High-Occupancy Vehicle (HOV) Lane Performance During Nonrecurrent Congestion

and

Alternative Operation Schemes for HOV Lanes: Occupancy Changes, Double HOV Lanes and Clean Air Vehicle Eligibility

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Executive Summary

Background

As California high-occupancy vehicle (HOV) lanes become more congested, operating authorities are looking for guidance on either decreasing the demand for HOV lanes or increasing their capacity. To this end, Caltrans is interested in two HOV-related issues:

- **HOV lane performance during nonrecurrent congestion.** Understanding the relationship between HOV lane performance and nonrecurrent congestion caused by traffic incidents, special events and inclement weather is important to Caltrans' compliance with Federal Highway Administration's (FHWA) HOV lane degradation requirements. According to FHWA guidelines, an HOV lane is considered degraded if the average traffic speed during the peak commute hour is less than 45 mph for more than 10 percent of the time. HOV lane degradation attributed to nonrecurrent congestion can be excluded from compliance with federal regulations.
- **Alternative operation schemes.** Caltrans is interested in learning how HOV lane performance is affected by alternative operation schemes, such as:
    - Increasing vehicle occupancy requirements from two persons per vehicle to three persons per vehicle (2+ to 3+).
    - Prohibiting clean air vehicles from accessing HOV lanes.
    - Implementing double HOV lanes.
    - Implementing some combination of these three.

  Caltrans is also interested in determining the criteria and threshold that should be considered when deciding to implement these changes.

To assist with this research need, CTC & Associates conducted a survey of transportation agencies and a literature search on both topics.

Summary of Findings

Survey of Transportation Agency Practices

Using a distribution list we developed in collaboration with the co-chair of the TRB Managed Lanes Committee, we distributed a brief email survey to gather information about HOV lane performance in relation to nonrecurrent congestion and the effect of alternative operation schemes on HOV lane performance. Eleven transportation agencies responded to our survey.

HOV Lane Performance During Nonrecurrent Congestion

Most respondents reported that their agency had not studied the relationship between HOV lane performance and nonrecurrent congestion. Minnesota DOT has performed some reliability analysis on the Interstate 35 West (I-35W) North MnPASS Project that factored in both recurrent and nonrecurrent congestion.

Most respondents reported that they do not have a method for determining degradation caused by nonrecurrent congestion. Some agencies report traffic incidents that result in significant lane degradation while others categorize the impact by incident type such as shoulder, one lane blocked and multiple lanes.

Respondents also had limited experience with mitigation strategies targeted at HOV facilities affected by recurrent congestion. Arizona DOT is currently considering whether to restrict HOV lane entry to certain locations to avoid the impact on operating speeds caused by unexpected entries. Minnesota DOT is currently documenting mitigation strategies as part of its MnPASS System Study—Phase 3 project. Georgia DOT provided its 2010 Managed Lane System Plan, a comprehensive evaluation of urban area managed lanes.

None of the respondents were aware of relevant research on HOV performance during nonrecurrent congestion.

Alternative Operation Schemes

Most agencies have tried alternative operation schemes, including converting high-occupancy toll (HOT) lanes to HOV lanes, increasing occupancy requirements from 2+ to 3+, prohibiting clean air vehicles and implementing double HOV lanes. But few have systematically studied their effects or can provide data.

Three respondents—Georgia, Ontario and the Texas Transportation Institute (TTI)—provided criteria that are used when implementing alternative operation schemes. Ontario and Oregon provided relevant research on the relationship between alternative operation schemes and HOV lane performance.

Related Resources

HOV Lane Performance During Nonrecurrent Congestion

While we found no research directly addressing the relationship between HOV lane performance and nonrecurrent congestion, several reports may be useful. A 2014 FHWA report catalogs design treatments that can be used to reduce nonrecurrent congestion. A 2011 Washington State DOT report describes key congestion performance measures and how the agency assesses HOV lane performance. A 2007 California PATH Program report evaluates vehicle travel, person travel, occupancy distribution, shape and duration of a peak period, congestion patterns and air quality of on-freeway HOV lanes.

Alternative Operation Schemes

The literature search also produced limited results about the effect of alternative operation schemes on HOV lane performance. A 2002 FHWA study found that lowering the vehicle-occupancy requirement from 3+ to 2+ on the El Monte Busway on the San Bernardino (I-10) Freeway had a detrimental effect. A 2016 analysis of I-270 and I-50 in Maryland found that converting from HOV to HOT lanes considerably improved the use of managed lanes. A 2013 analysis of the conversion of I-85 in Atlanta found that vehicle throughput decreased by 6.6 percent during the morning peak period and 2.9 percent during the afternoon peak period; average vehicle occupancy also decreased during the same period. Other reports provided guidelines for implementing managed lanes, improving their performance and evaluating their operational effects.

Gaps in Findings

Most respondents have not studied the relationship between HOV lane performance and nonrecurrent congestion, nor could they provide a method for determining degradation due to nonrecurrent congestion. They also were unable to point to research on these topics. The literature review also found no research directly addressing the relationship between HOV lane performance and nonrecurrent congestion.

Few states had systematically studied the effects of alternative operation schemes, nor could they point to criteria or other research. The literature search also found limited information on these topics.

Next Steps

Moving forward, Caltrans could consider:

- Following up with Arizona DOT, which is currently investigating mitigation strategies targeting HOV facilities affected by recurrent congestion.
- Following up with Minnesota DOT near the end of 2017 for the results of its MnPASS System Study—Phase 3, which is also documenting mitigation strategies.
- Contacting the North Central Texas Council of Governments and TTI, which had the most extensive information on both the effects of nonrecurrent congestion on HOV performance and on alternative operation schemes.

Detailed Findings

Survey of Transportation Agency Practices

Survey Approach

Using a distribution list we developed in collaboration with the co-chair of the TRB Managed Lanes Committee, we distributed a brief email survey to gather information about high-occupancy vehicle (HOV) lane performance in relation to nonrecurrent congestion and the effect of alternative operation schemes on HOV lane performance.

The survey consisted of the following questions:

HOV Lane Performance During Nonrecurrent Congestion

1. Has your agency studied the relationship between HOV lane performance and nonrecurrent congestion? If so, please provide any available data and documentation.
2. Do you have a method or tool for determining what percentage of HOV degradation (when average traffic speed during the peak commute hour is less than 45 mph for more than 10 percent of the time) is caused by nonrecurrent congestion? Please describe and provide documentation, if available.
3. Have you developed mitigation strategies targeting only HOV facilities affected by recurrent congestion? Please describe and provide documentation, if available.
4. Are you aware of studies by other transportation agencies on the relationship between HOV lane performance and nonrecurrent congestion, or other relevant research? If so, please provide links or contact information.

Alternative Operation Schemes

5. Has your agency:
    - Increased vehicle occupancy requirements from 2+ to 3+?
    - Prohibited clean air vehicles from accessing HOV lanes?
    - Implemented double HOV lanes?
    - Implemented some combination of these?

   If yes, have you studied the effects of these measures on HOV performance? If so, please provide any available data and documentation.
6. Do you have guidance, or have you conducted research, on the criteria that should be used when implementing such changes? If so, please provide any available data and documentation.
7. Are you aware of studies by other transportation agencies or other relevant research on the relationship between such alternative operation schemes and HOV lane performance? If so, please provide links or contact information.

Summary of Survey Results

Eleven transportation agencies responded to the survey. Respondents included eight state departments of transportation (DOTs) and one Canadian province:

- Arizona.
- Florida.
- Georgia.
- Hawaii.
- Minnesota.
- North Carolina.
- Ontario, Canada.
- Oregon.
- Utah.

Two Texas agencies—a regional council of governments and a transportation research organization—also responded to the survey:

- North Central Texas Council of Governments (NCTCOG).
- Texas Transportation Institute (TTI).

The full text of the survey responses appears in Appendix A. Below is a summary of survey responses in these topic areas:

- HOV lane performance during nonrecurrent congestion.
- Alternative operation schemes.

HOV Lane Performance During Nonrecurrent Congestion

When asked about HOV lane performance during nonrecurrent congestion caused by traffic incidents, special events and inclement weather, respondents described practices in the following categories:

- Relationship between HOV lane performance and nonrecurrent congestion.
- Method for determining degradation due to nonrecurrent congestion.
- Mitigation strategies.
- Other research.

Survey responses are provided below. Following the discussion of each topic are the research reports and related guidance provided by survey respondents.

Relationship Between HOV Lane Performance and Nonrecurrent Congestion

Most respondents reported that their agency had not studied the relationship between HOV lane performance and nonrecurrent congestion. The exceptions were Minnesota DOT and TTI.

- Minnesota has performed some reliability analysis on the Interstate 35 West (I-35W) North MnPASS Project that factored in both recurrent and nonrecurrent congestion (see Appendix B).
- TTI provided two reports on the effect of traffic incidents on travel time for HOV lane users.

Related Resources

Minnesota

I-35W North Corridor Preliminary Design Project: Travel Time Reliability Analysis, Minnesota Department of Transportation, September 2016.
See Appendix B
From the introduction (page 1):

> This memorandum documents the methodologies and results of the reliability analysis conducted for the I-35W North Corridor Preliminary Design Project. The reliability results were developed for existing (year 2014) conditions, year 2040 no build, and three year 2040 build alternatives which include the addition of one general purpose lane, a high occupancy vehicle (HOV) lane, and a high occupancy/toll (HOT) lane in each direction. This memorandum presents the assumptions and methods used in these analysis and the results of the evaluation. These alternatives will then be evaluated with a screening process to compare their effectiveness. Reliability is an emerging area of transportation evaluation that considers the variability in travel times that occur due to weather, crashes, and other non-recurring conditions. Understanding these effects for managed lanes is particularly important as these facilities are specially intended to provide freeflow travel for transit, carpools, and single-occupant vehicles willing to pay a congestion-sensitive toll. Communicating these results to stakeholders is critical in demonstrating the long-term value of this type of investment.

From the findings (page 12):

> The MnPASS alternative offers a 10 percent increase in total peak period person throughput over the GP [general purpose] alternative. Additionally, the MnPASS alternative provides a 75 percent increase in number of reliable trips. Through the screening process, the MnPASS alternative maximizes the benefit, and provides a more reliable travel facility for future I-35W users

Texas: Texas Transportation Institute

Improved Quantification of High-Occupancy Vehicle (HOV) Lane Delay Savings: Year Two Results, Texas Department of Transportation, April 2006.
https://static.tti.tamu.edu/tti.tamu.edu/documents/0-4740-3.pdf
From the abstract:

> This report documents the results of the second year of Project 0-4740, Improved Quantification of High-Occupancy Vehicle (HOV) Lane Delay Savings. Year two contained three tasks:
>
> - Task 4: document methodologies used for improved quantification of HOV lane travel time savings including incident conditions, which meets the requirements for Product 0-4740-P1;
> - Task 5: prepare guidelines for opening HOV lanes to all traffic during mainlane incidents, which meets the requirements for Product 0-4740-P2; and
> - Task 6: investigate an automated strategy to continue revising estimated HOV lane delay savings, which meets the requirements for Product 0-4740-P3.

The Effects of Incidents on Concurrent Flow High Occupancy Vehicle Lane Delay on IH-635 (LBJ Freeway) in Dallas, Texas, Texas Department of Transportation, October 2004.
https://tti.tamu.edu/publications/catalog/record/?id=26992
From the abstract:

> High occupancy vehicle (HOV) lanes provide travel time savings and offer a more reliable trip time to its users. Historically, the determination of travel time savings on HOV lanes as compared to general-purpose lanes is calculated using data collected on days without incidents. The objective of this research is to determine the effect on travel time to users of Dallas' concurrent flow buffer-separated HOV lanes on IH-635 (LBJ Freeway) during incident conditions. The research results will supplement research on Houston's barrier-separated HOV lanes on the same topic which are documented in Report 0-4740-1, developed concurrently. The data used to determine HOV lane user benefits/disbenefits during incidents included video data of actual peak period incidents from Dallas' Traffic Management Center and corresponding speed and travel time data in the corridor. Only a few incidents were available for intense data analysis due to the unanticipated speed and travel time data limitations. Incidents blocking one or more of the general-purpose lanes showed a maximum additional travel time savings to HOV lane users of 10 minutes per vehicle for incidents with a lane blockage of nearly 1 hour. Shorter duration incidents produced less added travel time savings. Incidents blocking the HOV lane, due to the incident itself or by responding emergency vehicles, resulted in the HOV lane users experiencing a maximum delay of approximately 10 minutes. Incidents in which both the HOV lane and Lane I are blocked delays HOV lane users a maximum of approximately 14 minutes. The overall net benefit offered to concurrent flow HOV lane users when both non-incident and incident days are included in the calculation equates to only about 1 minute round trip travel time savings per vehicle per day. An unanticipated result of this research is the realization of the importance of proper incident response for maintaining operation of the HOV lane during times of incidents. Simply stated, the HOV lane during certain general-purpose lane incidents appeared to be operating effectively until emergency vehicles came on the incident scene. Suggestions for incident response techniques are offered for maintaining HOV lane operation, including preferred placement of emergency vehicles and directing traffic proactively.

Method for Determining Degradation Due to Nonrecurrent Congestion

Most agencies do not have a method for determining degradation caused by nonrecurrent congestion.

- In its quarterly report on lane performance to Federal Highway Administration (FHWA), Minnesota DOT does include any traffic incident or snow event that caused significant lane degradation. Appendix C provides sample charts showing the percentage of congested time on HOV lanes in MnPASS segments.
- NCTCOG has established policies for express lanes and HOV lanes that include toll rates and procedures.
- TTI looked at travel speeds on general purpose (GP) lanes and HOV lanes, and then categorized the impact by incident type such as shoulder, one lane blocked and multiple lanes.

Related Resources

Minnesota

Percentage of Congested Time—I-394, I-35W, I-35E HOV Lanes: April 1-June 30, 2017, Minnesota Department of Transportation, July 2017.
See Appendix C
This document includes charts showing congested time on HOV lanes in MnPASS segments.

Texas: North Central Texas Council of Governments

Express Lane/HOV Lane Policies, North Central Texas Council of Governments, December 2012.
http://www.nctcog.org/trans/committees/rtc/12.13.12.ManagedLanePolicies_AdoptedRTC_121312.express.hov.pdf
This document establishes toll rates and procedures for NCTCOG express lanes and HOV lanes.

Texas: Texas Transportation Institute

Quantification of Incident and Non-Incident Travel Time Savings for Barrier-Separated High-Occupancy Vehicle (HOV) Lanes in Houston, Texas, Texas Department of Transportation, March 2005.
https://static.tti.tamu.edu/tti.tamu.edu/documents/0-4740-1.pdf
From the abstract:

> This project examined barrier-separated high-occupancy vehicle lane (HOV) travel time savings during incident conditions in Houston, Texas. Travel time studies, due to cost and manpower, are typically conducted infrequently and under non-incident conditions. Due to the high occurrence of incidents in large urban areas, travel time studies conducted under non-incident conditions underestimate the benefit of HOV lanes. During 2003, only an average of 17 percent of AM peak and 10 percent of PM peak periods were found to be incident free in the four HOV corridors studied: I-10 Katy, I-45 North, I-45 Gulf, and US-59 Southwest Freeways. Characteristics of the 9506 incidents reviewed from the incident database are detailed by corridor and direction, cross-section location, severity, number of vehicles, time of day, day of week, month of year, and weather conditions. A total of 341 incidents in these corridors were identified for further analysis and stratified into an incident matrix for each corridor with the extent of lane blockage versus duration of incident. Historical Automatic Vehicle Identification (AVI) data for these incident peak periods were analyzed using a Travel Time Generator software program developed in this project. This software used the AVI data to calculate segment and corridor mainlane and HOV lane travel times for 5-minute periods during the AM peak (6:00 – 9:00 AM) and PM peak periods (3:30 – 6:30 PM). Travel time savings during incident conditions were compared to non-incident conditions for the range of incidents in the matrix. The additional benefit of HOV lane travel time savings during incident conditions over non-incident travel time savings was estimated at 74 percent combining all corridors and peak periods. An important benefit of HOV lanes is shown in the travel time graphs detailing mainlane and HOV lane travel time comparisons for the range of incidents in the matrices. In comparison to average travel time savings over the entire 3-hour peak period, maximum travel time savings during incident conditions ranged up to 64 minutes in the AM peak and 49.5 minutes in the PM peak. An analysis of the entire year of 2003 AVI data (incident and non-incident conditions) estimated the benefit of HOV lanes in these four corridors during the combined AM and PM peak periods at

approximately $146,000 per day or approximately $38 million per year. The Katy Freeway HOV lane showed the greatest incident and non-incident savings at nearly $80,000 per day or $20.5 million per year.

Mitigation Strategies

Respondents had limited experience with mitigation strategies targeted at HOV facilities affected by recurrent congestion.

- Arizona DOT is currently conducting an investigation into HOV lane accidents. The agency is considering restricting HOV lane entry to certain locations to avoid the unexpected entries into HOV lanes that impact HOV lane operating speeds. This practice has been adopted in ADOT District 7.
- Georgia DOT has explored converting all existing HOV facilities to three person per vehicle high-occupancy toll (HOT 3+) lanes. The agency did not adopt this strategy, however, because of lack of public support. The Managed Lane System Plan, available on the agency's web site, describes this effort.
- Minnesota DOT is currently documenting mitigation strategies as part of the MnPASS System Study—Phase 3 (http://www.dot.state.mn.us/metro/projects/mnpass-study/index.html). The study, which will identify and evaluate highway corridors for future MnPASS lanes, is expected to be complete by the end of 2017.
- NCTCOG has implemented a limited number of mitigation strategies targeted at HOV facilities, including using enhanced enforcement, adding a toll or increasing occupancy.
- TTI reported on the effect of several strategies, such as increasing HOV occupancy, tolling and a combination of these methods, as part of the QuickRide program on the Katy Freeway HOV lane in Houston.

Related Resources

Georgia

2010 Managed Lane System Plan (MLSP), Georgia Department of Transportation, January 2010.
http://www.dot.ga.gov/BS/Studies/ManagedLanes
From the study web page:

> The Managed Lane System Plan (MLSP) is the first comprehensive system-wide evaluation of urban area managed lanes performed in the United States. GDOT believes that in most locations it is not feasible to construct additional general purpose lanes to meet current and future needs. Therefore, GDOT has developed the MLSP for Metro Atlanta that will utilize and expand the current HOV system footprint. Managed lane solutions would preserve mobility choices and provide financially feasible improvements. The study was conducted by the Georgia DOT between January 2007 and January 2010.

Texas: Texas Transportation Institute

An Evaluation of the Katy Freeway HOV Lane Pricing Project, Texas Transportation Institute, December 2000.
https://static.tti.tamu.edu/tti.tamu.edu/documents/E-305001.pdf
From the abstract:

> This paper describes the QuickRide program on the Katy high-occupancy vehicle (HOV) lane in Houston, Texas. The QuickRide program allows two-person carpools to use the HOV lane during peak periods for $2.00 when the lane has a three or more person restriction. The use of QuickRide during its first year is discussed along with an analysis of the demand for the program and an analysis of the effectiveness of the program. QuickRide usage and before-and-after implementation data are used to analyze user travel patterns, observed travel time savings, and changes in person throughput in the Katy Freeway corridor. QuickRide usage, reported travel behavior, and demographic data are used to analyze user travel patterns, travel time savings, and users' frequency of use. These results suggest: (1) the total demand for HOV2 value pricing may be limited in major travel corridors, despite large potential time savings; (2) substantial shifts in mode and time are possible with HOV2 value pricing; and, (3) household size and income are good indicators, but HOV lane use is a poor indicator, of the demand for HOV2 value pricing.

<u>Other Research</u>

None of the respondents were aware of other research on HOV performance during nonrecurrent congestion.

- The Utah respondent provided two reports about operations during traffic incidents: a TTI project that studied the safety issues associated with HOV lanes, and a Florida DOT study that investigated lifting HOV lane and shoulder use requirements during major incidents.

Related Resources

Utah

Crash Data Identify Safety Issues for High-Occupancy Vehicle Lanes in Selected Texas Corridors, A. Scott Cothron, Stephen E. Ranft, Carol H. Walters, David W. Fenno, and Dominique Lord, Texas Transportation Institute, January 2005.
https://static.tti.tamu.edu/tti.tamu.edu/documents/0-4434-S.pdf
From the abstract:

> The objective of this research was to develop a better understanding of the safety issues associated with HOV lanes, particularly buffer-separated concurrent flow HOV lanes. The research team increased understanding primarily through analyzing freeway corridors in Dallas, where HOV lanes have been implemented. These corridors offer a valuable opportunity to evaluate "before" and "after" crash data and determine whether there has been a change in injury crash occurrence. Based on the key findings of the crash data analysis, the research team developed guidance for future HOV lane projects.

Lifting HOV/HOT Lane Eligibility and Shoulder Use Restrictions for Traffic Incident Management, Yafeng Yin, Lily Elefteriadou, Ziqi Song, Nima Shirmohammadi, Grady Carrick, Alexandra Kondyli, Florida Department of Transportation, December 2013.
http://www.fdot.gov/research/Completed_Proj/Summary_TE/FDOT-BDK77-977-23-rpt.pdf
From the abstract:

> This report presents an investigation of the possibility of lifting HOV/HOT lane eligibility and shoulder use restrictions during major incidents on general-purpose (GP) lanes. Using traffic data from FDOT Districts 4 and 6, the impacts of incidents of GP lanes on the operation of HOV/HOT lanes were investigated. A methodology was developed to determine the appropriateness of diverting the GP traffic to HOV/HOT lanes under different incident scenarios. The methodology is theoretically sound and can be easily implemented in a spreadsheet tool requiring only a few critical inputs. The project also reviewed the regulations in Florida concerning the operations of HOV/HOT lanes and concluded that there was no legal obstacle or barrier that prevents opening HOV/HOT lanes to the GP traffic. Consequently, a two-stage decision-making procedure was proposed to implement a diversion plan. The procedure takes advantage of the existing partnership between FDOT and FHP on incident management and should allow quick decision making and ensure the integrity and credibility of the diversion policy. Lastly, the feasibility of shoulder use for incident management as well as simultaneous use of other freeway management techniques such as variable speed limits and ramp metering were investigated.

Alternative Operation Schemes

When asked about the alternative operation schemes implemented for managed lanes in their system, respondents described practices in the following categories:

- Performance data.
- Guidance and research on implementation criteria.
- Other research.

Survey responses are summarized below. Following the discussion of each topic are the research reports and related guidance provided by survey respondents.

Performance Data

Most agencies have tried alternative operation schemes, but few have systematically studied their effects or can provide data.

- Florida is phasing out HOV lanes and converting them to HOT 3+ lanes. The amount of HOV 3+ carpoolers is very small—for example, on one segment of I-95, about 500 out of 70,000 exempt vehicles out of 1.8 million recorded trips. Eighty percent of the exempt vehicles were hybrids. An agency web site provides monthly operations reports that summarize traffic statistics.
- Georgia has converted one corridor (I-85 in the northeast part of metro Atlanta) from HOV 2+ to HOT 3+. It has not prohibited low emission vehicles or implemented double HOV lanes.
- North Carolina is currently converting its only HOV lane facility on I-77 to an HOT 3+ lane. The facility is increasing from one to two lanes in each direction and is being

extended in each direction. The agency has not monitored or studied the HOV facility sufficiently to provide data.

- MnDOT has not increased occupancy requirements. It has prohibited clean air vehicles, and has a two-lane reversible segment on I-394, but has not formally studied the effects of these measures.
- NCTCOG prohibits single occupant, clean air vehicles from accessing HOV lanes, but has not studied the effects of these measures.
- The TTI respondent reported that Houston has tried increasing occupancy requirements from 2+ to 3+, prohibiting clean air vehicles and implementing double HOV lanes.

Related Resources

Florida

95 Express Performance Reports, District 6, Florida Department of Transportation, 2017.
http://www.sunguide.info/sunguide/index.php/tmc_reports/archives/98
This web site provides monthly traffic data for tolling segments of I-95 in Miami-Dade and Broward counties.

Texas: Texas Transportation Institute

Katy Freeway: An Evaluation of a Second-Generation Managed Lanes Project, Ginger Goodin, Robert Benz, Mark Burris, Marcus Brewer, Nick Wood and Tina Geiselbrecht, Texas Department of Transportation, September 2013.
https://static.tti.tamu.edu/tti.tamu.edu/documents/0-6688-1.pdf
From the abstract:

> The Katy Freeway Managed Lanes (KML) represents the first operational, multilane managed facility in Texas and provides an opportunity to benefit from the lessons learned from the project. This study evaluated multiple aspects of KML and the critical areas of project development, design, and operation. One sample finding is that travel time savings are approximately 5 minutes in the morning and 14 minutes in the afternoon in the peak directions, and the travel time advantage over the general-purpose lanes has increased as volumes have grown. Continual monitoring and adjustment of operating aspects of new managed lanes is required post-opening, especially during the ramp-up period in which drivers make travel adjustments to use the facility. The operating partners for the KML have continuously monitored the performance of the lanes since opening and have made adjustments in toll rates, lane configuration at the tolling zones, and access operations at the western terminus. These adjustments are critical to ensuring that the performance standards for the lanes are maintained.

Guidance and Research on Implementation Criteria

Only Georgia, Ontario and TTI provided criteria that should be used when implementing alternative operation schemes:

- Georgia criteria can be found in its Managed Lane System Plan (see **Mitigation Strategies** on page 10) and its follow-up Managed Lanes Implementation Plan. However, the Managed Lane Implementation Plan did not recommend converting HOV lanes to HOT lanes.

- Ontario is exploring the option of adding double HOV lanes, but they would have to be new lanes that add capacity on the corridor. The agency would never convert a GP lane to an HOV lane. If its facilities approach capacity, Ontario would consider changing the vehicle occupancy to 3+, but the agency's current analysis shows that less than 15 percent of vehicles on the corridor have 3+ occupancy. Ontario would not prohibit clean air vehicles from accessing HOV lanes.
- Guidance related to implementation criteria in Texas is available in the managed lane reports related to alternative operation schemes (see **Performance Data** on page 13).

Related Resources

Georgia

Atlanta Regional Managed Lanes Implementation Plan (MLIP), Georgia Department of Transportation, December 2015.
Executive summary:
http://www.dot.ga.gov/BuildSmart/Studies/ManagedLanesDocuments/MLIP/MLIP01%20Report%20Exec%20Summary.pdf

Final report:
http://www.dot.ga.gov/BuildSmart/Studies/ManagedLanesDocuments/MLIP/MLIP02%20Report%20FINAL.pdf
This report documents managed lane alternatives in the Atlanta area*. From page 4:*

> The MLIP found that managed lanes were an appropriate solution along I-20 East and West, I- 285 East and Northwest, I-85 North, SR 316, SR 400 North, and I-75 South. All of these corridors were deemed feasible for new lanes. A subset of these corridors was also deemed feasible for further engineering for the potential use of dynamic flex lanes, including I-20 East and West, I-285 Northwest, and I-75 South. How the managed lane will be delivered (new lane versus dynamic flex lane) will be determined during the project development process as part of an independent study or preliminary engineering, as well as the planning process, as part of the Atlanta MPO's [metropolitan planning organization's] Regional Transportation Plan. Various evaluation criteria, including project financeability index (PFI), were used to determine the feasibility of each priced managed lane treatment. Detailed analysis on the evaluation of all potential managed lanes is located in Chapter 7, beginning on page 101. A summary of MLIP findings is located in Chapter 9, beginning on page 120. Table 9.1 (New Lanes) and Table 9.2 (Dynamic Flex Lanes) provide a summary of the financial criteria, including the 30-year revenue, capital costs, and 30-year operation and maintenance costs for each of the managed lane strategies that could move forward for further analysis and consideration.

Appendices to the report and related factsheets and presentations are available at http://www.dot.ga.gov/BS/Studies/MLIP.

Other Research

Only Ontario and Oregon provided other relevant research on the relationship between alternative operation schemes and HOV lane performance.

- Ontario has been using Georgia DOT's findings on the conversion of vehicle occupancy requirements reported in the Managed Lanes Implementation Plan (see **Guidance and Research on Implementation Criteria** on page 14).
- The Oregon respondent provided a University of California Berkeley study verifying that slow speeds in HOV lanes are due to the increased use of managed lanes and slow speeds in adjacent GP lanes.

Related Resources

Oregon

Dual Influences on Vehicle Speeds in Special-Use Lanes and Policy Implications, Kitae Jang and Michael Cassidy, University of California Berkeley Center for Future Urban Transport, September 2011.
http://www.its.berkeley.edu/sites/default/files/publications/UCB/2011/VWP/UCB-ITS-VWP-2011-4.pdf
From the abstract:

> We verify that slow speeds in a special-use lane, such as a carpool or bus lane, can be due to both high demand for that lane and slow speeds in the adjacent regular-use lane. These dual influences are confirmed from months of data collected from all freeway carpool facilities in the San Francisco Bay Area. Additional data indicate that both influences hold not only for other types of special-use lanes, including bus lanes, but also for other parts of the world. The findings do not bode well for a new US regulation stipulating that most classes of Low Emitting Vehicles, or LEVs, are to vacate slow-moving carpool lanes. These LEVs invariably constitute small percentages of traffic; e.g. they are only about 1% of the freeway traffic demand in the San Francisco Bay Area. Yet, we show that relegating some or all of these vehicles to regular-use lanes can significantly add to regular-lane congestion, and that this, in turn, can also be damaging to vehicles that continue to use the carpool lanes. Counterproductive outcomes of this kind are predicted first by applying kinematic wave analysis to a real Bay Area freeway. The site stands to suffer less from the regulation than will others in the region. Yet, we predict that the site's people-hours and vehicle-hours traveled during the rush will each increase by more than 10%, and that carpool-lane traffic will share in the damages. Real data from the site support these predictions. Further parametric analysis of a hypothetical, but more generic freeway system indicates that these kinds of negative outcomes will be widespread. Constructive ways to amend the new regulation are discussed, as are promising strategies to increase the vehicle speeds in carpool lanes by improving the travel conditions in regular lanes.

Related Resources

The citations below are organized in the following categories:

- HOV lane performance during nonrecurrent congestion.
- Alternative operation schemes.
    - Occupancy requirements.
    - High-occupancy toll lane conversions.
    - Clean air vehicles.
    - Managed lane policies and performance measures.

HOV Lane Performance During Nonrecurrent Congestion

"Characterizing Variations of Congested Freeway Lane Flow Distribution Trends,"
Paulina Reina and Soyoung Ahn, *TRB 95th Annual Meeting Compendium of Papers*, Paper #16-3868, 2016.
Citation at http://trid.trb.org/view/1393430
From the abstract:

> This paper presents a large-scale study to characterize lane flow distribution (LFD), the proportion of total flow in each lane, in three-lane congested freeways. Empirical data from 70 sites were analyzed to investigate the traffic and geometric characteristics of freeways that affect the occurrence of between and within site variations in linear LFD trends with respect to flow. Multiple logistic and Dirichlet regression were employed in a three-stage modeling framework to model LFD behavior at several levels. Logistic regression was used to characterize the occurrence of LFD trends as opposed to constant LFD (stage 1) and the occurrence of two common varying-LFD classes (stage 2). Dirichlet regression was used in stage 3 to model linear LFD trends that account for the unit-sum and boundary constraints inherent in proportions data. A total of five recurrent classes of LFD trends were identified. Results revealed that proximity to freeway merges, a site's level of congestion, and the presence of HOV lanes are significant factors that influence class-specific LFD behavior. In addition, the estimated Dirichlet models were shown to be effective in representing linear LFD trends in congestion.

Design Guide for Addressing Nonrecurrent Congestion, Federal Highway Administration, SHRP 2 Report S2-L07-RR-2, 2014.
http://onlinepubs.trb.org/onlinepubs/shrp2/SHRP2prepubL07designguide.pdf
This report "catalogs highway design treatments that can be used to reduce nonrecurrent congestion and improve the reliability of urban and rural freeways." See page 130 of the guide (page 143 of the PDF) for a discussion of HOV and HOT lanes.

Related Resource:

> **Analysis Tool for Design Treatments to Address Nonrecurrent Congestion: Annotated Graphical User's Guide**, Version 2, Federal Highway Administration, SHRP 2 Report, 2014.
> Citation at http://trid.trb.org/view/1322140
> *From the abstract*:
>
> > The Transportation Research Board's second Strategic Highway Research Program (SHRP 2) Reliability Project L07 has released this guide to assist users of the Microsoft Excel-based Analysis Tool for Design Treatments to Address Nonrecurrent Congestion. The analysis tool is designed to analyze the effects of highway geometric design treatments on nonrecurrent congestion using a reliability framework. The tool can be used to analyze a homogenous segment of a freeway (typically between successive interchanges) by allowing users to input data about site geometry, traffic demand, incident history, weather, special events, and work zones. Based on these data, the tool calculates base reliability conditions which can be used to analyze the effectiveness of treatments by providing input data of the treatment effects and cost parameters. As outputs, the tool predicts cumulative travel time index curves for each hour of the day, from which other reliability variables are computed and displayed. The tool also calculates cost-effectiveness by assigning monetary values. This User Guide is pictorial and annotated. It displays most of the entry screens presented to the user by the tool, with descriptions of their respective meanings and usage. Much of this help content (and additional guidance) is also embedded in the tool via information buttons.

HOV Lane Performance Monitoring System, Ali Haghani and Masoud Hamedi, National Transportation Center at Maryland and Maryland State Highway Administration, December 2014.
http://ntc.umd.edu/sites/default/files/documents/Publications/NTC2014-SU-R-10%20Ali%20Haghani.pdf
From the executive summary:

> High occupancy vehicle (HOV) lanes promote carpooling, van and bus usage. The lanes maximize person throughput instead of just vehicle throughput. HOV lanes offer a travel time savings for multiple occupant vehicles over single occupant vehicles by restricting access to vehicles that have two or more occupants. Making more efficient use of existing road system through HOV lanes is a cost-effective solution to improve mobility. Continuous monitoring of the system performance is a key to a successful implementation. Proliferation of internet enabled and location aware electronic and navigation systems has made network wide travel time data available in recent years. However measuring HOV performance requires separate travel time data for HOV and general purpose lanes. Motivated by advancements in travel time measurement technologies, a pattern recognition algorithm for separating travel time on HOV and regular lanes collected by Bluetooth sensors is designed and implemented in this project. The algorithm is part of a framework for fusing traffic data from several sources to estimate key HOV indicators.

WSDOT's Congestion Measurement Approach: Evaluating System Performance, Washington State Department of Transportation, June 2011.
https://www.wsdot.wa.gov/NR/rdonlyres/821BF63A-BB4C-49C5-AEDE-3F27CC671813/0/CongestionFolioForWeb_June2011.pdf
This publication describes Washington State DOT's key congestion performance measures and how the agency assesses HOV lane performance.

“High Occupancy Vehicle Lane Performance Assessment Through Operational, Environmental Impacts and Cost-Benefit Analyses,” Virginia P. Sisiopiku, Ozge Cavusoglu and Saiyid Hassan Sikder, *Proceedings of the 2010 Spring Simulation Multiconference*, Article No. 56, 2010.
Citation at http://dl.acm.org/citation.cfm?id=1878596
From the abstract:

> High Occupancy Vehicle (HOV) lanes are in operation in the U.S. for more than 30 years and used as a tool to alleviate urban freeway congestion. For new HOV projects a need exists to study the feasibility of implementation as well as assess their potential operational and environmental impacts prior to deployment. Equally important is to obtain a clear picture of expected cost and benefits of available options in order to determine the most effective strategy for implementation. This paper reports on a study that was undertaken to determine the need for and impact from the potential deployment of HOV lanes in Birmingham, Alabama. To meet the study objectives, a detailed alternatives analysis and cost-benefit analysis were performed using Traffic Software Integrated System (TSIS) and Integrated Development Assessment System (IDAS) respectively. Three different scenarios and a total of ten options were considered to quantify the operational, environmental, and economic impacts of HOV lanes on traffic operations. The paper provides background information on the models used, data gathered, assumptions made, and outputs obtained. A detailed description of the analysis and results is also presented.

Implementing Active Traffic Management Strategies in the U.S., Virginia Sisiopiku, Andrew Sullivan and Germin Fadel, University Transportation Center for Alabama, October 2009.
https://ntl.bts.gov/lib/31000/31300/31399/Project_08206_Final_Report.pdf
From the abstract:

> Limited public funding for roadway expansion and improvement projects, coupled with continued growth in travel along congested urban freeway corridors, creates a pressing need for innovative congestion management approaches. Strategies to address congestion have been implemented in many areas of this country and include such options as variable message signs, High Occupancy Vehicle (HOV) lanes, toll lanes, ramp metering, and network surveillance. These strategies, however, have largely been deployed so that they function independently and are often implemented only on preset schedules or manually in response to an incident. Active Traffic Management (ATM) utilizes many of these same strategies but does so in concert in order to maximize the efficiency of transportation facilities during all periods of the day and under both recurrent and non-recurrent congestion conditions. This approach stresses automation to dynamically deploy strategies to quickly optimize performance and enhance throughput and safety.

A Review of HOV Lane Performance and Policy Options in the United States, Federal Highway Administration, December 2008.
https://ops.fhwa.dot.gov/publications/fhwahop09029/fhwahop09029.pdf
From the abstract:

> The report provides an assessment of performance of existing HOV lane facilities in the United States, and explores policy alternatives and effects related to conversion of existing HOV lanes to HOT lane operations. The report includes sketch planning tools for exploring policy alternatives, and is intended for an audience of transportation professionals responsible for planning, designing, funding, operating, enforcing, monitoring, and managing HOV and HOT lanes, and other stakeholders in policy decisions for improving HOV lane and highway mainline operations through conversion to HOT lanes.

Determining the Effectiveness of HOV Lanes, Adolf D. May, Lannon Leiman and John Billheimer, California PATH Program, Institute for Transportation Studies, November 2007.
http://www.path.berkeley.edu/sites/default/files/publications/PRR-2007-17.pdf
From the abstract:

> The primary objectives of this project have been to evaluate freeways having on-freeway HOV lanes in terms of vehicle-travel, person-travel, occupancy distribution, shape and duration of the peak period, congestion patterns, and air quality both in the HOV lane and the adjacent mixed-flow lanes. Based on a comprehensive literature review an extensive list of reference was developed, along with summaries synthesizing the state of the knowledge regarding the effectiveness of HOV lanes and their impact on air quality. … To demonstrate the types of analyses that would be useful in this process, the modified freeway simulation model FREQ was applied to two freeway study sites, one in Northern California and one in Southern California. The FREQ model proved to be well suited for investigating various combinations of HOV lane design and operating parameters. As traffic demands increase and HOV lanes generate changes in ridesharing choices, the continued success of HOV lane operation is likely to require changes in HOV lane design and operations. This will require careful monitoring of the HOV lane facility and further modeling analyses.

Alternative Operation Schemes

Occupancy Requirements

Impacts of Increasing Vehicle-Occupancy Requirements on HOV/HOT Lanes, Caltrans Division of Research and Innovation, March 2013.
http://www.dot.ca.gov/newtech/researchreports/preliminary_investigations/docs/HOV_and_HOT_Lanes_Preliminary_Investigation_03-25-13.pdf
From the abstract:

> Portions of California's high occupancy vehicle (HOV) lane network are becoming congested during peak periods. To address this congestion, the California Department of Transportation (Caltrans) is exploring several solutions: increased enforcement, bottleneck reductions, hybrid/electric vehicle exclusions, raising the minimum required occupancy, and converting lanes into high occupancy toll lanes. Caltrans is interested in conducting an investigation into the likely impacts of these measures on corridor performance. A literature review focused on identifying relevant studies; performance measures used; facilities that have increased requirements; whether alternative modes were available; and, research work on transportation modeling that addresses possible mode changes.

Related Resource:

> **"Managed Lanes Case Studies,"** a companion to *Impacts of Increasing Vehicle-Occupancy Requirements on HOV/HOT Lanes*, Caltrans Division of Research and Innovation, March 2013.
> http://www.dot.ca.gov/newtech/researchreports/preliminary_investigations/docs/HOV-to-HOT_Case_Studies_03-25-13.pdf
> This supplement to the Preliminary Investigation contains case studies of managed lanes projects in Florida, Georgia and Texas. The appendices comprise several stand-alone reports on managed lanes in those states.

"Influence of Vehicle Occupancy on the Valuation of Car Driver's Travel Time Savings: Identifying Important Behavioural Segments," David A. Hensher, *Transportation Research Part A: Policy and Practice*, Vol. 42, No. 1, pages 67-76, January 2008.
Citation at http://trid.trb.org/view/842553
From the abstract:

> Studies that develop estimates of the value of travel time savings (VTTS) for car travel typically assume that the VTTS of the driver is the only relevant measure of the worth of time savings. Although there is a recognition that the presence of passengers may condition the driver's choice of route and VTTS, the evidence is somewhat limited on the impact that the number of passengers has on the driver's VTTS. This is especially problematic when evaluating the role that policy instruments such as HOV lanes might play in delivering travel time savings for a specific occupancy, as well as the growing opportunities to have differentiated congestion charges and tolls according to occupancy. This paper investigates the role that the presence of the passenger plays in the VTTS of the non-commuting car driver. We find that the overall mean VTTS varies across the number of passengers (from $19.99 to $13.22 per person hour), declining as the number of passengers increases; however this is largely attributable to the decreasing mean VTTS for slowed down time in contrast to a 'flat' mean free flow time. The implications on travel time benefits ignored (through simple averaging) in previous studies, especially tollroad studies, and hence the impact on infrastructure justification, is potentially profound, given the important role played by VTTS and its variation over the number of passengers.

Effects of Changing HOV Lane Occupancy Requirements: El Monte Busway Case Study, Katherine F. Turnbull, Federal Highway Administration, June 2002.
https://ops.fhwa.dot.gov/freewaymgmt/publications/hov/ElMonteFinalReport.pdf
From the abstract:

> In 1999, the California Legislature passed Senate Bill (SB) 63, which lowered the vehicle-occupancy requirement on the El Monte Busway on the San Bernardino (I-10) Freeway from three persons per vehicle (3+) to two persons per vehicle (2+) full time. The California Department of Transportation (Caltrans) was directed to implement this change on January 1, 2000 and to monitor and evaluate the effects of the 2+ requirement on the operation of the Busway and the freeway. Based on the operational effects that resulted from this change, new legislation was approved increasing the vehicle-occupancy requirement back to 3+ during the morning and afternoon peak-periods effective July 24, 2000. This report represents information on the effect the change in the vehicle-occupancy requirement had on the operation of the Busway and freeway, public transit services, violation rates, accidents, local and feeder roadways, and public response. The assessment is based on available information from Caltrans, Foothill Transit, the Los Angeles County Metropolitan Transportation Authority, the California Highway Patrol, and other local agencies. Lowering the vehicle-occupancy requirement from 3+ to 2+ full time had a detrimental effect on the Busway. At the same time, significant improvements were not realized in the general-purpose freeway lanes. Morning peak-period travel speeds in the Busway were reduced from 65 mph to 20 mph, while travel speeds in the general-purpose lanes decreased from 25 mph to 23 mph for most of the demonstration. Hourly Busway vehicle volumes during the morning peak-period increased from 1,100 to 1,600 with the 2+ designation, but the number of persons carried declined from 5,900 to 5,200. The freeway lane vehicle volumes and passengers per lane per hour remained relatively similar. Peak-period travel times on the Busway increased by 20 to 30 minutes. Bus schedule adherence and on-time performance declined significantly and passengers reported delays.

High-Occupancy Toll Lane Conversions

Macro-Modeling and Micro-Modeling Tools for HOV-to-HOT Lane Analysis, Randall Guensler, Sara Khoeini and Adnan Sheikh, Georgia Department of Transportation, June 2016.
http://g92018.eos-intl.net/eLibSQL14_G92018_Documents/14-31.pdf
From the abstract:

> This report summarizes the analysis of observed commuting changes after conversion of an existing carpool lane into a high-occupancy toll lane, on 15.5 miles of Atlanta I-85. The team explored the correlations between observed changes in travel behavior and the socio-spatial characteristics of the users using 1.5 million license plate observations coupled with census demographic data. Commuter response was evident in the observed changes in commuter choice to continue to use the new managed lane, or move to the general purpose lane after conversion. Aggregate-level socio-spatial analysis of the impacts of the Atlanta I-85 high-occupancy vehicle (HOV) to high-occupancy toll (HOT) conversion across demographic groups and socio-economic attributes are presented in this report. This study enhances the ability of modelers to integrate managed lanes into travel demand models, with respect to travel demand response across user characteristics. The report also introduces a comprehensive modeling framework for socioeconomic analysis of managed lanes. The methods developed through this can inform future Traffic and Revenue Studies and help to better predict the socio-spatial characteristics of the target market.

"Assessing HOV to HOT Lane Conversion: Multiscale Analysis in Maryland," Wenbo Fan, Sevgi Erdogan and Timothy Welch, *TRB 95th Annual Meeting Compendium of Papers*, Paper #16-1369, 2016.
Citation at http://trid.trb.org/view/1392503
From the abstract:

> This paper examines the emissions and traffic pattern impacts of converting high-occupancy vehicle (HOV) lanes into high-occupancy toll (HOT) lanes in Maryland. A multi-state integrated travel demand and mobile emissions model is used to measure emission changes at multiple scales, specifically at statewide, county, corridor and individual highway lane levels. A case study is conducted on two existing HOV facilities, I-270 and US 50, in the state of Maryland. The results of the analysis show that the emission impacts of HOV-to-HOT conversion are minor at the statewide and county levels, but prominent when measured at a corridor and lane scale. Additional network performance measures indicate that the utilization of managed lanes is considerably improved after the conversion. The study illustrates the importance of conducting analyses at multiple scales, leading to important implications for policy and decision-making.

Atlanta I-85 HOV-to-HOT Conversion: Analysis of Vehicle and Person Throughput, Randall Guensler, Vetri Elango, Angshuman Guin, Michael Hunter, Jorge Laval, Santiago Araque, Kate Colberg, Felipe Castrillon, Kate D'Ambrosio, David Duarte, Sara Khoeini, Lakshmi Peesapati, Adnan Sheikh, Katie Smith, Christopher Toth and Stephanie Zinner, Georgia Department of Transportation, October 2013.
https://smartech.gatech.edu/bitstream/handle/1853/51624/022720141307_hov-to-hot_I-85_throughput_analysis_final_report_033114.pdf?sequence=1
From the abstract:

> This report summarizes the vehicle and person throughput analysis for the High Occupancy Vehicle (HOV) to High Occupancy Toll (HOT) Lane conversion in Atlanta, Georgia, undertaken by the Georgia Institute of Technology research team. The team tracked changes in observed vehicle throughput on the corridor and collected average vehicle

occupancy (persons/vehicle) data to assess changes in person throughput. Traffic volumes were collected by vehicle detection systems (VDS) systems on the Georgia NaviGAtor system and the team implemented a large scale quarterly data collection effort for vehicle occupancy across all travel lanes. Between the baseline year (2011) and HOT implementation year (2012), significant changes were noted in both the vehicle and person throughput on the corridor at Center Way. Vehicle throughput on the I-85 HOT corridor decreased by about 6.6% (2698 vehicles) during the morning peak period, but only by about 2.9% (1148 vehicles) during the afternoon peak period. Average vehicle occupancy (persons/vehicle) also decreased during the same period. Reduced vehicle throughput and decrease in observed vehicle occupancy had a synergistic impact on estimated corridor person throughput, which declined significantly at a much faster rate than vehicle throughput. While traffic volumes declined by 6.6%, person throughput concurrently declined by about 9.9% (4868 individuals). While traffic volumes declined by approximately 2.9% in the afternoon peak period, person throughput concurrently declined by about 6.3% (3123 individuals). The data reveal that the majority of two-person carpools have been diverted from the HOV lane into the general purpose lanes after HOT lane implementation. Based upon vehicle throughput and occupancy distributions, the largest reduction in vehicle throughput in both the morning and afternoon peak periods came from a reduction in carpools (HOV2 and HOV3+ vehicles). Carpool mode share declined by more than 30% in the AM peak and by 25% in the PM peak, and average managed lane vehicle occupancy decreased from approximately 2.0 persons/vehicle to approximately 1.2 persons/vehicle.

Clean Air Vehicles

Impact of Exempt Vehicles on Managed Lanes, Katherine F. Turnbull, Federal Highway Administration, January 2014.
https://ntl.bts.gov/lib/51000/51700/51786/fhwahop14006.pdf
From the abstract:

In order to better utilize available capacity in high-occupancy vehicle (HOV) lanes, states are permitted to allow certain qualifying non-HOVs to use HOV lanes. In general, states may allow motorcycles, public transportation vehicles, high-occupancy toll (HOT) vehicles, and low-emission and energy-efficient vehicles to use HOV lanes. For any or all of these types of vehicles, the states must establish programs addressing candidacy, enrollment, and management of the lanes. In the case of tolled vehicles, dynamic pricing is the primary control that limits the potential to cause congestion in the lanes. In the case of the energy-efficient vehicles, the programs typically include decals, licenses, license plates, or stickers, that serve to identify and, in some cases, cap the number of allowed to use the lanes vehicles. Concerns may arise that the number of exempted vehicles may overburden the capacity of the HOV lanes to perform their primary function, which is to provide an incentive to form carpools (and thereby reduce the number of cars on the road) and to “reward” such an incentive by guaranteeing a mostly delay-free trip. Use by non-HOVs may overburden the HOV lanes, causing the integrity of the HOV lanes to suffer. The Moving Ahead for Progress in the 21st Century Act (MAP-21) 2012 now mandates that any HOV facility that allows tolled vehicles or any class of qualifying energy-efficient vehicles must annually certify that the subject lanes are “not degraded.” By definition, this constitutes that for a 180-day continuous reporting period, the lane(s) operate at greater than 45 mph for 90% of the time. (See Section 166, Title 23 of United States Code for the full language.) This report examines programs in use by states allowing low-emission and energy efficient vehicles to use HOV, HOT, and managed lanes without meeting the vehicle-occupancy requirements.

Information is presented on the enabling legislation, the program elements, use of the programs, and impacts of the HOV, HOT, and managed lanes in 13 states.

"Analysis of Impact of Further Restricting Access to High-Occupancy-Vehicle Lanes: Case Study on I-210 East," Varun Kohli, Gabriel Gomes, Mohammad Sharafsaleh, Pravin Varaiya and Ali Mortazavi*, TRB 91st Annual Meeting Compendium of Papers DVD*, Paper #12-1567, 2012.
Citation at http://trid.trb.org/view/1129322
From the abstract:

In this paper, the impact of disallowing the eligible Single Occupancy Hybrid vehicles (SOHVs) from using High Occupancy Vehicle (HOV) lane make on passenger delay is [analyzed]. A simulation model of I-210 East (with one HOV lane and four mixed-flow lanes) created in TOPL is used to study the change in total daily passenger delay for the HOV lane and the system as a whole. Different scenarios of removal ratios (1%-14%) cover a sufficiently large range of values. These scenarios not only cover the possible SOHV ratios but also other cases such as increasing occupancy requirement from 2+ to 3+ people per vehicle. Results showed that reduction in vehicles eligible to use HOV lane could reduce not only the delay experienced by HOV vehicles but also the total system delay. Removal of 1% vehicles led to an average reduction of around 8% in the total system passenger delay, and an optimal removal ratio of around 7% could reduce the system delay by around 50% on average. This reduction could be attributed to three factors: (i) Reduction in HOV delays, (ii) HOV delays are weighted more than Single Occupancy Vehicle (SOV) delays and (iii) smoothing effect of HOV lanes due to which total system delay is reduced even when HOV lane is a bit underutilized.

"High-Occupancy Vehicle Lanes and Hybrid Vehicles," Katherine F. Turnbull*,* *Transportation Research Record 2012*, pages 121-126, 2007.
Citation at http://trid.trb.org/view/801409
From the abstract:

This paper describes the use of high-occupancy vehicle (HOV) lanes by inherently low-emission vehicles (ILEVs) and hybrid vehicles. On the basis of the provisions of the Transportation Equity Act for the 21st Century, at least 10 states approved legislation allowing ILEVs to use HOV lanes without meeting the vehicle-occupancy requirements. The Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) allows states also to exempt qualifying hybrid vehicles from vehicle-occupancy requirements. Since the passage of SAFETEA-LU, FHWA has granted conditional approvals to Arizona, California, and New York for hybrid use of some or all HOV lanes in those states. Contrary to federal legislation, hybrid vehicles have been allowed to access HOV lanes in Virginia since 2000. As described in this paper, few ILEVs are in operation, and thus use of HOV lanes by ILEVs is minimal. On the basis of the experience in Virginia, California, and New York, however, owners of hybrid vehicles are using HOV lanes in those states.

Managed Lane Policies and Performance Measures

NCHRP Report 835: Guidelines for Implementing Managed Lanes, Kay Fitzpatrick, Marcus Brewer, Susan Chrysler, Nick Wood, Beverly Kuhn, Ginger Goodin, Chuck Fuhs, David Ungemah, Benjamin Perez, Vickie Dewey, Nick Thompson, Chris Swenson, Darren Henderson and Herb Levinson, 2016.
http://www.trb.org/main/blurbs/175082.aspx
From the abstract:

> Managed lanes are highway facilities or a set of lanes where operational strategies are proactively implemented, such as pricing (e.g., tolls, value pricing), vehicle eligibility (e.g., vehicle occupancy, vehicle type), access control (e.g., limited entry/exit points, use of shoulders), traffic control (e.g., variable speed limits, reversible lanes), or a combination of these strategies. Managed lanes provide a holistic approach based upon flexible operating strategies and the proactive management of both the facility and travel demand to improve or maintain system performance. Numerous domestic and international agencies have either constructed or are planning managed lanes. Each of these facilities is unique and presents issues and challenges as they are often implemented in high demand, congested, or constrained corridors. Currently, there is no singular guidance to assist transportation agencies implementing managed lanes. The American Association of State Highway and Transportation Officials (AASHTO's) A Policy on Geometric Design of Highways and Streets (The "Green Book") and other similar guides do not explicitly address the wide range of issues and complexity associated with managed lanes. Some information on managed lanes is included in the AASHTO Guide for High-Occupancy Vehicle Facilities and the AASHTO Guide for the Design of Park-and-Ride Facilities, but since the primary subject matter of these documents is related to high occupancy vehicle (HOV) lanes, they do not address all of the complex managed lanes issues in sufficient detail to serve as a national guide document on the subject. Research is needed to facilitate a better understanding of the unique planning, design, operations, and maintenance considerations associated with managed lanes, and how these factors interact. Managed lanes also have unique aspects related to financing, project delivery, public outreach, enforcement, and system integration that should be considered in each step of the project development process. A guide is needed to support decisionmaking by practitioners at all levels of experience with managed lanes so they can be implemented with the highest probability of success. The objective of this research is to develop guidelines for the planning, design, operations, and maintenance of managed lanes. The final product should be the primary reference on managed lanes and complement other national guidelines. It should be applicable to practitioners at all levels of experience with managed lanes and be used to support informed decisionmaking. The scope of this project is limited to managed lanes on freeways and expressways.

Identifying Strategies to Improve Lane Use Management in Indiana, Chaitanya Paleti, Srinivas Peeta and Kumares C. Sinha, Indiana Department of Transportation, August 2014.
http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=3058&context=jtrp
From the abstract:

> The limited funding available for roadway capacity expansion and the growing funding gap, in conjunction with the increasing congestion, creates a critical need for innovative lane use management options for Indiana. Various cost-effective lane use management strategies have been implemented in the U.S. and worldwide to address these challenges. However, all the strategies have their own costs, operational characteristics, and additional requirements for field deployment. Hence there is a need for systematic simulation-based methodology to perform a comprehensive study to identify congested corridors and the specific set of lane use management strategies that are effective in Indiana. A systematic

simulation-based methodology is proposed for evaluating lane use management strategies. A 10-mile stretch of the I-65 corridor south of downtown Indianapolis was selected as the study corridor using traffic analysis. The demand volumes for the study area were determined using subarea analysis. Its performance was evaluated using a microsimulation-based analysis in the context of alleviating congestion for three strategies: reversible lanes, high occupancy vehicle (HOV) lanes and ramp metering. Furthermore, an economic evaluation of these strategies was performed to determine the financial feasibility of their implementation. Results from this analysis indicated that reversible lanes and the ramp metering strategies improved traffic conditions on the freeway in the major flow direction. Implementation of the HOV lane strategy resulted in improved traffic flow conditions on the HOV lanes but aggravated congestion on the general purpose (GP) lanes. The HOV lane strategy was found to be economically infeasible due to low HOV volume on these lanes. The reversible lane and ramp metering strategies were found to be economically feasible with positive net present values (NPV), with the NPV for the reversible lane strategy being the highest.

"Evaluation of Operational Effects of Joint Managed Lane Policies," Chih-Lin Chung and Will W. Recker, *Journal of Transportation Engineering*, Vol. 138, No. 7, pages 882-892, 2012.
Citation at http://trid.trb.org/view/1216194
From the abstract:

> This paper presents a method to evaluate the operational effects of managed lane policies—vehicle eligibility, access control, pricing, and the number of managed lanes—that form a policy combination set. Two macroscopic methods are developed to prescreen the set via simple criteria, followed by integer linear programming with multiple objectives and constraints to identify the noninferior policies among the downsized set. The approach is demonstrated on the Southern California SR-57 corridor. The application eliminates twelve of possible twenty policy combinations by the macroscopic methods, and generates four noninferior policies—the existing high-occupancy vehicle lane operation and three additional potential high-occupancy toll lane policies—in terms of maximum vehicle and passenger throughput, minimum vehicle hour traveled, and travel time variance. The prescreening efficiency of the macroscopic stage, ranging from 0 to 95%, is affected by the initial policies and traffic conditions. It is concluded that the approach can substantially assess a larger policy set and effectively identify the operational effects of joint managed lane policies.

"Predetermining Performance-Based Measures for Managed Lanes," Mark W. Burris, Tina Collier Geiselbrecht, Ginger D. Goodin and Matthew E. MacGregor, *TRB 90th Annual Meeting Compendium of Papers DVD*, Paper #11-1482, 2011.
Citation at http://trid.trb.org/view/1091963
From the abstract:

> The objective of this research was to develop a multi-faceted framework to aid in operational decision-making over the life of a managed lane facility. To begin, this study reviewed the state-of-practice in operational performance management of tolled and managed lane facilities and captured the methods by which agencies are setting toll rates to manage performance. The authors found most agencies had some goals and objectives in writing. However, there is no advanced policy framework that addresses changes in the number of passengers required for free travel on a high occupancy toll (HOT) lane, which are always left to the governing body. In conducting this review many organizations from around the country were investigated for any 'performance promises' they might have on any of their facilities. A performance promise is where the operator of the facility indicates what changes will be made (for example not allowing high occupancy vehicle for 2 person (HOV2s) in the

event some measure (for example speed) drops below a set threshold. Although many verbally expressed interest in the idea, only one had clearly defined triggers that when hit, specific actions were undertaken to ensure performance. The goals and objectives for the surveyed projects proved interesting and insightful in the development of the multi-faceted framework. Results of this state-of-practice review, in conjunction with guiding principles, performance measures and data collection elements, will be used to develop a decision framework to guide the changes in operational strategies for a facility over time.

Appendix A: Survey Results

The full text of each survey response is provided below. For reference, an abbreviated version of each question is included before the response; the full question text is available on page 5 of this Preliminary Investigation. Responses have been edited for clarity.

Arizona

Contact: Keith Killough, Director, Transportation Systems Analysis, Arizona Department of Transportation, 602-712-6407, kkillough@azdot.gov.

HOV Lane Performance During Nonrecurrent Congestion

1. **Relationship between performance/nonrecurrent congestion:** I have only recently begun compiling information on HOV lane accidents. I am not aware of any other analysis within ADOT [Arizona Department of Transportation]. With ADOT's free access to HOV [high-occupancy vehicle] lanes from general purpose lanes (white line only rather than the double-yellow prohibition and dashed white permission employed in District 7), it is observed that HOV lane rear-end accidents occur at a higher proportion than either the general purpose lanes or when the HOV lane operates as a general purpose lane.
2. **Method for determining degradation due to nonrecurrent congestion:** We use the NPMRDS [National Performance Management Research Data Set] data for determining HOV speed degradation, but are only beginning to explore the correlation between the HOV lane speed degradation with HOV lane accidents.
3. **Mitigation strategies:** This is the subject of the investigation into HOV lane accidents that is now underway. One possible option may be to restrict HOV lane entry to certain locations as done in District 7 in order to avoid the unexpected entries into HOV lanes that impacts HOV lane operating speeds.
4. **Other research:** Not aware.

Alternative Operation Schemes

5. **Alternative operation schemes/performance data:** We haven't implemented any of these alternatives, but have examined the impact of clean air vehicles in the past. To date, there [have] been no actions taken.
6. **Criteria guidance/research:** N/A.
7. **Other research:** Not aware.

Florida Department of Transportation

Contact: Gregg Letts, Senior Advisor, SunGuide Transportation Management Center, District VI, Florida Department of Transportation, 305-470-5757, gregg.letts2@sunguide.info.

HOV Lane Performance During Nonrecurrent Congestion

1. **Relationship between performance/nonrecurrent congestion:** Florida is phasing out HOV lanes and converting them to HOT [high-occupancy toll] 3+ lanes. HOV lanes ran poorly because drivers didn't pay attention to the white lines separating the lanes. On I-95 before conversion to an HOT lane, there were about 300,000 vehicles a day, running

in peak periods at 15-18 mph. Now they run in the 40s. 95 percent of the time, the facility is above 45 mph during the peak period. Facilities are closed during incidents.

2. **Method for determining degradation due to nonrecurrent congestion:** None.
3. **Mitigation strategies:** None.
4. **Other research:** Not aware.

Alternative Operation Schemes

5. **Alternative operation schemes/performance data:** Florida is phasing out HOV lanes and converting them to HOT 3+ lanes. The amount of HOV 3+ carpoolers is very small—for example, on one segment, about 500 out of 70,000 exempt vehicles out of 1.8 million recorded trips. 80 percent of exempt vehicles were hybrids. For data, see: **95 Express Performance Reports**, http://www.sunguide.info/sunguide/index.php/tmc_reports/archives/98
6. **Criteria guidance/research:** None.
7. **Other research:** Not aware.

Georgia Department of Transportation

Contact: Matthew Fowler, Program Delivery Manager, Special Projects, Planning, Georgia Department of Transportation, 404-631-1977, mfowler@dot.ga.gov.

HOV Lane Performance During Nonrecurrent Congestion

1. **Relationship between performance/nonrecurrent congestion:** Have not studied.
2. **Method for determining degradation due to nonrecurrent congestion:** None.
3. **Mitigation strategies:** In the past, the Department explored converting all existing HOV facilities (which all operate at HOV 2+) to HOT 3+; however, this effort is no longer being pursued due to current lack of public support. This effort was documented in our Managed Lane System Plan (http://www.dot.ga.gov/BS/Studies/ManagedLanes).
4. **Other research:** Not aware.

Alternative Operation Schemes

5. **Alternative operation schemes/performance data:** GDOT has converted one corridor (I-85 in the northeast part of Metro Atlanta) from HOV 2+ to HOT 3+. We have not prohibited low emission vehicles nor have we implemented double HOV lanes.
6. **Criteria guidance/research:** Primarily in our Managed Lane System Plan (link provided above) and our follow up Managed Lane Implementation Plan (http://www.dot.ga.gov/BS/Studies/MLIP); however, the Managed Lane Implementation Plan did not recommend converting HOV to HOT. In the Managed Lane System Plan study, we primarily used existing and future congestion levels (using the Atlanta MPO's [metropolitan planning organization] regional travel demand forecasting model) to identify corridors for converting from HOV to HOT.
7. **Other research:** Not aware.

Hawaii Department of Transportation

Contact: Bryan Kimura, State Traffic Engineer, Highways Division, Traffic Branch, Hawaii Department of Transportation, 808-692-7670, bryan.kimura@hawaii.gov.

HOV Lane Performance During Nonrecurrent Congestion

1. **Relationship between performance/nonrecurrent congestion:** Have not studied.
2. **Method for determining degradation due to nonrecurrent congestion:** None.
3. **Mitigation strategies:** None.
4. **Other research:** Not aware.

Alternative Operation Schemes

5. **Alternative operation schemes/performance data:** Hawaii did increase occupancy requirements from 2+ to 3+ in the past, but 3+ was reduced to 2+ because of underutilization of the HOV lane. It has not tried prohibiting clean air vehicles. It has implemented double HOV lanes in two locations (HOV 2+), but has not studied the effects of this or other measures.
6. **Criteria guidance/research:** None.
7. **Other research:** Not aware.

Minnesota Department of Transportation

Contact: Brad Larsen, Program Director, MnPASS Policy & Planning, Minnesota Department of Transportation, 651-234-7024, brad.larsen@state.mn.us.

HOV Lane Performance During Nonrecurrent Congestion

1. **Relationship between performance/nonrecurrent congestion:** Not extensively, but we recently did some reliability analysis on the I-35W North MnPASS Project that factored in both recurrent and nonrecurrent congestion (see Appendix B).
2. **Method for determining degradation due to nonrecurrent congestion:** No, but we do report quarterly to FHWA on lane performance, and if we know of days when there was an incident or snow event that caused significant lane degradation, we indicate it in the report (Appendix C).
3. **Mitigation strategies:** Yes. We are currently in the process of documenting these strategies in the MnPASS Phase 3 System Study, which should be completed by the end of the year.
4. **Other research:** Not aware.

Alternative Operation Schemes

5. **Alternative operation schemes/performance data:** MnDOT has not increased occupancy requirements. It has prohibited clean air vehicles, and has a 2 lane reversible segment on I-394. We have not done any formal studies on these.
6. **Criteria guidance/research:** None.
7. **Other research:** Not aware.

North Carolina Department of Transportation

Contact: J. Scott Cole, Deputy Division Engineer, Division 10, North Carolina Department of Transportation, 704-983-4400, scole@ncdot.gov.

HOV Lane Performance During Nonrecurrent Congestion

1. **Relationship between performance/nonrecurrent congestion:** Have not studied.
2. **Method for determining degradation due to nonrecurrent congestion:** None.
3. **Mitigation strategies:** None.
4. **Other research:** Not aware.

Alternative Operation Schemes

5. **Alternative operation schemes/performance data:** North Carolina's only HOV lane facility on I-77 is currently under construction to an HOT 3+, is being increased from 1 to 2 lanes in each direction, and is being extended in each direction. We have not been monitoring or studying the HOV facility to a level such that we have the data to provide feedback.
6. **Criteria guidance/research:** None.
7. **Other research:** Not aware.

Ontario Ministry of Transportation

Contact: Nancy Adriano, Traffic Area Manager—West, Ministry of Transportation, Ontario, Canada, 416-235-3925, nancy.adriano@ontario.ca.

HOV Lane Performance During Nonrecurrent Congestion

1. **Relationship between performance/nonrecurrent congestion:** No, we haven't studied the relationship between HOV lane performance and nonrecurrent congestion. We are constantly collecting HOV lane speeds and tracking incidents at our Operations Centre so we do have the required data to correlate impacts of incidents on the HOV lane performance. To date we haven't undertaken this analysis.
2. **Method for determining degradation due to nonrecurrent congestion:** We are reporting speeds along the HOV corridor every 2 km and we monitor the speeds in 15 min increments to identify when the speed is less than 70 km/h. We are aware of speeds dropping below 70 km/h at one location due to recurrent congestion at the terminus of the HOV lane but we have never undertaken analysis for nonrecurrent congestion. We usually remove the data from our analysis if there was an incident.
3. **Mitigation strategies:** The recurrent congestion on our HOV facilities is concentrated around the terminus of the HOV lane where there is extensive weaving of vehicles at the freeway-freeway interchange. This is a design issue. We don't have recurrent congestion due to high traffic volumes in the HOV lanes.
4. **Other research:** Not aware.

Alternative Operation Schemes

5. **Alternative operation schemes/performance data:** None.

6. **Criteria guidance/research:** We are giving consideration to double HOV lanes but it would have to be a new lane that adds capacity on the corridor. We would never convert a GPL [general purpose lane] to HOV. If our facilities approach capacity we would give consideration to changing the vehicle occupancy to 3+ but our current analysis shows that less than 15% of vehicles on the corridor have 3+ occupancy. We are not giving consideration to prohibiting clean air vehicles from accessing the HOV lanes.
7. **Other research:** We have been using the findings from Georgia DOT on the conversion of vehicle occupancy requirement from 2+ to 3+ on I-85 in Atlanta. Their study showed that when 3+ was first implemented they had an empty lane and it took quite a while to get carpoolers back in the lane.

Oregon Department of Transportation

Contact: Kate Freitag, Traffic Operations Engineer, Region 1, Oregon Department of Transportation, 503-731-8220, kathleen.m.freitag@odot.state.or.us.

HOV Lane Performance During Nonrecurrent Congestion

1. **Relationship between performance/nonrecurrent congestion:** Not that I am aware of. The I-5 HOV lane (ODOT's only HOV lane) only operates on weekdays from 3-6p.m., when recurrent congestion is at its worst.
2. **Method for determining degradation due to nonrecurrent congestion:** We do have detector data available but no concentrated effort has been made to study HOV degradation caused by nonrecurrent congestion. Our studies (operations updates) of the HOV lane have focused primarily on traffic volumes, occupancy, persons throughput, and travel times.
3. **Mitigation strategies:** None.
4. **Other research:** Not aware.

Alternative Operation Schemes

5. **Alternative operation schemes/performance data:** None.
6. **Criteria guidance/research:** None.
7. **Other research:** http://www.its.berkeley.edu/sites/default/files/publications/UCB/2011/VWP/UCB-ITS-VWP-2011-4.pdf

Texas: North Central Texas Council of Governments

Contact: Natalie Bettger, Senior Program Manager, Congestion Management and System Operation, North Central Texas Council of Governments, 817-695-9280, nbettger@nctcog.org.

HOV Lane Performance During Nonrecurrent Congestion

1. **Relationship between performance/nonrecurrent congestion:** Have not studied.
2. **Method for determining degradation due to nonrecurrent congestion:** None. NCTCOG does have Express Lane /HOV Lane Policies. These policies can be found at the following link: http://www.nctcog.org/trans/committees/rtc/12.13.12.ManagedLanePolicies_AdoptedRTC_121312.express.hov.pdf

3. **Mitigation strategies:** The only mitigation strategies we have targeted for HOV facilities affected by recurrent congestion include enhanced enforcement to keep violators out of the lane (which is hard to do with little space to pull folks over in a corridor), adding a toll or increasing occupancy. The violation rate on some of our corridors [is] over 30% based on information provided by the County Sheriff's Office.
4. **Other research:** Not aware.

Alternative Operation Schemes

5. **Alternative operation schemes/performance data:** Our region does prohibit single occupant, clean air vehicles from accessing the HOV lane. We have not studied the effects of these measures.
6. **Criteria guidance/research:** To date, NCTCOG has not changed the region's vehicle occupancy requirement and we have not developed triggers of when we need to implement.
7. **Other research:** Not aware.

Texas: Texas Transportation Institute

Contact: Robert Benz, Research Engineer, Teens in the Driver Seat Regional Coordinator, Texas Transportation Institute, 713-613-9218, r-benz@tamu.edu.

HOV Lane Performance During Nonrecurrent Congestion

1. **Relationship between performance/nonrecurrent congestion:** Yes.
   a. https://static.tti.tamu.edu/tti.tamu.edu/documents/0-4740-3.pdf
   b. https://tti.tamu.edu/publications/catalog/record/?id=26992
2. **Method for determining degradation due to nonrecurrent congestion:** In the above report we looked at travel speeds on GP [general purpose] lanes and HOV lanes and we categorized the impact by incident type (shoulder, one lane blocked, multiple lanes, etc.): https://static.tti.tamu.edu/tti.tamu.edu/documents/0-4740-1.pdf
3. **Mitigation strategies:** Several strategies have been [tried] and/or implemented: Increase HOV occupancy, tolling, and both: https://static.tti.tamu.edu/tti.tamu.edu/documents/E-305001.pdf
4. **Other research:** Not aware.

Alternative Operation Schemes

5. **Alternative operation schemes/performance data:** Houston has tried increasing occupancy requirements from 2+ to 3+; prohibiting clean air vehicles (https://static.tti.tamu.edu/tti.tamu.edu/documents/1353-5.pdf); and implementing double HOV lanes (https://static.tti.tamu.edu/tti.tamu.edu/documents/0-6688-1.pdf).
6. **Criteria guidance/research:** See studies linked to in question 5.
7. **Other research:** Not aware.

Utah Department of Transportation

Contact: Mark Parry, Freeway Operations Engineer, Utah Department of Transportation, 801-633-7609, moparry@utah.gov.

HOV Lane Performance During Nonrecurrent Congestion

1. **Relationship between performance/nonrecurrent congestion:** Have not studied.
2. **Method for determining degradation due to nonrecurrent congestion:** None.
3. **Mitigation strategies:** None.
4. **Other research:** Not aware of any directly related studies, but see [the publications on page 11] on operations during incidents.

Alternative Operation Schemes

5. **Alternative operation schemes/performance data:** None.
6. **Criteria guidance/research:** None.
7. **Other research:** Not aware.

To: Jerome Adams, PE
Minnesota Department of Transportation

From: Paul Morris, PE
Matthew Knight, AICP
Ning Zhang, EIT

Date: September 1, 2016

Subject: I-35W North Corridor Preliminary Design Project
Travel Time Reliability Analysis

Introduction

This memorandum documents the methodologies and results of the reliability analysis conducted for the I-35W North Corridor Preliminary Design Project. The reliability results were developed for existing (year 2014) conditions, year 2040 no build, and three year 2040 build alternatives which include the addition of one general purpose lane, a high occupancy vehicle (HOV) lane, and a high occupancy/toll (HOT) lane in each direction. This memorandum presents the assumptions and methods used in these analysis and the results of the evaluation. These alternatives will then be evaluated with a screening process to compare their effectiveness.

Reliability is an emerging area of transportation evaluation that considers the variability in travel times that occur due to weather, crashes, and other non-recurring conditions. Understanding these effects for managed lanes is particularly important as these facilities are specially intended to provide free-flow travel for transit, carpools, and single-occupant vehicles willing to pay a congestion-sensitive toll. Communicating these results to stakeholders is critical in demonstrating the long-term value of this type of investment.

Data Sources

Analysis of the I-35W corridor was broken into eight segments, four in each direction. Data for the analysis came from a variety of sources. Travel time and volume data from the MnDOT's loop detector system were extracted using both MnDOT's Data Extract tool and the Traffic Information and Condition Analysis System (TICAS). Weather and precipitation data was obtained from the National Oceanic and Atmospheric Administration (NOAA), and Minnesota Department of Public Safety (DPS) crash records were accessed through the Minnesota Crash Mapping Analysis Tool (MnCMAT).

Methodologies

To fully understand the travel time reliability for the existing condition, one year of travel time data along the project corridor were collected for calendar year 2014. Reliability indices such as Planning Time Index (PTI), Travel Time Index (TTI), and Buffer Index (BI) were calculated. In addition, weather and crash data were obtained and integrated with travel time data for the full year of 2014 to isolate the effects of these factors.

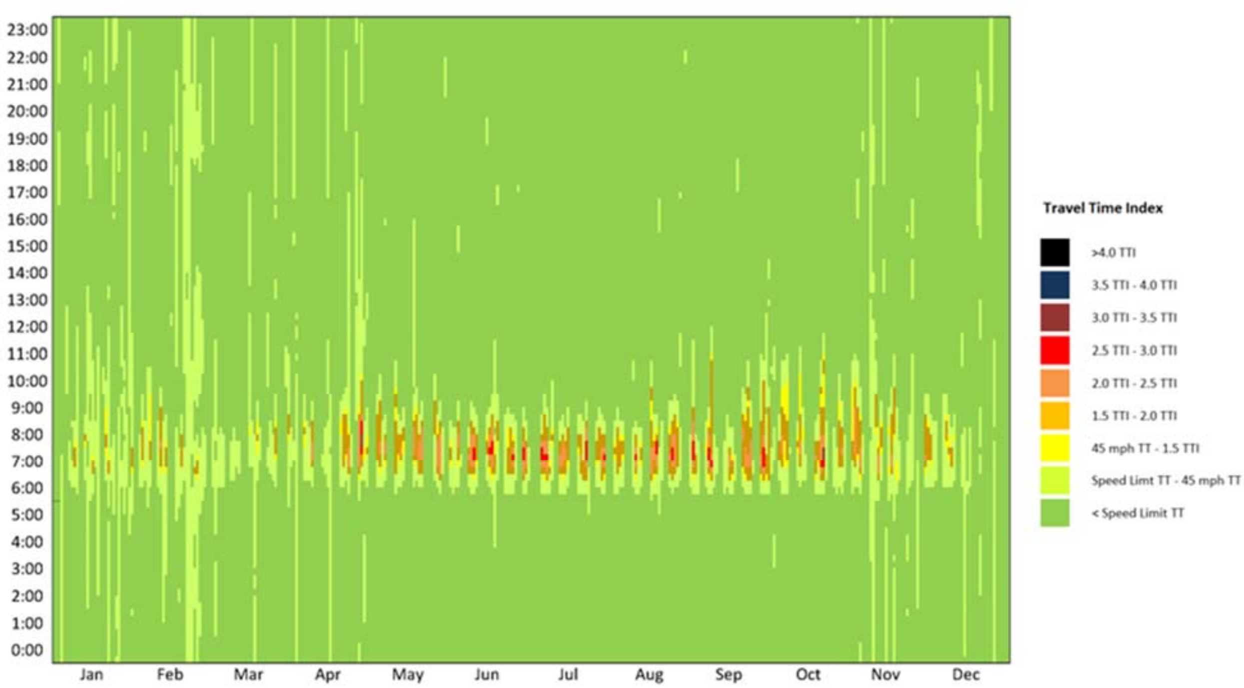
To characterize relationship between the general purpose (GP) and MnPASS lanes and to project travel time savings for the I-35W North MnPASS project, one year of travel time data in along existing GP and MnPASS lanes on I-394 and I-35W South were collected and analyzed. In terms of future year travel demands, traffic volume and transit ridership forecasts were prepared using the Twin Cities Regional Travel Demand Model (RTDM) for both existing and 2040 alternatives.

The reliability analysis was ultimately summarized using a variety of outputs to illustrate the variability of travel times and throughput under the alternatives considered.

Surface Plots (Existing and Future Projection)

A surface plot is the visual representation of travel times every 15 minutes for an entire year relative to free flow travel time. The plot for existing conditions (Figure 1) used the loop detector speed data downloaded from the TICAS, and converted it to travel time index (TTI) values, which is the ratio of observed travel time to the free flow travel time.

Figure 1 I-35W Southbound Travel Time Surface Plot – Existing Condition



Estimating Demand-Speed Curves

According to the existing speed-flow relationships (Figure 2 left), the capacities of the segments can be identified for different percentiles of speed. Traffic under the critical speed (speed at capacity) were assumed to be the unserved demand (Figure 2 right). Basing on the scatter plots, the demand-speed curves were estimated (Figure 3), and were used to project future demand-speed relationships.

Figure 2 Flow-Speed vs. Demand-Speed Curves (I-35W southbound example from US 10 to I-694)

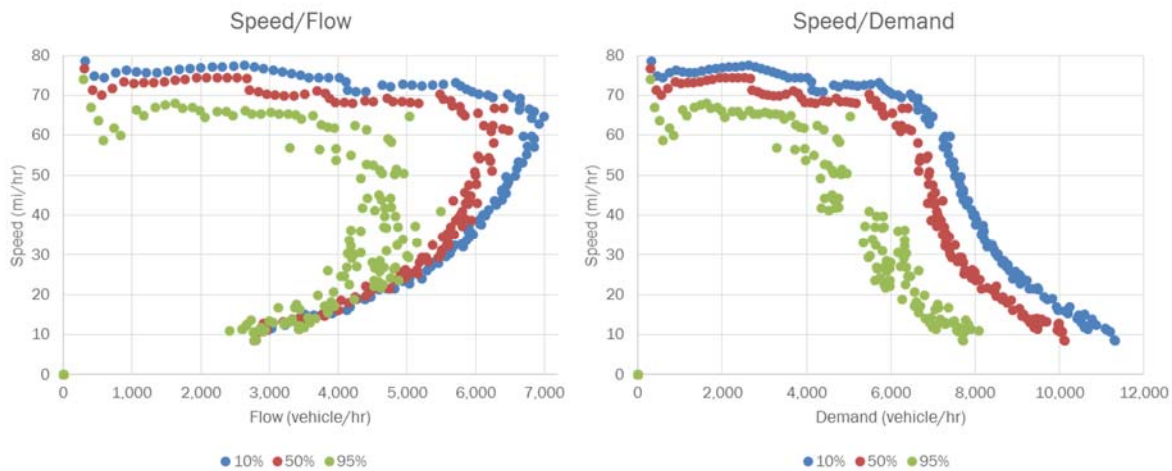
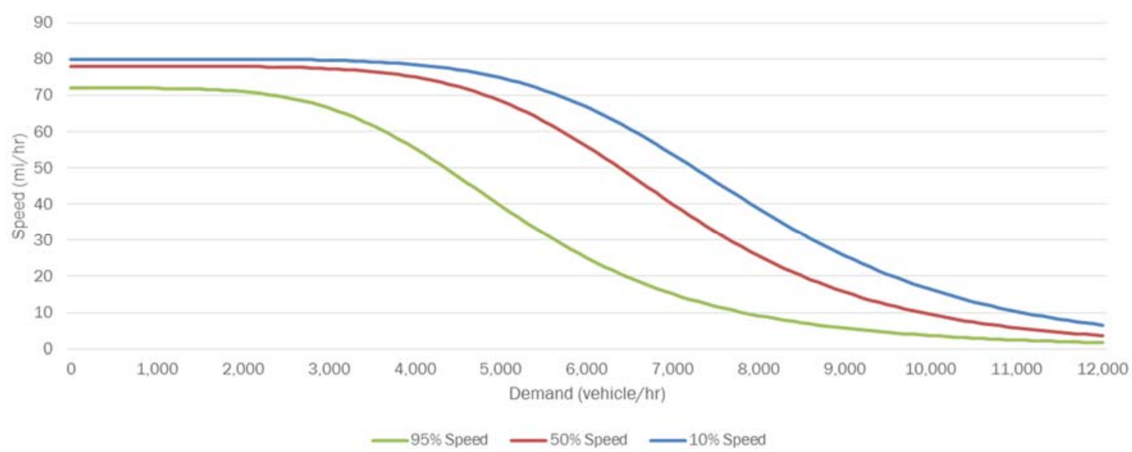


Figure 3 Estimated Demand-Speed Curves (I-35W southbound example from US 10 to I-694)

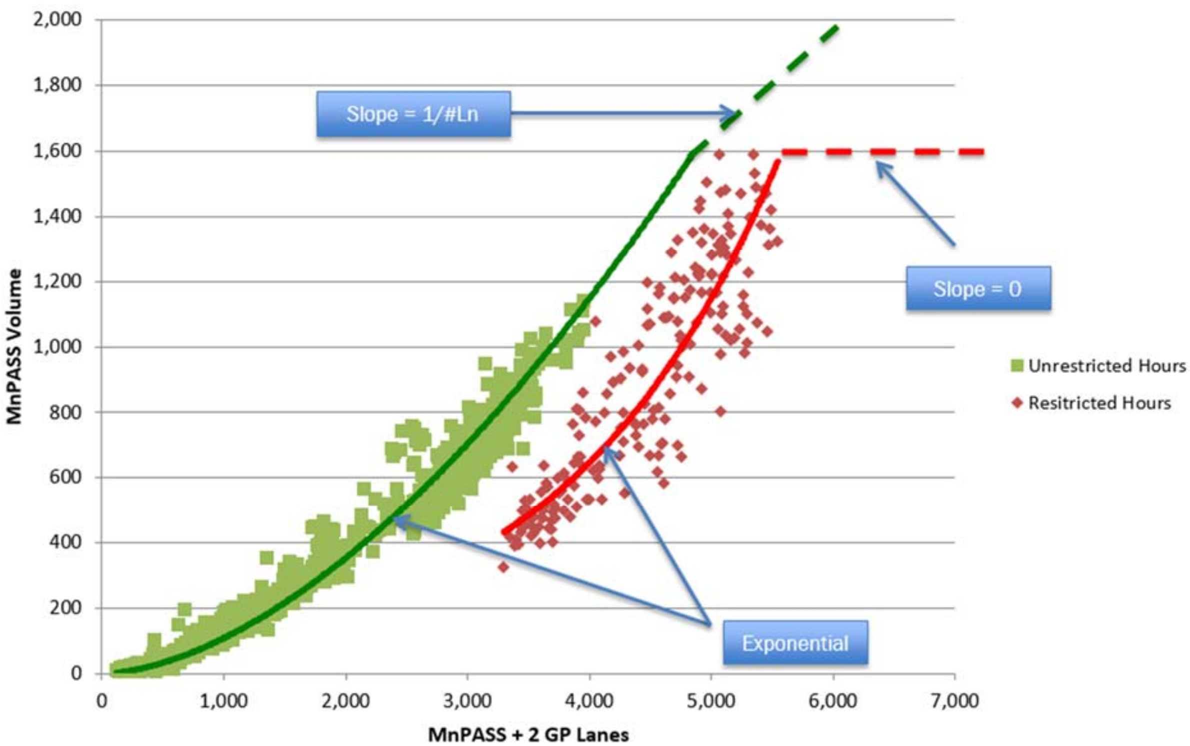


The 2040 alternatives applied the same demand distributions for both recurring and non-recurring conditions, but scaled the volume profiles based on the AADT forecasts generated by the RTDM. Using the speed curves estimated based on the speed-demand relationship, each 15-minute volume was evaluated to assign a travel time, and to determine whether any unserved demand must be carried forward to the next time interval if the current demand is over capacity.

Relationship between MnPASS (MP) and General Purpose (GP) Lanes

To project the reliability conditions among MnPASS and GP lanes in 2040, the existing volume data of the road segments having similar MnPASS facilities were collected and analyzed. The example in Figure 4 shows the existing MnPASS and GP relationship of the northbound I-35W at the Minnesota River. The scatter plot reveals the relationship between the MnPASS and GP volumes during unrestricted and restricted hours. Exponential equations were found to provide the best fit for volumes under capacity, and were applied for future MnPASS build alternative.

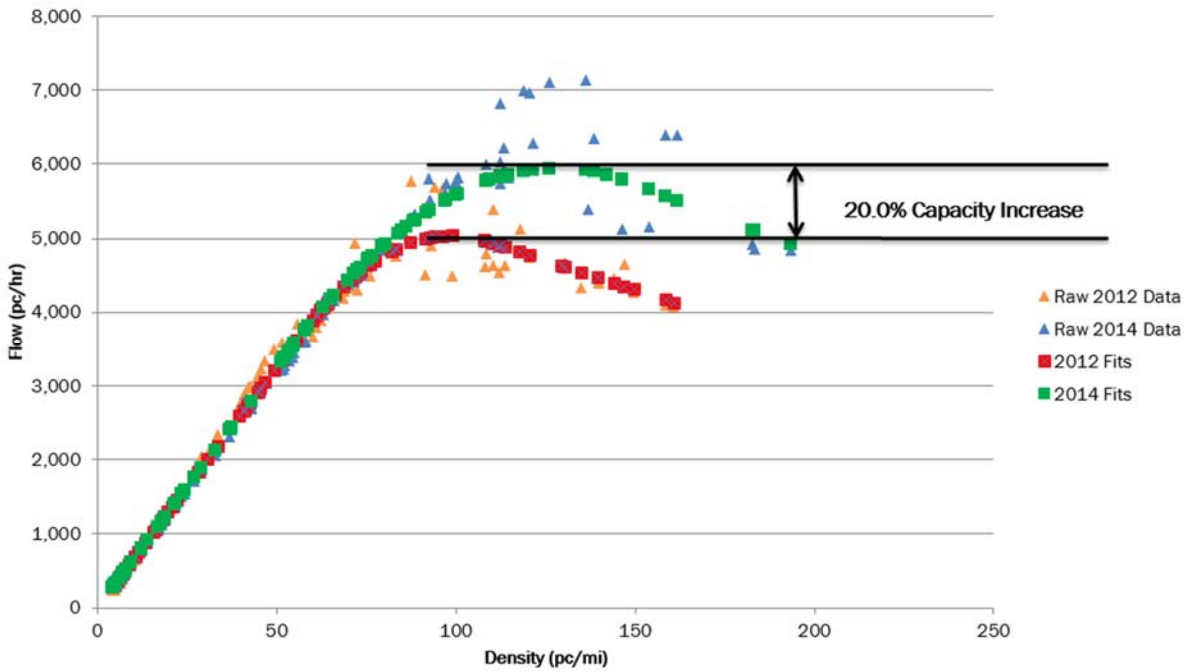
Figure 4 Existing MnPASS and GP Relationship Example



Additional Capacity of Adding GP Lanes

For the 2040 GP lane alternative, the capacity increase is a critical factor to the reliability analysis. A few completed projects which added additional lanes were used as guidance to establish the additional capacity impacts. Figure 5 shows an example of a recent existing GP lane addition on westbound I-494 from I-35W to France Avenue. Flow and density data were collected before and after the lane expansion. The results indicate a 20 percent capacity increase after adding one additional general purpose lane to the three existing general purpose lanes.

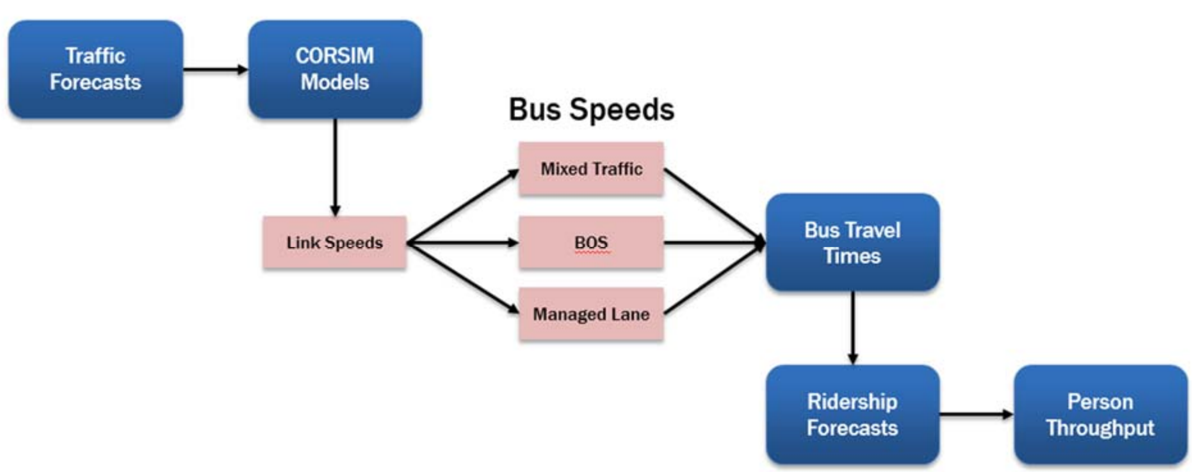
Figure 5 Capacity Increase with GP Lane Addition



Transit Ridership Forecasts

Transit ridership was a key factor to this reliability evaluation, as the proposed MnPASS lanes are expected to provide travel time and person-through benefits for express buses. Figure 6 shows the flow chart of the ridership forecasting. Bus travel time were obtained from the CORSIM models and ridership were forecast using the RTDM. With bus travel time and ridership, travel time savings and person throughput can be calculated for different alternatives in the year of 2040.

Figure 6 Transit Forecast Flow Chat



With all the assumptions summarized above, the travel times for the 2040 no-build and build alternatives were projected. Figures 7 through 10 show the travel time surface plots for 2040 No-build, General Purpose, MnPASS, and HOV alternatives. Figure 11 shows the congestion conditions for MnPASS/HOV lanes. Although the general purpose (GP) lanes under the MnPASS and HOV alternatives are more congested than the General Purpose alternative, the MnPASS and HOV alternatives offer users a congestion-free option by using these managed lanes.

Figure 7 I-35W Southbound Travel Time Surface Plot – 2040 No-Build Alternative

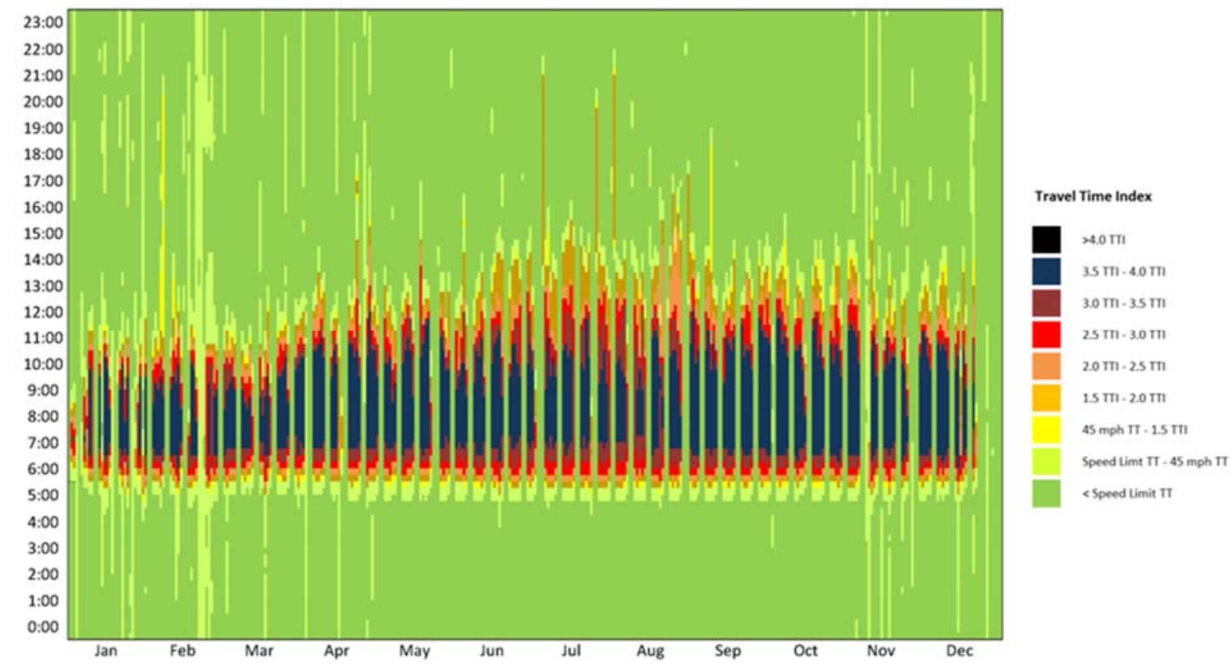


Figure 8 I-35W Southbound Travel Time Surface Plot – 2040 General Purpose Alternative

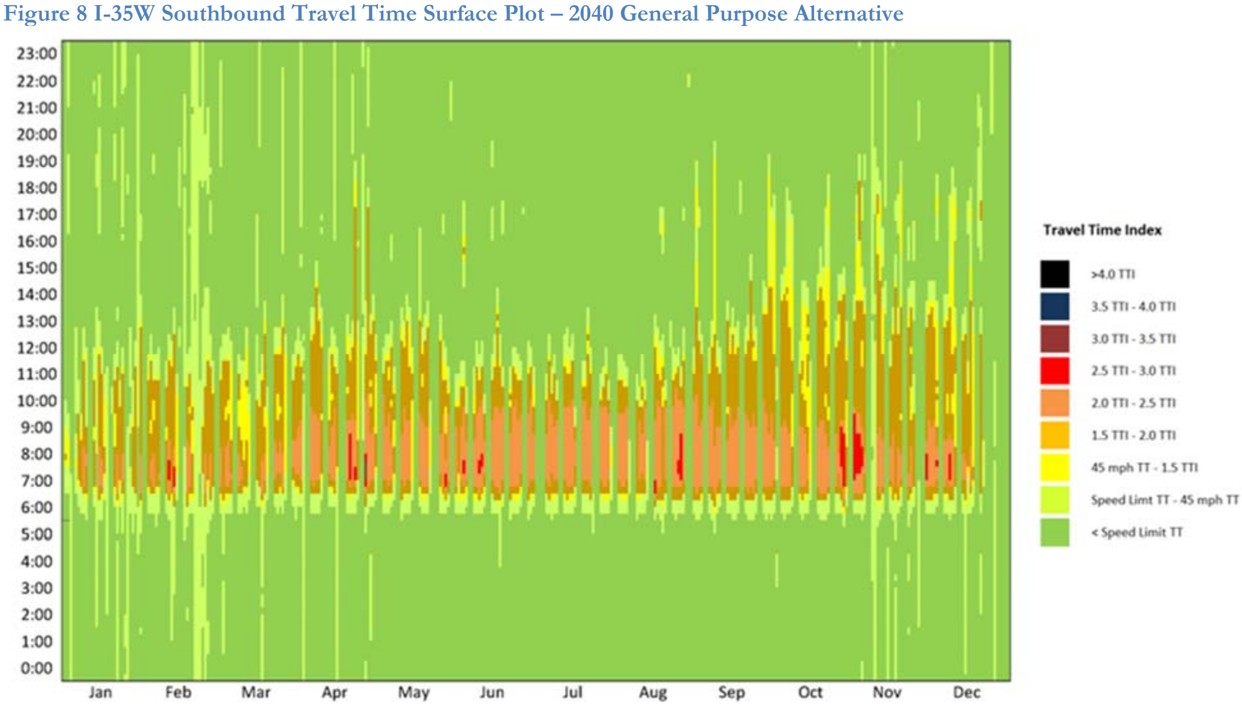


Figure 9 I-35W Southbound Travel Time Surface Plot – 2040 MnPASS Alternative (General Purpose Lanes)

Figure 10 I-35W Southbound Travel Time Surface Plot – 2040 HOV Alternative (General Purpose Lanes)

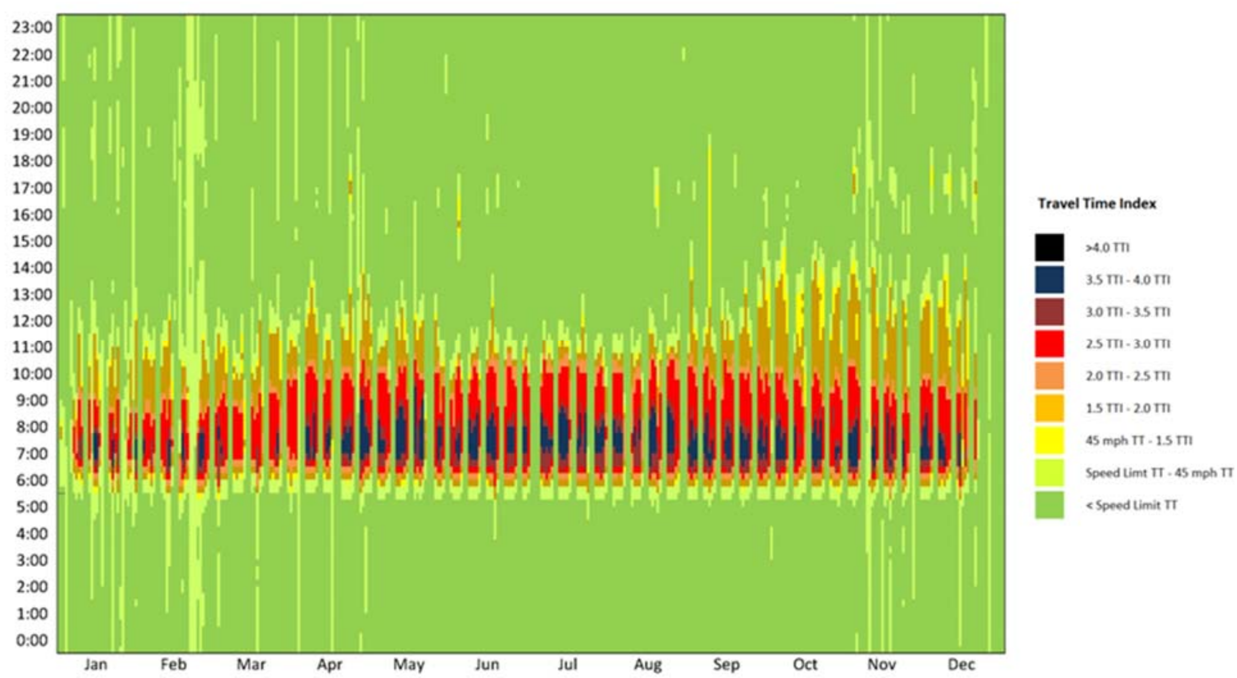
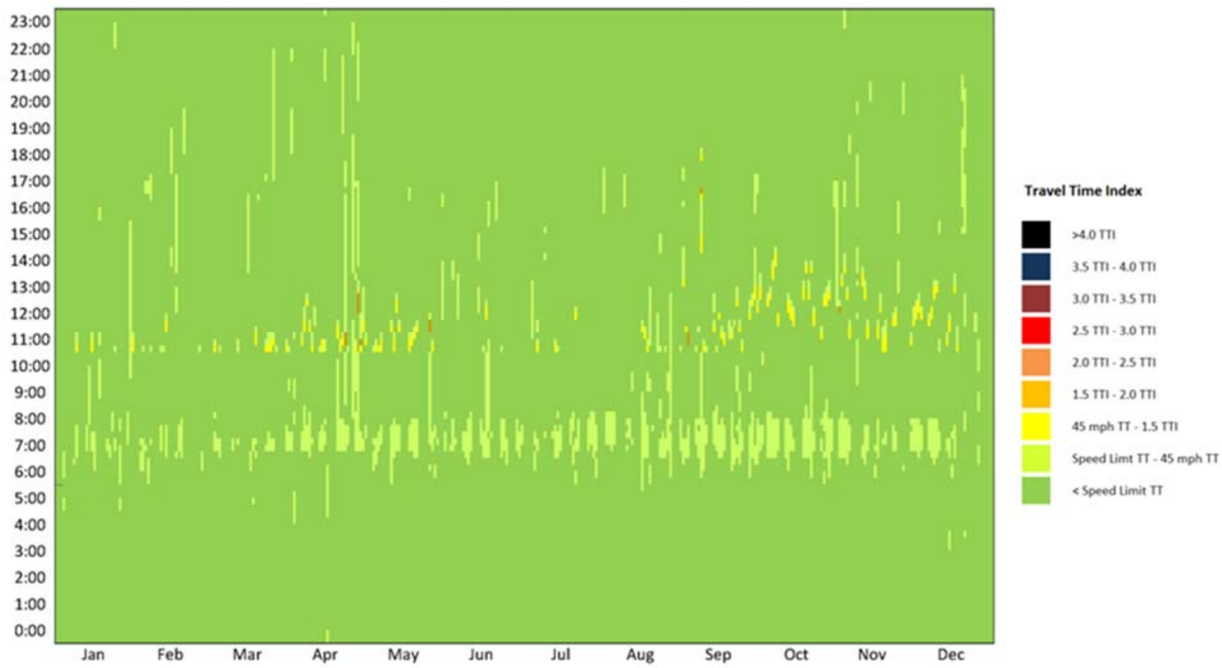


Figure 11 I-35W Southbound Travel Time Surface Plot –2040 MnPASS/HOV Lanes



Travel Time Thermometers

The travel time thermometers provide a representation of the typical variability in travel times experienced by a user along the corridor. There are 20 increments for each thermometer, and each represents the percentile of the travel time during a specific time range. The percentile is ranging from 2.5th to 97.5th with a 5 percent increment. These increments were selected to represent 20 typical perk period commutes that may occur within one month (5 days/week times 4 weeks).

Figure 12 shows the comparison of thermometers for southbound I-35W during the AM peak hours. The values are shown in minutes and the colors show the TTI ranges consistent with the surface plots. By comparing the congestion conditions for general purpose lanes, the GP alternative offers the best reliability. However, the MnPASS alternative offers a congestion free condition in the MnPASS lane (Figure 13).

Figure 12 I-35W Southbound Travel Time Thermometer (General Purpose Lanes) - AM Peak Hours

Mon-Fri 06:00 to 09:00 (Travel Time)

Rank	Existing	No Build	2040 GP	2040 MnPASS	2040 HOV
1	14.6	14.7	14.7	14.7	14.7
2	14.9	18.7	15.4	15.9	16.5
3	15.1	28.3	16.0	16.7	18.5
4	15.4	33.6	16.6	17.8	21.0
5	15.6	39.5	17.4	19.3	23.9
6	15.9	43.6	18.6	21.3	27.3
7	16.2	47.8	20.3	23.5	32.2
8	16.5	50.2	22.4	25.6	36.6
9	16.8	52.3	24.2	27.5	40.7
10	17.2	55.0	25.2	29.6	43.0
11	17.7	57.2	26.9	32.2	43.5
12	18.4	58.5	29.3	34.6	44.4
13	19.3	58.8	32.3	36.6	46.2
14	20.3	58.8	34.4	38.2	48.3
15	21.6	58.8	35.3	39.7	50.8
16	23.5	58.8	35.5	41.4	54.1
17	25.3	58.8	35.7	43.0	56.7
18	27.6	58.8	35.9	43.9	58.6
19	31.6	58.8	36.4	45.0	58.8
20	37.9	58.8	40.5	48.3	58.8

Figure 13 I-35W Southbound Travel Time Thermometer (GP vs MnPASS) - AM Peak Hours

Mon-Fri 06:00 to 09:00 (Travel Time)

Rank	2040 GP	2040 MnPASS (GP Lanes)	2040 MnPASS (MnPASS Lane)
1	14.7	14.7	14.5
2	15.4	15.9	15.0
3	16.0	16.7	15.3
4	16.6	17.8	15.5
5	17.4	19.3	15.6
6	18.6	21.3	15.7
7	20.3	23.5	15.7
8	22.4	25.6	15.8
9	24.2	27.5	15.9
10	25.2	29.6	15.9
11	26.9	32.2	16.0
12	29.3	34.6	16.1
13	32.3	36.6	16.2
14	34.4	38.2	16.2
15	35.3	39.7	16.2
16	35.5	41.4	16.3
17	35.7	43.0	16.3
18	35.9	43.9	16.4
19	36.4	45.0	16.7
20	40.5	48.3	17.6

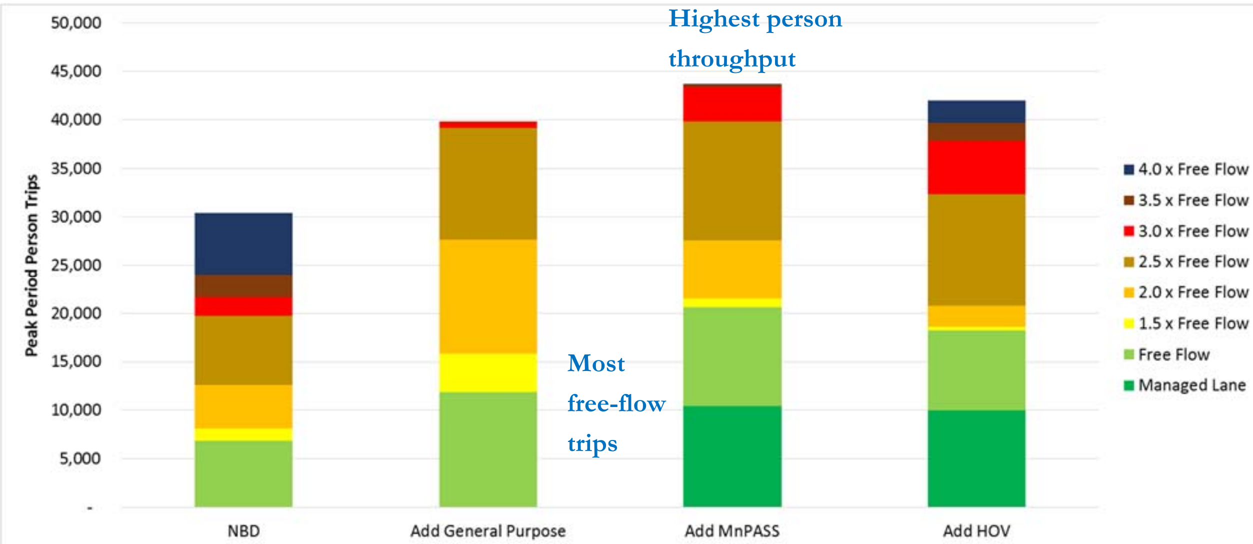
Person Throughput Bar Charts

Scaling the thermometers based on person throughput produces stacked bar charts incorporating travel time and throughput data into a single visual figure, showing not only the total person throughput in each alternative, but the throughput at different travel time ranges.

The person throughput is calculated with volume and vehicle occupancy. The existing volumes were collected from the loop detectors, and the occupancies were from filed data collection. For 2040 alternatives, RTDM generated the volumes and SOV/HOV ratios, which were used to interpolate occupancies. In addition, the congestion levels are displayed by different colors consistent with the thermometer and the surface plots.

Figure 14 represents the person throughout along I-35W during peak hours and peak directions by TTI level. The stacked bar charts show both the number of users being served under each alternative and their respective travel times. The MnPASS alternative offers a 10 percent increase in total person-throughput over the GP alternative. Additionally, the MnPASS alternative provides a 75 percent increase in the number of reliable trips.

Figure 14 Reliability by Person Throughput - Peak Hours and Peak Directions



Screening Process

The purpose of the screening process is to understand the traffic performance under different alternatives, and to select the best build alternative for year 2040. The screening criteria includes travel time savings, transit advantages, person throughput, level of service (LOS), and benefit-cost analysis. Most criteria rely on elements of the travel time reliability analysis results.

Travel Time Savings

The criteria for travel time savings is set as percent delay reduction between No Build and Free Flow conditions. By measuring the Person Hours of Travel (PHT) and person delay, the percent delay reduction is highest (68.8%) for the MnPASS alternative compared to the No Build alternative.

Table 1 Travel Time Savings

Criteria	No Build	Free Flow	Add General Purpose	Add MnPASS	Add HOV
Travel Time Savings (PHT)	11.9M	5.5M	PHT: 8.1 M (-3.8M) Delay: 2.6M Pct Decr: 59%	7.5 M (-4.4M) Delay: 2.0M Pct Decr: 69%	8.1 M (-3.8M) Delay: 2.6M Pct Decr: 59%

Transit Advantages

The criteria for transit advantages is set as transit time savings during peak hours versus No Build alternative. In addition, the ridership is considered. The MnPASS and HOV alternatives have the lowest travel time and highest ridership.

Table 2 Transit Advantages

Criteria	No Build	Free Flow	Add General Purpose	Add MnPASS	Add HOV
Transit Advantages - Transit Travel Time SB AM + NB PM Peak Hour total round trip (min)	59	40	53	45	45
Transit Ridership (Routes 250, 252, 288)	4,300	4,600	4,200	4,600	4,600

Person Throughput

The criteria is set as the weighted person throughput by segment. The MnPASS alternative has the highest person throughput, and it is 40 percent higher than the No Build alternative.

Table 3 Person Throughput

Criteria	No Build	Free Flow	Add General Purpose	Add MnPASS	Add HOV
Person Throughput (SB AM + NB PM Peak Hours; weighted by segment length)	13,200	18,300	16,000	18,300	17,300

Level of Service

The criteria is set as percent lane-mile-hours at LOS D or better based on traffic operations modeling completed using CORSIM software. As the results are within a few percentage points for the three build alternatives, this measure is not a meaningful differentiator of performance.

Table 4 Level of Service

Criteria	No Build	Free Flow	Add General Purpose	Add MnPASS	Add HOV
Level of Service (Percent of peak period/peak direction at LOS D or better)	54%	100%	60%	56%	57%

Benefit-Cost Analysis

The Benefic-Cost Analysis (BCA) is a comprehensive analysis considering travel times based on the reliability analysis, person throughput, and incremental costs for all the build alternatives. In terms of the BCA ratios, the MnPASS alternative is 8.11 compared to the General Purpose alternative, and the ratio for HOV alternative is 0.16. This shows that the additional investment to operate the proposed lanes as MnPASS will provide benefits that exceed the cost compared to general purpose lanes.

Table 5 Benefit-Cost Analysis

Criteria	No Build	Free Flow	Add General Purpose	Add MnPASS	Add HOV
Benefit-Cost Analysis	-	-	-	8.11 vs. GP	0.16 vs. GP

Findings

The MnPASS and high-occupancy vehicle (HOV) alternatives offer users a congestion-free option. In exchange, the general purpose (GP) lanes under the MnPASS and HOV alternatives are slightly more congested than under the GP alternative. This can be seen in both the surface plots and thermometers. Unlike the HOV alternative, the MnPASS option provides a congestion-free alternative to single-occupancy vehicles (SOVs), while still providing an advantage to HOVs and transit. The bar charts show both the number of users served under each alternative and their respective travel times. The MnPASS alternative offers a 10 percent increase in total peak period person throughput over the GP alternative. Additionally, the MnPASS alternative provides a 75 percent increase in number of reliable trips. Through the screening process, the MnPASS alternative maximizes the benefit, and provides a more reliable travel facility for future I-35W users.

Percentage of Congested Time

I-394, I-35W, I-35E HOV Lanes

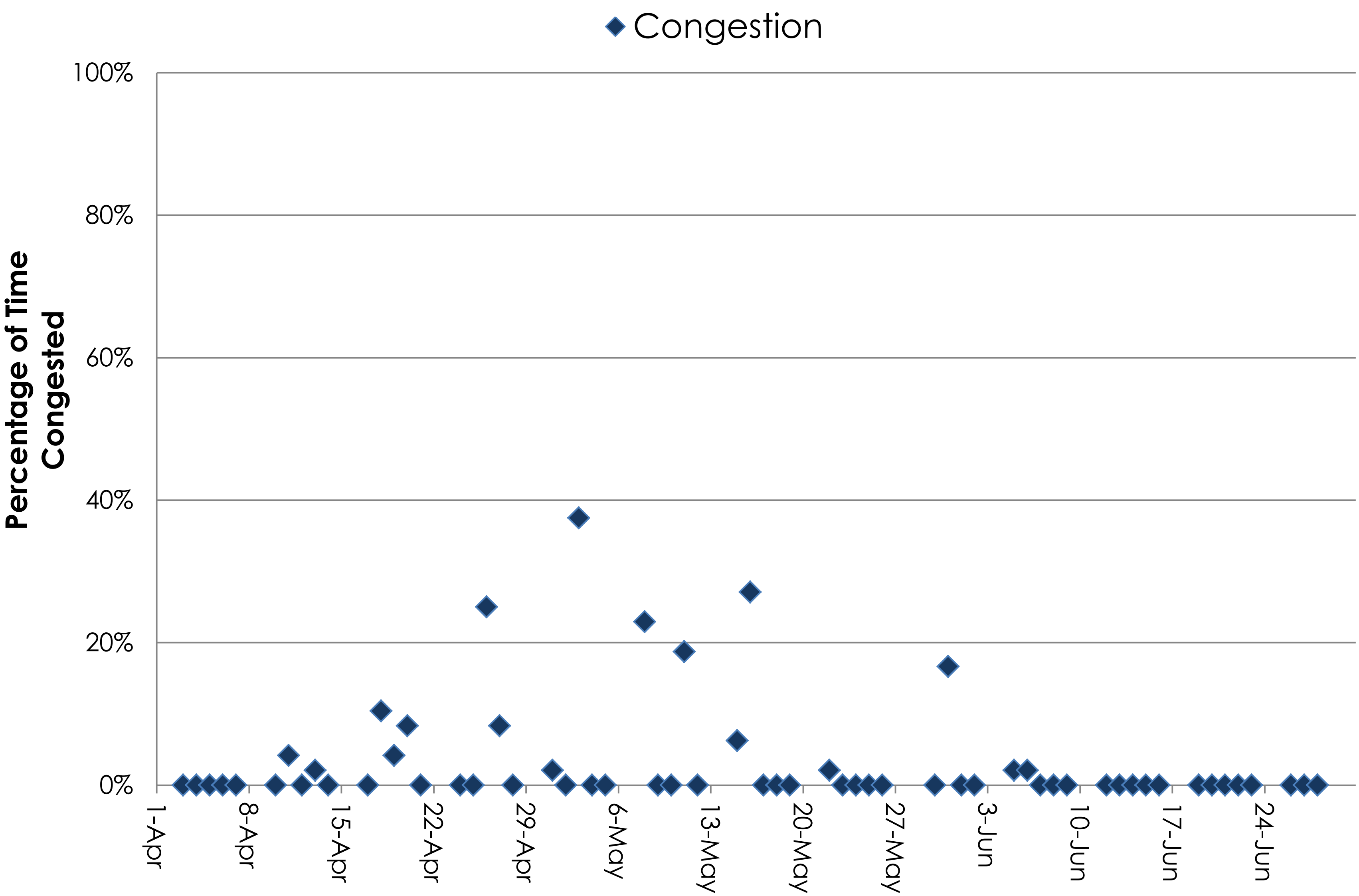
April 1 - June 30, 2017

Road Segment & Time	Congested Time
I-394 EB - I-494 to TH100 - 6 to 10 AM	3.1%
I-394 EB - TH100 to Downtown - 6 to 10 AM	1.1%
I-394 WB - Downtown to TH100 - 3 to 7 PM	15.2%
I-394 WB - TH100 to I-494 - 3 to 7 PM	0.7%
I-35W NB - Split to 494 - 6 to 10 AM	1.9%
I-35W NB - 494 to Downtown - 6 to 10 AM	5.2%
I-35W NB - 494 to Downtown - 3 to 7 PM	0.6%
I-35W SB - Downtown to 494 - 6 to 10 AM	1.4%
I-35W SB - Downtown to 494 - 3 to 7 PM	0.8%
I-35W SB - 494 to Cliff Road - 3 to 7 PM	0.5%
I-35E SB - CoRd96 to GooseLkRd - 6 to 10 AM	0.2%
I-35E SB - Hwy 36 to Maryland - 6 to 10 AM	3.2%
I-35E NB - Maryland to Hwy 36 - 3 to 7 PM	1.8%
I-35E NB - Goose Lk Rd to Co Rd H2 - 3 to 7 PM	0.0%

I-394 Charts

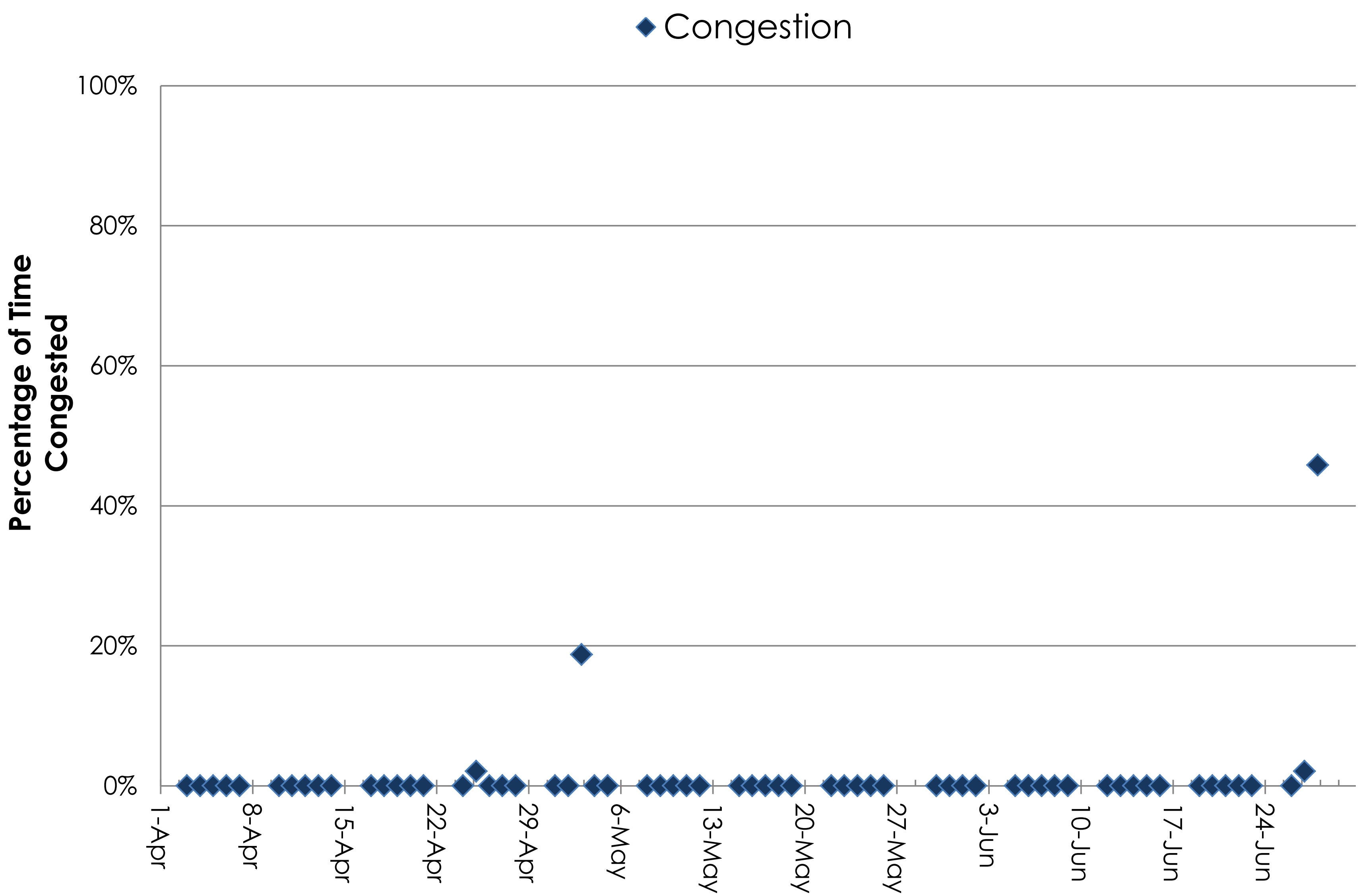
I-394 EB - I-494 to TH100 - 6 to 10 AM

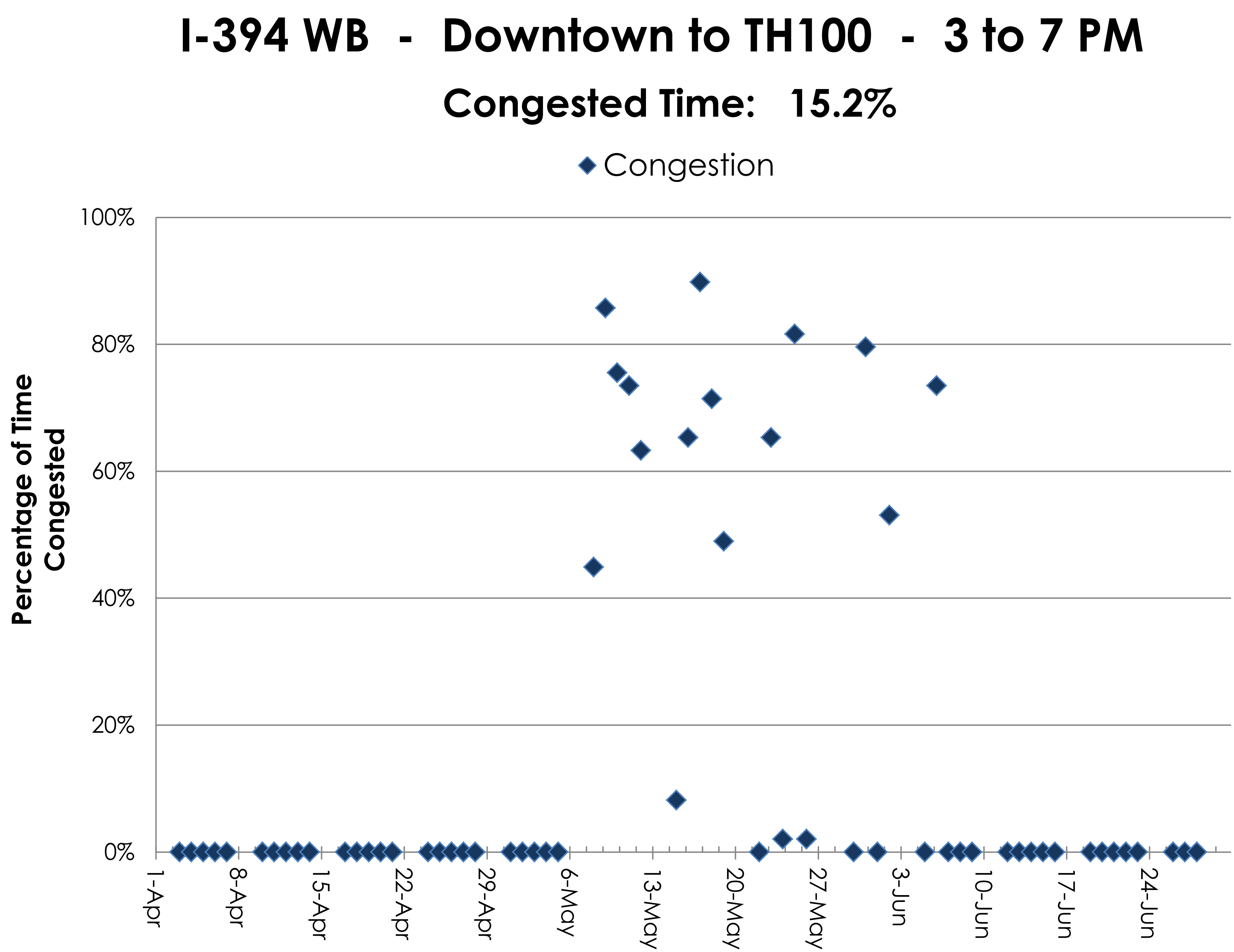
Congested Time: 3.1%



I-394 EB - TH100 to Downtown - 6 to 10 AM

Congested Time: 1.1%




I-394 WB - Downtown to TH100 - 3 to 7 PM
Congested Time: 15.2%
Congestion
Percentage of Time Congested
100%
80%
60%
40%
20%
0%
1-Apr
8-Apr
15-Apr
22-Apr
29-Apr
6-May
13-May
20-May
27-May
3-Jun
10-Jun
17-Jun
24-Jun

You'll see that westbound I-394, Downtown to TH100, had 15.2% congestion. A construction project for I-94 affected the I-394 HOV lanes from May 8th through June 7th. Westbound I-94 to westbound I-394 traffic used the HOV reversible lane. The MnDOT bulletin that follows contains additional information.

https://content.govdelivery.com/accounts/MNDOT/bulletins/1984ae2

Metro - I-94 between Minneapolis and Brooklyn Center: 2017 construction

Upcoming closure details

Watch out for some closures coming Monday in the I-94 Minneapolis to Brooklyn Center project.

Southbound Hwy 252 to eastbound I-94 will be a single-lane starting at 8 p.m. Fri, May 5 until early Monday, May 8. Access from southbound 252 to eastbound I-94 will be closed for two months for work on the westbound I-94 bridge. The detour is southbound Hwy 100. Maps are available on the project website.

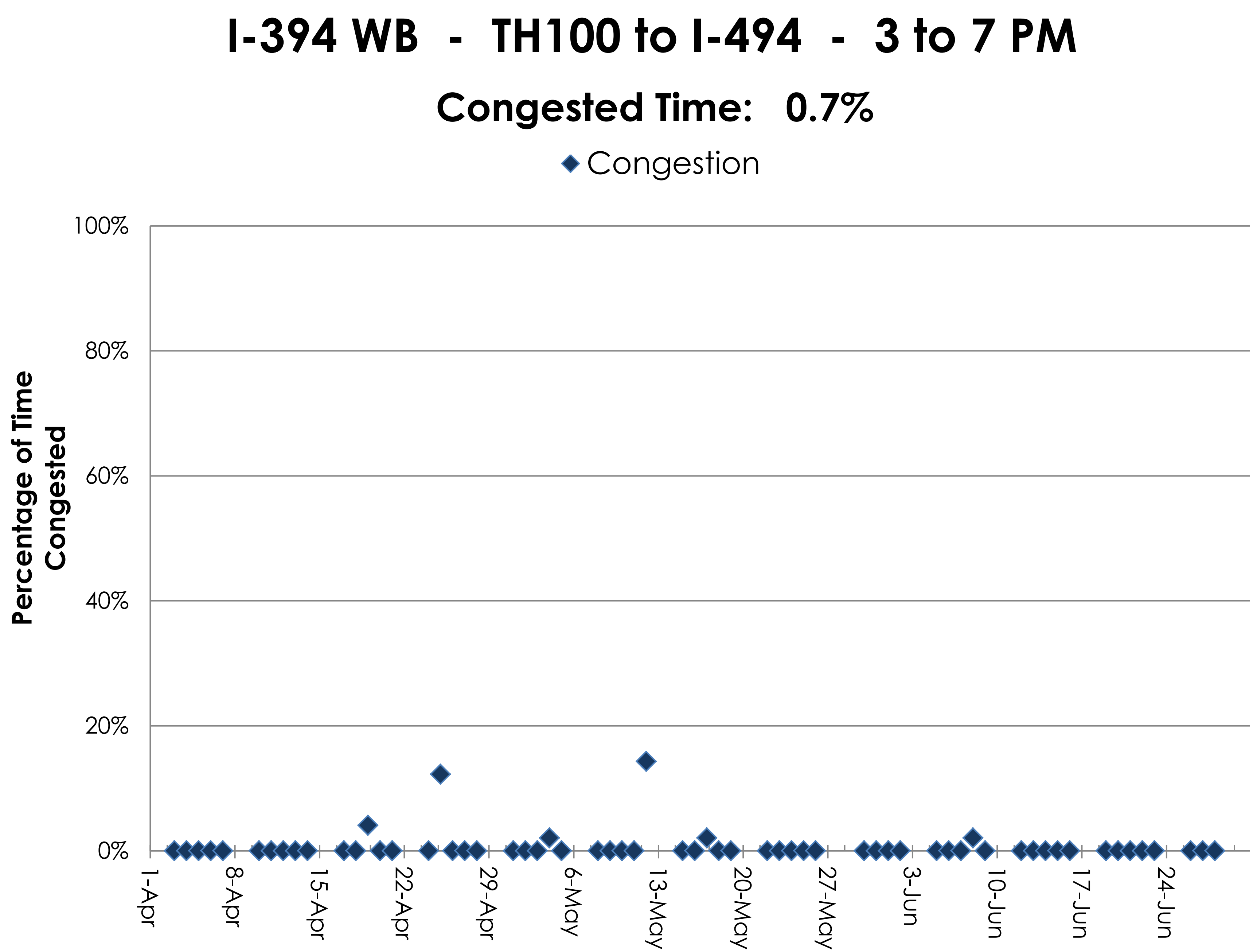
The eastbound I-94 ramp to westbound I-394 ramp will close Monday.

The ramp from Lyndale Avenue to westbound I-394 is closed. The detour is Hwy 55 to southbound Hwy 100.

Westbound I-94 to westbound I-394 will be a single lane and the westbound traffic will use the HOV reversible lane. All traffic, including MnPass customers, will use the general purpose lanes. MnPass users will not be charged.

More about this project

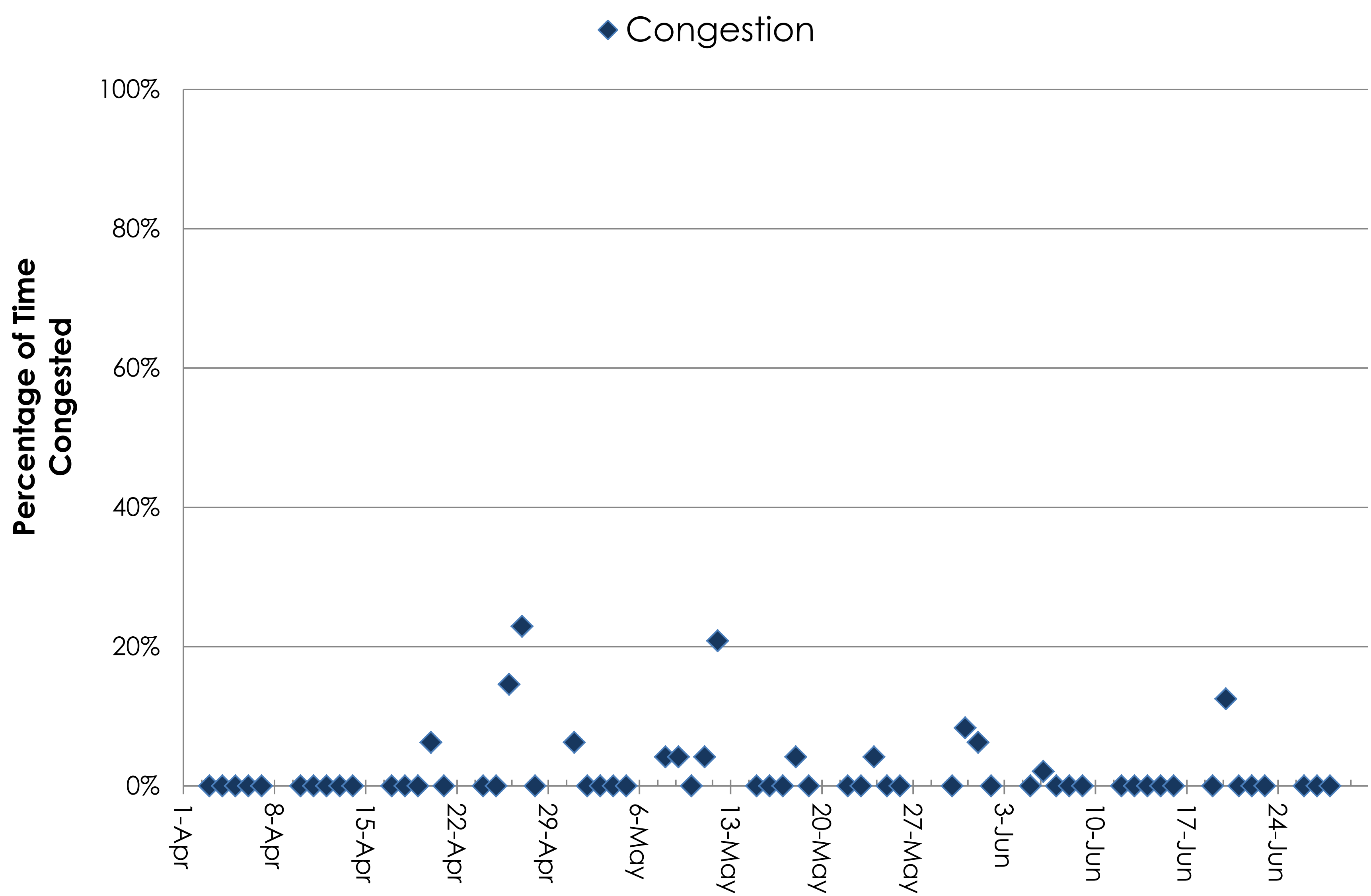
Visit: www.mndot.gov/metro/projects/i94brooklyncntr.

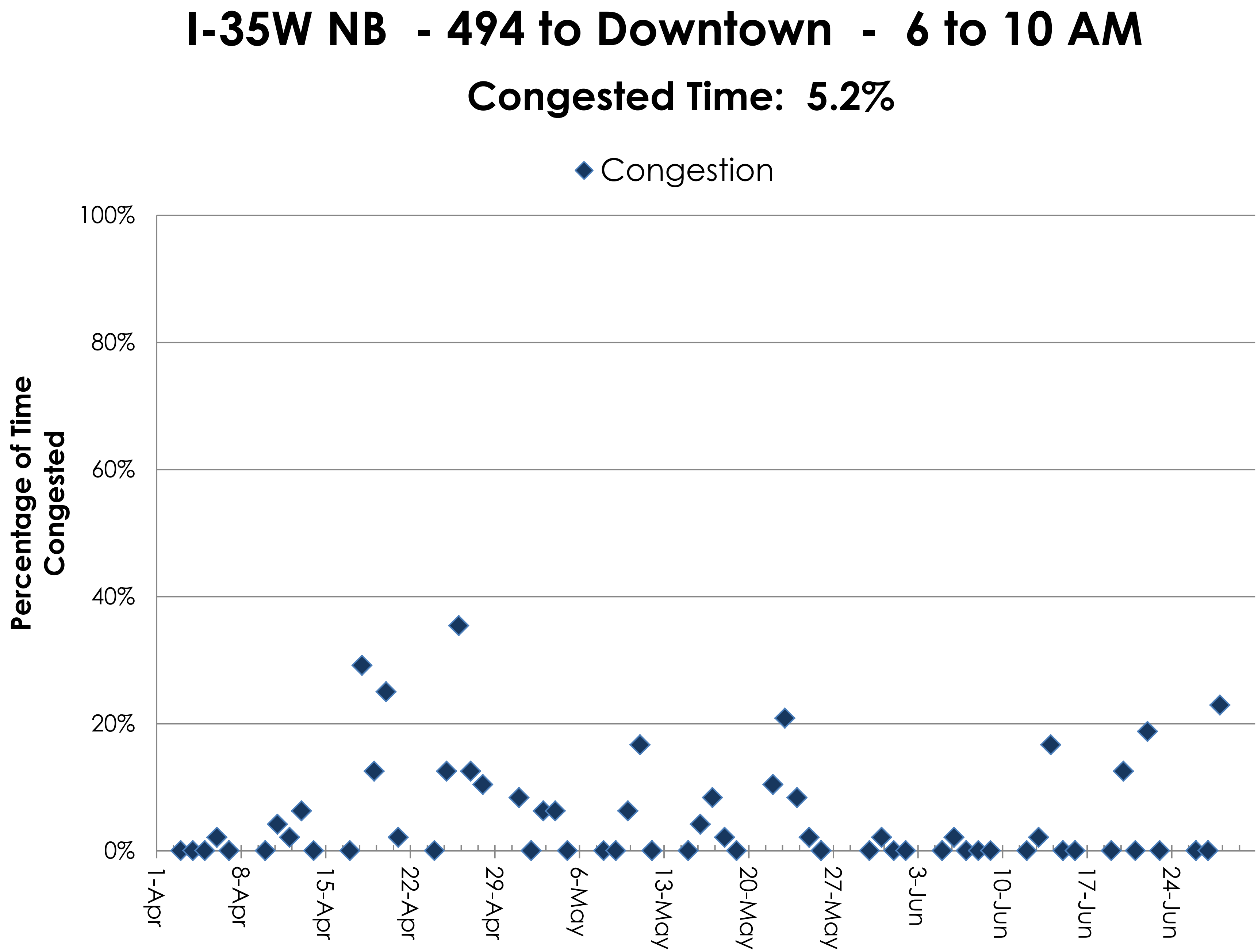

I-394 WB - TH100 to I-494 - 3 to 7 PM
Congested Time: 0.7%
Congestion
Percentage of Time Congested
100%
80%
60%
40%
20%
0%
1-Apr
8-Apr
15-Apr
22-Apr
29-Apr
6-May
13-May
20-May
27-May
3-Jun
10-Jun
17-Jun
24-Jun

I-35W Charts

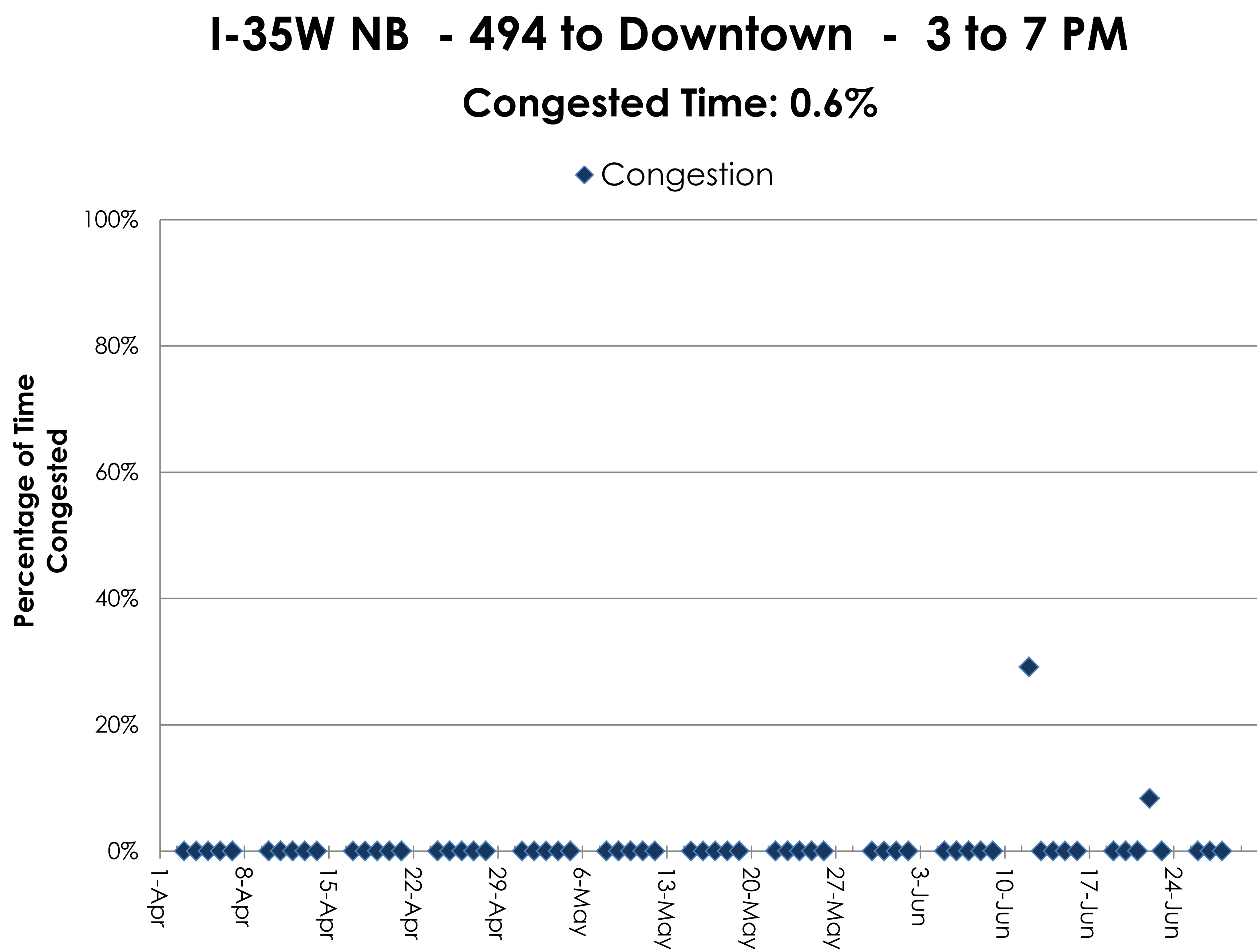
I-35W NB - Split to 494 - 6 to 10 AM

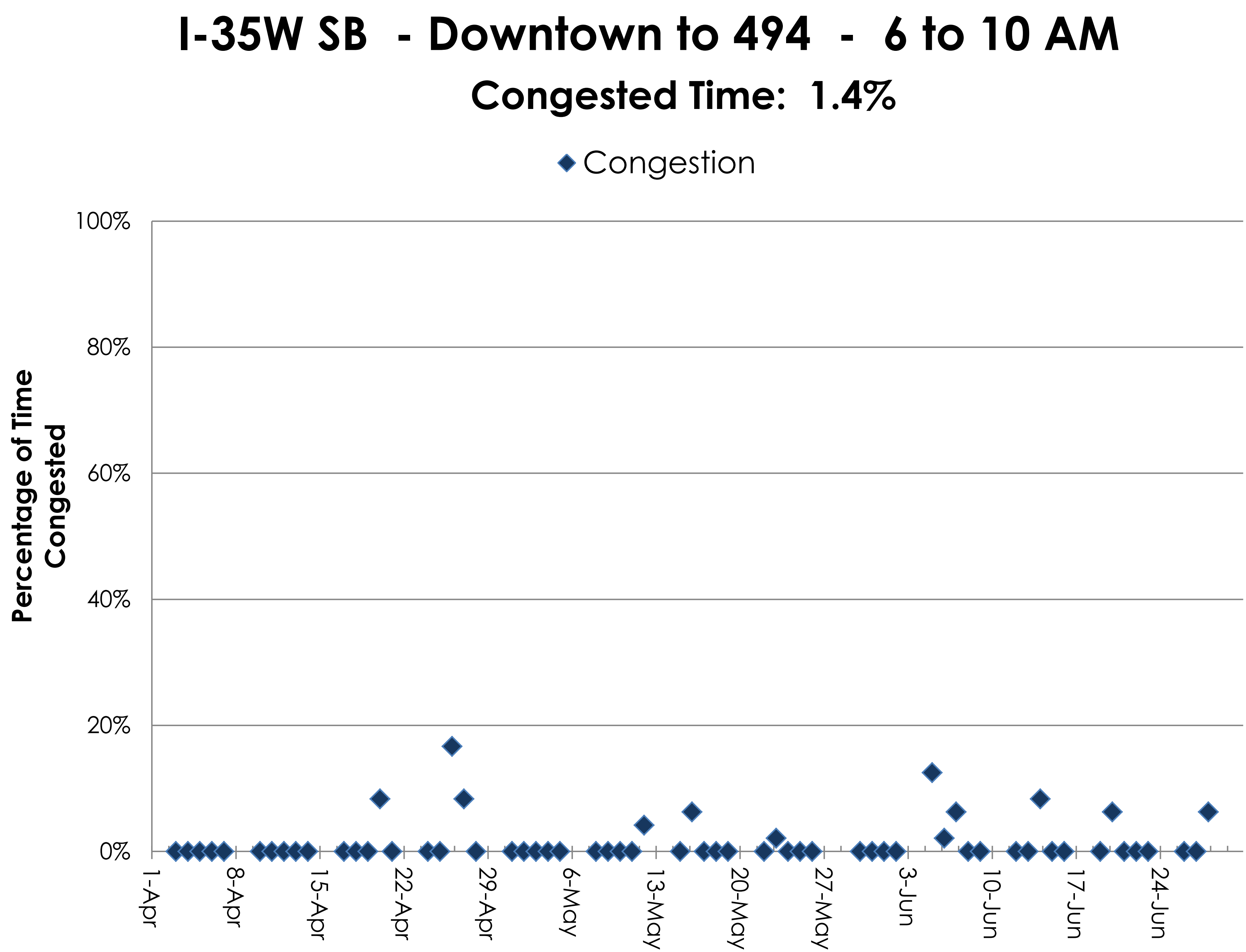
Congested Time: 1.9%





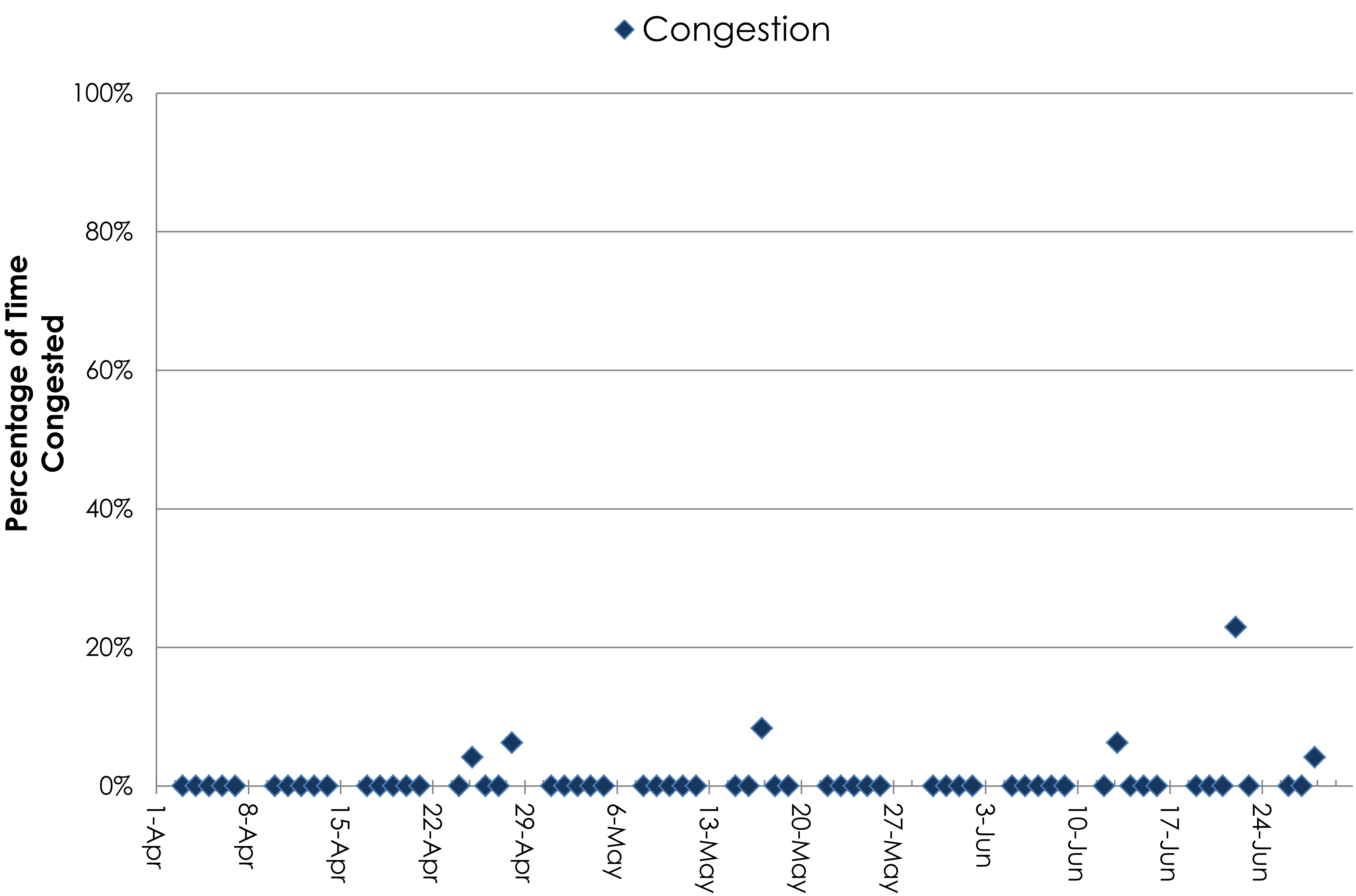
I-35W NB - 494 to Downtown - 6 to 10 AM
Congested Time: 5.2%
Congestion
Percentage of Time Congested
100%
80%
60%
40%
20%
0%
1-Apr
8-Apr
15-Apr
22-Apr
29-Apr
6-May
13-May
20-May
27-May
3-Jun
10-Jun
17-Jun
24-Jun


I-35W NB - 494 to Downtown - 3 to 7 PM
Congested Time: 0.6%
Congestion
Percentage of Time Congested
100%
80%
60%
40%
20%
0%
1-Apr
8-Apr
15-Apr
22-Apr
29-Apr
6-May
13-May
20-May
27-May
3-Jun
10-Jun
17-Jun
24-Jun


I-35W SB - Downtown to 494 - 6 to 10 AM
Congested Time: 1.4%
Congestion
Percentage of Time Congested
100%
80%
60%
40%
20%
0%
1-Apr
8-Apr
15-Apr
22-Apr
29-Apr
6-May
13-May
20-May
27-May
3-Jun
10-Jun
17-Jun
24-Jun

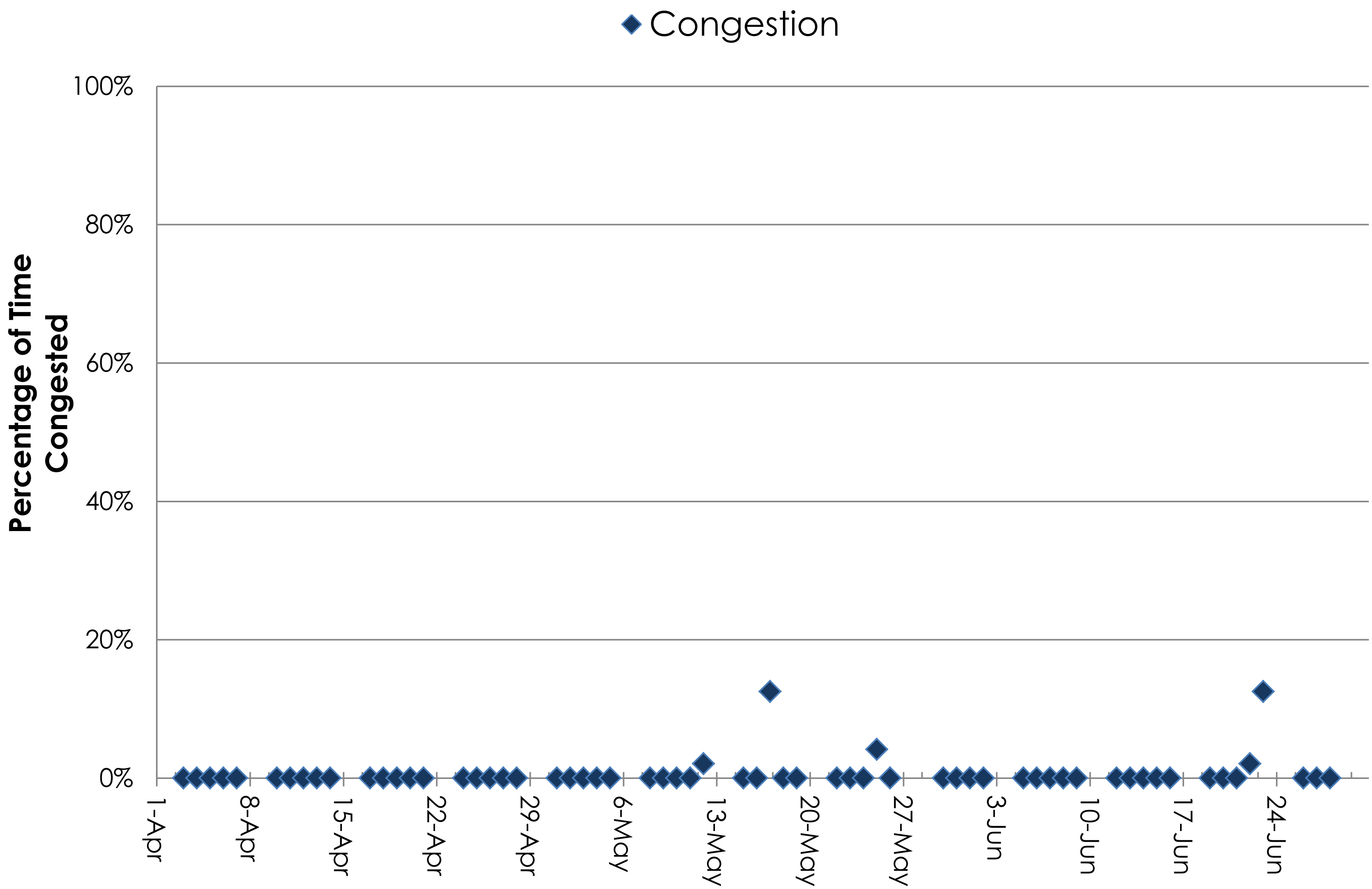
I-35W SB - Downtown to 494 - 3 to 7 PM

Congested Time: 0.8%



I-35W SB - 494 to Cliff Rd. - 3 to 7 PM

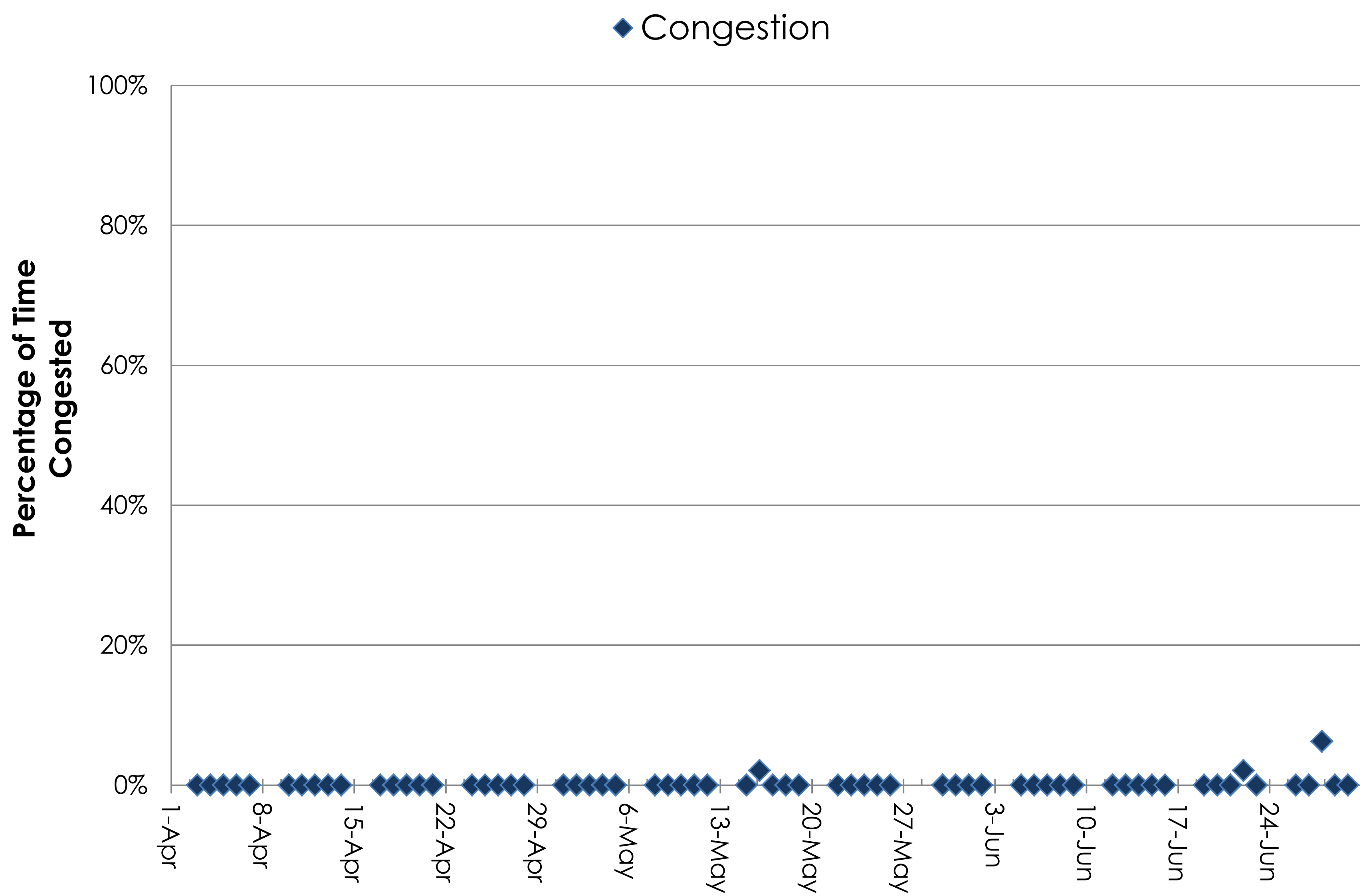
Congested Time: 0.5%

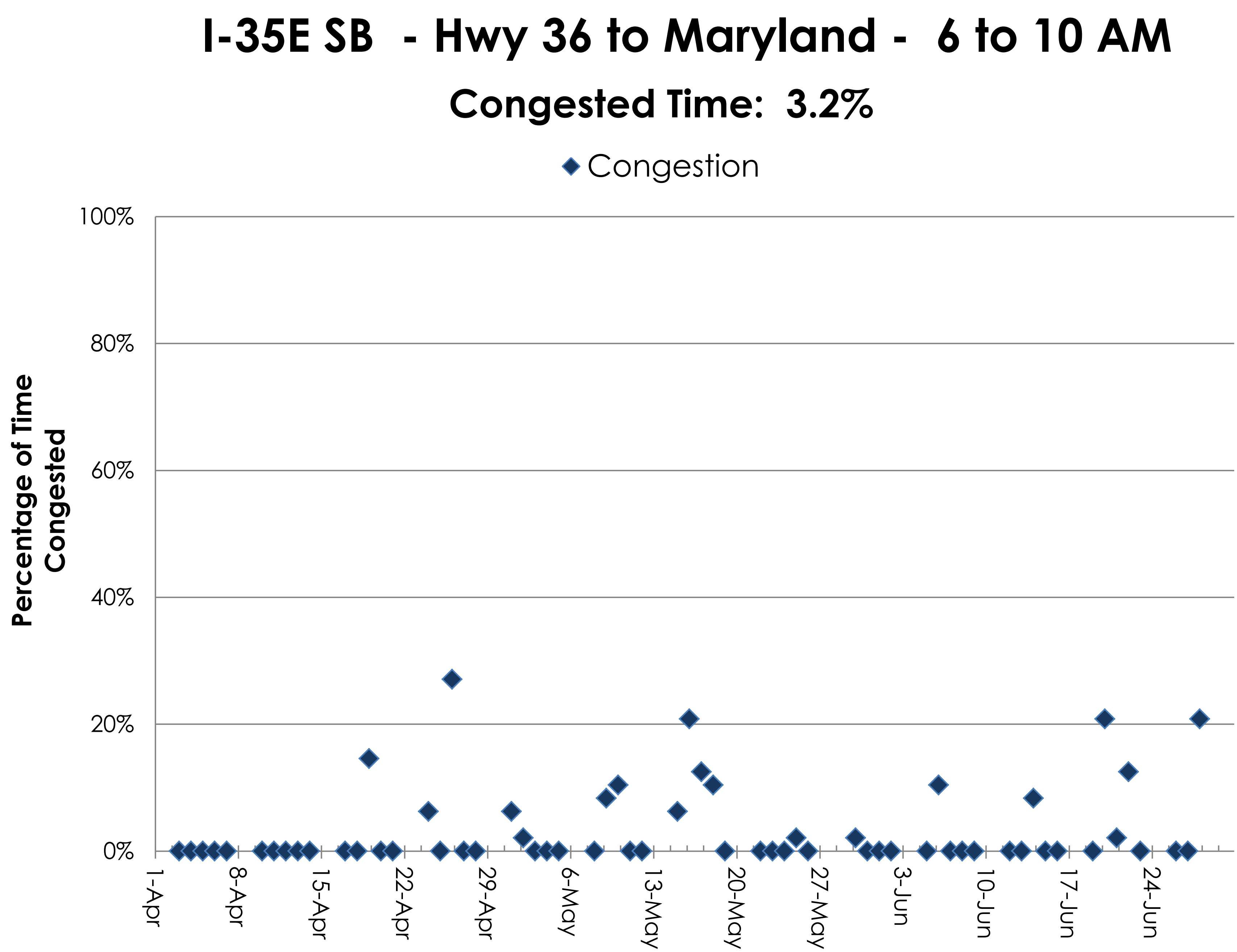


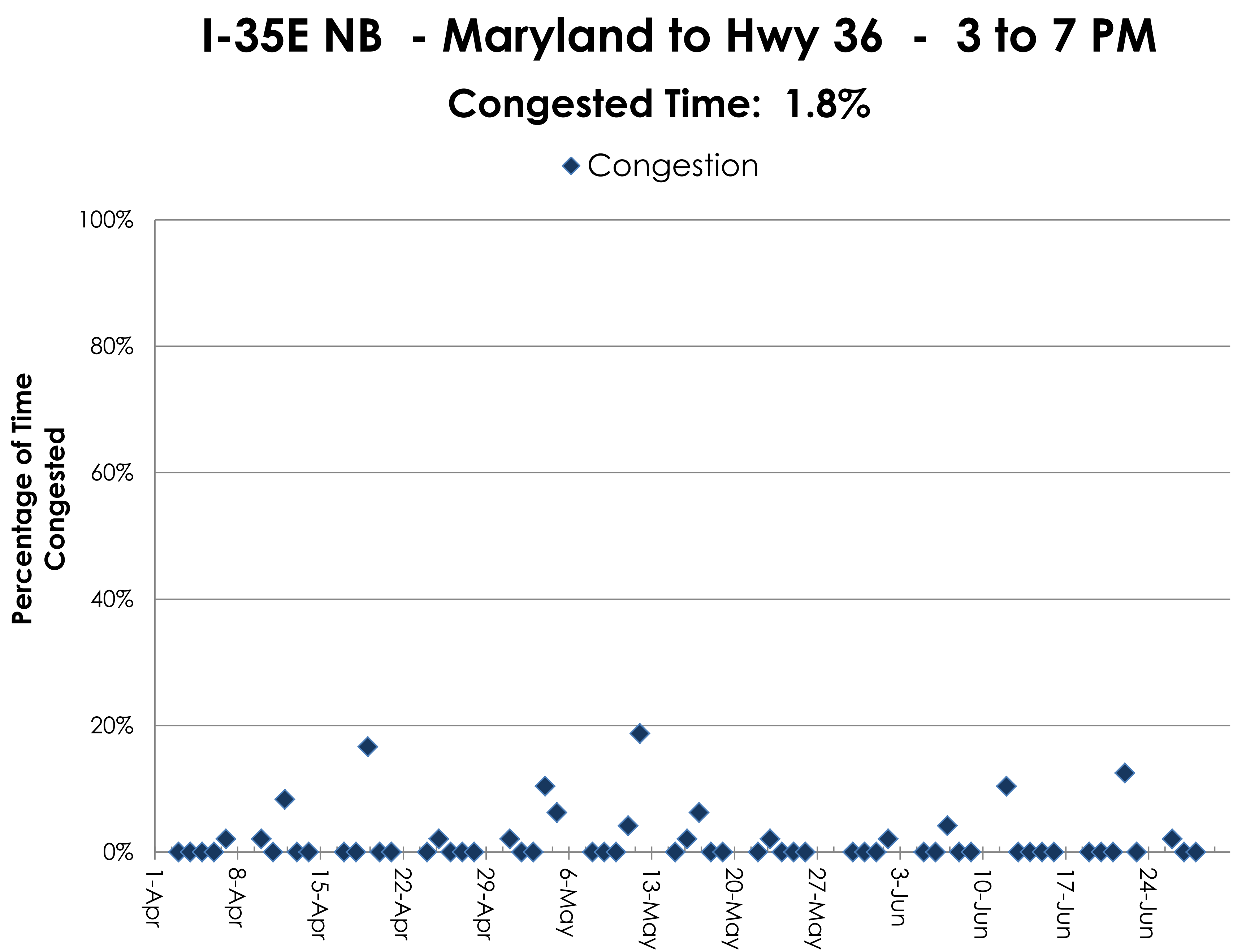
I-35E Charts

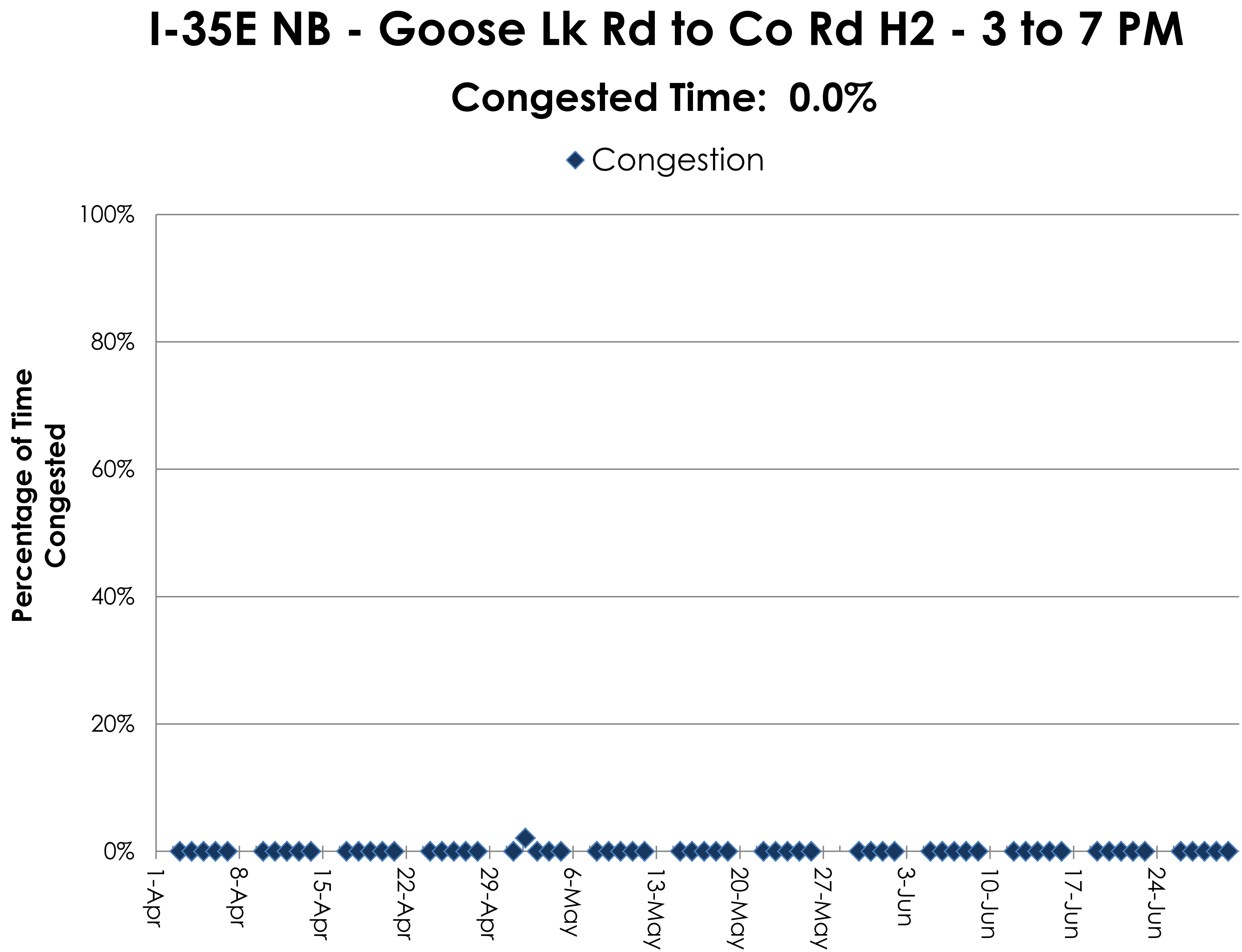
I-35E SB - CoRd96 to GooseLkRd - 6 to 10 AM

Congested Time: 0.2%




I-35E SB - Hwy 36 to Maryland - 6 to 10 AM
Congested Time: 3.2%
Congestion
Percentage of Time Congested
100%
80%
60%
40%
20%
0%
1-Apr
8-Apr
15-Apr
22-Apr
29-Apr
6-May
13-May
20-May
27-May
3-Jun
10-Jun
17-Jun
24-Jun


I-35E NB - Maryland to Hwy 36 - 3 to 7 PM
Congested Time: 1.8%
Congestion
Percentage of Time Congested
100%
80%
60%
40%
20%
0%
1-Apr
8-Apr
15-Apr
22-Apr
29-Apr
6-May
13-May
20-May
27-May
3-Jun
10-Jun
17-Jun
24-Jun


I-35E NB - Goose Lk Rd to Co Rd H2 - 3 to 7 PM
Congested Time: 0.0%
Congestion
Percentage of Time Congested
100%
80%
60%
40%
20%
0%
1-Apr
8-Apr
15-Apr
22-Apr
29-Apr
6-May
13-May
20-May
27-May
3-Jun
10-Jun
17-Jun
24-Jun

How We Arrive at the Results

The I-394, I-35W, and I-35E HOV Lanes Congestion Report is based on travel time data extracted using the Traffic Information & Condition Analysis System (TICAS). TICAS is a software tool developed by the University of Minnesota – Duluth for the extraction of MnDOT loop detector data.

Each MnPASS road segment is defined as a route in TICAS. For this report, we have defined the following routes:

- I-394 EB I-494 to TH 100
- I-394 EB TH100 to Downtown Minneapolis

- I-394 WB Downtown Minneapolis to TH100
- I-394 WB TH 100 to I-494

- I-35W NB I-35 Split to I-494
- I-35W NB I-494 to Downtown Minneapolis
- I-35W NB I-494 to Downtown Minneapolis (PM hours)

- I-35W SB Downtown Minneapolis to I-494 (AM hours)
- I-35W SB Downtown Minneapolis to I-494
- I-35W SB I-494 to Cliff Rd.

- I-35E SB CoRd 96 to Goose Lk Rd
- I-35E SB - Hwy 36 to Maryland

- I-35E NB - Maryland to Hwy 36
- I-35E NB - Goose Lk Rd to Co Rd H2

Here's an example of a road segment, its length, and the calculated travel time at 45 MPH.

I-35W Southbound from 42nd St. to I-494

- Length is 3.7 miles
- Travel Time at 45 MPH is 4.93 minutes
- 4.93 = (3.7 miles / 45 MPH) * 60 minutes in an hour

$$\text{travel time}\left[\text{minutes}\right] = \frac{\text{distance}\left[\text{miles}\right]}{45\left[\text{miles}/\text{hour}\right]} \times 60\left[\text{minutes}/\text{hour}\right]$$

The length value is pulled from the TICAS extract. 45 MPH is the minimum acceptable speed. At 45 MPH the maximum acceptable travel time is calculated using the formula above. In our example, the maximum acceptable travel time is 4.93 minutes. By dividing the length, 3.7 miles, by 45 MPH, then multiplying by 60 we get 4.93.

Once travel time data is extracted from TICAS, we can analyze it using the formula above to see how many times the maximum acceptable travel time was exceeded for a road segment. In our example, we have 48 data points for a single day, collected from 3PM to 7PM. The maximum acceptable travel time was exceeded 10 times or 21% of the time on this day:

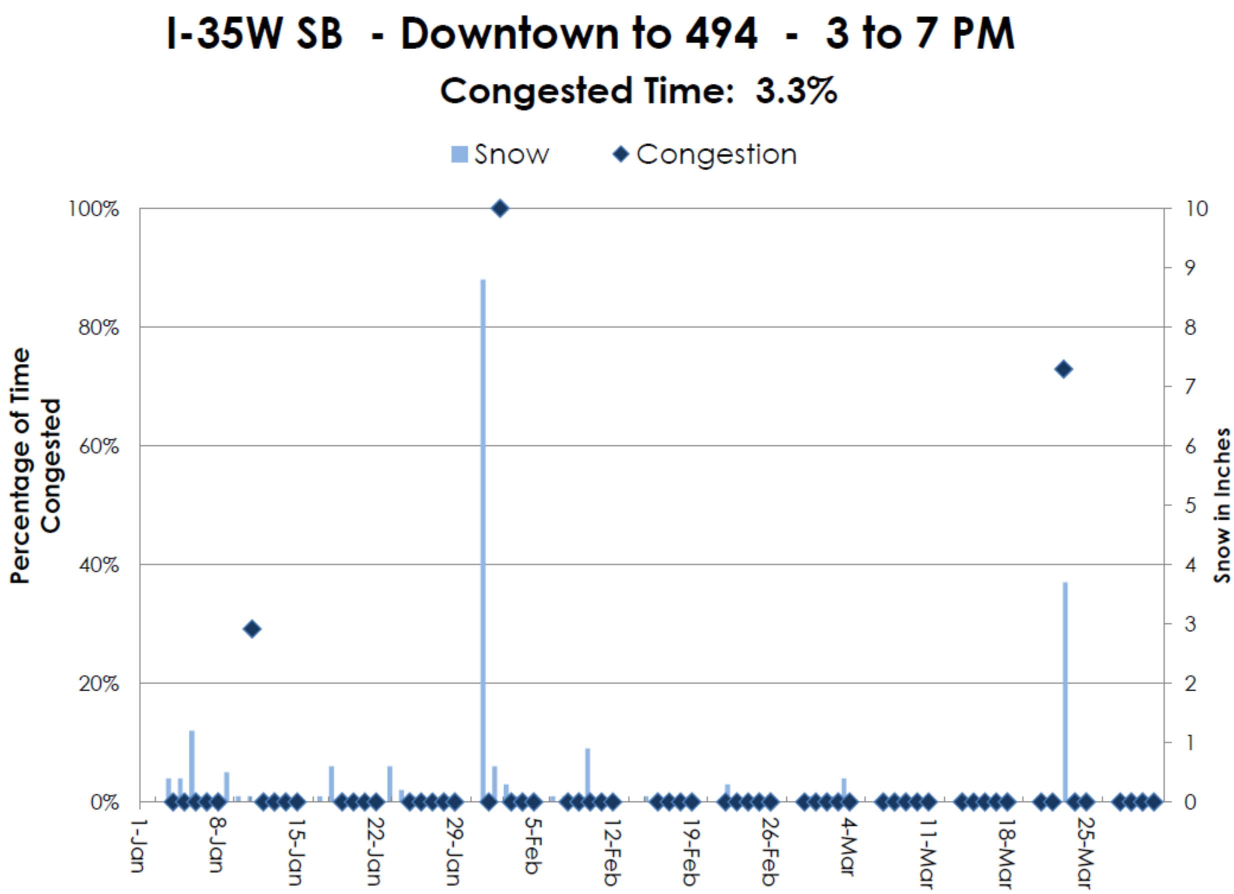
Maximum allowed travel time	4.93 minutes
Total data points	48
How many greater than 4.93	10
Percentage	21%

January 7, 2013 **Time of Day**	**Travel Time** **in Minutes**
15:05:00	3.68
15:10:00	3.58
15:15:00	3.68
...	
18:45:00	4.99
18:50:00	4.20
18:55:00	4.10
19:00:00	3.71

48 data points

In our one day example with 48 data points (using 5 minute intervals from 3 PM to 7 PM), up to 3 instances of exceeding the maximum acceptable travel time is considered okay. 3 instances equates to 6 percent (3/48). This is intended to weed out small issues which may be due to traffic stops, etc.

A chart is prepared for each route showing the percentage each day exceeded the maximum acceptable travel time. For example, if July 15th exceeded the maximum acceptable travel time 20 times, you'll see a marker above July 15th. The marker will be placed at 42% since 20 instances divided by 48 is 42%. Here's an example chart:



Charts display a summary in the title. In this example, “Congested Time: 3.3%” indicates that 3.3% of all the 5 minute time periods had travel times with speeds below 45 MPH.

The congested time for each road segment also appears in a summary table, like this example:

Percentage of Congested Time

I-394, I-35W, I-35E HOV Lanes

January 1 - March 31, 2017

Road Segment & Time	Congested Time
I-394 EB - I-494 to TH100 - 6 to 10 AM	5.3%
I-394 EB - TH100 to Downtown - 6 to 10 AM	8.7%
I-394 WB - Downtown to TH100 - 3 to 7 PM	2.3%
I-394 WB - TH100 to I-494 - 3 to 7 PM	1.0%
I-35W NB - Split to 494 - 6 to 10 AM	10.7%
I-35W NB - 494 to Downtown - 6 to 10 AM	8.1%
I-35W NB - 494 to Downtown - 3 to 7 PM	1.5%
I-35W SB - Downtown to 494 - 6 to 10 AM	6.9%
I-35W SB - Downtown to 494 - 3 to 7 PM	3.2%
I-35W SB - 494 to Split - 3 to 7 PM	2.7%
I-35E SB - CoRd 96 to Goose Lk Rd - 6 to 10 AM	0.1%
I-35E SB - Hwy 36 to Maryland - 6 to 10 AM	8.0%
I-35E NB - Maryland to Hwy 36 - 3 to 7 PM	0.8%
I-35E NB - Goose Lk Rd to Co Rd H2 - 3 to 7 PM	0.1%

Notes:

- When snow days occur, they are noted on the chart.
- Calculations are not rounded. Standard Excel decimal values are used in all calculations.