposed to be in the same corridor the same value for *CorridorID*.

To define an attribute for a section, navigate to that section in the network and double-click on it. In the *Attributes* tab, specify the attribute values for the section in the corresponding space (see Figure 4-9). Click *OK* to save changes.

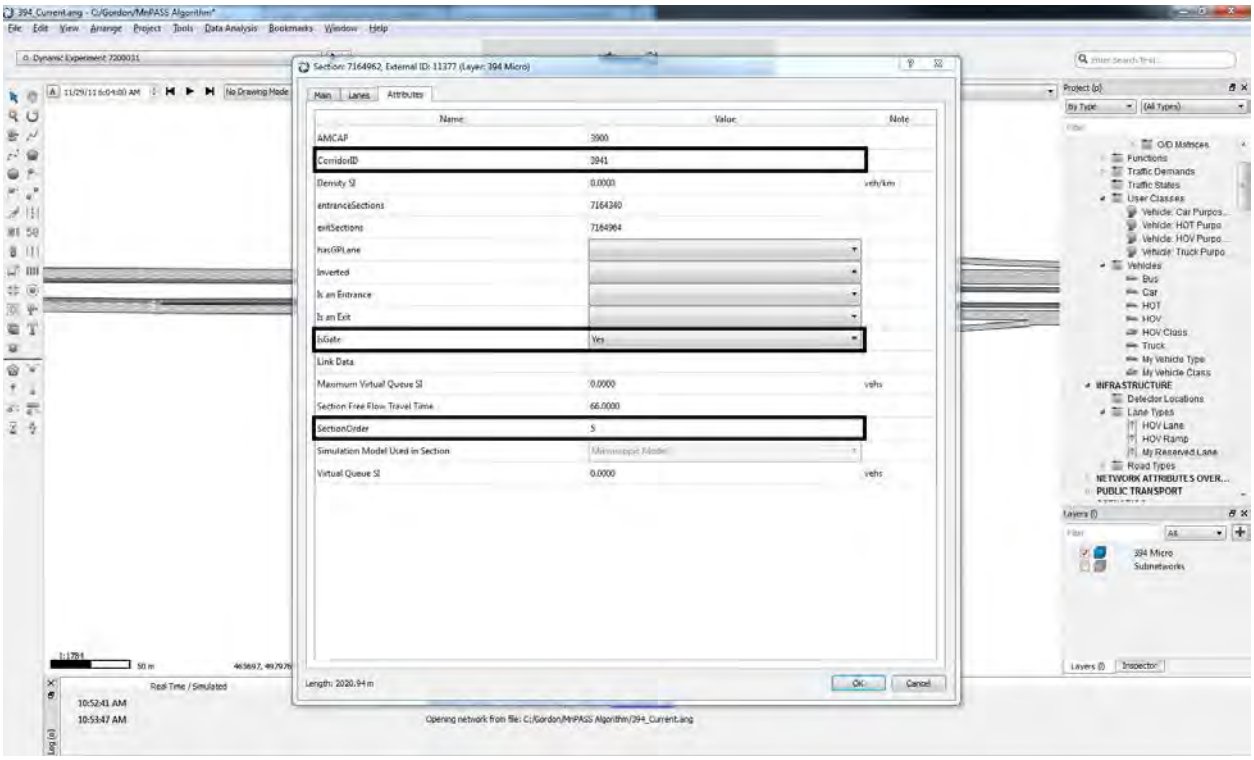

Figure 4-9 Defining values for section attributes

4.3.2.3 Running the "scanSections" Script

Once you have defined these attributes, the network needs one more modification before you can run the MnPASS algorithm. This has been written into a Python script, "scanSections.py" which has been included in the project files. To execute this script, simply create a new Python script by clicking *Project -> New -> Python Script*, and open the script by double clicking on the newly-created entry in the *Scripts* menu of the Project Explorer. Copy and paste the entire contents of the file "scanSections.py" into the text box and click *OK*. You may change the name of the script, although it is not necessary. Right-click on the script and select *Execute*. The script will notify you when it finishes, in likely only a second or two. Be sure to save your changes in the model.

4.3.3 Creating/Modifying the Configuration Files

The project files should have been distributed in a directory structure that minimizes the configuration needed to run the Simulation Control Module. The table below indicates the contents of the configuration files for your reference, along with a brief description of the changes you will have to make.

Table 4-3 Configuration file contents

File Name	Contents	Important Modifications
general.cfg	Location of price log file and the program's log level (error, warn, info, etc.)	You may wish to change the DefaultLogLevel to adjust the screen output to your liking. This will not affect the program's execution
Corridor_meta.cfg	List of all CorridorIDs in the model, the name of the file containing the rate tables for that pricing corridor, and the start and end time of the corridor's enforcement.	You will need to add entries for each corridor in your model. The file has instructions on how to create an entry.
defaultZone.cfg	Default rate and delta table for corridors without an entry in Corridor_meta.cfg	No modifications are necessary. You may use this file as a template for other corridors.
LaneChoice.cfg	Location of files used to inform the modelling of traffic in the MnPASS lanes	You should not need to modify these unless you would like to change the location of the files being output.

The most difficult part of this will be creating the corridor rate and delta tables. It is recommended that you copy defaultZone.cfg and modify the values in the table, to reduce the chance of a formatting error. Entries in the rate table consist of a Level of Service, a minimum and maximum traffic density for that LOS, and a minimum, maximum, and default rate for that LOS (see Figure 9).

```
# Each level of service is in following format
# LOS_(letter [A-Z]) = (min TD) (Max TD) (Minimum Rate) (Default Rate) (Maximum Rate)
LOS_A = 0   11  0.25    0.25    0.25
LOS_B = 12  18  0.25    0.25    0.25
LOS_C = 19  29  1.5     1.5     2.5
LOS_D = 30  35  2.5     3.0     3.5
LOS_E = 36  45  3.5     5.0     6.0
LOS_F = 46  50  6.0     8.0     8.0
```

Figure 4-10 Rate Table from defaultZone.cfg

Entries in the delta table consist of a traffic density value, and a price change for each integer change in density (see Figure 10). In this table, each row will correspond to a density value and each column to a change in density. These values are used to adjust the rate when the LOS does not change. The value chosen for any particular rate calculation will be a function of the previous and current densities, with the previous density indicating the row that should be selected and the absolute value of the integer difference indicating the column. For example if the previous density was 20 and the current density is 22, the price change would be that in row 16, column 2 ($0.25). If the previous density was 23 and the current density 20, the price change would be the negative of that in row 23, column 3 (-$0.50).

```
# Level of service delta settings
# Format:
# TD_(VALUE) = (TD +/- 1) (TD +/- 2) (TD +/- 3) (TD +/- 4) (TD +/- 5) (TD +/- 6)
TD_1    =   0.0     0.0     0.0     0.0     0.0     0.0
TD_2    =   0.0     0.0     0.0     0.0     0.0     0.0
TD_3    =   0.0     0.0     0.0     0.0     0.0     0.0
TD_4    =   0.0     0.0     0.0     0.0     0.0     0.0
TD_5    =   0.0     0.0     0.0     0.0     0.0     0.0
TD_6    =   0.0     0.0     0.0     0.0     0.0     0.0
TD_7    =   0.0     0.0     0.0     0.0     0.0     0.0
TD_8    =   0.0     0.0     0.0     0.0     0.0     0.0
TD_9    =   0.0     0.0     0.0     0.0     0.0     0.0
TD_10   =   0.0     0.0     0.0     0.0     0.0     0.0
TD_11   =   0.0     0.0     0.0     0.0     0.0     0.0
TD_12   =   0.0     0.0     0.0     0.0     0.0     0.0
TD_13   =   0.0     0.0     0.0     0.0     0.0     0.0
TD_14   =   0.0     0.0     0.0     0.0     0.0     0.0
TD_15   =   0.0     0.0     0.0     0.0     0.0     0.0
TD_16   =   0.0     0.0     0.0     0.0     0.0     0.0
TD_17   =   0.0     0.0     0.0     0.0     0.0     0.0
TD_18   =   0.0     0.0     0.0     0.0     0.0     0.0
TD_19   =   0.0     0.0     0.0     0.0     0.0     0.0
TD_20   =   0.0     0.25    0.50    0.75    1.0     1.25
TD_21   =   0.0     0.25    0.50    0.75    1.0     1.25
TD_22   =   0.0     0.25    0.50    0.75    1.0     1.25
TD_23   =   0.0     0.25    0.50    0.75    1.0     1.25
TD_24   =   0.0     0.25    0.50    0.75    1.0     1.25
TD_25   =   0.0     0.25    0.50    0.75    1.0     1.25
TD_26   =   0.0     0.25    0.50    0.75    1.0     1.25
```

Figure 4-11 First half of delta table from defaultZone.cfg

4.3.4 Running the MnPASS Algorithm simulation control module

Once you have set up the MnPASS lanes in your network and created or modified the necessary configuration files, you are ready to start running the MnPASS simulation control module. Figure 4-12 shows the directory structure you should be using to run the simulation control module. This is the structure that is used to distribute the simulation control module, so you should not have to change anything. The most important thing to remember is that *buildHistory.py*, *simload.py*, and your network file must be in the root directory of the program, like they are in the figure.

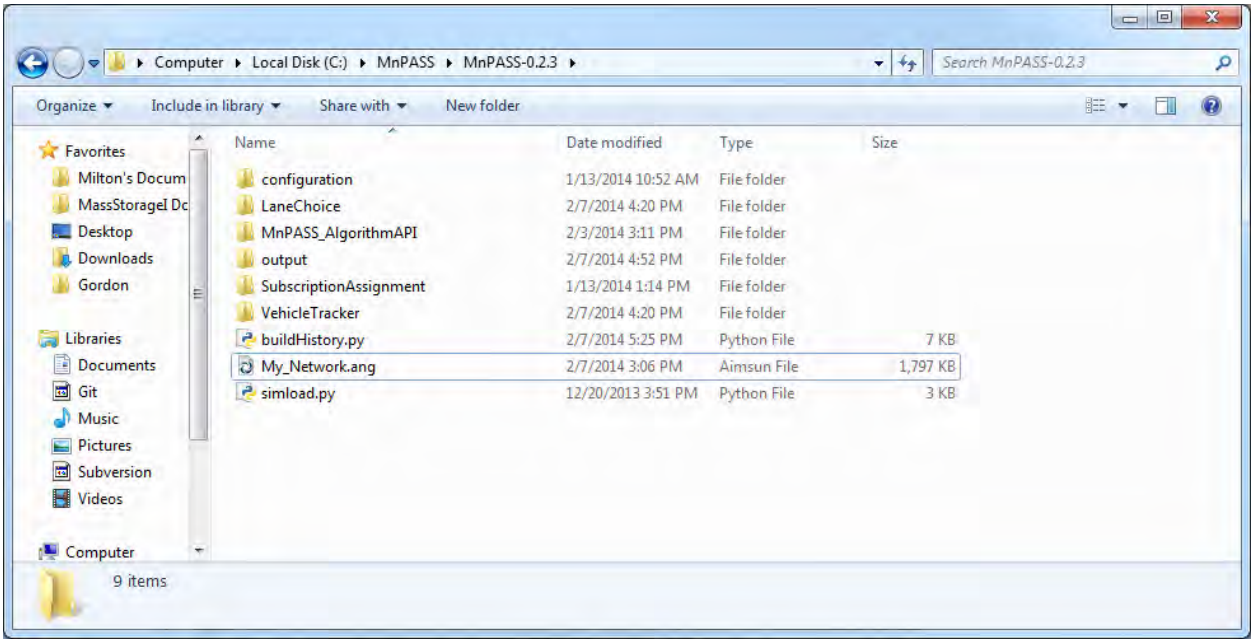

Figure 4-12 Directory structure of MnPASS simulation control module

With the files organizes like this, you can now specify the location of the Aimsun APIs that are responsible for simulating MnPASS operations by following these steps:

1) Open your network and find the Scenario you will use to perform simulations in the *Scenarios* menu of the Project explorer. Double-click it to open its Properties window.
2) In the *Aimsun API* tab, delete any entries that are already in the *Aimsun API* groupbox. Click *Add* and navigate to the MnPASS project files.
3) Open the *MnPASS_AlgorithmAPI/* directory and select *AAPI_R.dll*. Click *Open* to add the file to the APIs to be used for this scenario (see Figure 4-13).

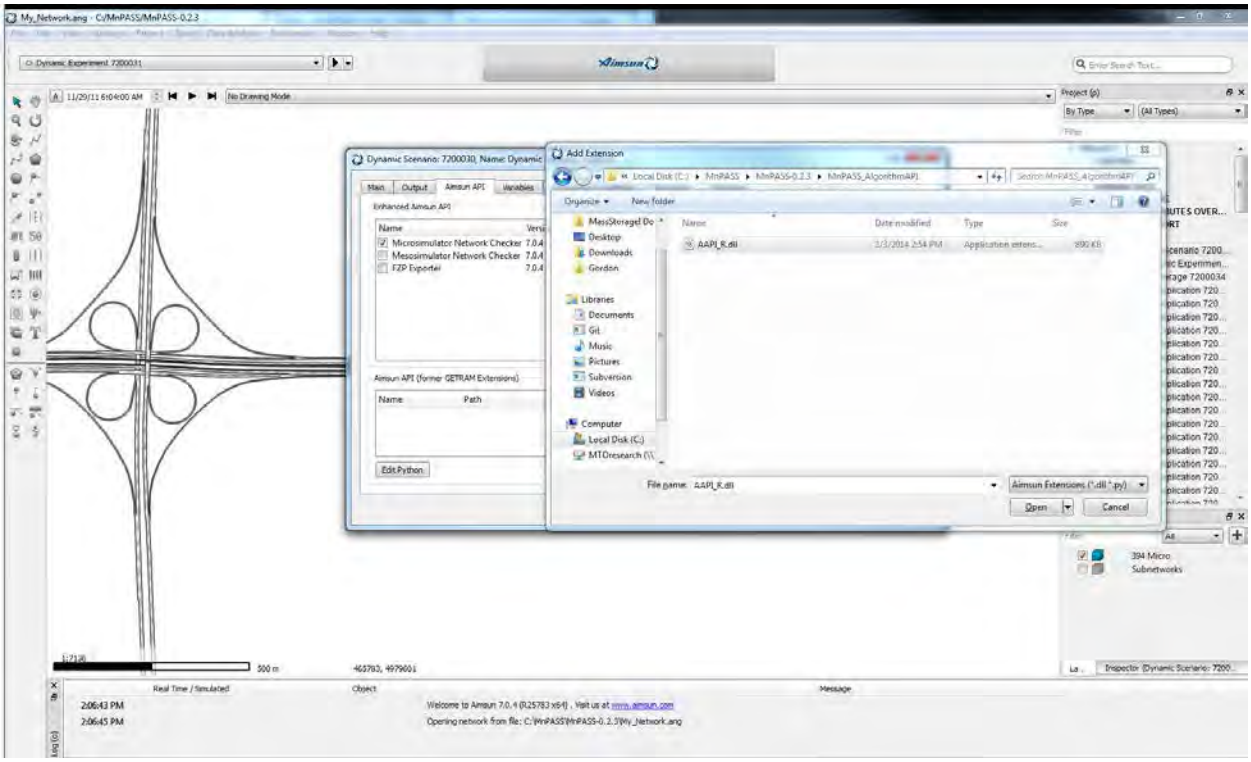

Figure 4-13 Selecting an API file in Aimsun

4) Click the *Add* button again and go to the *VehicleTracker/* directory. Select *VehicleTracker.py* and click *Open*.
5) Click *OK* to apply the changes and save the file.

Any replications you run that belong to the scenario you just modified will now be run with MnPASS. In order to test a pricing framework, however, you must first build a history.

4.3.5 Building a LaneChoice History

To create a historical database for the vehicles in your network, first you must create a number of duplicate replications with the same random seed so that vehicle trips are the same but data is not overwritten. A script *CopyReplication.py* has been included to do this for you. To execute this script, create a new Python script by going to *Project -> New -> Python Script*. Double-click on the newly created script and copy the entire contents of *CopyReplication.py* into the text box. Go to the *Settings* tab and check the box next to *Add Script to a Menu*. In the dropdown, select *Replication* (see Figure 4-14). Click OK to apply changes and save the model.

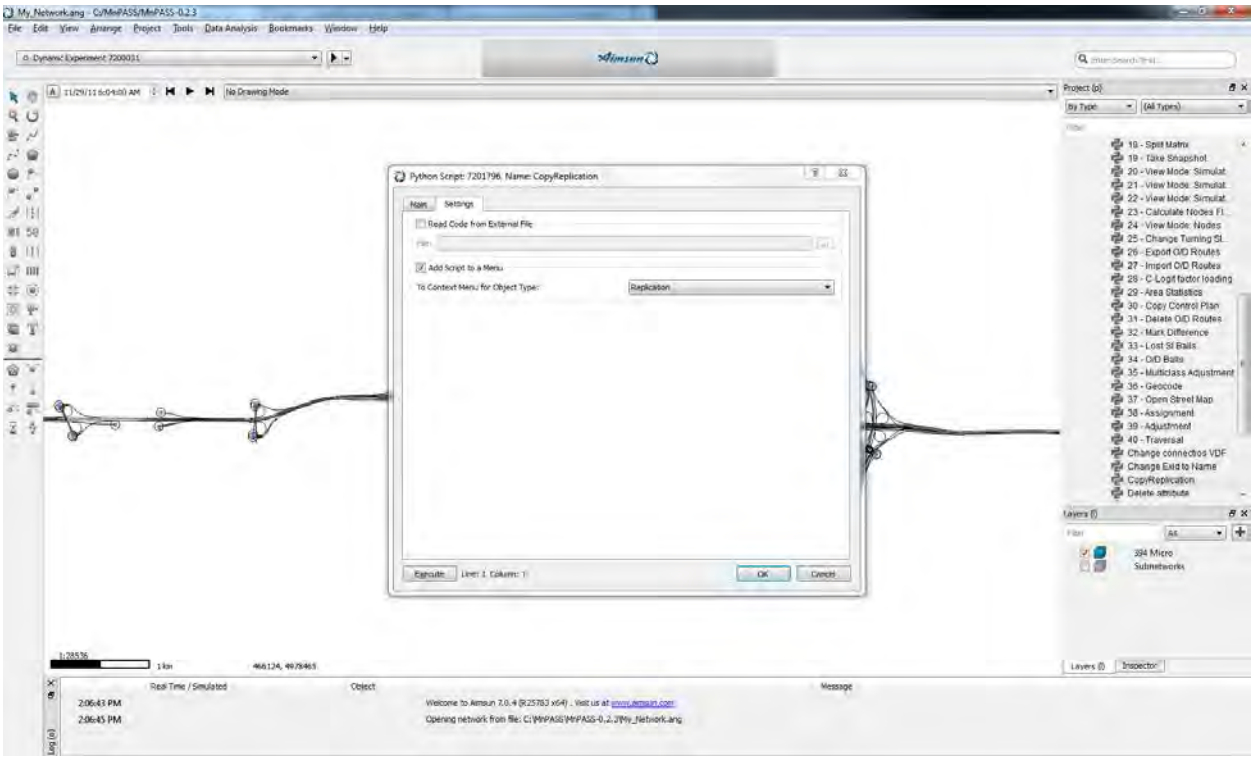

Figure 4-14 Settings tab for script CopyReplication

You may now execute this script from the context menu of any replication. For instance, if you wanted to run 25 simulations with the same random seed as replication 7200035, you would right-click on Replication 7200035 in the Project explorer, select *Scripts -> CopyReplication*, enter 25 in the dialog that pops up, and click *OK*. The routine will then create 24 new replications with the same random seed as Replication 7200035, but with consecutively-numbered Aimsun IDs (so you would now see Replication 7200036, Replication 7200037, etc. in the same Experiment as Replication 7200035.

With a unique replication for each run and everything installed, you may now save and close the network so you can build a history using the included script *buildHistory.py*. To do this, follow these instructions:

1) Open a Command Prompt by going to *Start -> All Programs -> Accessories -> Command Prompt*.
2) Change the directory by typing *cd C:\Path\To\MnPASS\Files*. If the files are on a different drive, you must first change the drive by typing *<drive_letter>:* (e.g. *D:*).
3) Execute the script by typing: *python buildHistory.py <name_of_network.ang> <start_replication_id> <number_of_simulations>* and hitting *Enter* to run. For instance if you wanted to run 25 simulations of a network with a starting replication of 7200035, you would type: *python buildHistory.py network.ang 7200035 50*
4) The script will begin building the simulation. Each simulation will take 10-15 minutes, so a 25-run history will take 4-6 hours to complete.

4.3.6 Testing Pricing Frameworks

Once you have a LaneChoice historical database, you may run simulations to test pricing frameworks by adjusting the corridor pricing tables in the configuration files and running simulations using the graphical interface. When the APIs are enabled and simulations are run from the graphical interface, vehicles will make decisions based on the data in this database but not add any information to it. Outputs from the MnPASS routines will be in the form of .csv files in the *output/* directory, if these parameters have not been adjusted in the configuration files. Output from Aimsun can be viewed from inside the graphical interface, or in a database specified in the properties of the Scenario you are simulating. For information on how to set this up, consult the Aimsun Users' Manual.

4.4 Conclusion

While the simulation control module is capable of modelling the MnPASS lanes with reasonable accuracy, there is still room for improving or refining the model's abilities. These include improving the handling of multiple pricing corridors so that more complicated networks can be simulated (cases with non-priced regions in between priced ones), and adjusting the way vehicles are rerouted to use the MnPASS lanes to better ensure compliance. These developments could improve the accuracy and flexibility of this model, but could also increase its complexity, therefore requiring continued testing of the model's computational performance to keep simulations at a reasonable length.

5 Development and Testing of New Pricing Algorithms

Four new pricing strategies were developed as alternatives to the current system used on the MnPASS HOT lanes. The continuous function is similar to the current pricing algorithm in that it relies strictly on HOT density for determining price, but calculating it from an equation as opposed to a set of tables. The other three value pricing strategies incorporate the density of the general-purpose lanes into the equations, using the difference between the densities to determine price. In all cases, prices are confined to several constraints to match the existing pricing algorithm; prices have a minimum of $0.25, a maximum of $8.00, and are rounded to the nearest $0.25. All constraints are applied after the calculation of the price. While these equations can be used to generate price tables that can be more easily integrated into the MnPASS system, as is demonstrated in Janson (2013), for the purposes of simulation they have been kept as equations. In order to keep the prices near the existing levels, all equations include constants that were calibrated using a least squares fit so that they would closely match the prices produced by the current algorithm. The details of this calibration are presented in Janson (2013). Results for the implementation of these pricing strategies in the simulation framework for the I-394 AM peak period can be seen in the Section 6.3.

5.1 Continuous Function

This function calculates the price based only on the density on the HOT lane, using the following equation:

$$P_{continuous} = \alpha * K_{HOT}^{\beta} \tag{5.1}$$

where P represents the price in USD and K the density in vehicles/mile/lane. K_{HOT} is found using the same method as the current algorithm, taken as the maximum downstream density averaged over last 6 minutes. α and β are constants that can be adjusted to achieve the desired curve. This strategy is designed as a close alternative to the current MnPASS pricing algorithm, using coefficients that have been calibrated to produce a similar price-density curve to that produced by the table-based algorithm.

5.2 Unweighted Value Pricing

While the current pricing algorithm only evaluates the density in the HOT lane, this pricing strategy would compute price based on the difference in density between the general-purpose and HOT lanes. The difference in density between the lane groups is correlated with a difference in time savings and therefore, the value provided by the HOT lane. The price is calculated using the following equation:

$$P_{value_{unweighted}} = \gamma * [K_{GP} - K_{HOT}] \tag{5.2}$$

Implementation of this pricing scheme (and subsequent strategies), will require the integration of general-purpose density as a factor in determining price. General-purpose density, taken as the average over the last 6 minutes, is averaged among parallel detectors. The maximum downstream general-purpose density is then used to determine price, along with the density of the parallel HOT detector, as determined by MnDOT's All Detector Report.

5.3 HOT-Weighted Value Pricing

Differences in density between GP and HOT lanes do not correlate directly to travel speeds. Rather, there is a correlation with the magnitude of densities. For example, little speed difference exists between 10 and 20 vehicles/mi/ln, both likely experience free flow speeds. However, a greater speed difference exists at higher densities (between 40 and 50 veh/mi/ln). Therefore, it makes more sense to weight the density difference between the GP and HOT, based on the magnitude of density. This function weights the difference based on the magnitude of the HOT lane density. Similarly to the current algorithm, price will increase proportionally with HOT density:

$$P_{value_{HOTweighted}} = \delta * [K_{GP} - K_{HOT}] * K_{HOT} \tag{5.3}$$

5.4 GP-Weighted Value Pricing

This pricing strategy is weighted based on GP density instead of HOT density. If K_{GP} is much greater than K_{HOT} and K_{HOT} is very low, then the HOT weighted value pricing strategy would yield a low price even though there would be a significant value in using the HOT lane. By weighting based on K_{GP}, this strategy ties price more directly to the GP lane congestion and the actual time savings gained by using the HOT lane.

$$P_{value_{GPweighted}} = \sigma * [K_{GP} - K_{HOT}] * K_{GP} \tag{5.4}$$

6 Results and Discussion of Simulation Experiments

The following sections outline the results of the implementation of the MnPASS simulation framework on the I-394 and I-35W networks, as well as the results of tests of the alternate pricing strategies implemented in the I-394 AM peak period. Several alternatives for the implementation of the Lane Choice model were also tested on the I-394 EB MnPASS lanes for their effect on HOT usage. The results for all of these implementations are presented in the following sections.

6.1 Results from Implementations on I-394 Eastbound

While the Lane Choice model was developed in order to capture the way different drivers decide to use the HOT lane or not, the geometry and pricing structure of the MnPASS lanes meant that its integration into the simulation still left room for a few alternative implementations. In order to determine the best method for doing this, a number of alternatives were compared for the I-394 EB MnPASS lanes in the development of the simulation platform. The first two implementations both placed the choice to use the HOT lane at the freeway entrance ramp. This was based on observation of the I-35W MnPASS users in previous research, who typically showed intent to use the HOT lane immediately after entering the freeway. These two implementations differed in the number of choices given to subscribers, with one giving only one choice for the full trip, and the other giving one choice for each destination. All of these implementations use the same subscription probability modification factor for the whole network and for the centroids corresponding to the TH 100 entrances to the reversible HOT section, the justification for which is presented in Section 6.1.1. The results of these implementations are shown below.

Table 6-1 Results from Implementation of the Lane Choice Model for the I-394 AM Peak Period with One Decision Taken at the Entrance Ramp

	Simulated Data			Real Data	
First Plaza	HOT Users	Total Eligible Subscribers	% HOT of Eligible Subscribers	Average HOT Users (St. Dev.)	% Error (Modeled vs. Real)
1001	764	1389	55.0%	541 (233)	41.2%
1002	569	2417	23.5%	663 (225)	-14.2%
1003	202	1986	10.2%	219 (123)	-7.76%
1004	379	2322	16.3%	267 (84)	41.9%
Total	1914			1690	13.3%
1005	950	3841	24.7%	1200 (158)	-20.8%

Table 6-2 Results from Implementation of the Lane Choice Model for the I-394 AM Peak Period with Two Decisions Taken at the Entrance Ramp

	Simulated Data			Real Data	
First Plaza	HOT Users	Total Eligible Subscribers	% HOT of Eligible Subscribers	Average HOT Users (St. Dev.)	% Error (Modeled vs. Real)
1001	521	1329	39.2%	541 (233)	3.70%
1002	476	2374	20.1%	663 (225)	-28.2%
1003	120	1981	6.06%	219 (123)	-45.2%
1004	180	2285	7.88%	267 (84)	-32.6%
Total	1297			1690	-23.3%
1005	1633	3828	42.7%	1200 (158)	36.1%

In this table, the plaza number indicates the MnPASS tolling location where vehicles are first captured using the HOT and the HOT users are the total number of simulated vehicles that reported using that section of the MnPASS lane. This is compared to the real data averages as measured by the MnPASS system at each location, for which percent error is calculated. The total number of subscribers generated for the simulation is also shown to emphasize the two-phased process that underlies the model. For each pricing zone, the HOT users from all plazas have been summed to show the results from that pricing zone as a whole. Pricing zones are separated by a line, and the sum for zones with more than one plaza displayed as the "Total" for that zone.

As can be seen in the data, the first of these was incapable of creating sufficient in the reversible HOT section east of TH-100. After allowing subscribers to make the choice of using the two sections separately, the demand in the reversible section increased, albeit at the cost of the demand in the non-reversible section. In addition to this, the demand in the reversible section was fairly high above the level seen in the real data, largely attributable to the fact that placing the decision to use the HOT at the entrance ramp presented subscribers with the option to take the reversible with a generally lower price than they would pay in real life. Therefore a third implementation was devised, where subscribers were still given the option to make separate choices for the two destinations, but the choice would be taken at the entrance to each zone. Subscribers that decided to use the HOT lane at any point would then continue to use it for the full trip, while those that decided not to would be presented with the option to use it at each of the downstream entrances they passed by. The results from this implementation are shown below.

Table 6-3 Results from Implementation of the Lane Choice Model for the I-394 AM Peak Period with Two Decisions, Taken at the HOT Entrances, and Multiple Chances for Entry

	Simulated Data			Real Data	
First Plaza	HOT Users	Total Eligible Subscribers	% HOT of Eligible Subscribers	Average HOT Users (St. Dev.)	% Error (Modeled vs. Real)
1001	481	1420	33.9%	541 (233)	11.1%
1002	539	2441	22.1%	663 (225)	-18.7%
1003	209	1977	10.6%	219 (123)	-4.57%
1004	298	2305	12.9%	267 (84)	11.6%
Total	1527			1690	-9.64%
1005	1339	3807	35.2%	1200 (158)	11.6%

This implementation showed the least error for each plaza, with the number of HOT users for all plazas within a standard deviation of the average real usage. Because of these results, this implementation was chosen for the implementation on the I-394 WB and I-35W MnPASS lanes, as well as for the testing of alternative pricing strategies, the results for which are presented in following sections.

6.1.1 Discussion of MnPASS Subscription Model

As discussed in the Methodology Section, it was discovered earlier in the development of the model that the Subscription Estimation model was not always accurate in matching subscribers and non-subscribers to destinations, routes, and freeway entrances. One area with particularly noticeable impact from this is at the entrance to the I-394 reversible HOT section from TH-100. This discussion specifically refers to Plaza 1005 on I-394 EB, however since Plaza 2001 is the reverse of Plaza 1005, it follows that this section would experience similar issues given that many of the vehicles using this section in the morning and afternoon of a given day would be the same. Table 6-3 displays the vehicles counted at the given HOT lane detector, both real and simulated, as well as the count of simulated high-occupancy vehicles (HOV), used to calculate the number of HOT vehicles from the total HOT lane count. Given that the HOV demand has been calibrated in the regional planning model with real data and the simulation copies this demand, it was assumed that the number of HOVs generated during simulation was close enough to the real data that it could be used to calculate a rough target for the number of real HOT vehicles observed.

Table 6-4 Real and Simulated Vehicle Counts by Detector

Location	HOT Detector	HOV + HOT (Real)	HOV + HOT (Simulated)	HOV (Simulated)	HOT Target (Real)	HOT (Simulated)
TH 100 NB -> I-394 EB (Plaza 1005)	D1727	1471	797	601	870	196
TH 100 SB -> I-394 EB (Plaza 1005)	D2083	614	354	290	324	29
I-394 EB at Plaza 1001	D1653	1596	1182	301	1295	881

As can be seen in this table the number of simulated HOT vehicles is underestimated for the sections associated with Plaza 1005, with usage from TH 100 NB at 22.53% of real data and usage from TH 100 SB at only 8.95% of real data, compared to 68.0% for Plaza 1001. Viewed in the context of the subscription data generated by the subscription estimation model (Table 6), it is clear that this issue is related to this model. Subscribers only make up 8.5% and 2.0% of vehicles associated with this plaza, compared to 19.5% associated with Plaza 1001.

Table 6-5 Subscriber Counts by Associated HOT Detector

Location	HOT Detector	Total Vehicles (Simulated)	Subscribers	% Subscribers	HOT (Simulated)	% HOT of Subscribers
TH 100 NB -> I-394 EB (Plaza 1005)	D1727	3174	271	8.5%	196	72.3%
TH 100 SB -> I-394 EB (Plaza 1005)	D2083	1770	36	2.0%	29	80.6%
I-394 EB at Plaza 1001	D1653	8264	1611	19.5%	881	54.7%

To remedy this so that the alternative pricing strategies could be accurately tested on this corridor, a separate subscription modification factor was used for vehicles entering only from the relevant centroids, corresponding to TH 100 NB and TH 100 SB. Using this the results from the I-394 EB MnPASS lanes was improved sufficiently so that the alternative pricing strategies could be compared using a more accurate representation of conditions on the HOT lane. Future development on the subscription model, particularly in the subscriber route choice model, will be able to eliminate the need for this altogether.

6.2 Results from Implementation on I-394 Westbound and I-35W

Although the Lane Choice model was calibrated to the I-394 EB MnPASS lanes during the AM Peak Period, the simulation platform was also tested for its performance on I-394 WB during the PM Peak Period (Table 6-6), as well as the I-35W MnPASS Lanes during the AM and PM peak periods (Tables 6-7 and 6-8, respectively). While these models all show similar issues with the distribution of vehicles among the plazas, they nonetheless underscore the general utility of the simulation framework for implementation across the MnPASS system. Further calibration of the simulation models, as well as improvements to the Lane Choice model will allow the MnPASS Simulation Platform to better simulate the operations on existing MnPASS lanes, as well as in locations where MnPASS lanes have not yet been implemented.

Table 6-6 Results from Implementation of the Lane Choice Model for the I-394 PM Peak Period

	Simulated Data			Real Data	
First Plaza	HOT Users	Eligible Subscribers	% HOT of Subscribers	Average HOT Users (Std. Dev.)	% Error (Modeled vs. Real)
2001	1105	1322	83.6%	1780 (284)	-37.9%
2002	177	1318	13.4%	140 (52)	26.4%
2003	494	1434	34.4%	166 (86)	197.6%
2004	435	1843	23.6%	93 (52)	367.7%
2005	43	754	5.70%	33 (12)	30.3%
Total	1149			432	166.0%

Table 6-7 Results from Implementation of the Lane Choice Model for the I-35W AM Peak

	Simulated Data			Real Data	
Plaza	HOT Users	Total Eligible Subscribers	% HOT of Eligible Subscribers	Average HOT Users (Std. Dev.)	% Error (Modeled vs. Real)
3004	891	1576	56.5%	771 (264)	15.6%
3005	327	2021	16.2%	1064 (383)	-69.4%
3006	275	2712	10.1%	447 (104)	-38.5%
3007	67	2805	2.39%	70 (92)	-4.3%
3008	75	2415	3.11%	65 (16)	15.4%
3009	29	1387	2.09%	41 (11)	-29.3%
Total	1664			2458	-32.4%
3010	112	1005	11.1%	61 (22)	83.6%
3011	137	1691	8.10%	195 (63)	-29.7%
3012	116	1563	7.42%	195 (55)	-40.5%
Total	365			451	-19.1%
3013	97	1592	6.09%	90 (26)	7.8%

Table 6-8 Results from Implementation of the Lane Choice Model for the I-35W PM Peak

	Simulated Data			Real Data	
Plaza	HOT Users	Eligible Subscribers	% HOT of Subscribers	Average HOT Users	% Error (Modeled vs. Real)
4005	1031	2305	44.7%	363 (86)	184.0%
4006	53	478	11.1%	103 (25)	-48.5%
Total	1084			466	132.6%
4007	175	915	19.1%	453 (102)	-61.4%
4008	477	1864	25.6%	379 (65)	25.9%
4009	329	2254	14.6%	161 (31)	104.3%
4010	317	2652	12.0%	91 (15)	248.4%
4011	46	2652	1.73%	56 (15)	-17.9%
Total	1344			1140	17.9%

6.3 Results from Alternate Pricing Strategies

In order to test the performance of the alternate pricing strategies discussed in section 5, results from simulations using these pricing strategies were compared to data from a simulation run with the existing pricing algorithm. A graph of the actual price and density in Plaza 1001 from the AM peak period on 02/28/2012 is shown in Figure 6-1 for comparison. All strategies were tested using the I-394 network during the AM peak period. The results shown are from the last iteration of the lane choice model training period, so vehicles have a full history of travel time and toll information to inform their choices. Because all simulations were performed on the I-394 network, the same subscriber probability modification factor was used for all pricing strategies. Each pricing strategy has a graph showing the price and density on the HOT lane on Plaza 1001, as well as a graph comparing the travel times from the given strategy to those from the existing pricing algorithm. Pricing strategies that take the density of the general purpose lanes into account also display that information.

As can be seen in the first two graphs, the MnPASS simulation framework shows a similar demand response pattern to that of the real data. This can also be seen in the continuous pricing strategy (Figure 6-3), albeit with smaller fluctuations due to the differences between this method and the existing table-based method. The value pricing methods (Figures 6-5, 6-7, and 6-9), however, are considerably more stable, given that the price is a function of the difference between the densities in the HOT and general purpose lanes, with the price rising as the difference between the two increases. Densities for the alternate pricing strategies tend to be more stable than those for the existing pricing algorithm, as the use of equations to generate the price results in a quicker response to changes in density. Since the price changes more quickly to

respond to the vehicles entering the HOT lane, subscribers are given a more accurate picture of the current conditions thus making them less likely to enter the HOT lane when the density is higher, and reducing the instances of the spikes seen in the existing method. As can be seen in Figures 6-4, 6-6, 6-8, and 6-10, the alternate pricing strategies show slightly reduced travel times between 7:30 AM and 8:00 AM, while the Unweighted Value pricing strategy shows slightly higher travel times between 8:30 AM and 9:00 AM. Over the course of the simulation, however, the travel times on the HOT lane are largely consistent, as can also be seen in Table 6-9.

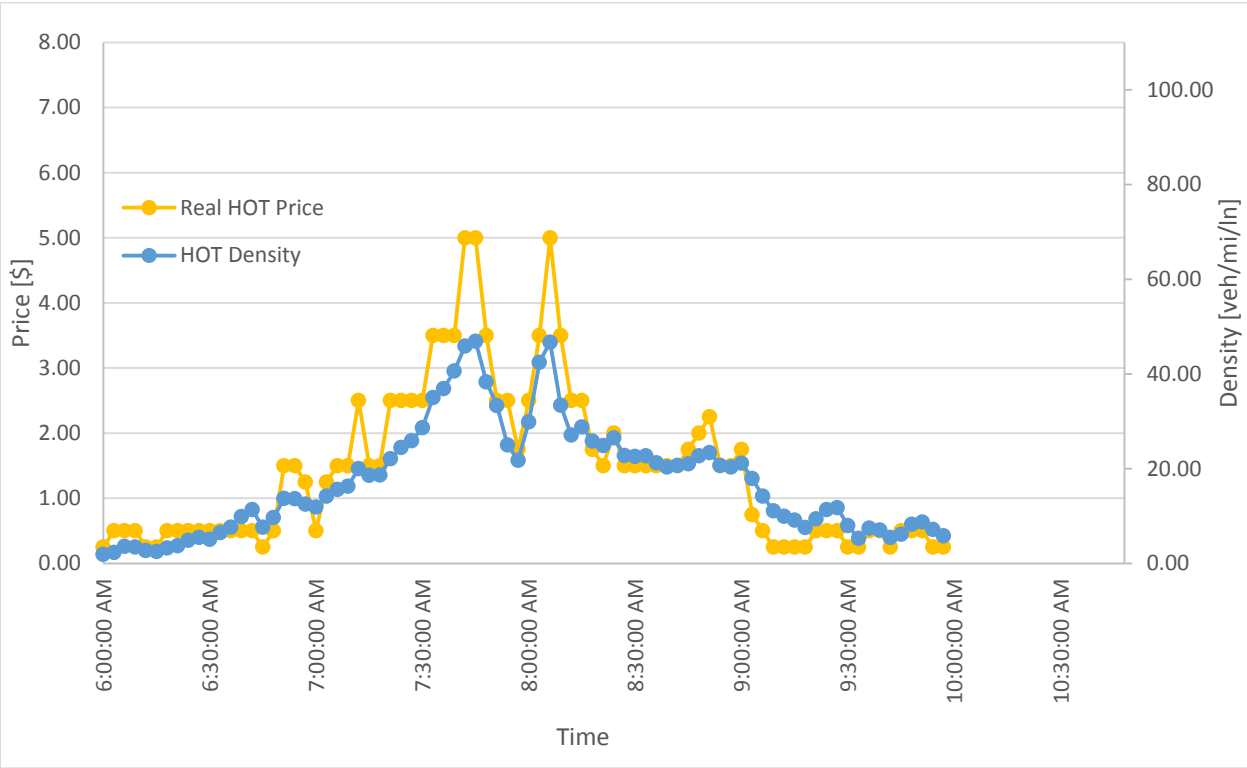

Figure 6-1 Real Pricing Algorithm and HOT Lane Density (02/28/2012)

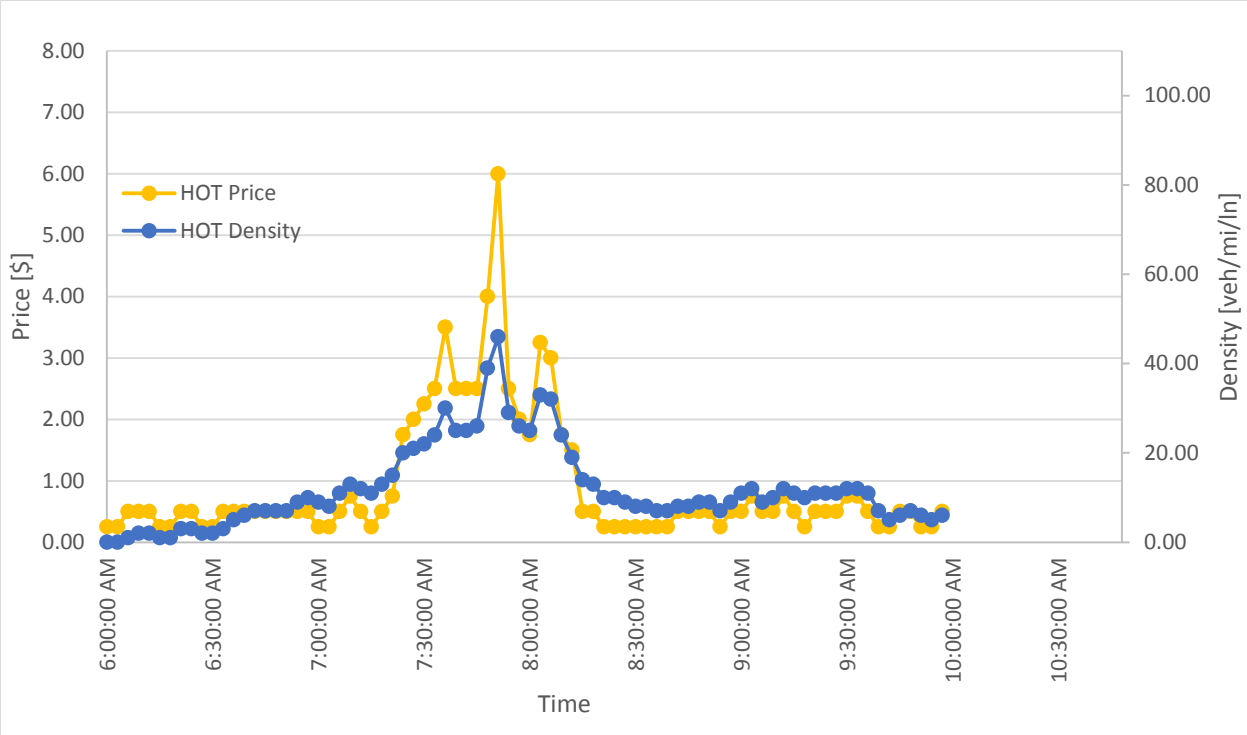

Figure 6-2 Existing Pricing Algorithm and HOT Lane Density (Simulated Data)

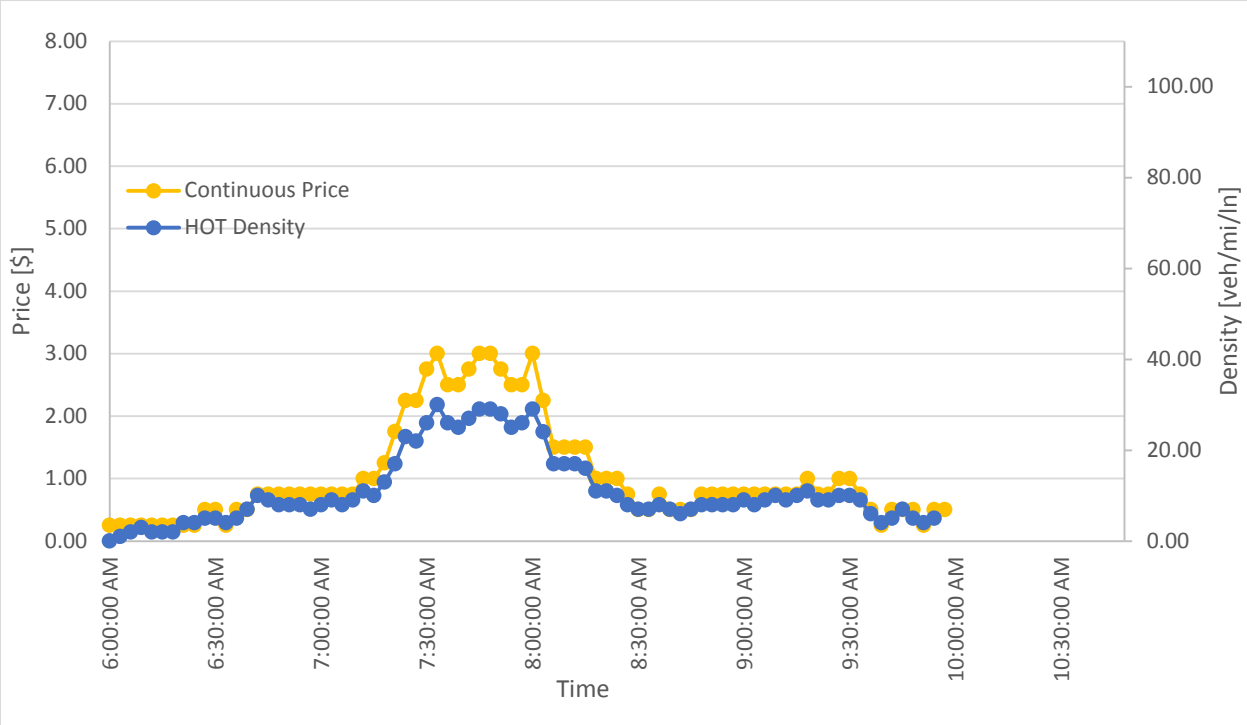

Figure 6-3 Continuous Pricing Function and HOT Lane Density

$$P = \alpha * K_{HOT}^{\beta}, where\ \alpha = 0.059\ and\ \beta = 1.156$$

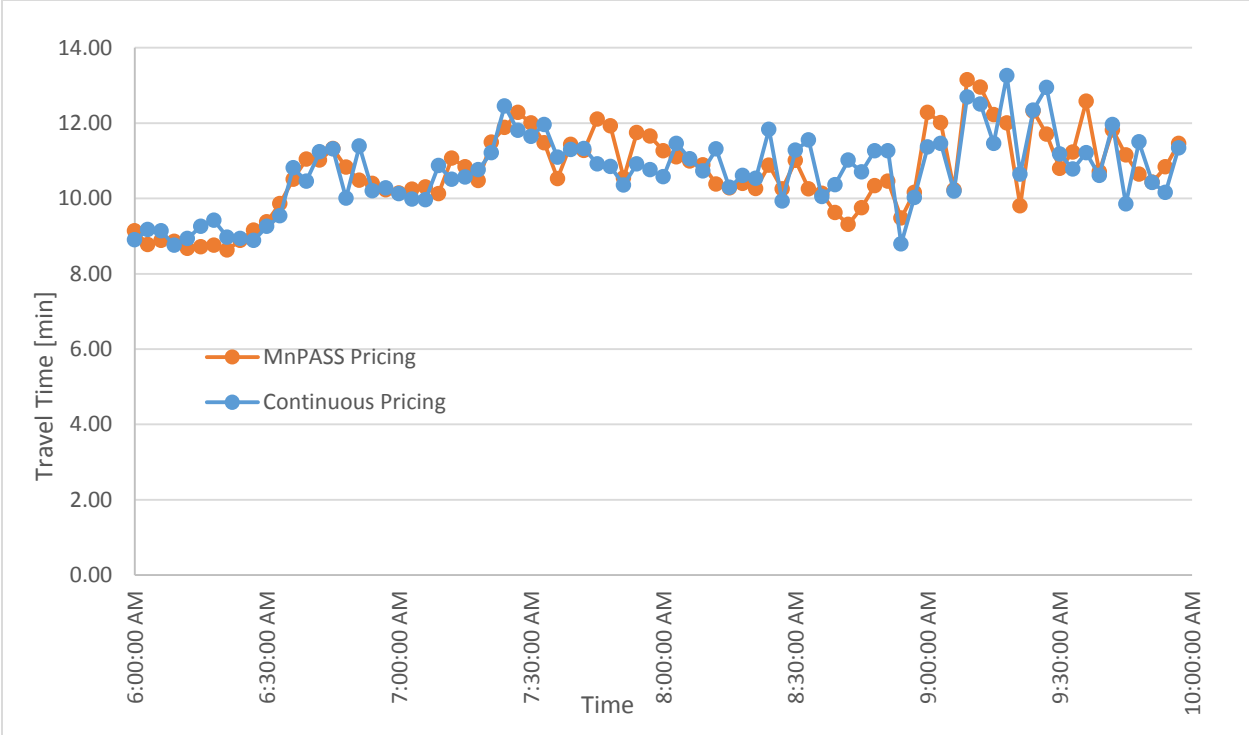

Figure 6-4 Average HOT Lane Travel Time for Existing Pricing Algorithm and Continuous Pricing Function

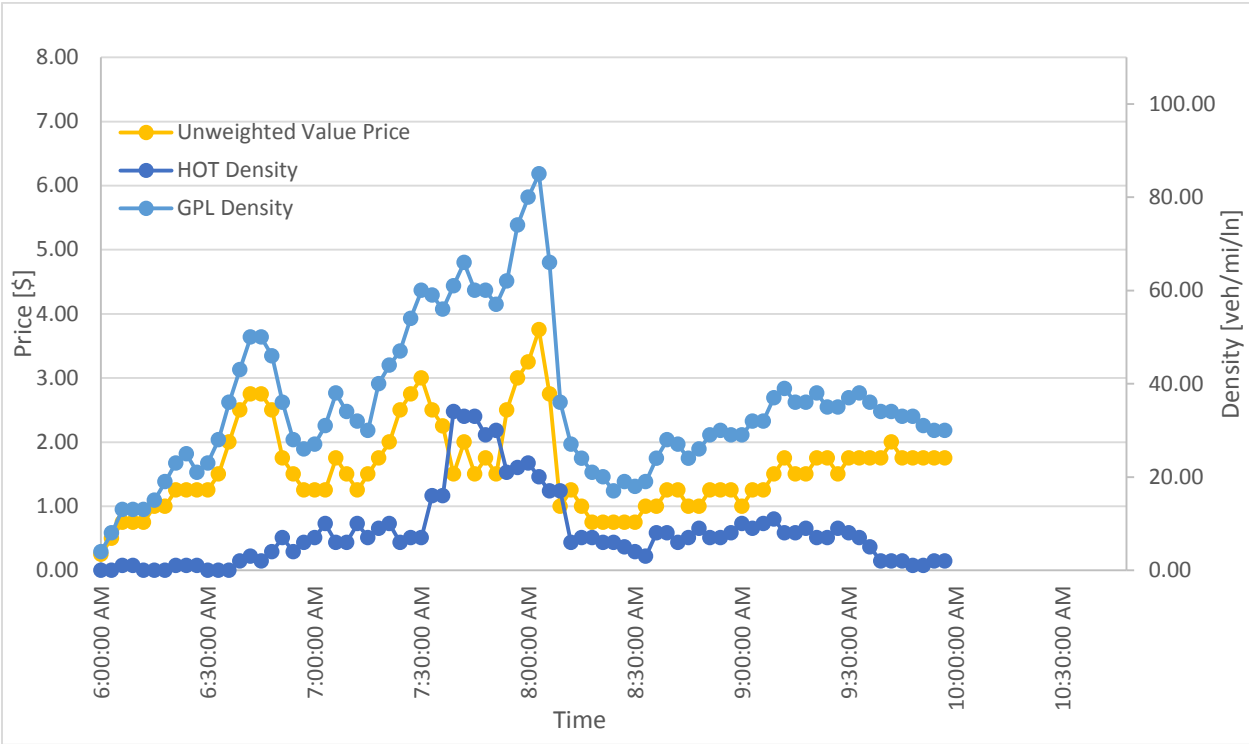

Figure 6-5 Unweighted Value Pricing Function and Density

$$P = \gamma * [K_{GP} - K_{HOT}]\,, where\ \gamma = 0.058$$

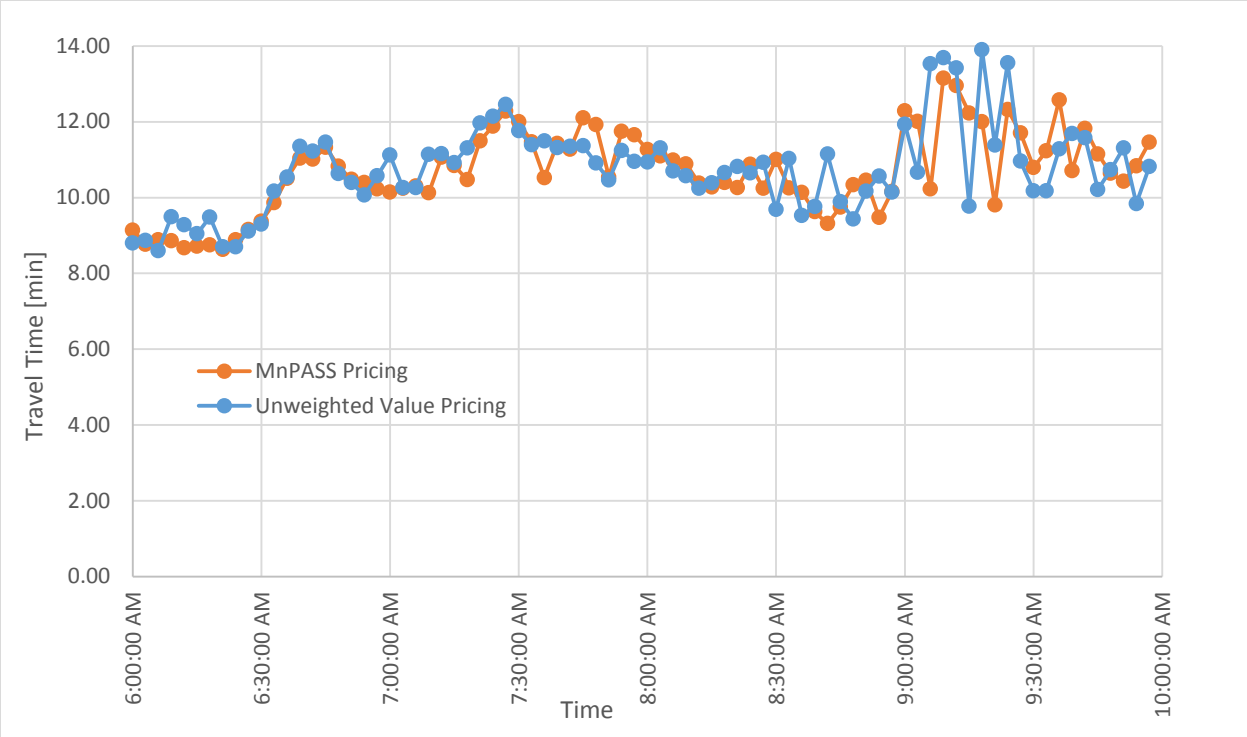

Figure 6-6 Average HOT Lane Travel Time for Existing Pricing Algorithm and Unweighted Value Pricing Function

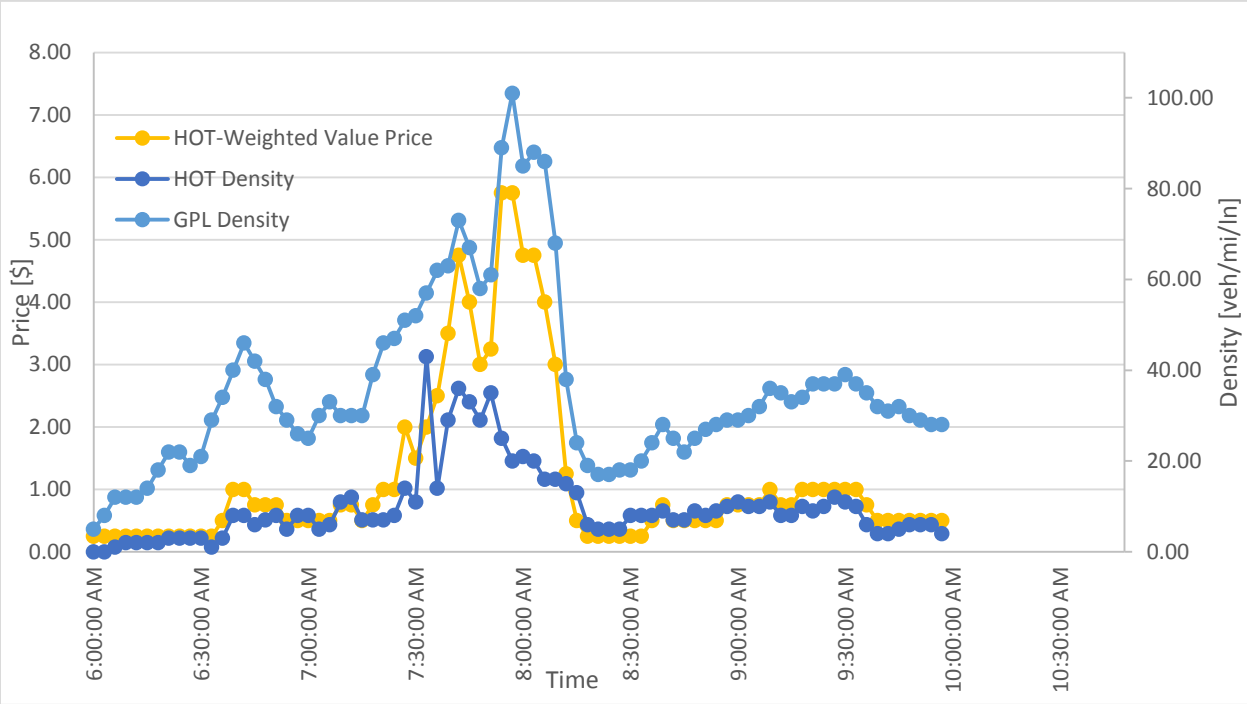

Figure 6-7 HOT-Weighted Value Pricing Function and Density

$$P = \delta * [K_{GP} - K_{HOT}] * K_{HOT}\ , where\ \delta = 0.0034$$

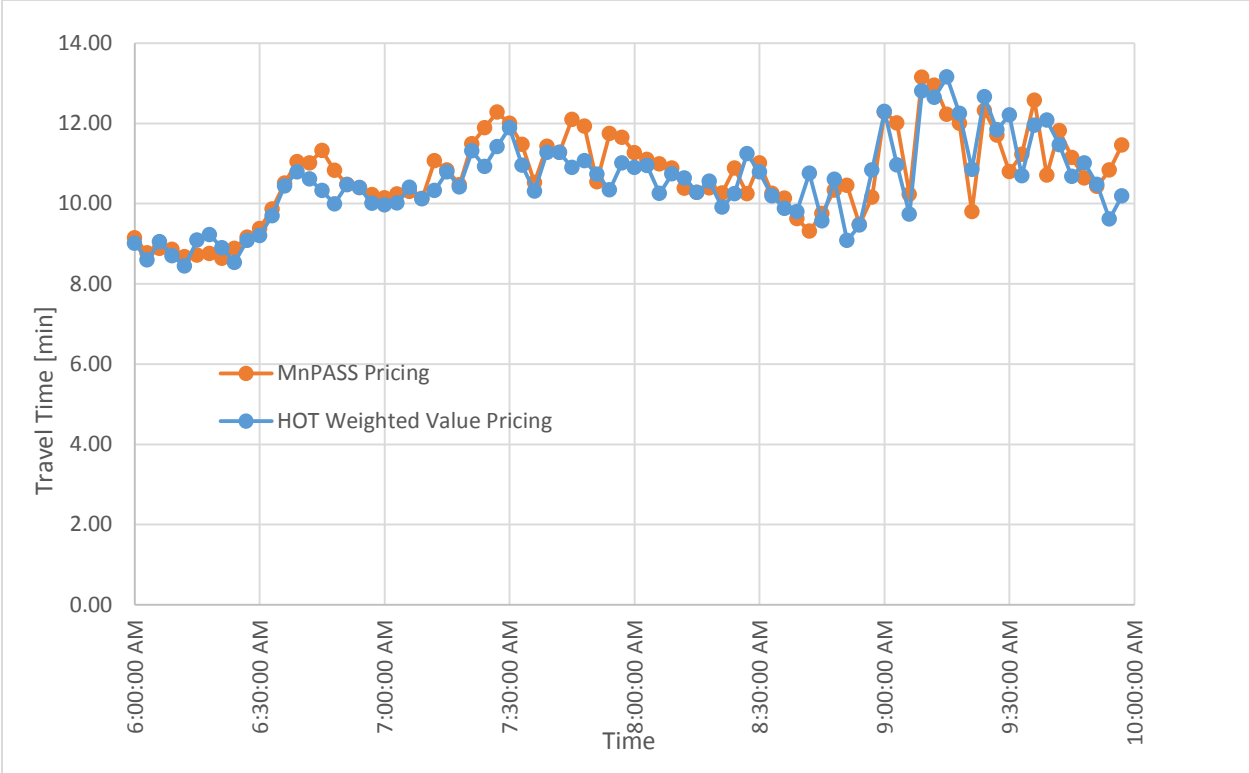

Figure 6-8 Average HOT Lane Travel Time for Existing Pricing Algorithm and HOT-Weighted Value Pricing Function

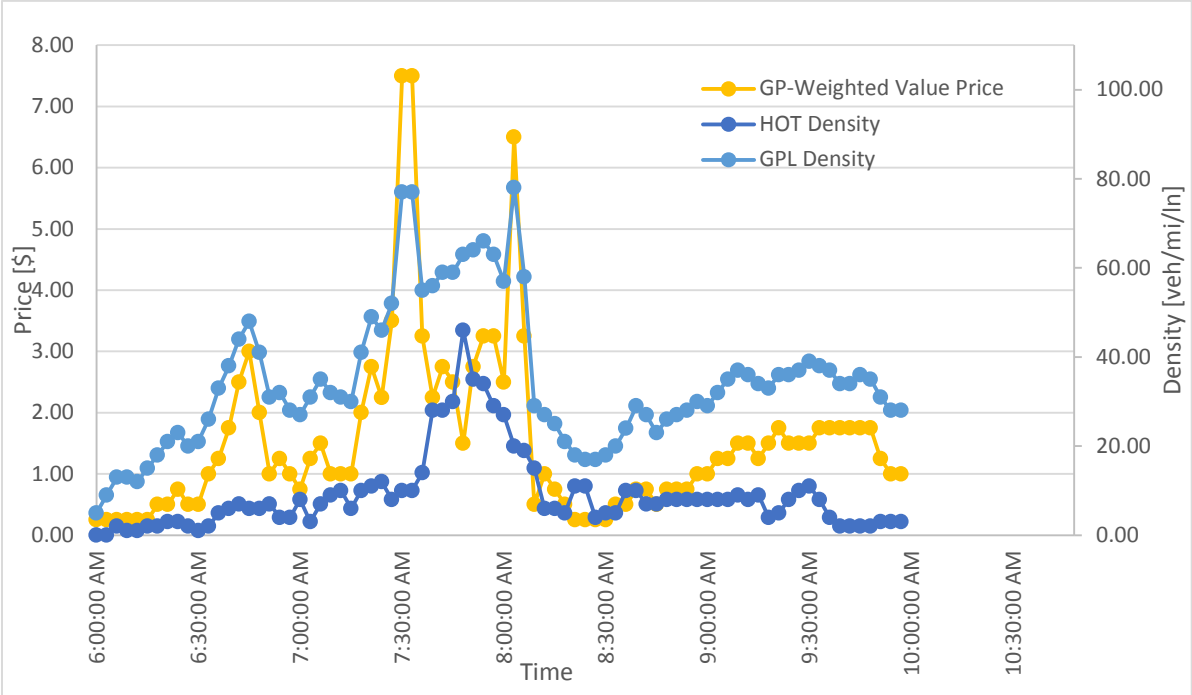

Figure 6-9 GP-Weighted Value Pricing Function and Density

$$P = \sigma * [K_{GP} - K_{HOT}] * K_{GP}\ , where\ \sigma = 0.0015$$

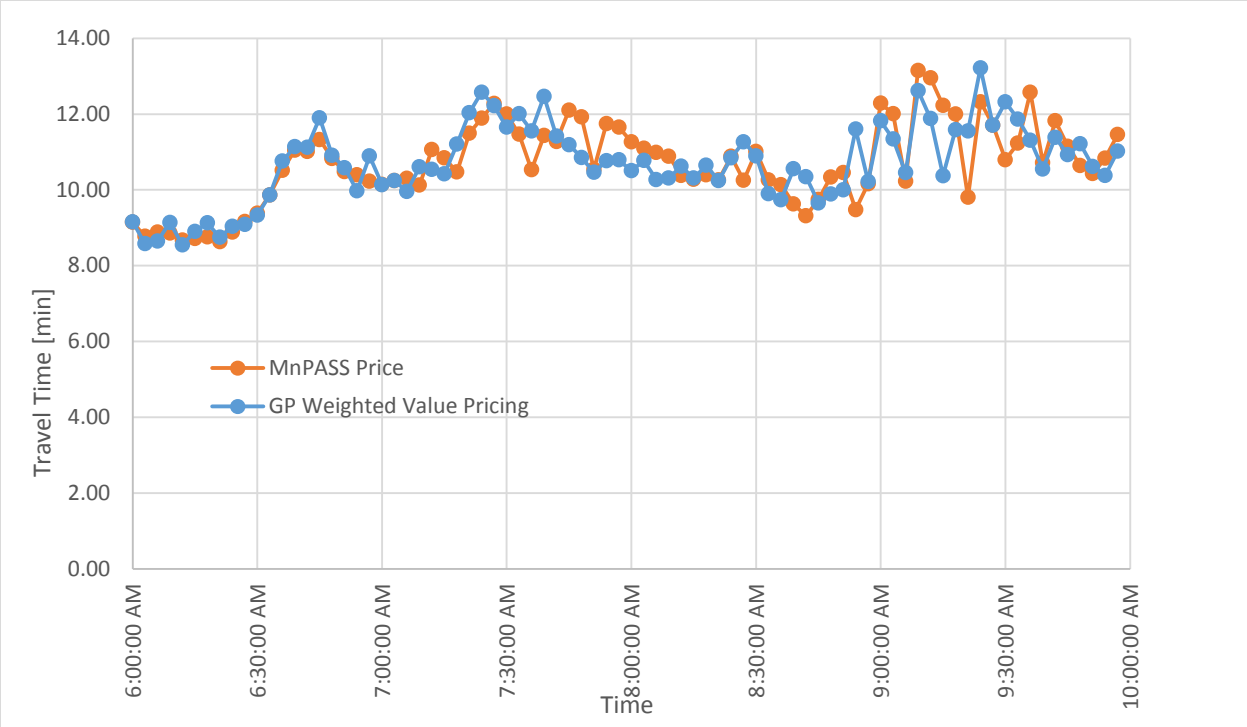

Figure 6-10 Average HOT Lane Travel Time for Existing Pricing Algorithm and GP-Weighted Value Pricing Function

Table 6-9 displays the usage at each plaza and the total usage during the simulation, as well as the total revenue, average price per vehicle, average full-trip travel time, and travel time variability for each pricing strategy. The average real HOT usage is provided for comparison. Travel time variability is calculated as the 90th percentile travel time minus the 50th percentile, as is used in the Lane Choice Model. All value pricing strategies increased HOT usage in the reversible section considerably, while keeping usage in the non-reversible lanes more consistent with real averages. The continuous pricing function resulted in increased revenue over the course of the 4 hour operation period, whereas the value pricing functions resulted in slightly decreased revenue.

Table 6-9 Usage, Revenue, and Travel Time Statistics for all Pricing Strategies

Plaza	Existing Pricing Algorithm	Continuous Pricing	Unweighted Value Pricing	HOT-Weighted Value Pricing	GP-Weighted Value Pricing	Average Real HOT Usage
1001	481	422	281	425	314	541
1002	539	496	362	506	433	663
1003	209	229	101	199	166	219
1004	298	257	291	368	428	267
1005	1339	1234	1860	1594	1886	1200
Total Usage	2866	2638	2895	3092	3227	
Total Revenue	$5,729	$6,165	$4,440	$4,917	$4,522	
Average Vehicle Price (Revenue/Usage)	$2.00	$2.34	$1.53	$1.59	$1.40	
Average Full Trip Travel Time [min]	10.8	10.8	10.8	10.5	10.7	
Travel Time Variability (90th-50th Percentile) [min]	3.0	2.8	2.6	2.9	3.0	

6.4 Investigation of Lane Choice Model Convergence

In order to verify the convergence of the lane choice model, an analysis of the HOT lane usage over all the iterations was carried out for each of the pricing strategies. The graph below displays the change in percent HOT users of subscribers from the last iteration, averaged over all the plazas, for each of the pricing strategies. As can be seen on the graph, the change in percent HOT usage from one iteration to the next drops below 1% at the 4th iteration and stays below this point for the remainder of the training period, indicating that after this point the model will produce consistent results for identical demand and subscription data. This is consistent with observations of individual vehicles in the simulation, who tend to make the same decision of whether or not to use the HOT lane after this point in the experiment.

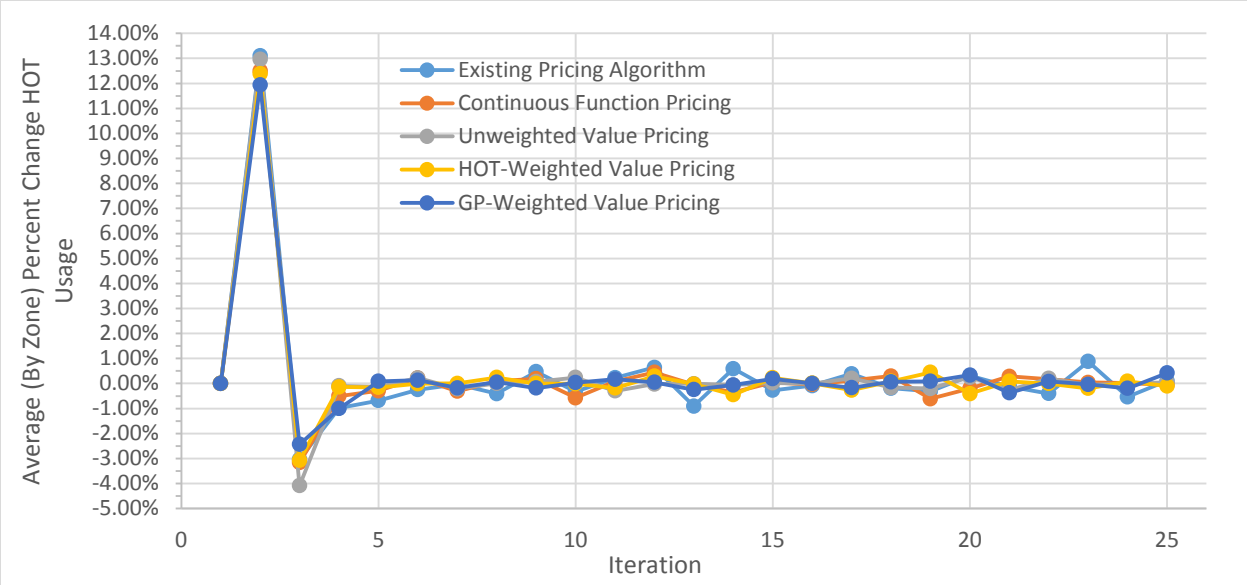

Figure 6-11 Average (By Zone) Percent Change HOT Usage vs. Iteration

7 Conclusion

The effort in this project was focused on two related targets, from field experiments understand and measure the value-of-time mechanism of the MnPASS users, and then develop a simulation tool which, given a good description of this demand and supply relationship, will allow experimentation with other pricing strategies and/or price levels. From the field experiments the most interesting result was that the MnPASS system does not always follow the normal law of demand. Its operational philosophy actually depends on following the regular relationship between the price of a good and its demand, since the desired control is to discourage use of the HOT lane by raising the price. As it was presented in chapter two, up to a certain price level this is not the case, actually the opposite was observed. Specifically, it was observed that more people were selecting to pay the toll as the price increased. Although we can offer only hypotheses on why that happens one logical explanation is that the users misinterpret what the good for sale is. Instead of understanding that the good is a spot at the HOT lane, they believe that the good is avoiding congestion, meaning that the greater the congestion encountered downstream the greater the price they will have to pay to avoid it. Although such a pricing scheme is implementable as shown in the simulation experiments this is not how the MnPASS system is working today. Since this behavior of the drivers is now known one could exploit it and develop a more stable system.

Given the results from the implementation of this model on the I-394 EB network, this framework for simulating the MnPASS lanes shows promise as a truly demand-responsive method for modeling HOT lanes. Issues with the subscription estimation model affect the distribution of users along the corridors being simulated, which can be resolved with improvements to the subscriber route choice model and adjustment in the algorithm logic. These are now possible since the main engine for experimentation is available and has proof of concept.

In addition to this the use of the Lane Choice model discussed in Section 4.2.2, which was calibrated to the I-394 EB network for the AM peak period using real data, on the I-394 WB network during the PM peak period and on the I-35W NB and SB networks seems to not accurately capture the value of time of users on these networks. Again, now that the simulation engine is available, the Lane Choice model parameters can be calibrated to take into account varying destinations. In addition to this, the Lane Choice model could also be adjusted to provide greater generality in its decision making. By incorporating the length of the trip into the model it could better capture the decisions made by drivers in a variety of situations. The use of a new vehicle identification scheme based on origin, destination, and entry time could also allow for more realistic simulations, by eliminating the need to keep random seeds consistent between iterations.

Results obtained from simulations using the alternate pricing functions indicate that these strategies may be useful in managing the MnPASS lanes. The quicker price response afforded by the continuous pricing function, as opposed to the density and level of service tables used by the current MnPASS algorithm, would provide drivers with a more accurate picture of the conditions on the HOT lane, thus reducing the likelihood of breakdown in the HOT lane due to the delay in price increase. Equation-based price algorithms would also be more easily integrated into

MnDOT's current traffic management software than the current MnPASS system, allowing greater control over the system and its calculations. Given these encouraging simulation-based results, a field implementation experiment may be the next step.

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