STATE OF CALIFORNIA DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT DOCUMENTATION PAGE

TR0003 (REV. 10/98)

1. REPORT NUMBER	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
CA11-2187		

4. TITLE AND SUBTITLE	5. REPORT DATE
High Occupancy Vehicle (HOV) Lane Management System	December 12, 2011
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Pravin Varaiya, Ashkan Sharafsaleh, Varun Kohli, Daniel Edwards, and Gabriel Gomes	UCB-ITS-PRR-2011-10
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. WORK UNIT NUMBER
University of California Berkeley – PATH Richmond Field Station, Bldg. 452 1357 South 46th Street Richmond, CA 94804-4698	11. CONTRACT OR GRANT NUMBER 65A0375
12. SPONSORING AGENCY AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
California Department of Transportation Division of Research and Innovation, MS-83 1227 O Street Sacramento CA 95814	Final Report 1/2011-10/2011 14. SPONSORING AGENCY CODE

15. SUPPLEMENTAL NOTES

16. ABSTRACT

This report describes a system designed to provide Single Occupancy Hybrid Vehicles (SOHVs) restriction messages dynamically to drivers through variable message signs. This system will allow California to comply with federal requirements (that Single Occupancy Hybrid Vehicles (SOHVs) must be excluded from High Occupancy Vehicle (HOV) lanes if their speed performance is degraded) by providing a way for Caltrans Traffic Management Centers (TMCs) to determine whether or not SOHVs should be permitted in HOV facilities. In turn, they could disseminate that information through control of variable message signs that indicate to drivers which vehicles are permitted in the HOV lane.

The work performed under this project represents a step forward to understanding various HOV restriction scenarios and their impact on HOV lane and mainline congestion. In this project, researchers studied, via simulations, the effects of permitting or restricting eligible single occupant hybrid vehicles (SOHV) from use of HOV facilities. The team simulated various control scenarios on a selected corridor (25 mile segment of California Interstate-210 Eastbound). Results from the simulations showed that reduction in vehicles eligible to use HOV lane (not just SOHV but any vehicle) could reduce not only the delay experienced by HOV vehicles but also the total system delay.

This high-level system design was presented in sufficient detail to allow implementation as software or a relational database. Implementation would allow for the simulation of traffic scenarios to be tested against real data. This should be the next step in the development of this system.

17. KEY WORDS	18. DISTRIBUTION STATEMENT	
SOHV, HOV, TMC, variable message, HOV restriction, HOV lane	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161	
19. SECURITY CLASSIFICATION (of this report)	20. NUMBER OF PAGES	21. PRICE
Unclassified	88	

Caltrans-Division of Research and Innovation

High Occupancy Vehicle Lane Management System-Amendment A

65A0375, Amendment A01
California PATH Research Report
UCB-ITS-PRR-2011-08

January 1, 2011 – October 31, 2011

California PATH Program

University of California, Berkeley

DISCLAIMER STATEMENT

High Occupancy Vehicle Lane Management System - Extension

Prepared for Caltrans by:

Ashkan Sharafsaleh

Varun Kohli

Daniel Edwards

Gabriel Gomes

Professor Pravin Varaiya

California PATH Program Final Research Report

This work was performed by California PATH Program, a research group at the University of California, Berkeley, in cooperation with the State of California Business, Transportation, and Housing Agency's Department of Transportation, and the United States Department of Transportation's Federal Highway Administration.

Executive Summary

Effectively managing traffic congestion on California's highway system and minimizing environmental impacts are high priority objectives for transportation management agencies in the state of California. Providing single occupant hybrid vehicles (SOHV) access to high occupancy vehicle (HOV) lane creates a significant incentive for consumers to choose these low emission vehicles, thus reducing the environmental impact of traffic flow. However, there is an additional cost with such a policy in the form of increased congestion in the HOV facility and related regulatory compliance. Federal law mandates that single occupant hybrid vehicles (SOHV) be prohibited from using HOV lanes if speed performance falls below a minimum threshold. Specifically, traffic must maintain an average speed of at least 45 mph during 90% of peak hours over a 180-day period.

This report should be considered as a compliment to a previous report for the phase one of this project. The project is aimed at determining the impact of removing SOHVs from the HOV lane. While the previous report covered the identification of study segment and SOHV sticker detection system, this report provides an analysis of the impact (through simulation studies) and description of a system architecture to implement a message system to convey to drivers the access rules to HOV lane.

Disclaimer Statement

This document is disseminated in the interest of information exchange. The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This publication does not constitute a standard, specification or regulation. This report does not constitute an endorsement by the California Department of Transportation for any product described herein.

Acknowledgements

The project team warmly thanks, in no particular order, the following people who invaluably helped the project by committing their time and knowledge. Anyone who may have been forgotten additionally receives our deep apologies.

Monica Kress, Division of Traffic Operations, Caltrans

Khanh Vu, Division of Traffic Operations, Caltrans

Joseph Rouse, Division of Traffic Operations, Caltrans

Greg Larson, Division of Research and Innovation, Caltrans

Pete Hansra, Division of Research and Innovation, Caltrans

Jose Perez, Division of Research and Innovation, Caltrans

This work was supported by Caltrans Division of Research and Innovation.

Table of Contents

List of Tables

List of Figures

Glossary

Throughout this report, the following terms are used as defined below:

HOV lane: High Occupancy Vehicle lane

MF or ML(mainline lane): Mixed flow or general-purpose lane

SOV: Single occupancy vehicle

Caltrans: California Department of Transportation

SOHV: Eligible Single Occupancy Hybrid (or low emission) Vehicle with a valid Department of Motor Vehicles decal authorized to use HOV facilities

Carpoolers: All vehicles eligible to use HOV lane (may include buses, motorcycles, HOV vehicles, SOHVs etc)

CCIT: California Center for Innovative Transportation

DDMS: Dedicated Dynamic Message Signs

DHLMS: Dynamic HOV Lane Management System

GUI: Graphical User Interface

MITTENS: Messaging Infrastructure for Travel Time Estimates to a Network of Signs

PATH: Partners for Advanced Transportation Technology

TMC: Traffic Management Center

VMS: Variable Message Sign

Pax: Passenger

PeMS: Performance Measurement System

TOPL: Tools for Operational Planning

1. Project Background

This report has been prepared and submitted to continue the work that was partially completed as part of Research Technical Agreement (RTA) C809 under master contract 65A0310. The original contract expired due a delay in processing the request for a no-cost extension. This report describes the remaining tasks from RTA C809 as well as new tasks that fall within the scope of this project.

1.1. Introduction

The 1300 miles of High Occupancy Vehicle (HOV) lanes in California are an integral part of California's transportation management strategy. Optimum performance of the transportation system as a whole is the goal of System Management and is the cornerstone of California's Transportation Vision 2025 and the Governor's Strategic Growth Plan.

The State of California legislation initiated a program in 2005 to grant certain electric-gas hybrid (clean air) vehicles access to the HOV lane without meeting the minimum occupancy requirement. However, since federal money was used to build most of the HOV network, the program would need to be approved by the Federal Highway Administration (FHWA).

In April 2006, the Federal Highway Administration (FHWA) granted conditional approval and required the State to monitor, report and develop a mitigation plan to reduce degradation on any HOV facility that participates in this program. On June 15, 2007 FHWA requested that Caltrans submit a plan for improving performance to address degradation or discontinue hybrid access to congested HOV segments.

The goal of this project is to:

- Assess and design a dynamic HOV lane management system that prohibits eligible hybrid vehicles in the HOV facility when it is operating under degraded conditions.
- Scope out a plan to conduct a proof of concept demonstration[1] for a dynamic HOV lane management system.
- Assess a potential method to effectively facilitate traffic management decision making.

[1] A proof of concept is a test of a technology made by building a scaled-down version of an application which later is intended to be developed and deployed in large scale. In Caltrans 5 stages of research deployment, proof of concept stage falls within the 1st phase.

This report is prepared under recommendation of Caltrans Traffic Operations to complete the remaining deliverables of the expired "HOV Lane Management" project (contract 65A0310).

1.2. Project Objective

The project's goal is to assess and develop a proof of concept demonstration to dynamically notify eligible single occupant hybrid vehicles when they are allowed or not allowed into HOV facilities based on traffic data.

This project aims to address issues related to effects of allowing SOHV (Single Occupancy Hybrid Vehicle) into HOV lanes. It will also try to propose a solution to manage degraded HOV facilities.

The project will focus on three major areas:

1. Looking into the contribution of hybrid vehicles to HOV lane degradation. This assessment addresses the impact of hybrid vehicles on degradation increase in HOV lanes.
2. Assessing technical solutions to the degradation problem due to SOHV flow.
3. Developing a proof of concept system to manage an under-utilized HOV facility.

1.3. Research Approach

The project team aims to answer the following questions:

1. Under existing conditions, is the effect of hybrid vehicles on HOV lane traffic significant?
2. If yes, what is the best access policy to control SOHV?

1.4. Document Organization

This document focuses on presenting the work completed under this contract. The remainder of this final report is organized as follows (Section 1 is this Introduction):

Section 2: Analysis of SOHV access control scenarios and results – presents and evaluates various controlling scenarios using TOPL simulation tool

Section 3: HOV lane management system design – documents high-level design of a basic HOV lane management system necessary for controlling SOHV access to HOV facilities.

Sections 4: Challenges – presents some of the hurdles that could be faced during the implementation of the system and how those challenges can be addressed

Section 5: Conclusion

2. Analysis of impact of SOHVs on HOV lane using TOPL

The previous report (of master contract) presented the study of 6 possible study sections and the analysis concluded that I-210 East would be an ideal section due to high flow in the HOV and general purpose lanes. In this section, we analyze the effect of removing SOHVs from this HOV facility.

The HOV lane on I-210 East is approximately 27-miles long, beginning from the intersection of Long Beach Freeway with Ventura Freeway, and ending a couple of miles downstream of the on- and off-ramps from Towne Avenue (post miles 25.7 to 51.8). The corridor has 5 lanes for the most of its length with one lane for HOV vehicles and four general purpose lanes. The HOV lane is a full-time operation; meaning minimum occupancy requirement is enforced 24-hour a day. Demand peaks during the evening commute rush period between 3 and 6 PM [[2]]. On average, peak flows of 1650 vph/lane have been observed, well in excess of the minimum expected volume of 800 vph as specified in the *HOV Guidelines for Planning, Design and Operations*. The State of California's 2008 District 7 HOV Annual Report estimates that total traffic flow flows for the entire freeway (inclusive of the HOV lane) exceed capacity during peak commuting hour. Traffic measurements indicated that the HOV lane on I-210 experienced the same level of congestion as the adjacent mixed-flow lane. This may explain why 680 eligible HOV were observed to travel in the MF lane instead of the HOV lane since the congestion had eliminated much of the travel time saving benefit that the HOV lane would had provided to its users.

On July 1, 2000, new California state legislation AB 71 was introduced to allow certain clean air vehicles with a valid Department of Motor Vehicles' decal to use HOV facilities, regardless of occupancy. This permission was extended through subsequent state legislation, namely AB 2628 and AB 2600, a view echoed by federal authorities and endorsed by the landmark SAFETEA-LU. However, given the significant levels of congestion often observed on many of these facilities, SAFETEA-LU provides for "*limiting or discontinuing the use of the facility by the [single-occupant hybrid] vehicles if the presence of the vehicles has degraded the operation of the facility… The operation of a HOV facility shall be considered to be degraded if vehicles operating on the facility are failing to maintain a minimum average operating speed 90 percent of the time over*

---

[2] 2008 District 7 HOV Annual Report, Caltrans

a consecutive 180-day period during morning or evening weekday peak hour periods (or both)." The average operating speed as defined by SAFETEA-LU is 45 mph "*in the case of a HOV facility with a speed limit of 50 mph or greater; and not more than 10 miles per hour below the speed limit, in the case of a HOV facility with a speed limit of less than 50 mph.*"

Figure 1: The 27-mile HOV facility on I-210 East

Table 1 presents a summary of the vehicle modes on the section of the freeway during peak commuting hour (which is PM peak hour for this direction). As can be seen, the segment sees high HOV vehicle volumes and some of them (680 carpoolers/hour) elect to use the mixed-flow lanes since both the mainline and HOV lane experience the same level of congestion and no time saving can be benefited from using the HOV lane. [2]. Though hybrids comprise less than 1% of total traffic on the HOV lane (*2008 District 7 HOV Annual Report*), diverting them on to the mainline could aggravate the already congested mainline even further. The extent of the negative impact depends upon the spatial and temporal correlation between speed degradation on the mainline and the HOV lane. In the case of I-210 East, the HOV lane is found to be degraded almost at the same segments and at exactly the same times as the mainline.

Table 1: Flow of vehicles (split by vehicle occupancy and type)

	HOV vehicles	SOV vehicles	Hybrid vehicles	Total
Peak Hour Flows (vph)	2293	5895	57	8245
Percentage split	28%	71%	1%	100%
People Flow (people per hour)	5025	5895	57	11097
Pax per vehicle	2.2	1	1	1.33

This report describes several different scheduling scenarios to control eligible SOHV access to HOV lanes, on the segment under study, based on past detector data (to account for daily and seasonal fluctuations in traffic) and current conditions. Given the high correlation between HOV and mainline traffic conditions, the effectiveness of any scenario is measured not only by its impact on the performance of the HOV facility but also by how seriously it compromises mainline functionality. The preliminary report compares historical data for 20 weekdays lying between 2 February 2009 and 27 February 2009 and provides simulation studies for those weekdays. This particular window of days was chosen based on the health of the vehicle detectors (more than 80 percent on all days), since the process of network calibration using TOPL relies heavily upon the robustness of detector data.

2.1. Analysis of Historical Data

The *2008 District 7 HOV Annual Report* stated traffic flows on the HOV lane for I-210 East to be around 20 percent of total traffic flow during the evening peak rush (whereas demand for total eligible HOV users across all lanes is around 29 %). I-210 East, for most of its length, is a five-lane freeway, with 1 lane a dedicated HOV lane and four for mixed-flow. Thus, for this corridor, it is we believe that as long as traffic flows on the HOV lane are lower than a fifth of total traffic volume (one HOV lane to five total lanes), HOV lane users will be at an advantage. However, as the share of HOV users nears 21 percent that advantage should reduce.

If the HOV lane on this corridor is to witness any marked improvement and reduction in delays, we believe that the demand for HOV lane on this segment needs to be contained at around 18-20 percent. Single-occupant hybrid vehicles (SOHVs) making use of the HOV facility are found by the report to be less than 1 percent of total traffic. Given these numbers, we do not expect a significant benefit from merely denying SOHV access to the HOV lane. *Moreover, it should be noted that since around 30% of eligible carpoolers (~680 vph) are already using the mainline. If we remove SOVHs from HOV lane, those 680 eligible HOV vehicles on the general purpose lane might divert onto the HOV lane and thus we may end up with the status quo (this is discussed in more detail in* ***Section 2.2****).*

2.1.1. Analysis of Historical Data

Speed contour data for the year 2009 was downloaded for all 261 weekdays from the PeMS website. Based on the percentage of days on which speeds fell below 45 mph on a particular link during a particular 5-minute time step, four levels of degradation were defined: not degraded (0-10 percent), lightly degraded (10-50 percent), very degraded (50-80 percent), and extremely degraded (80-100 percent). The contour data is examined for the presence of any weekly and seasonal variations.

Figure 2 (left and right) presents the aggregated degradation maps for the HOV lane for summer (April to September) and winter (January to March and October to December) respectively. Congestion on the HOV lane on most weekdays sets in around 2 to 3 PM and lasts until 7 to 8 PM.

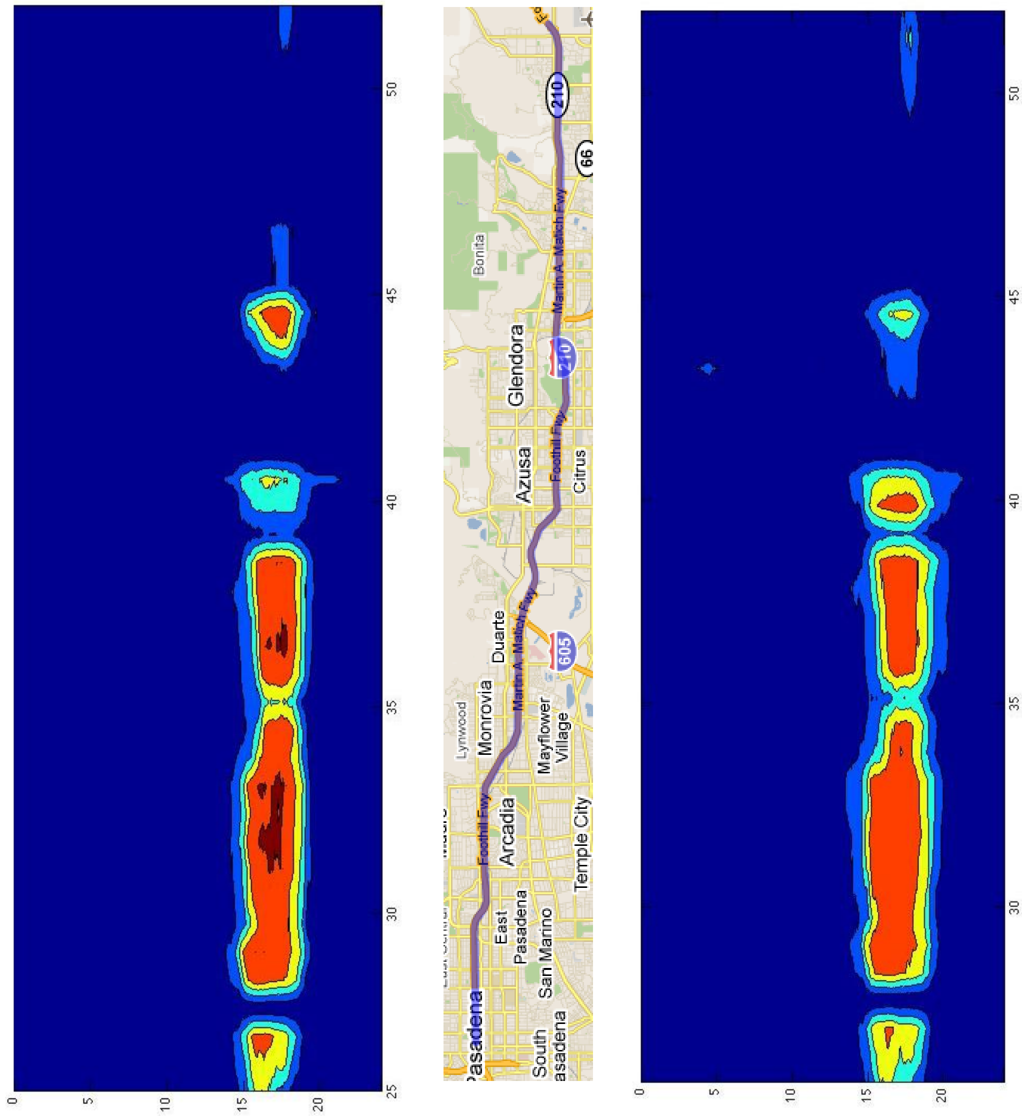


Figure 2: Congestion as observed on different links of the HOV lane on weekdays summer months (April to September) on left and Winter months (January to March and October to December) on right during the year 2009

The stronger trend appears to be weekly. Congestion on Mondays is relatively low, it increases progressively through the week and peaks rather dramatically on Friday. Figure 3 presents a comparison of the aggregated degradation maps for the HOV lanes for Wednesdays, Thursdays and Fridays. As is readily observed, congestion is much worse on Fridays than it is on

Wednesdays. With this in mind, the five weekdays are treated independently and separate control strategies are evaluated for each.

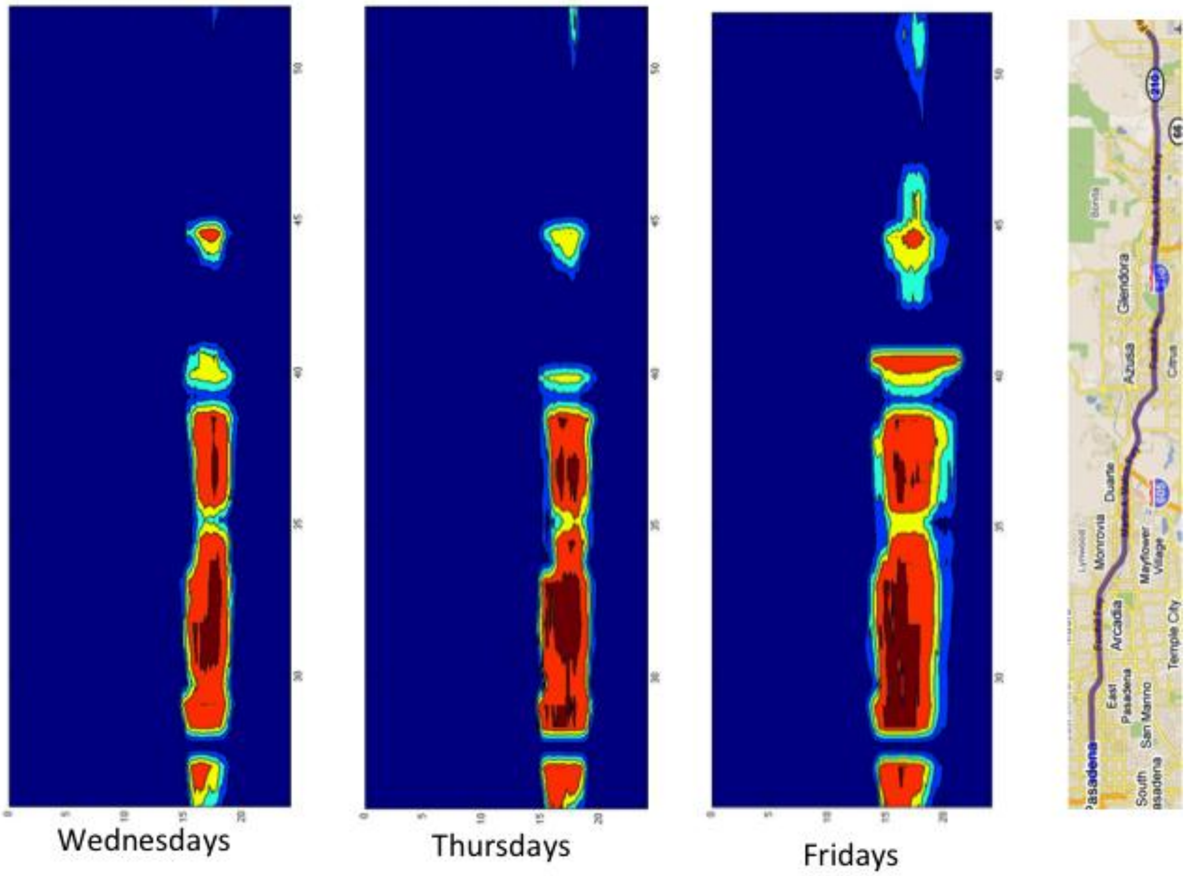


Figure 3: Congestion as observed on the HOV lane

2.1.2. Identifying the Bottlenecks

Aggregated traffic flow data from vehicle detector stations was obtained from the PeMS online repository, and was used to differentiate recurrent from non-recurrent congestion. Based on the data, five major bottlenecks were identified. All five bottlenecks were observed consistently throughout the observation period, and were confirmed using supplementary traffic data from Google Maps. Based on the location of the bottlenecks and the access points to the HOV lane, the corridor was divided into three segments:

- *Segment 1:* From post mile 25.7 - 35.4, may be divided into two sub-segments. The first, spanning from post miles 25.7 - 31.2, ends immediately downstream of the first bottleneck formed somewhere between the on ramp from Michillinda Avenue and Baldwin Avenue. It is a minor bottleneck that on most days is overridden by queues formed at more severe downstream bottlenecks, in particular the bottleneck on Myrtle

Avenue. The second segment includes the bottleneck at the on-ramp from Myrtle Avenue, attributable to high peak-time demand from the on-ramp and a significant capacity drop

- *Segment 2:* From post mile 35.4 – 45.9, initially divided into three sub-segments. The first, from post mile 35.4 - 37.6, is witness to a minor bottleneck downstream of the intersection with the San Gabriel Freeway, near the on-ramp from Irwindale Avenue, visible on some days and hidden on others. The second sub-segment, from post miles 37.6 - 40.9, contains the worst of the five bottlenecks. It is formed between the on ramps from Azusa Avenue and Citrus Avenue. The cause seems to be the high volume entering the freeway from the on-ramp from Citrus Ave. The third sub-segment includes the interchange with Orange Freeway, and is not as congested as the second sub-segment. This may be due to the bottleneck at Citrus Ave acting as a flow meter. Congestion is usually short-lived in relation to the two other major bottlenecks. It sets in around 5 PM and clears up by about 6 PM.
- *Segment 3:* From post mile 45.9 – 51.8, traffic conditions are in free flow almost always, and a control strategy appears superfluous.

It is worth mentioning here that the precise location of the bottleneck varies from day to day. The split is shown below:

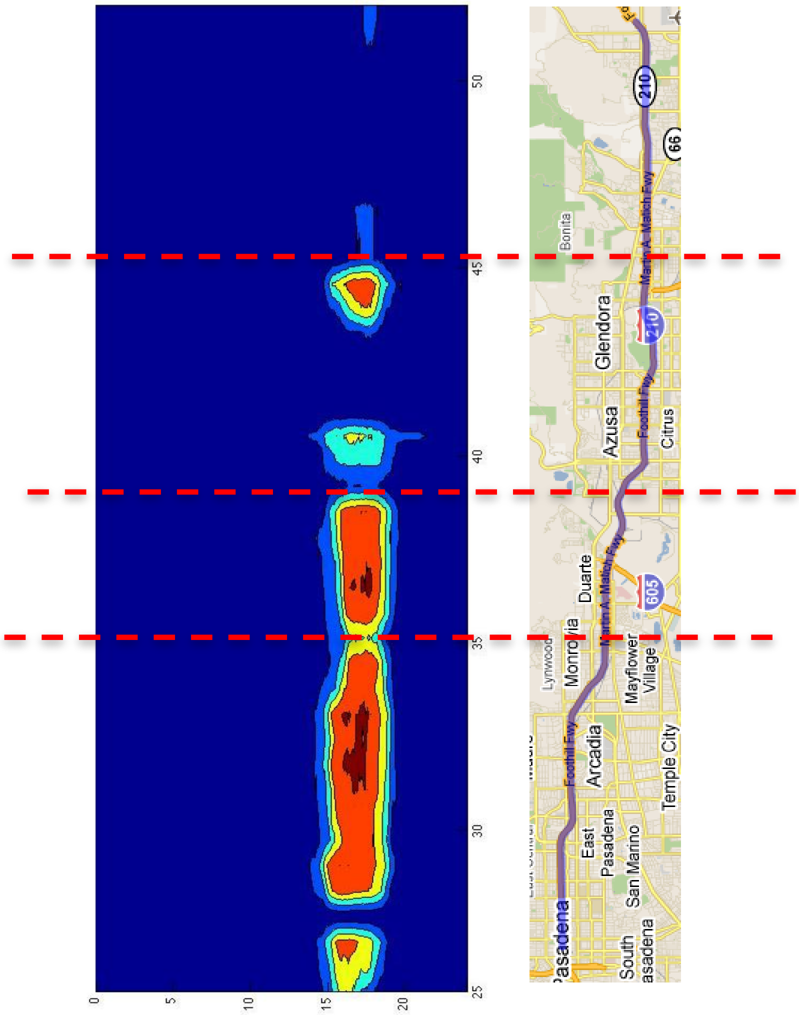


Figure 4: Location of major bottlenecks

2.2. Theoretical Analysis

In **Table 1**, we presented a description of the traffic profile through the corridor during the peak hour. We saw that HOV flows are around 29% of the total flow – HOV = 2350 veh/hr, General Purpose vehicles = 5895 veh/hr and Total flow = 8245 veh/hr (far greater than the amount of roadway provided for them - 20%). Thus, we believe that removing just the SOHVs would not alleviate the congestion on the HOV lane since the total eligible HOVs are already exceeding its capacity. This might not be the case if the destination of those carpoolers is close and they don't find any need to shift to the HOV lane, in which case removing SOHVs from HOV lane may lead to some improvement in passenger delays as delays are transferred onto the SOV vehicles.

In this section, we provide a theoretical analysis to find the appropriate percent of vehicles (beyond the exiting 1% SOHVs) needed to be removed from the HOV lane so that its conditions are considerably improved and congestion eliminated. In order to calculate how the vehicles distributed themselves among the various lanes, we used the speed, occupancy and flow contours for the entire section to determine the approximate capacity of each lane. From the contours (obtained from PeMS [3]), we saw that the capacities of the lanes are reduced, to around 1350 veh/hr/lane, at the bottlenecks at the ramps. The best viable way to alleviate congestion at these points would be to manage the demand by controlling the ramps. In order to relieve congestion on the HOV lane, around 1000 veh/hr would need to be removed. This 1000veh/hr could be vehicles that are removed by raising the HOV lane occupancy requirement to '3 or more persons'.

The corridor has a capacity of around 1700 veh/hr/lane. In order to alleviate congestion on the HOV lane, we consider to restrict approximately 650veh/hr access to it (i.e. 7% of the total traffic). SOHVs constitute of only 1% of the total traffic stream. Even if we restrict their access, there would still be around 2265 veh/hr eligible carpoolers and 1495 veh/hr/lane SOVs. Hence, the demand for the HOV lane still exceeds its capacity. Some carpoolers (around 600 HOV vehicles) may elect to shift to the Mainline (which we see in reality) since there is no longer an advantage to use the HOV lane over the Mainline. As such, the flow may evenly distribute itself out to be 1650 veh/hr/lane for the HOV and mainline lane. Thus, restricting access to such a small percent is expected to only redistribute the traffic flow (with carpoolers that were initially on the mainline shifting to HOV lane when the spaces previously occupied by the SOHVs are now empty). Hence, we believe such a change would not have a huge effect on the system as well as HOV lane delay. Since the vehicles leaving the HOV lane are single occupancy (and these may experience more delay) while vehicles entering the HOV lane are multiple occupancy – 2.2 passengers per car on average [3] (and these may experience lower delay), an overall reduction in passenger delay would be expected. For example, say there is an extra delay of Δ when an SOHV moves from HOV to mainline. Since we are removing around 82veh/hr SOHVs from HOV to mainline and replacing them with carpoolers, change in passenger delay per hour for the facility can be calculated as:

$$+ 82 \times 1 \times \Delta - 82 \times 2.2 \times \Delta \approx (-98.4)\ \Delta$$

In this scenario, we may see a reduction in net passenger delay. In the following sections (Section 5), we shall discuss the impacts of removing vehicles out of HOV lanes via simulation studies.

[3] *2008 HOV Annual Report, Caltrans*

Figure 5 (a,b,c): Contours for ML lanes

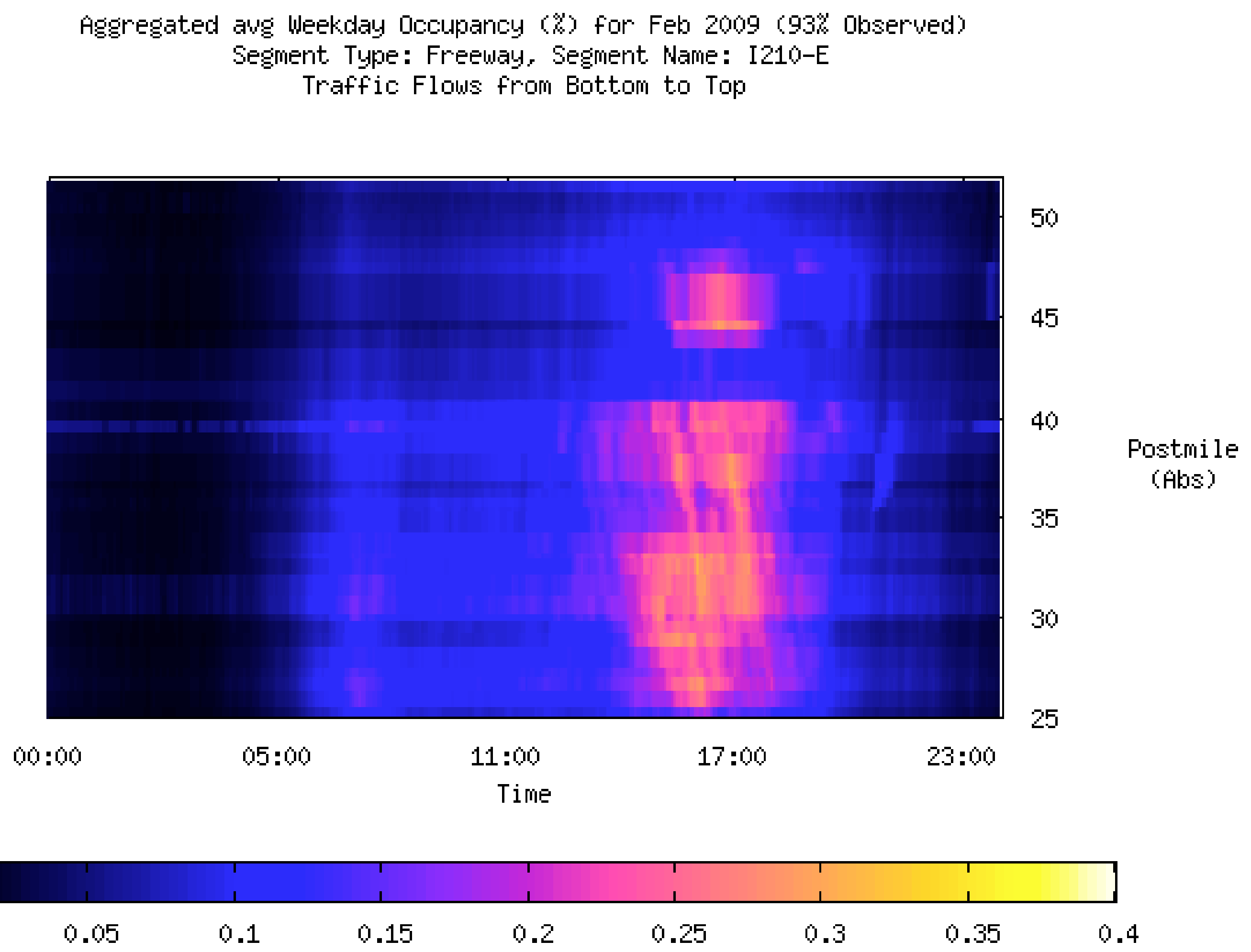


Figure 5a: Occupancy contours for ML lanes

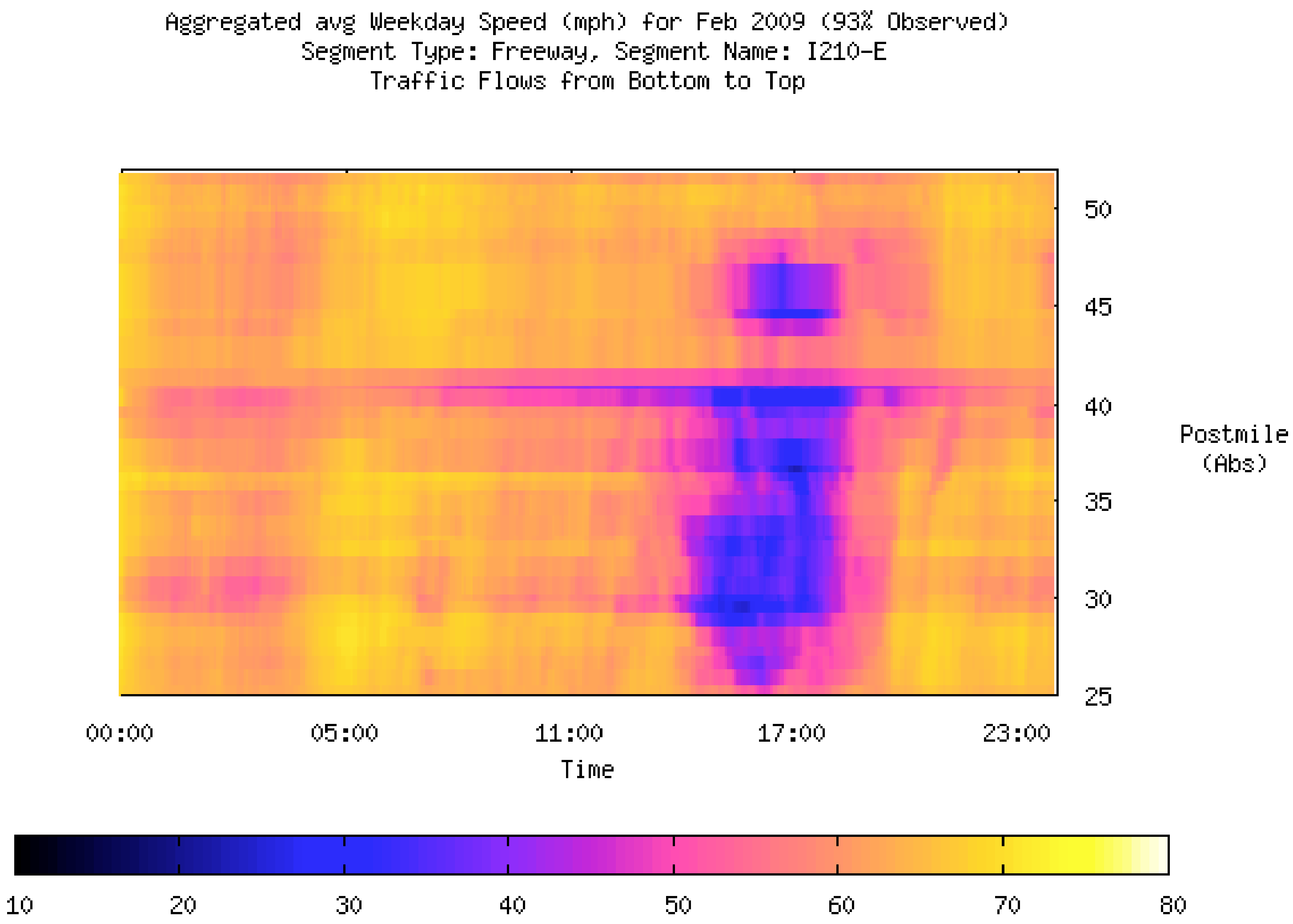


Figure 5b: Speed contours for ML lanes

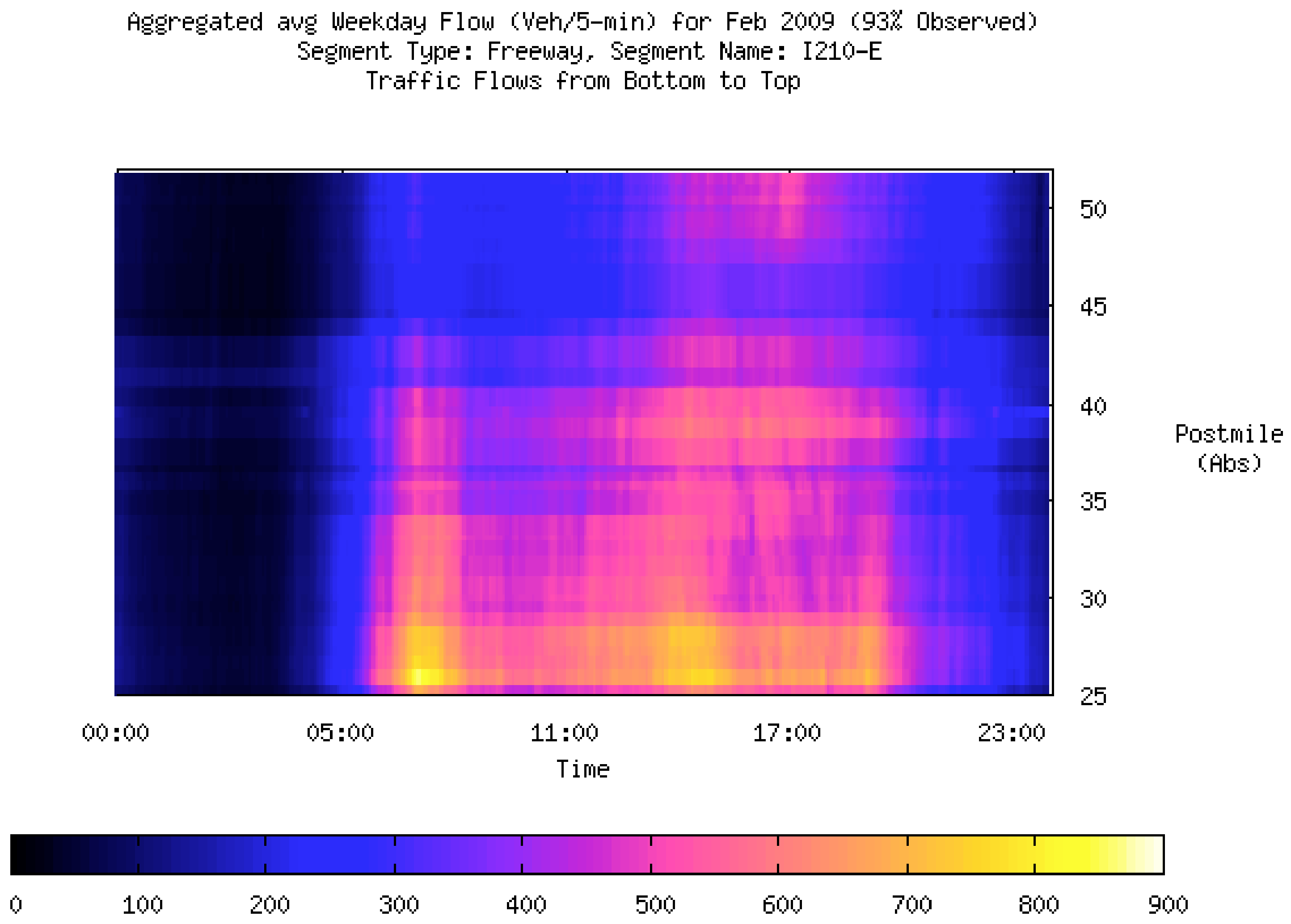


Figure 5c : Flow contours for ML lanes

Figure 6 (a,b,c): Contours for HOV lane

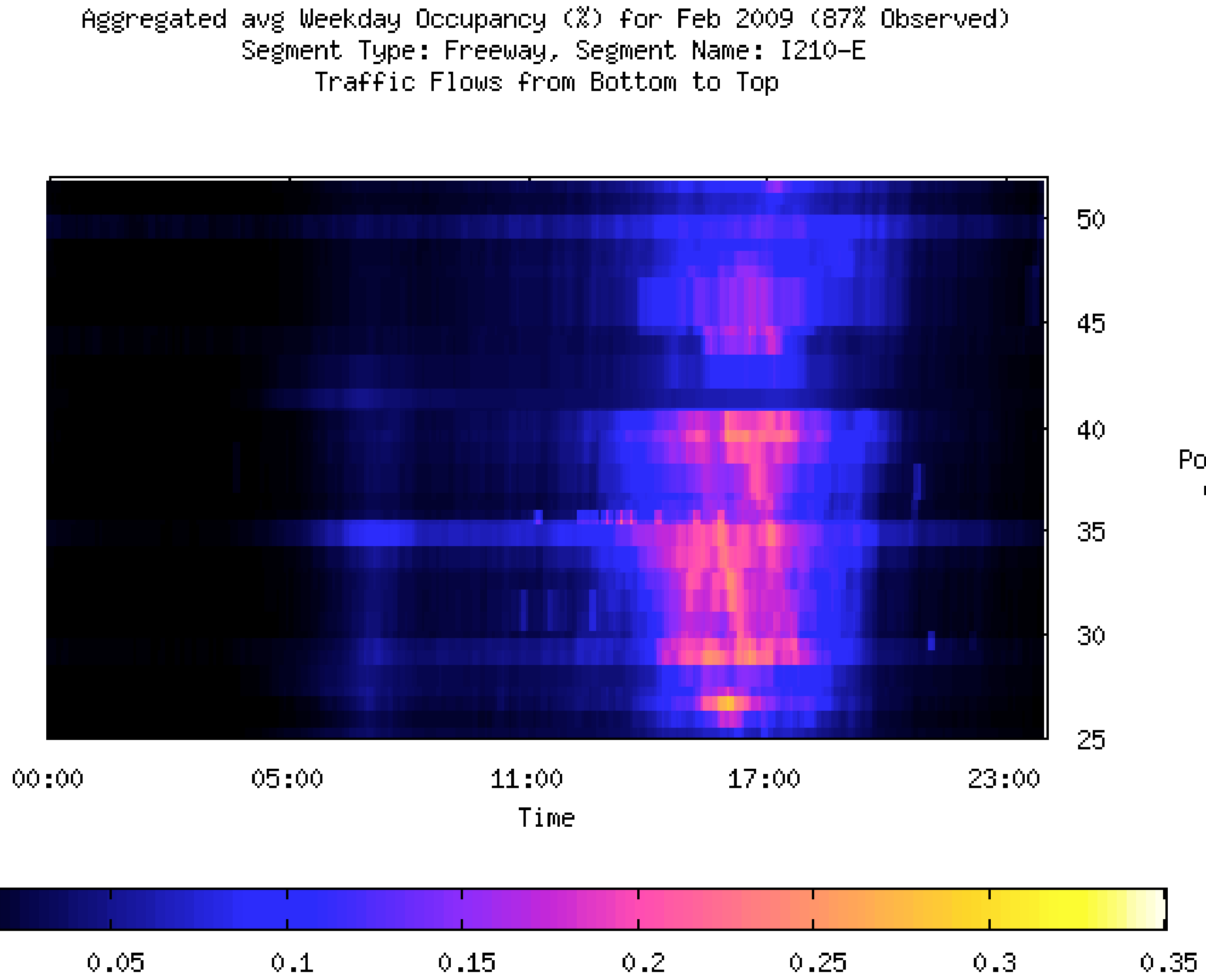


Figure 6a: Occupancy contours for HOV lanes

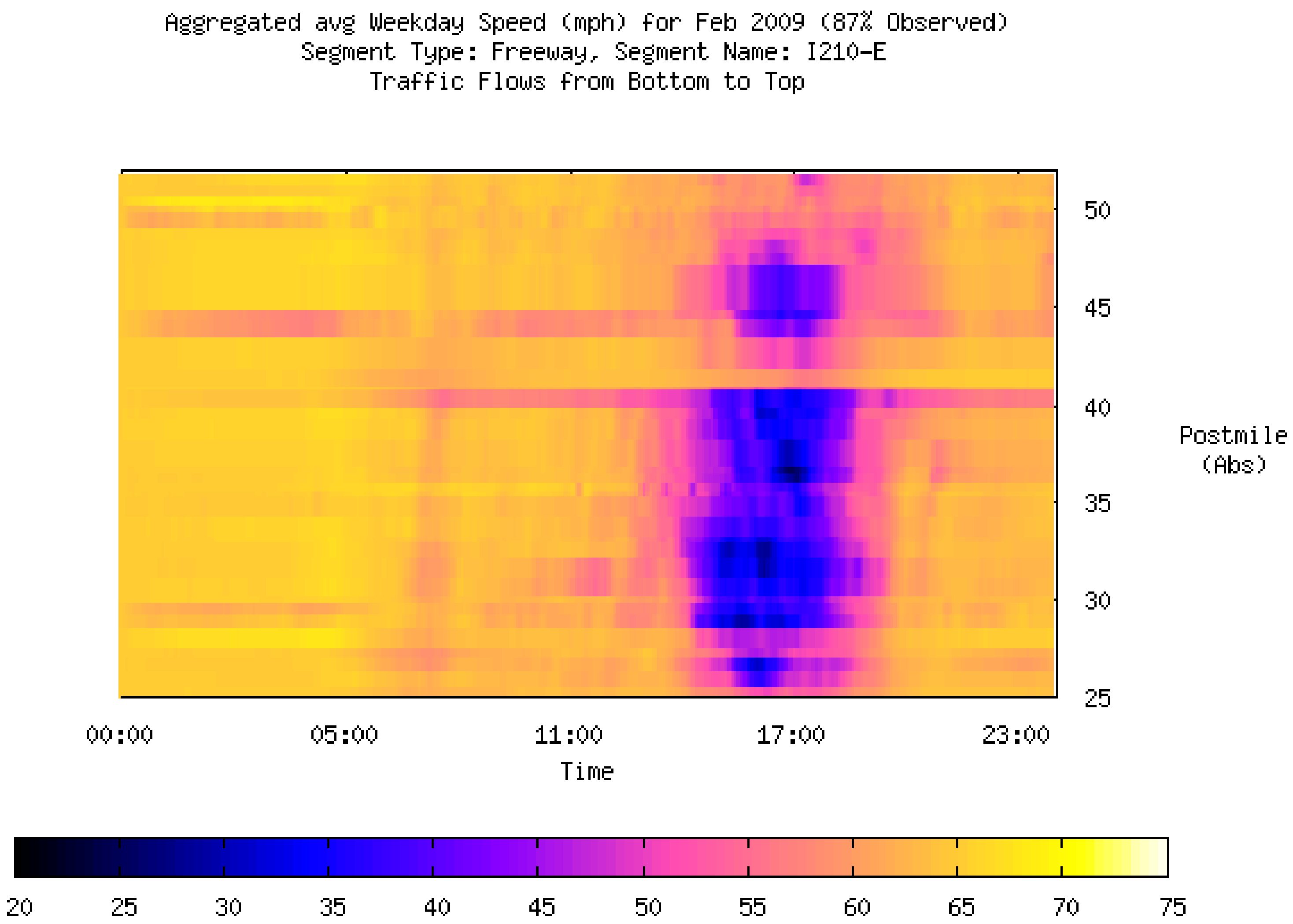


Figure 6b: Speed contours for HOV lanes

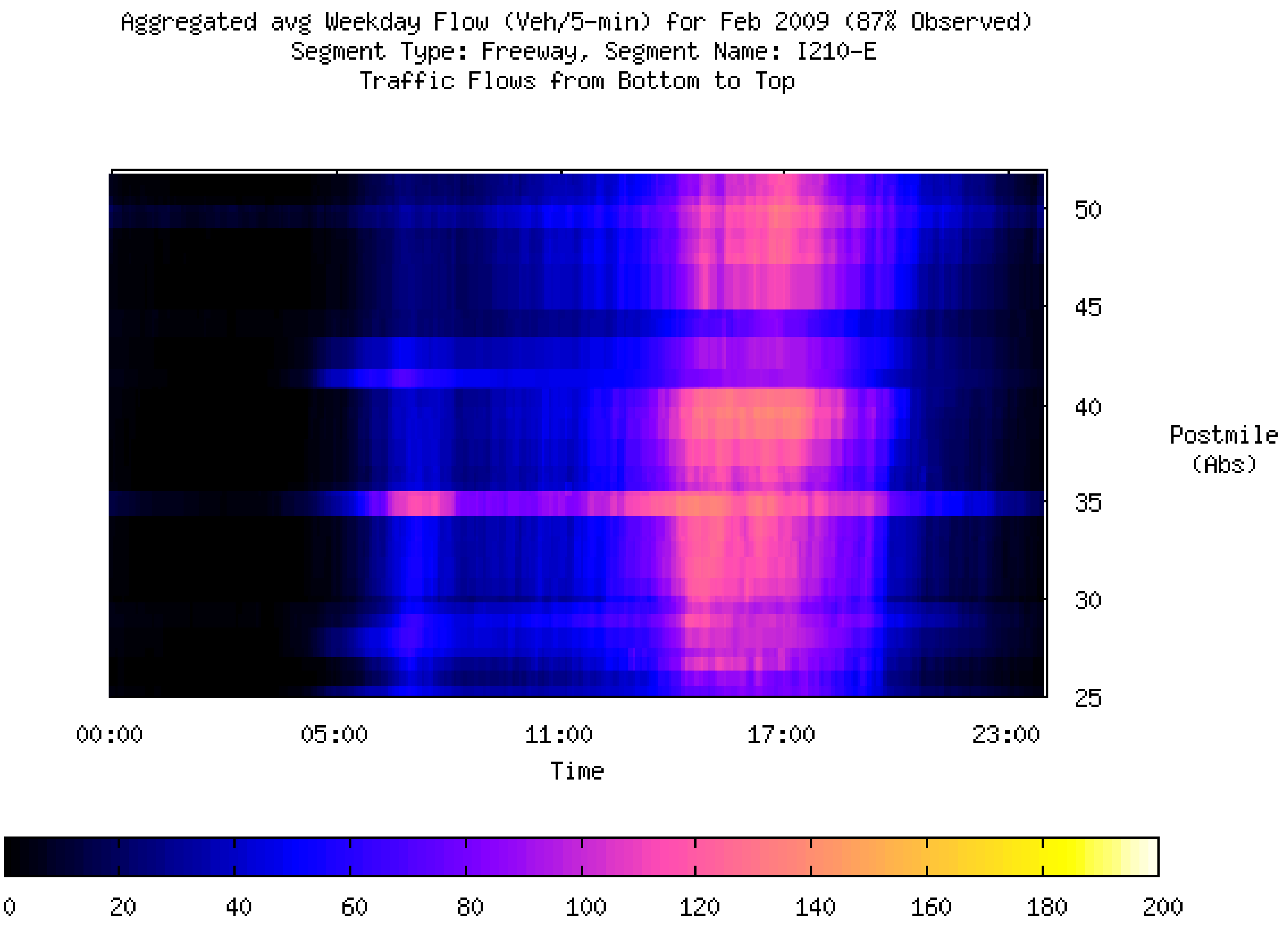


Figure 6c: Flow contours for HOV lane

2.3. Model and Simulation

A simulation model for the 27-mile section (PM 25 to PM 52) for the East bound direction was created using TOPL network editor. The model consisted of 145 nodes with each node having two input links (HOV and Mainline) and 2 output links. In the model, each link represents a finite element of the freeway representation and each node is a point where these links are connected and interact with each other. We had a total of 346 links (including on and off ramps). The 132 sensors along the route were also included in the model.

2.3.1. Model Calibration

The simulation was calibrated using a MATLAB-based application that uses PeMS data to define freeway geometry, obtain fundamental diagrams and set up demand profiles based off data for a sample day.

2.3.2. Delay Statistics

In this report, we use the delay statistic given by the simulator for our analysis. The delay is calculated as:

$$delay_{i,t} = L_i \times \max[0, \rho_{i,t} - \frac{f_{i,t}}{vf_i}]$$

Where: $delay_{i,t}$ = Delay on link 'i' for time interval 't'; L_i = Length of link 'i', $\rho_{i,t}$ = density of link 'i' in time interval 't', $f_{i,t}$ = flow on link 'i' in time interval 't', vf_i = free flow speed for link 'i'

It should be noted here that delay calculations are based on the free flow speed of each link and not a specific speed threshold (which is used by other software like PeMS). This should give a better estimation of actual delay by not giving much weight to inherently slow links while taking into account links that have a free flow speed that is high. Total network delay is calculated as:

$$TotalDelay = \sum_t \sum_i delay_{i,t}$$

TOPL also provides delay for the HOV lanes and mainline lanes. Since these delays are in vehicle hours, we convert them to passenger hours by assuming an average number of 2.2 passengers for 1 HOV vehicle and 1 passenger other vehicles. Thus, total passenger delay is calculated as:

$$TotalPassengerDelay = TotalDelay_{HOV} \times 2.2 + TotalDelay_{ML} \times 1$$

2.4. Evaluating the Effect of Different Control Strategies

In section 2.1.1, we saw that a higher variation in congestion happens during the week rather than seasonally. In view of that, simulations were done for each day for the month of February 2009. The results in this section are grouped by each day of the week.

Various scenarios were simulated by using different percentages of vehicles removed from the HOV lane. They are as follows:

- Base Case: Normal Vehicles (HOV lane ineligible vehicles): 71%, HOV lane eligible vehicles 29% [28% HOV and 1 % SOHV with no restrictions]
- Mainline 72%, HOV lane 28% [1% removed]
- Mainline 74%, HOV lane 26% [3% removed]
- Mainline 76.5%, HOV lane 23.5% [5.5% removed]
- Mainline 78%, HOV lane 22% [7% removed]
- Mainline 81%, HOV lane 19% [10% removed]
- Mainline 85%, HOV lane 15% [14% removed]

These cases cover a wide range of possibilities. While they cover the possible SOHV vehicle ratios of 1-7%, they also simulate the scenario if HOV lane minimum occupancy requirement is increased to 3 or more persons. Also, to study the impact of the strategies, we use passenger-hours (pax-hrs) of delay on the network and HOV lane as a metric since one of the primary goals of implementing an HOV lane is to increase the system person throughput. Graphs for changes in veh-hrs are also provided for reference.

Also, we validate our results from TOPL by comparing the daily delay in veh-hrs with that obtained from PeMS. Although the exact values may vary since the two systems use different mechanisms to calculate delay (as noted in section 2.3.2) the order of magnitude should be comparable. Figure 7 graphs the comparison between the two. The points marked in red are the days that show high level of differences. They could be the result of non-recurrent delay (i.e. accidents) that is accounted in PeMS but not included in TOPL. We remove these days from our analysis. Also, Figure 8 shows a good match between the speed contour plots from PeMS and TOPL (graph is for 4 Feb. 2009).

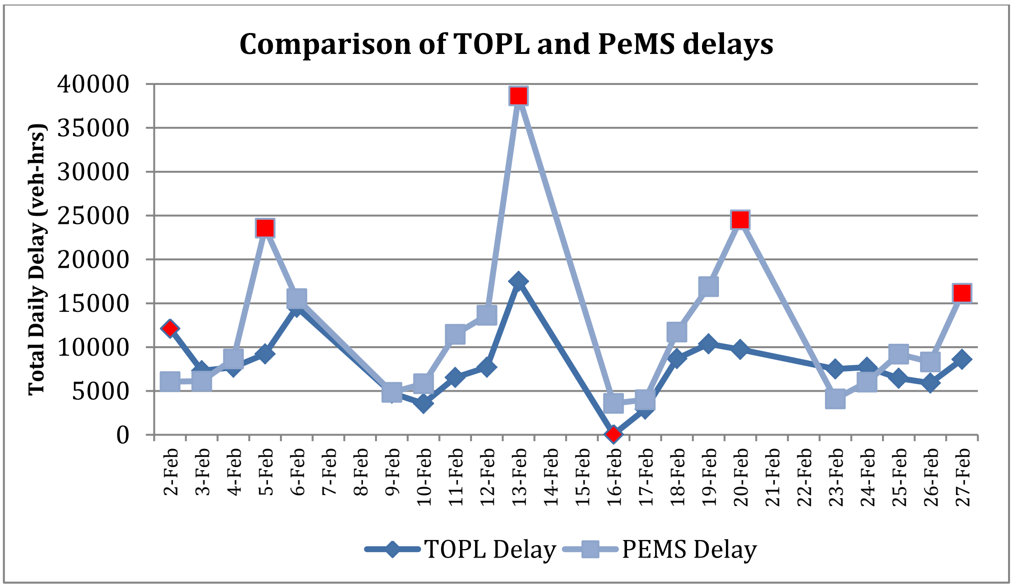
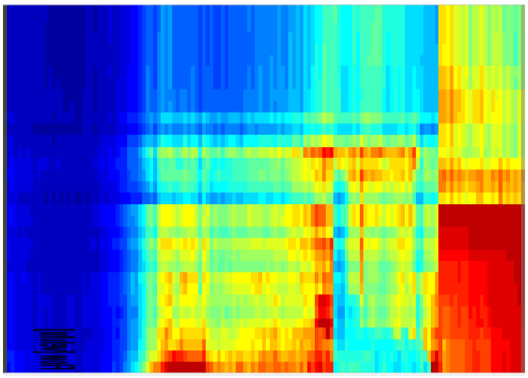
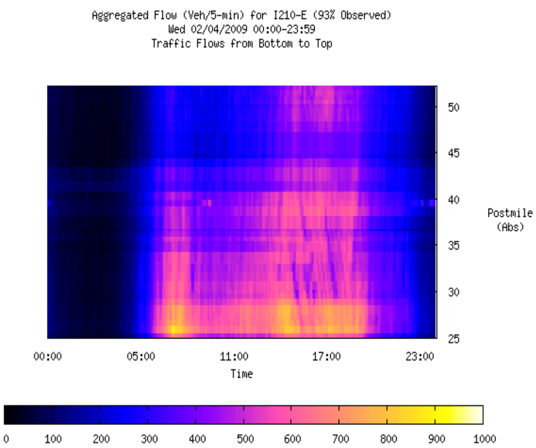


Figure 7: Comparison of delay from TOPL and PeMS



(a) TOPL



(b) PeMS

Figure 8: Comparison of contour plots from (a) TOPL and (b)PeMS

The following sub-sections provide a discussion of the results, grouped together by each day of the week.

2.4.1. Wednesdays

We start our discussion with Wednesdays because they best represent the 'average' weekdays. They are neither the worst nor the best days of the week in terms of congestion. Thus, analyzing the results for Wednesdays should give us a good sense of the effect different control strategies may have on an 'average' day.

Figure 9 shows the impact of the different strategies on the pax-hrs delay in the system for the study corridor and **Table 3**, **Table 4**, **Table 5** and **Table 6** [Section 2.7] provides the details. We see that restricting access to the HOV lane has a positive impact (reduction) on the delay of both the HOV lane and the whole system. While the HOV lane delay is practically eliminated after removing 7% of the vehicles from HOV lane and shifting them to MF lane; the system delay is also minimized by keeping the removed ratio around 7%[4]. While the reduction in HOV lane delay is expected due to reduction in number of vehicles in the lane, the reduction in total system delay can be attributed to the following factors:

- Reduction in person travel time: Since the travel time of an HOV vehicle is valued more (by a factor of ~2.2) due to the higher occupancy requirement, the reduction in delay of HOV lane vehicles has a greater impact on the total system delay when delay is measured in pax-hrs. This reduction is more than the increased delay on the mainline due to increased congestion on those lanes.
- Smoothing effect: As shown by Cassidy and Daganzo in [5], allocation of space to a dedicated carpool lane can increase overall bottleneck discharge by restricting disruptive lane change movements and creating a smoothing effect. Moreover, they showed that this smoothing effect is seen even if the HOV lane is a bit underutilized, which is the case we see in our scenario. In our base case, the HOV volume is high (about 30% vehicles eligible). This high eligibility does not make for a clear separation between the HOV lane and mainline lanes and thus vehicles enter and exit the lane frequently cause disruption in the flow. On the other hand, once the HOV volume is reduced to 20% vehicles, a clear separation is made between HOV lane vehicles and other vehicles. This separation not only reduces delay in the HOV lane, it also increases the net bottleneck

[4] It should be noted that these values are valid only for the segment under study and are specific to its demand patterns. Although, we expect similar results for other segments, actual results may vary due to each segment's specific geometry and demand. Here we present only a methodology to predict the effect.

[5] Cassidy, M.J., Jang, K., and Daganzo, C.F., 2008. The smoothing effect of carpool lanes on freeway bottlenecks. Berkeley, CA: Institute of Transportation Studies, University of California, UCB-ITS-VWP-2008-9.

throughput, thus resulted in a positive impact on the total system delay. Although these observations may seem counterintuitive, in [5] the authors provide a detailed empirical analysis of why and how this happens on freeways.

Also, after 10%, restricting access to more vehicles causes demand on the mainline lanes to be over the capacity of those lanes, causing high impact on them and an increase in total system delay of around 10% with respect to the base case.

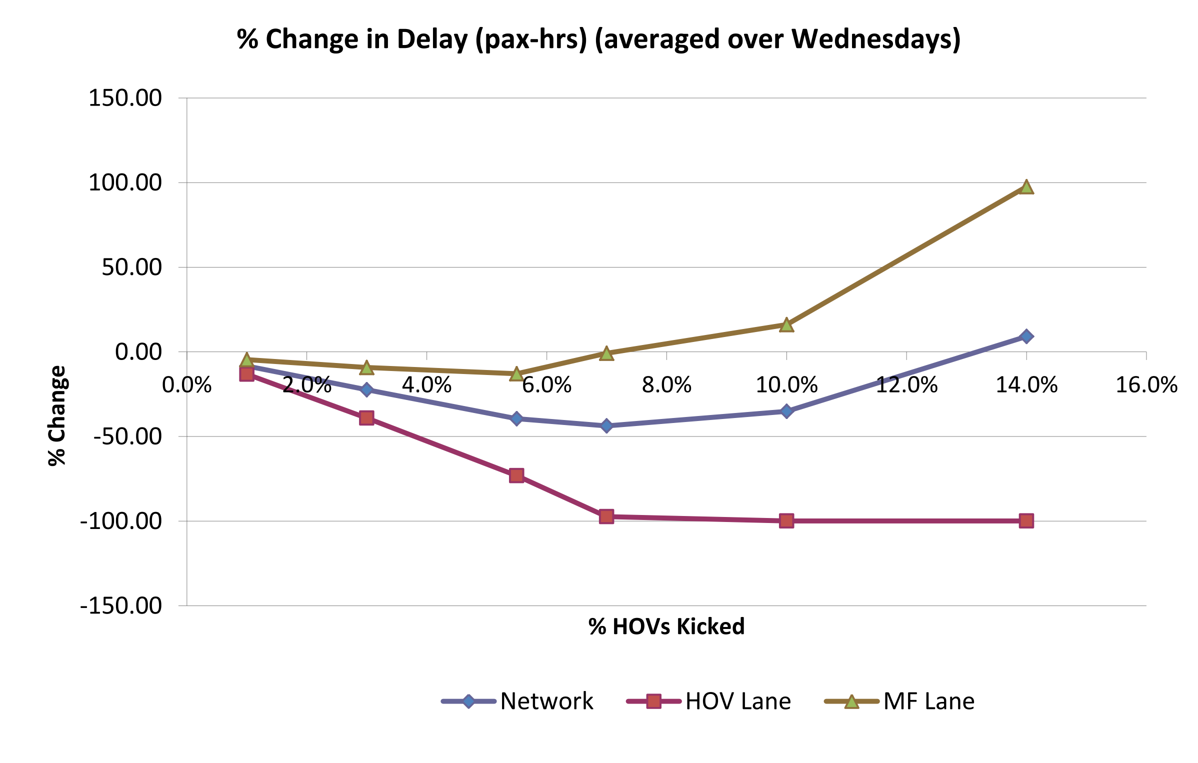


Figure 9: % Change in pax delay (Wednesdays)

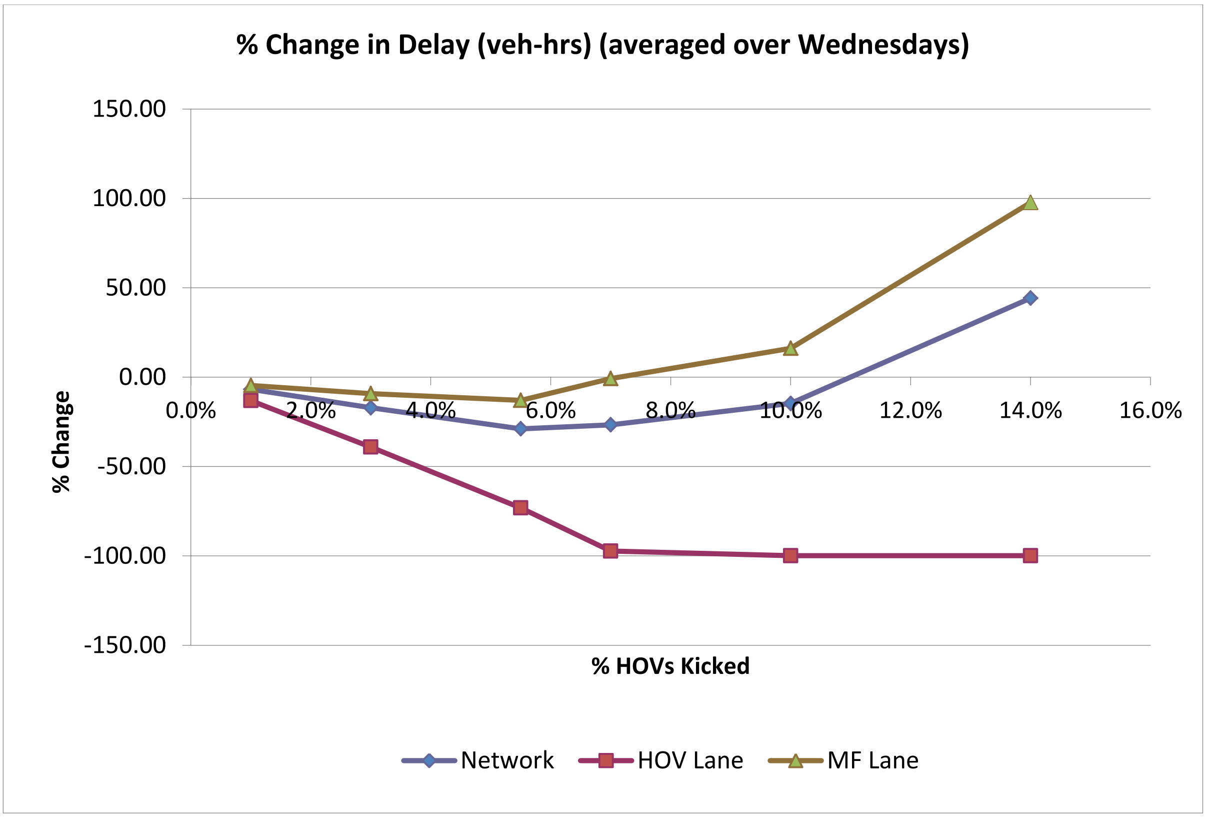


Figure 10: % Change in pax delay (Wednesdays)

Thus, we predict that in our study section, removing just the SOHVs (1% vehicles) would have a modest impact of reducing pax-hrs of delay by 8% while removing 7% vehicles can cut the total delay by more than a third (reduce it by 43%).

2.4.2. Mondays

We proceed with our analysis by discussing simulations for Mondays. As discussed in Figure 7, we remove February 2nd and 16th from our analysis and use only 9th and 23rd February. Figure 11 shows the impact of the strategies on Mondays. The trend is similar to the one seen for Wednesday but we see the following differences:

- For the 1% SOHV removal situation, restricting access to them has negligible impact on the system with overall system delay remaining the same
- System optimal is reached at approximately 5-7% removal ratio as compared to 7-10% for Wednesdays. This difference may be attributed to different demand flows for the two days. Overall demand on Mondays is lower and hence removal of just 5-7% vehicles is enough to create the appropriate full capacity HOV lane conditions.
- At system optimal, delay is 67% less than the current situation (base case).

- There is an abnormal increase in delay for the mixed-flow lane for the case with 3% removal which is against the trend. The abnormality appears consistently in multiple simulation runs.

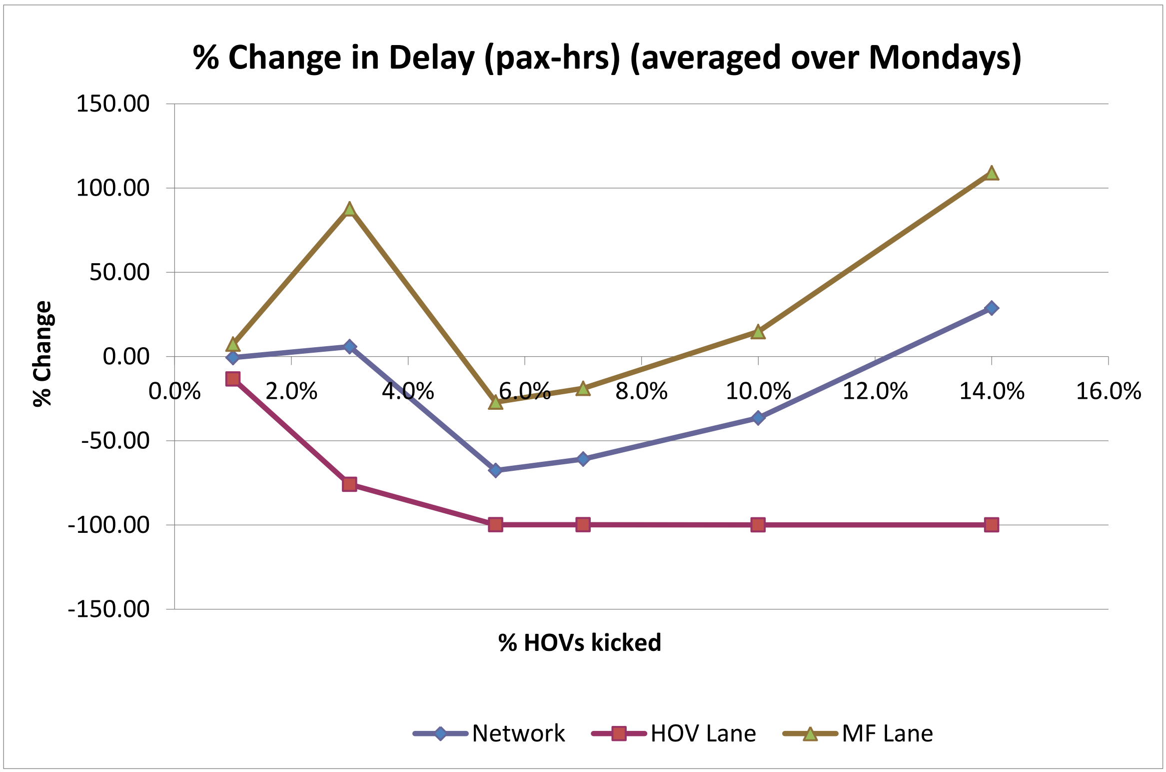


Figure 11: % Change in pax delay (Mondays)

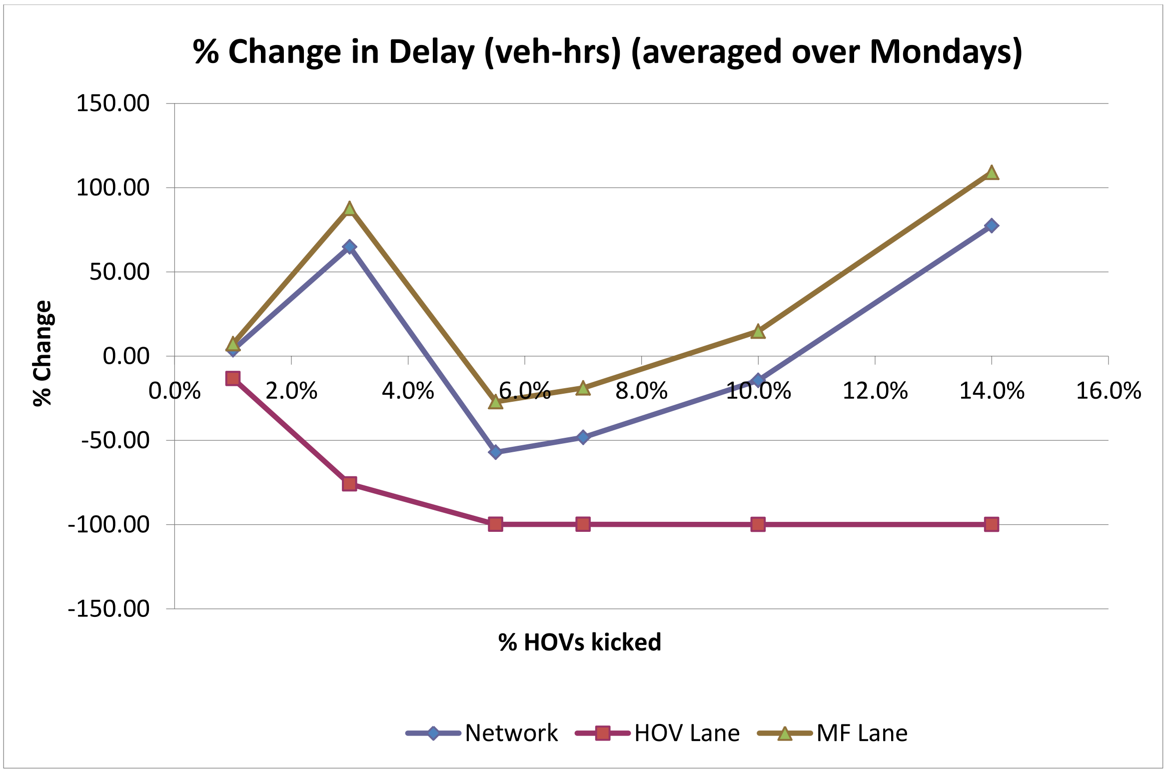


Figure 12: % Change in veh delay (Mondays)

2.4.3. Tuesdays

The impact curve (Figure 13) for Tuesdays follows a similar trend as seen with Wednesdays and Mondays. While removing 1% vehicles reduced system delay by 15%, system optimal is observed around 7% with a reduction in delays of up to 73%.

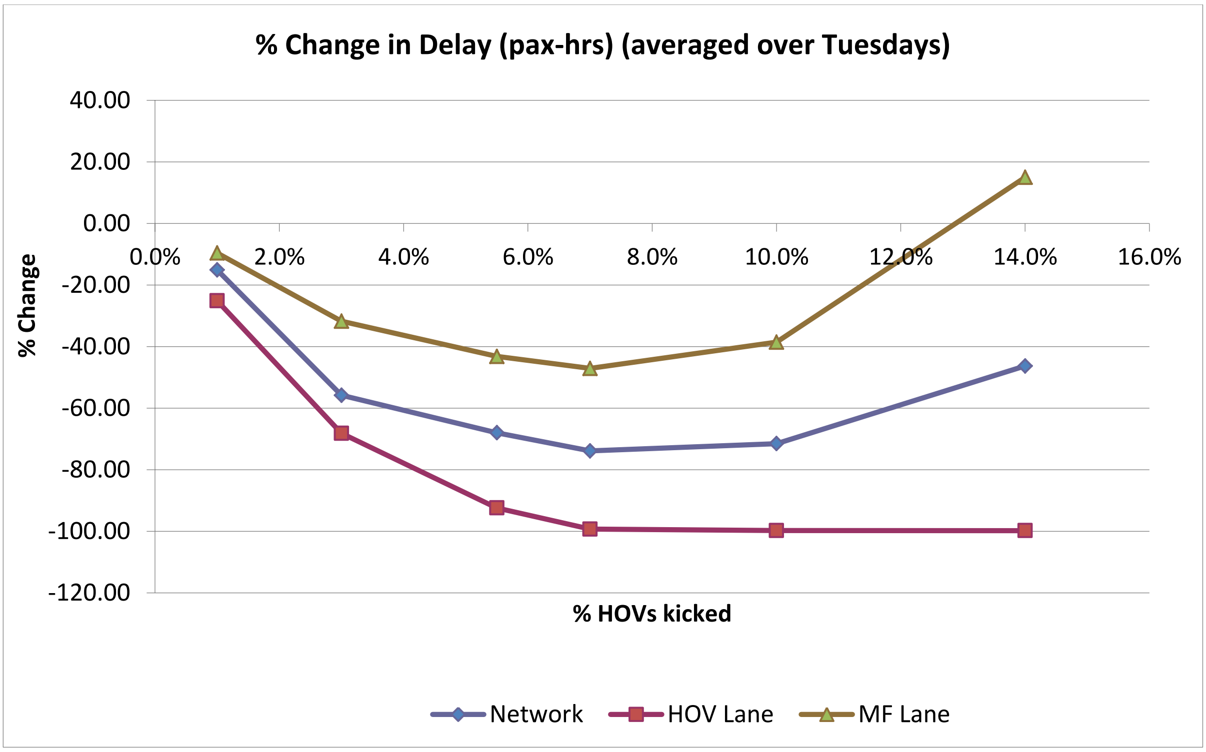


Figure 13: % Change in pax delay (Tuesdays)

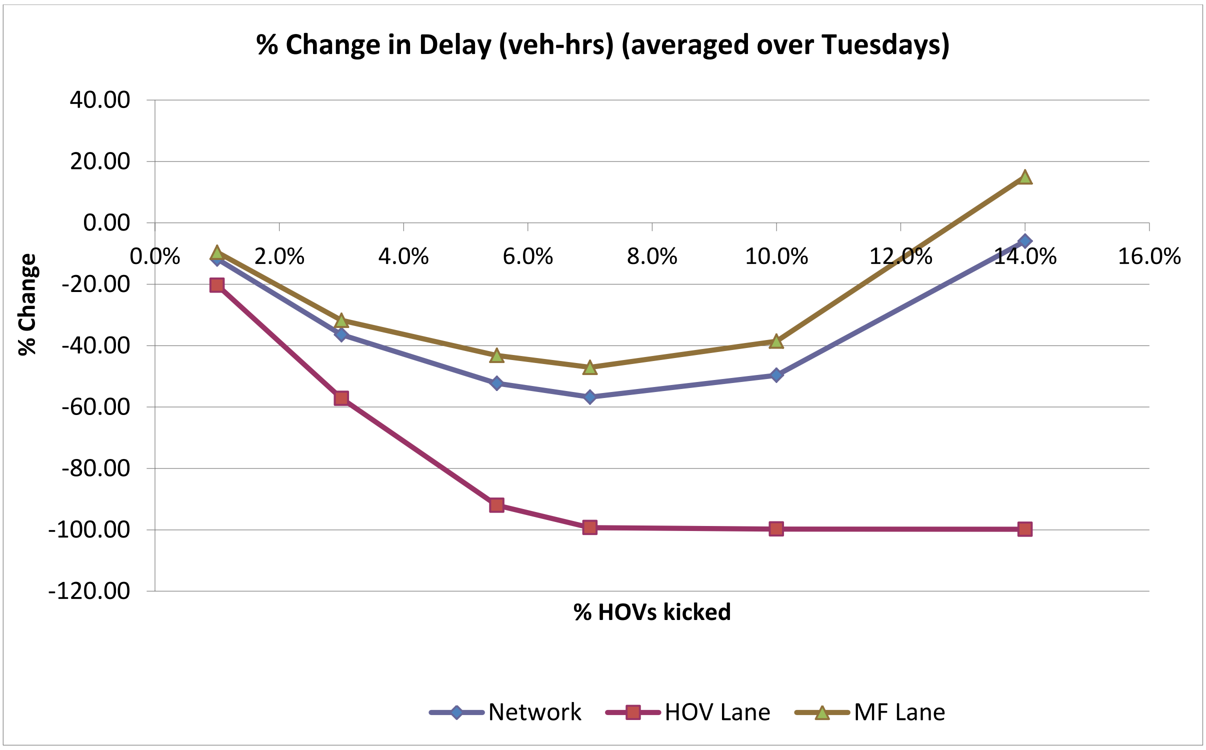


Figure 14: % Change in veh delay (Tuesdays)

2.4.4. Thursdays

From Figure 7, data validation for TOPL versus PeMS matches except for February 5th which was removed from the analysis. Figure 15 shows the impact of the different control strategies for Thursdays. We see a similar curve as with the previous days. Here, 1% removal has a reduction of 9% system delay while system optimal is observed at around 7% with a reduction of 50% system delay.

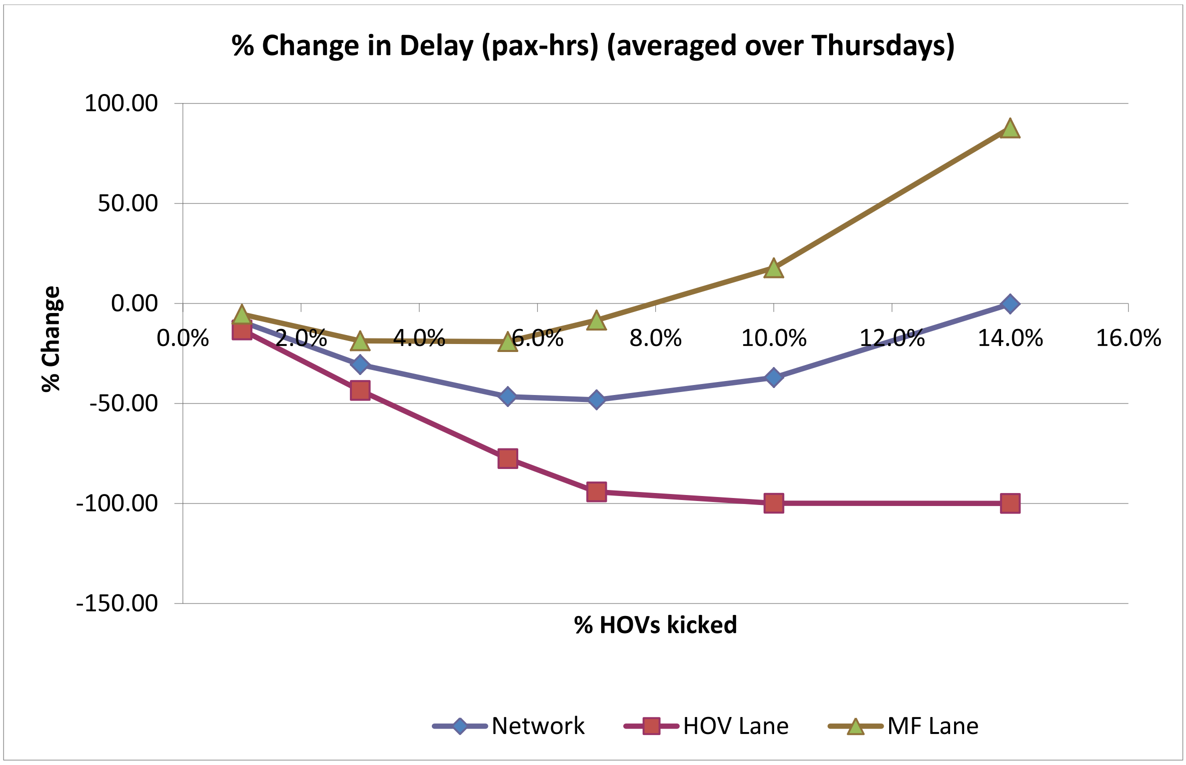


Figure 15: % Change in pax delay (Thursdays)

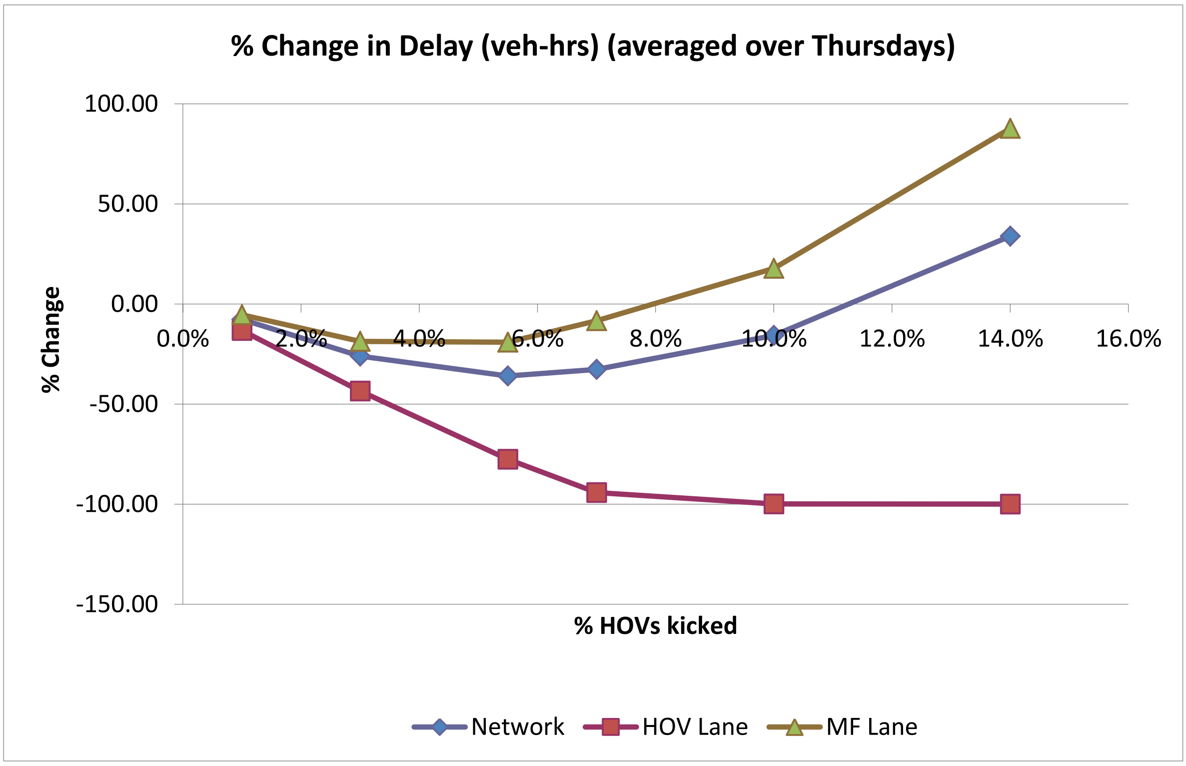


Figure 16: % Change in veh delay (Thursdays)

2.4.5. Fridays

Fridays are the worst days of the week on the corridor with high delays experienced due to demand that is far greater than the other days. Due to such a higher demand pattern, we believe that the impact of removal of vehicles from the HOV lane would have a minimal effect on the system as it is expected to just redistribute the congestion. Some minor gains may be seen due to transfer of delay from HOV to SOV vehicles.

From Figure 7, we see that only February 6th provide matching result between TOPL and PeMS. The reason behind this could be attributed to the fact that other days experience significantly high delays, which are probably non-recurrent delays caused by incidents that are not accounted for in TOPL. The shape of the curve is similar to the curves for the rest of the weekdays.

Figure 17 shows the impact of the control strategies if applied on 6 February. As expected, we see small gains with a removal of 1% providing for 7% reduction in system delay whereas system optimal is seen to be around 7% with reduction of up to 25%.

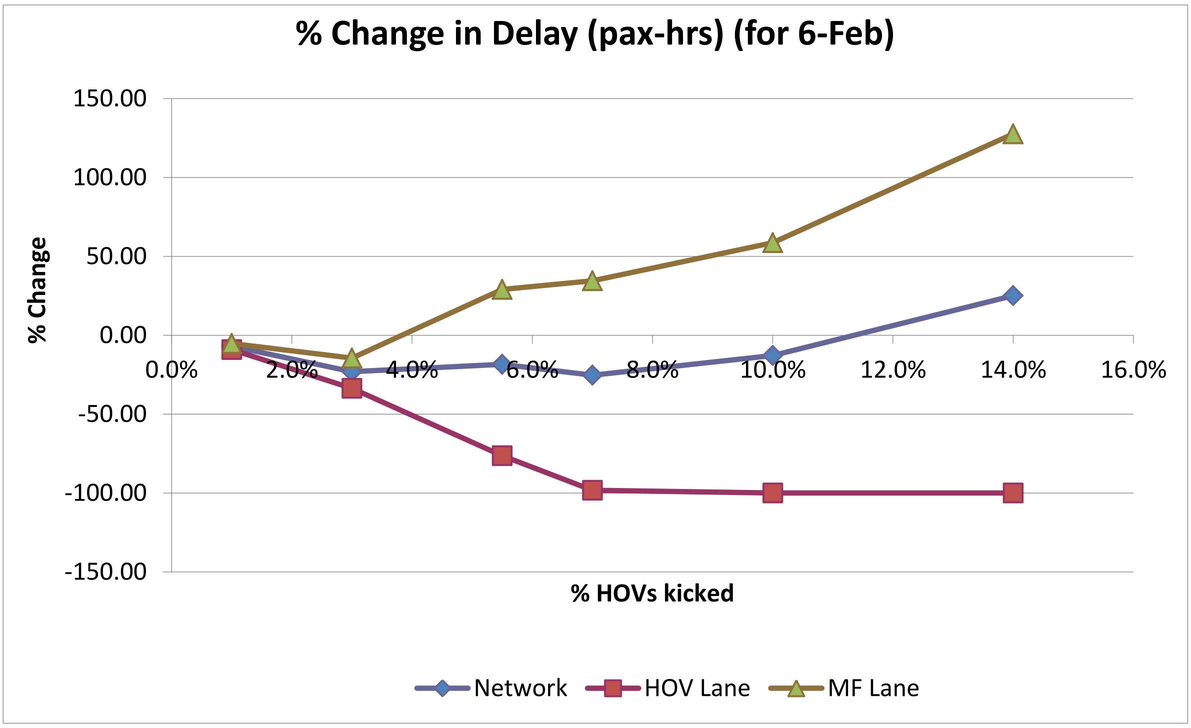


Figure 17: % Change in pax delay (Fridays)

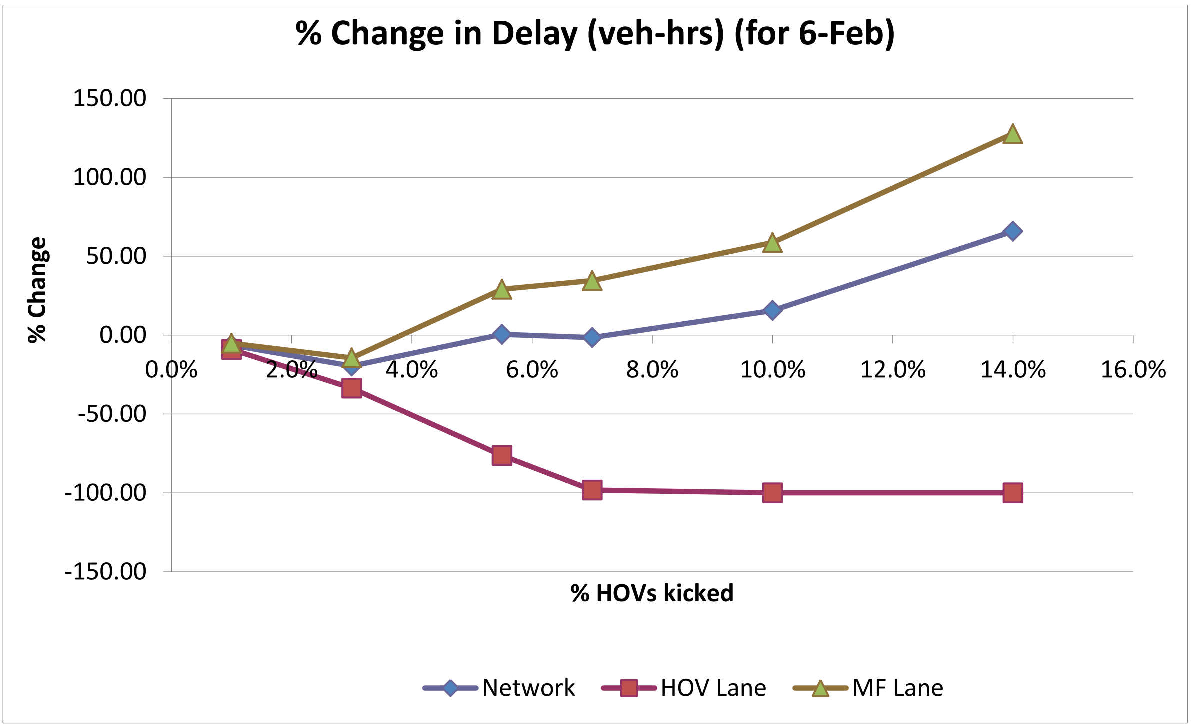


Figure 18: % Change in veh delay (Fridays)

2.5. Discussion and Summary

In Section 2.4, we used simulation studies to predict the impact of the different control strategies on the system delay (measured in pax-hrs). We saw that the 'impact curve' follows a specific pattern for our study corridor, with initial reduction in delays for small values of removal ratios and then an increase in delay for values greater than 10%. The predicted impact of removing SOHV vehicles from the HOV lane varied from 9-25% reduction in HOV delays and 0-15% reductions in system delays. Also, we saw that the optimal removal ratio would be between 5-7% and varied by the day and the type of traffic that is observed. It should be noted that this specific number (of optimal removal ratio) is dependent on the specific freeway geometry (4 MF lanes and 1 HOV lane) and demand and may not be the same for another facility.

Table 2: Summary of key observations

	Monday	Tuesday	Wednesday	Thursday	Friday
% change in network delay with 1% removal	-0.6%	-15%	-8%	-9%	-7%
Optimal removal ratio	5.5%	7%	7%	7%	7%
% change in network delay with optimal ratio	-67%	-73%	-43%	-48%	-25%

In **Table 2**, we see that the nature and scale of impact varies by each day. Annual traffic data reveals that Mondays and Tuesdays are days with low demand, Fridays are days with high demand while Wednesdays and Thursdays experience moderate demand (**Figure 19**). From the simulations, we observe that on low demand days, we can reduce delays by up to 73% while on high demand days, we can only have an impact of 25%. This is probably because during high demand, the numbers of vehicles on the road are just too high to see any smoothing effect.

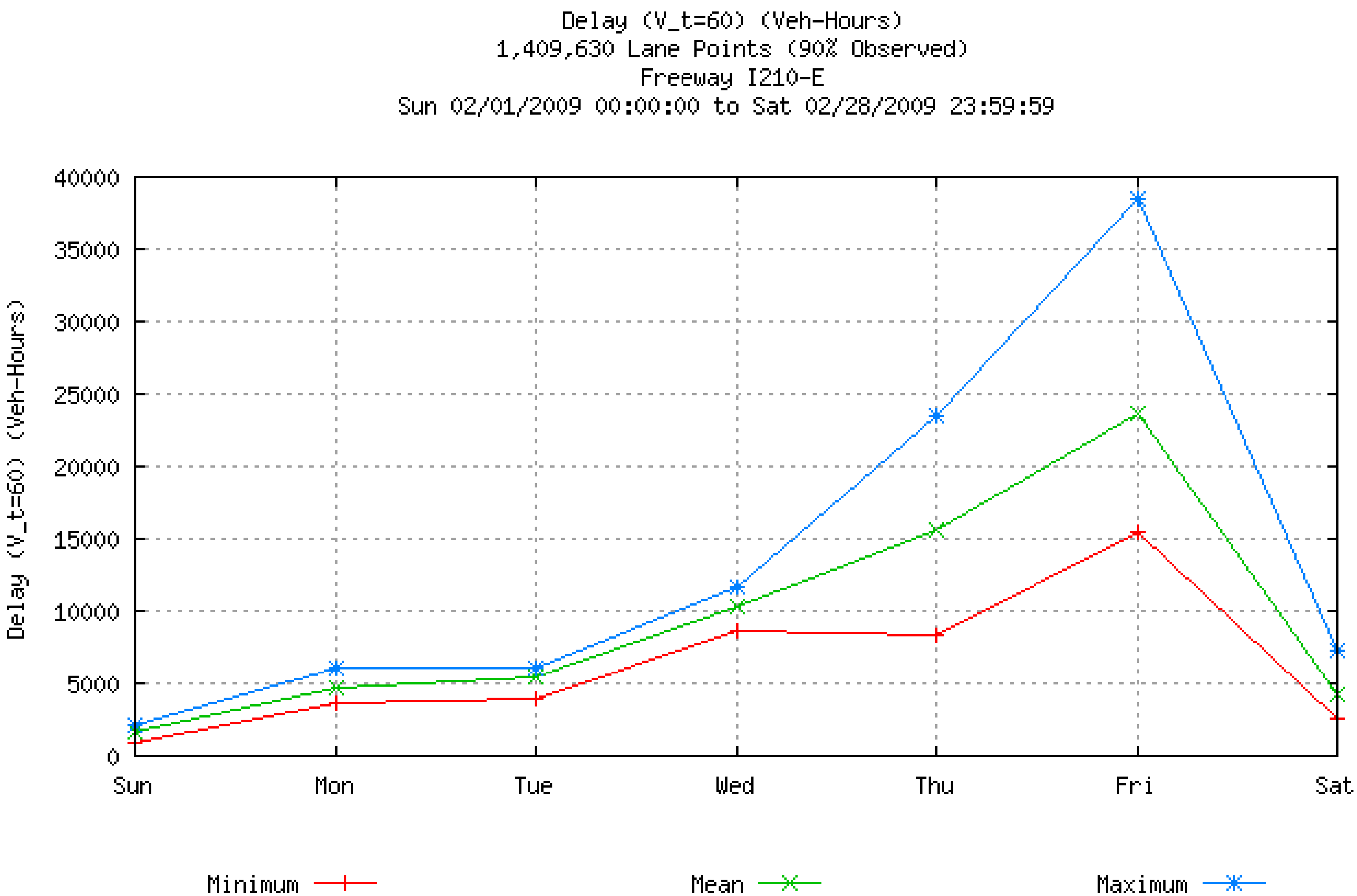


Figure 19: Daily variation in delay (from PeMS)

2.6. Application of Methodology to Other Managed Lanes

In the previous discussion, we presented a methodology that uses simulation studies to predict the impact of restricting the access to HOV lane. Although we started our discussion with focus on impact of SOHVs on the HOV lane, we showed that this methodology could be used for other managed lanes also. As an example, we used a scenario of allowing access to only 20% of the whole demand flow. This scenario represents the case when we raise the occupancy requirements from '2 or more persons' to '3 or more persons'. Since our simulations take the traffic split percentages as an input, other scenarios could be tested just as easily.

One example of such a scenario could be an HOT lane. Using our methodology, agencies could predict the impact of using the HOT lanes as a congestion mitigation tool. In that case, in addition to the HOVs (say with '3 or more persons'), toll-paying customers would be allowed. Our methodology could help the agencies to determine the optimal toll for which the facility operates at the optimal HOT-ML demand ratios.

2.7. Delay Statistics

2.7.1. Delay Tables – Wednesdays

Table 3: Delay statistics for Feb 4

	HOV lane delay		% change in HOV lane delay (w.r.t. base case)		MF lane Delay		% change in MF lane delay (w.r.t. base case)		Network Delay		% change in Network delay (w.r.t. base case)	
	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs
Base Case (71% on ML, 29% on HOV lane)	4184.4	1902	0	0	1450	1450	0	0	9984.4	7702	0	0
1% Removed	3610.2	1641	-13.72	-13.72	1405	1405	-3.10	-3.10	9230.2	7261	-7.55	-5.73
3% Removed	2503.6	1138	-40.17	-40.17	1326	1326	-8.55	-8.55	7807.6	6442	-21.8	-16.36
5.5% Removed	728.2	331	-82.6	-82.6	1489	1489	2.69	2.69	6684.2	6287	-33.05	-18.37
7% Removed	55	25	-98.69	-98.69	1418	1418	-2.21	-2.21	5727	5697	-42.64	-26.03
10% Removed	4.4	2	-99.89	-99.89	1817	1817	25.31	25.31	7272.4	7270	-27.16	-5.61
14% Removed	4.4	2	-99.89	-99.89	2857	2857	97.03	97.03	11432.4	11430	14.5	48.4

Table 4: Delay statistics for Feb 11

	HOV lane delay		% change in HOV lane delay (w.r.t. base case)		MF lane Delay		% change in MF lane delay (w.r.t. base case)		Network Delay		% change in Network delay (w.r.t. base case)	
	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs
Base Case (71% on ML, 29% on HOV lane)	3113	1415	0	0	1282	1282	0	0	8241	6543	0	0
1% Removed	2615.8	1189	-15.97	-15.97	1202	1202	-6.24	-6.24	7423.8	5997	-9.92	-8.34
3% Removed	1839.2	836	-40.92	-40.91	1139	1139	-11.15	-11.15	6395.2	5392	-22.4	-17.59
5.5% Removed	862.4	392	-72.3	-72.29	910	910	-29.02	-29.02	4502.4	4032	-45.37	-38.37
7% Removed	30.8	14	-99.01	-99.01	1065	1065	-16.93	-16.93	4290.8	4274	-47.93	-34.67
10% Removed	4.4	2	-99.86	-99.85	1382	1382	7.8	7.8	5532.4	5530	-32.87	-15.48
14% Removed	4.4	2	-99.86	-99.85	1940	1940	51.33	51.33	7764.4	7762	-5.78	18.63

Table 5: Delay statistics for Feb 18

	HOV lane delay		% change in HOV lane delay (w.r.t. base case)		MF lane Delay		% change in MF lane delay (w.r.t. base case)		Network Delay		% change in Network delay (w.r.t. base case)	
	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs
Base Case (71% on ML, 29% on HOV lane)	5638.6	2563	0	0	1535	1535	0	0	11778.6	8703	0	0
1% Removed	5062.2	2301	-10.22	-10.22	1421	1421	-7.43	-7.43	10746.2	7985	-8.77	-8.25
3% Removed	3726.8	1694	-33.91	-33.91	1525	1525	-0.65	-0.65	9826.8	7794	-16.57	-10.44
5.5% Removed	1762.2	801	-68.75	-68.75	1700	1700	10.75	10.75	8562.2	7601	-27.31	-12.66
7% Removed	92.4	42	-98.36	-98.36	2081	2081	35.57	35.57	8416.4	8366	-28.54	-3.87
10% Removed	4.4	2	-99.92	-99.92	1954	1954	27.30	27.30	7820.4	7818	-33.61	-10.17
14% Removed	4.4	2	-99.92	-99.92	3442	3442	124.23	124.23	13772.4	13770	16.93	58.22

Table 6: Delay statistics for Feb 25

	HOV lane delay		% change in HOV lane delay (w.r.t. base case)		MF lane Delay		% change in MF lane delay (w.r.t. base case)		Network Delay		% change in Network delay (w.r.t. base case)	
	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs
Base Case (71% on ML, 29% on HOV lane)	4336.2	1971	0	0	1121	1121	0	0	8820.2	6455	0	0
1% Removed	3786.2	1721	-12.68	-12.68	1102	1102	-1.69	-1.69	8194.2	6129	-7.1	-5.05
3% Removed	2538.8	1154	-41.45	-41.45	937	937	-16.41	-16.41	6286.8	4902	-28.72	-24.06
5.5% Removed	1342	610	-69.05	-69.05	715	715	-36.22	-36.22	4202	3470	-52.36	-46.24
7% Removed	297	135	-93.15	-93.15	901	901	-19.63	-19.63	3901	3739	-55.77	-42.08
10% Removed	6.6	3	-99.85	-99.85	1168	1168	4.19	4.19	4678.6	4675	-46.96	-27.58
14% Removed	4.4	2	-99.9	-99.9	2444	2444	118.02	118.02	9780.4	9778	10.89	51.48

2.7.2. Delay Tables – Mondays

Table 7: Delay statistics for Feb 9

	HOV lane delay		% change in HOV lane delay (w.r.t. base case)		MF lane Delay		% change in MF lane delay (w.r.t. base case)		Network Delay		% change in Network delay (w.r.t. base case)	
	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs
Base Case (71% on ML, 29% on HOV lane)	4052.4	1842	0	0	727	727	0	0	6960.4	4750	0	0
1% Removed	3575	1625	-11.78	-11.78	771	771	6.05	6.05	6659	4709	-4.33	-0.86
3% Removed	1172.6	533	-71.06	-71.06	1810	1810	148.97	148.97	8412.6	7773	20.86	63.64
5.5% Removed	11	5	-99.73	-99.72	203	203	-72.08	-72.08	823	817	-88.18	-82.8
7% Removed	4.4	2	-99.89	-99.89	233	233	-67.95	-67.95	936.4	934	-86.55	-80.34
10% Removed	2.2	1	-99.95	-99.94	671	671	-7.70	-7.70	2686.2	2685	-61.41	-43.47
14% Removed	2.2	1	-99.95	-99.94	2184	2184	200.41	200.41	8738.2	8737	25.54	83.94

Table 8: Delay statistics for Feb 16

	HOV lane delay		% change in HOV lane delay (w.r.t. base case)		MF lane Delay		% change in MF lane delay (w.r.t. base case)		Network Delay		% change in Network delay (w.r.t. base case)	
	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs
Base Case (71% on ML, 29% on HOV lane)	66	30	0	0	7	7	0	0	94	58	0	0
1% Removed	22	10	-66.67	-66.67	7	7	0.00	0.00	50	38	-46.81	-34.48
3% Removed	4.4	2	-93.33	-93.33	7	7	0.00	0.00	32.4	30	-65.53	-48.27
5.5% Removed	4.4	2	-93.33	-93.33	7	7	0.00	0.00	32.4	30	-65.53	-48.27
7% Removed	4.4	2	-93.33	-93.33	7	7	0.00	0.00	32.4	30	-65.53	-48.27
10% Removed	2.2	1	-96.67	-96.67	7	7	0.00	0.00	30.2	29	-67.87	-50
14% Removed	2.2	1	-96.67	-96.67	7	7	0.00	0.00	30.2	29	-67.87	-50

Table 9: Delay statistics for Feb 23

	HOV lane delay		% change in HOV lane delay (w.r.t. base case)		MF lane Delay		% change in MF lane delay (w.r.t. base case)		Network Delay		% change in Network delay (w.r.t. base case)	
	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs
Base Case (71% on ML, 29% on HOV lane)	4070	1850	0	0	1414	1414	0	0	9726	7506	0	0
1% Removed	3465	1575	-14.86	-14.86	1641	1641	16.05	16.05	10029	8139	3.12	8.43
3% Removed	781	355	-80.81	-80.81	3028	3028	114.14	114.14	12893	12467	32.56	66.09
5.5% Removed	4.4	2	-99.89	-99.89	1287	1287	-8.98	-8.98	5152.4	5150	-47.02	-31.38
7% Removed	4.4	2	-99.89	-99.89	1574	1574	11.32	11.32	6300.4	6298	-35.22	-16.09
10% Removed	2.2	1	-99.95	-99.94	2150	2150	52.05	52.05	8602.2	8601	-11.55	14.58
14% Removed	2.2	1	-99.95	-99.94	3207	3207	126.80	126.80	12830.2	12829	31.92	70.91

2.7.3. Delay Tables – Tuesdays

Table 10: Delay statistics for Feb 3

	HOV lane delay		% change in HOV lane delay (w.r.t. base case)		MF lane Delay		% change in MF lane delay (w.r.t. base case)		Network Delay		% change in Network delay (w.r.t. base case)	
	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs
Base Case (71% on ML, 29% on HOV lane)	3355	1525	0	0	1445	1445	0	0	9135	7305	0	0
1% Removed	2851.2	1296	-15.02	-15.02	1351	1351	-6.51	-6.51	8255.2	6700	-9.63	-8.28
3% Removed	1993.2	906	-40.59	-40.59	1246	1246	-13.77	-13.77	6977.2	5890	-23.62	-19.37
5.5% Removed	946	430	-71.8	-71.8	1426	1426	-1.31	-1.31	6650	6134	-27.2	-16.03
7% Removed	68.2	31	-97.97	-97.97	1154	1154	-20.14	-20.14	4684.2	4647	-48.72	-36.39
10% Removed	4.4	2	-99.87	-99.87	842	842	-41.73	-41.73	3372.4	3370	-63.08	-53.87
14% Removed	4.4	2	-99.87	-99.87	1822	1822	26.09	26.09	7292.4	7290	-20.17	-0.21

Table 11: Delay statistics for Feb 10

	HOV lane delay		% change in HOV lane delay (w.r.t. base case)		MF lane Delay		% change in MF lane delay (w.r.t. base case)		Network Delay		% change in Network delay (w.r.t. base case)	
	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs
Base Case (71% on ML, 29% on HOV lane)	1157.2	526	0	0	762	762	0	0	4205.2	3574	0	0
1% Removed	1003.2	456	-13.31	-32.47	698	698	-8.40	-8.40	3795.2	3248	-9.75	-9.12
3% Removed	675.4	307	-41.63	-85.62	690	690	-9.45	-9.45	3435.4	3067	-18.31	-14.19
5.5% Removed	28.6	13	-97.53	-99.19	483	483	-36.61	-36.61	1960.6	1945	-53.38	-45.58
7% Removed	4.4	2	-99.62	-99.68	523	523	-31.36	-31.36	2096.4	2094	-50.15	-41.41
10% Removed	4.4	2	-99.62	-99.68	704	704	-7.61	-7.61	2820.4	2818	-32.93	-21.15
14% Removed	2.2	1	-99.81	-99.68	1273	1273	67.06	67.06	5094.2	5093	21.14	42.5

Table 12: Delay statistics for Feb 17

	HOV lane delay		% change in HOV lane delay (w.r.t. base case)		MF lane Delay		% change in MF lane delay (w.r.t. base case)		Network Delay		% change in Network delay (w.r.t. base case)	
	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs
Base Case (71% on ML, 29% on HOV lane)	1361.8	619	0	0	577	577	0	0	3669.8	2927	0	0
1% Removed	919.6	418	-32.47	-32.47	537	537	-6.93	-6.93	3067.6	2566	-16.41	-12.33
3% Removed	195.8	89	-85.62	-85.62	126	126	-78.16	-78.16	699.8	593	-80.93	-79.74
5.5% Removed	11	5	-99.19	-99.19	113	113	-80.42	-80.42	463	457	-87.38	-84.39
7% Removed	4.4	2	-99.68	-99.68	110	110	-80.94	-80.94	444.4	442	-87.89	-84.9
10% Removed	4.4	2	-99.68	-99.68	138	138	-76.08	-76.08	556.4	554	-84.84	-81.07
14% Removed	4.4	2	-99.68	-99.68	244	244	-57.71	-57.71	980.4	978	-73.28	-66.59

Table 13: Delay statistics for Feb 24

	HOV lane delay		% change in HOV lane delay (w.r.t. base case)		MF lane Delay		% change in MF lane delay (w.r.t. base case)		Network Delay		% change in Network delay (w.r.t. base case)	
	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs
Base Case (71% on ML, 29% on HOV lane)	3278	1490	0	0	1554	1554	0	0	9494	7706	0	0
1% Removed	2604.8	1184	-20.54	-20.54	1297	1297	-16.54	-16.54	7792.8	6372	-17.92	-17.31
3% Removed	1282.6	583	-60.87	-60.87	1156	1156	-25.61	-25.61	5906.6	5207	-37.79	-32.43
5.5% Removed	17.6	8	-99.46	-99.46	708	708	-54.44	-54.44	2849.6	2840	-69.99	-63.15
7% Removed	4.4	2	-99.87	-99.87	686	686	-55.86	-55.86	2748.4	2746	-71.05	-64.37
10% Removed	4.4	2	-99.87	-99.87	1107	1107	-28.76	-28.76	4432.4	4430	-53.31	-42.51
14% Removed	2.2	1	-99.93	-99.93	1934	1934	24.45	24.45	7738.2	7737	-18.49	0.4

2.7.4. Delay Tables – Thursdays

Table 14: Delay statistics for Feb 12

	HOV lane delay		% change in HOV lane delay (w.r.t. base case)		MF lane Delay		% change in MF lane delay (w.r.t. base case)		Network Delay		% change in Network delay (w.r.t. base case)	
	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs
Base Case (71% on ML, 29% on HOV lane)	4994	2270	0	0	1358	1358	0	0	10426	7702	0	0
1% Removed	4389	1995	-12.11	-12.11	1310	1310	-3.53	-3.53	9629	7235	-7.64	-6.06
3% Removed	3172.4	1442	-36.48	-36.48	1050	1050	-22.68	-22.68	7372.4	5642	-29.29	-26.75
5.5% Removed	1449.8	659	-70.97	-70.97	908	908	-33.14	-33.14	5081.8	4291	-51.26	-44.29
7% Removed	19.8	9	-99.6	-99.6	1133	1133	-16.57	-16.57	4551.8	4541	-56.34	-41.04
10% Removed	4.4	2	-99.91	-99.91	1575	1575	15.98	15.98	6304.4	6302	-39.53	-18.18
14% Removed	2.2	1	-99.96	-99.96	2378	2378	75.11	75.11	9514.2	9513	-8.75	23.51

Table 15: Delay statistics for Feb 19

	HOV lane delay		% change in HOV lane delay (w.r.t. base case)		MF lane Delay		% change in MF lane delay (w.r.t. base case)		Network Delay		% change in Network delay (w.r.t. base case)	
	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs
Base Case (71% on ML, 29% on HOV lane)	5713.4	2597	0	0	1943	1943	0	0	13485.4	10369	0	0
1% Removed	5170	2350	-9.51	-9.51	1878	1878	-3.35	-3.35	12682	9862	-5.96	-4.89
3% Removed	4006.2	1821	-29.88	-29.88	1769	1769	-8.96	-8.96	11082.2	8897	-17.82	-14.2
5.5% Removed	2147.2	976	-62.42	-62.42	1993	1993	2.57	2.57	10119.2	8948	-24.96	-13.7
7% Removed	968	440	-83.06	-83.06	2385	2385	22.75	22.75	10508	9980	-22.08	-3.75
10% Removed	6.6	3	-99.88	-99.88	2676	2676	37.73	37.73	10710.6	10707	-20.58	3.26
14% Removed	4.4	2	-99.92	-99.92	3984	3984	105.04	105.04	15940.4	15938	18.2	53.71

Table 16: Delay statistics for Feb 26

	HOV lane delay		% change in HOV lane delay (w.r.t. base case)		MF lane Delay		% change in MF lane delay (w.r.t. base case)		Network Delay		% change in Network delay (w.r.t. base case)	
	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs
Base Case (71% on ML, 29% on HOV lane)	4164.6	1893	0	0	1002	1002	0	0	8172.6	5901	0	0
1% Removed	3410	1550	-18.12	-12.12	909	909	-9.28	-9.28	7046	5186	-13.79	-12.12
3% Removed	1498.2	681	-64.03	-37.08	758	758	-24.35	-24.35	4530.2	3713	-44.57	-37.08
5.5% Removed	33	15	-99.21	-49.99	734	734	-26.75	-26.75	2969	2951	-63.67	-49.99
7% Removed	4.4	2	-99.89	-53.33	688	688	-31.34	-31.34	2756.4	2754	-66.27	-53.33
10% Removed	4.4	2	-99.89	-32.25	999	999	-0.30	-0.30	4000.4	3998	-51.05	-32.25
14% Removed	2.2	1	-99.95	24.33	1834	1834	83.03	83.03	7338.2	7337	-10.21	24.33

Delay Tables – Fridays

Table 17: Delay statistics for Feb 6

	HOV lane delay		% change in HOV lane delay (w.r.t. base case)		MF lane Delay		% change in MF lane delay (w.r.t. base case)		Network Delay		% change in Network delay (w.r.t. base case)	
	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs	pax-hrs	Veh-hrs
Base Case (71% on ML, 29% on HOV lane)	8701	3955	0	0	2650	2650	0	0	19301	14555	0	0
1% Removed	7906.8	3594	-9.13	-9.13	2510	2510	-5.28	-5.28	17946.8	13634	-7.02	-6.33
3% Removed	5768.4	2622	-33.7	-33.7	2266	2266	-14.49	-14.49	14832.4	11686	-23.15	-19.71
5.5% Removed	2057	935	-76.36	-76.36	3419	3419	29.02	29.02	15733	14611	-18.49	0.38
7% Removed	147.4	67	-98.31	-98.31	3563	3563	34.45	34.45	14399.4	14319	-25.4	-1.62
10% Removed	4.4	2	-99.95	-99.95	4204	4204	58.64	58.64	16820.4	16818	-12.85	15.55
14% Removed	4.4	2	-99.95	-99.95	6032	6032	127.62	127.62	24132.4	24130	25.03	65.78

3. HOV Lane Management System Design

To meet the legal requirements for HOV lane use by SOHV, California requires a process for:

a) determining if an HOV facility has suffered performance degradation

b) restricting SOHV from using HOV lanes during periods of degraded performance

The proposed solution is a system which uses variable message signs (VMS) to notify eligible SOHVs when they can and cannot use an HOV facility. SOHV access permission for a freeway segment would be determined according to an algorithm which gathers information, such as live sensor data and historical traffic data, and applies logic. The access status would form part of a message which is subsequently displayed on a VMS. This is an example of a dynamic lane management system.

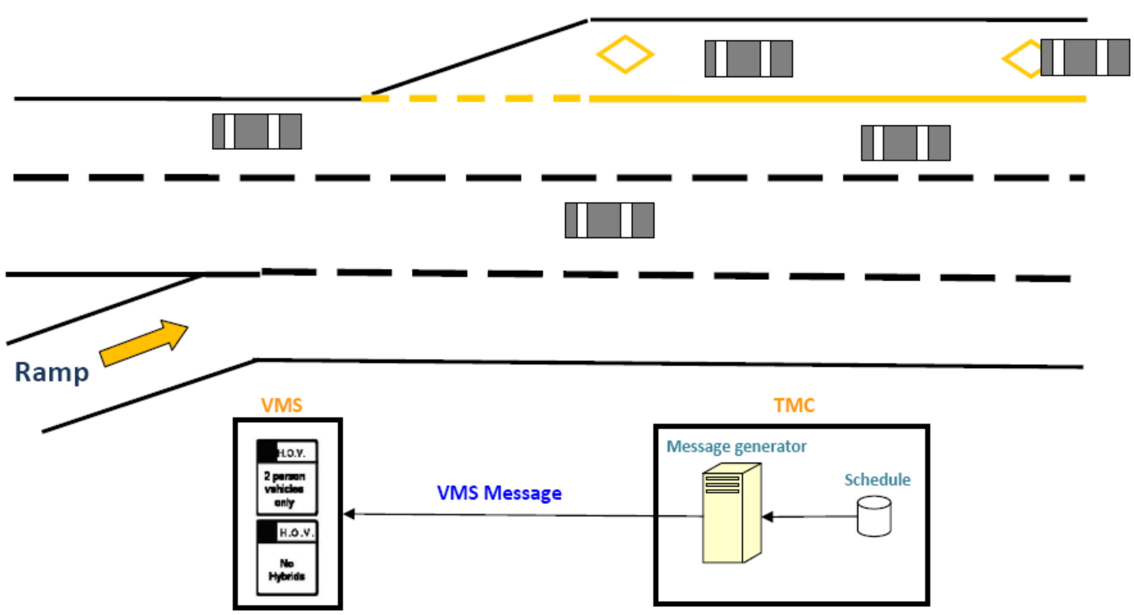


Figure 20: HOV lane control using VMS.

At the highest level, the Dynamic HOV Lane Management System (DHLMS) endeavors to meet the following objectives:

- Deliver clear, concise HOV facility access information to drivers in a safe, timely and effective manner.
- Determine SOHV access status using different sources of available information.
- Be flexible to allow for various VMS types/configurations and different HOV policies.
- Permit operators to monitor the output in real time and change parameters manually.

The use of VMS has proven to be an effective means of delivering information to motorists. One example is the MITTENS project, which displays estimated freeway and CalTrain travel times to users. In 2004, CCIT (now merged with PATH) deployed changeable message signs to freeways in Caltrans District 4 that displayed travel times.

Like the proposed solution for HOV lane management, MITTENS also employs an algorithm which determines travel time by using available information and internal logic. The design described in this document is based on the MITTENS architecture.

Figure 21: MITTENS

At this early stage of this project, many aspects of the system remain abstract. The design described in this document is intended to be flexible and applicable to a variety of use cases which may be defined later. For example, there are different methods for determining whether a freeway has degraded performance and SOHV should be barred from the HOV lanes (these methods are described later). A simple approach would be to prohibit during the same hours every day, while a more complex model would use real time loop sensor data (if available) and historical average speeds to determine access.

The system design permits different algorithms to be used at different times and locations, just as it employs a message generation process that can be applied to different types of VMS and configurations. Furthermore, the data model for the system allows for operators to control its parameters and monitor the system through an interface.

3.1. Scope

The system described in this document is designed to meet the goals described above and is made up of several components. All of them are described in this document, but not all of them fall within the purview of the design submitted by PATH. The exact delineation of internal and external responsibilities is covered later in this document, but, in general, the goal is to define a system which uses existing infrastructure and devices and adds a data processing component.

For example, while loop sensors and VMS are important system components, developing a speed measurement system and designing electronic message signs are not part of this project. The components of interest from a design perspective are the data model and algorithms which use an existing speed data feed or historical database to determine SOHV access and display that information on Variable Message Signs which can be installed on the roadway.

The design considerations presented vary in specificity. In the case of the data model, it is fairly rigorous, with entities and relationships defined explicitly. In contrast, the Graphical User Interface is described in general terms: desired features and user capabilities are explored, but their implementation is left as a future work.

Overall, this system design seeks to establish high level view of the entire system needed to control SOHV access to HOV facilities, defining the overall architecture and data structures while leaving some aspects to be defined when the system design is actually implemented.

3.2. System Overview

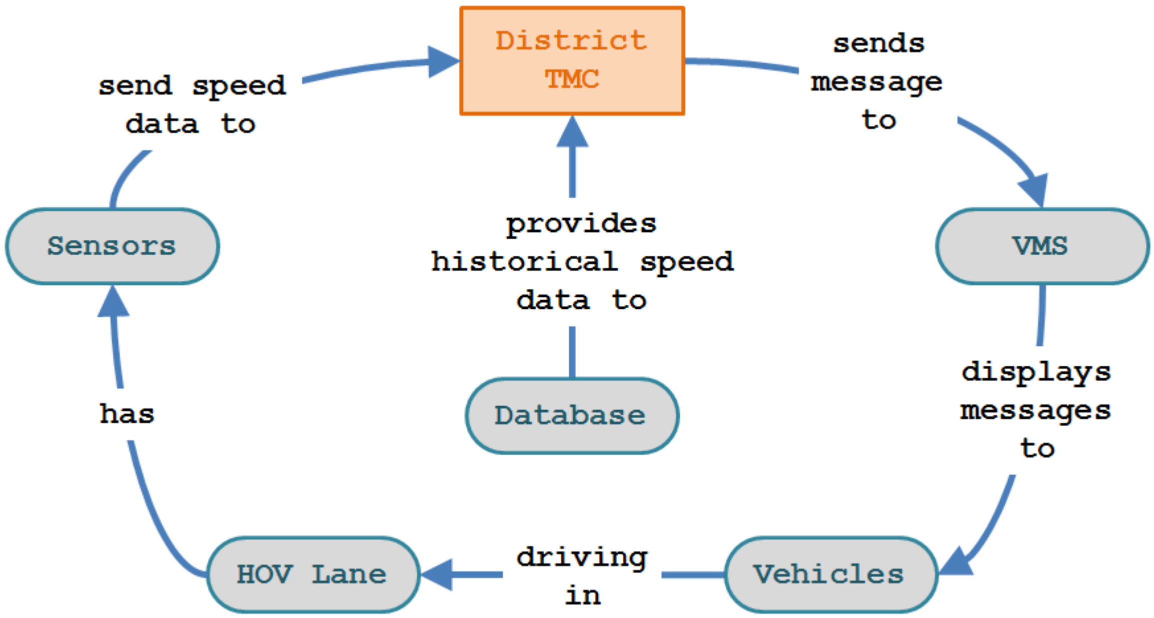


Figure 22: Operational concept

The diagram above shows the basic operational concept of the DHLMS. The Traffic Management center (TMC) controls the VMS which display messages to drivers indicating whether SOHV are permitted in the HOV lane. The HOV lane is equipped with sensors to measure the speed of traffic, which is transmitted back to the TMC. This is a highly simplified view; the TMC itself contains several different components which generate the HOV lane control messages.

The system components can be classified in a few different ways. At the highest level, the DHLMS is composed of *internal* and *external* components. External components refer to those which are outside of a TMC and exist in the "real" world. Internal components are those which are part of the computer system running at the TMC. The diagram below shows the internal components.

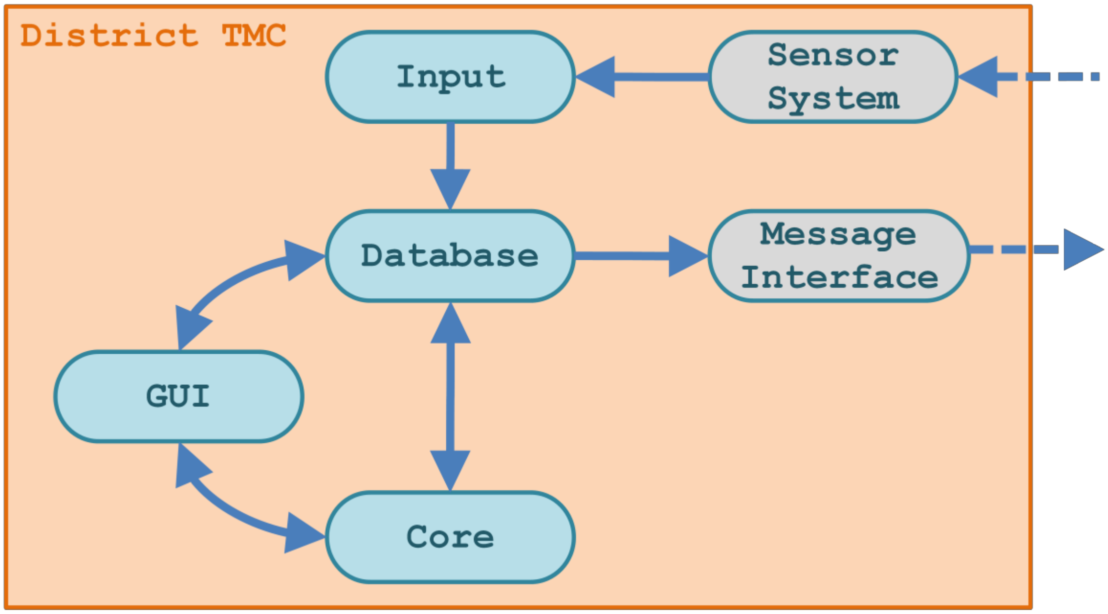


Figure 23: Internal system components. Arrows indicate information flow.

It is also important to identify which components are within the design scope of this project, i.e. which components are new and must be built and which are presumed to exist already. The two gray items in Figure 23 are outside this project's design scope: it is presumed that a TMC can provide the interface for controlling message signs and can collect data from a speed sensor system.

Also outside of the design scope are the external components shown in Figure 23. This leaves the following components (blue components in Figure 23):

- *Core:* This component is responsible for generating HOV lane control messages. For each VMS, it analyzes the access rules for the HOV lane, the time and day, and real time and historical traffic speed data to determine if SOHV should be allowed in the HOV lane.
- *Database:* The database contains all information necessary to control the access to the HOV lane, including static and dynamic information. The tables and relations are described later in this document.
- *GUI:* The graphical user interface allows system operators to monitor and control the system.

- *Input:* This module filters incoming speed data and stores it in the database in a format which can be used by the Core.

3.3. System Architecture

3.3.1. Core Algorithm

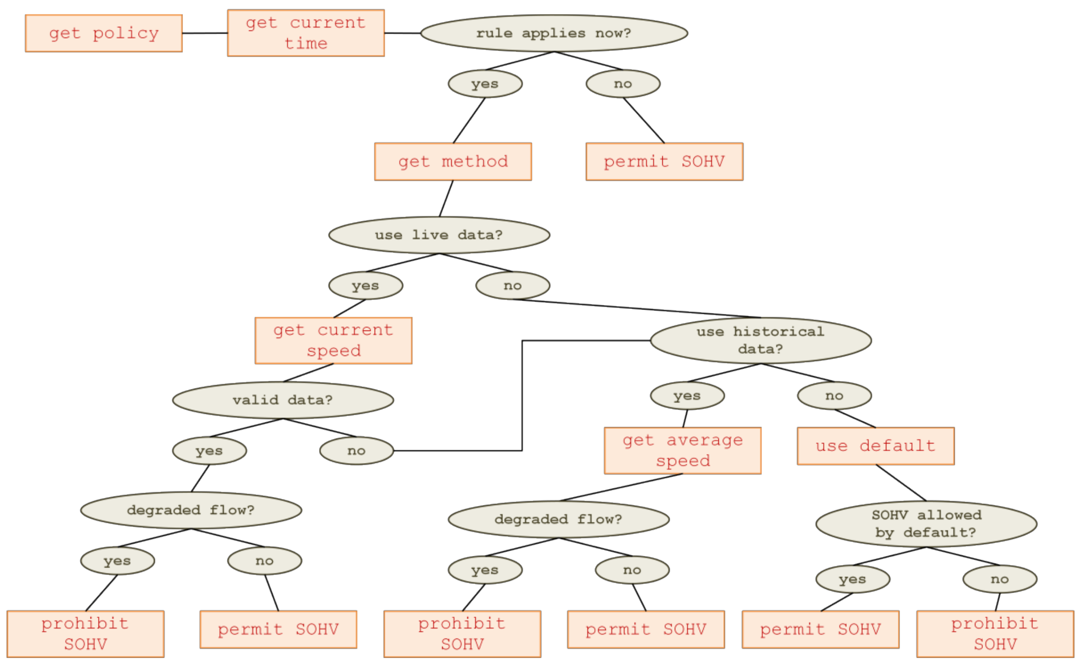


Figure 24: SOHV access determination algorithm for each VMS

The figure above describes the algorithm for determining whether a VMS will display a message permitting or prohibiting SOHV access to HOV lanes. This algorithm is executed on each VMS within the system at an update frequency specified by the operator.

For a given VMS, the system analyzes the **HOV Policy** (this and other terms appearing in **bold** refer to data entities which are described in the next section) to determine if the policy contains an **HOV Rule** which is currently in effect. Each rule has a **Method** which describes which types of available speed data (if any) are used to determine access.

Live speed data is considered the most desirable and is examined first. If the **Freeway Segment** is reporting a valid, current speed, then that speed will be used to determine

SOHV access. Historical speed (an average speed during peak hours over the last 180 days) is used when live speed data is not to be used or is unavailable. The rule also contains a default access value which is used when neither type of speed data is used or is unavailable.

There is another option not included in this algorithm which may worth considering by implementers of a DHLMS: a hybrid of live and historical data using weighted averages based on data confidence.

3.3.2. Data Model Diagram

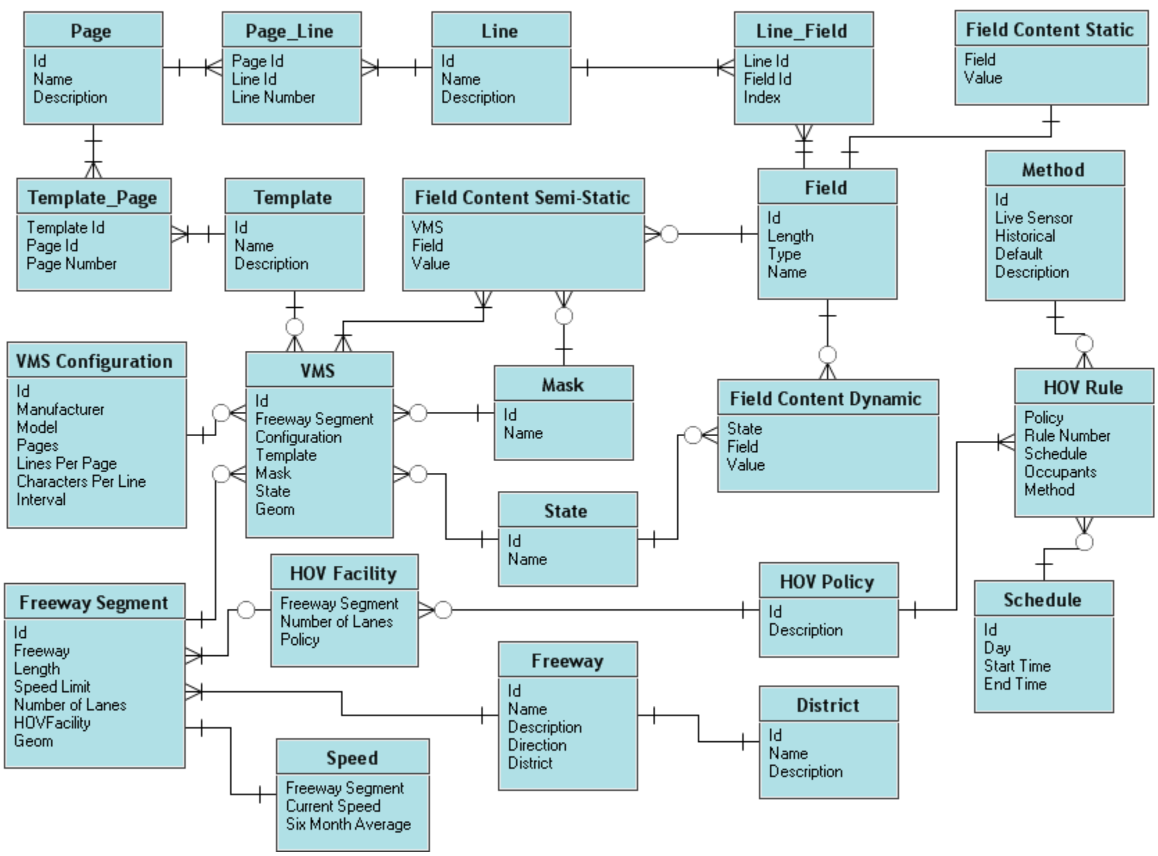


Figure 25: Data Model Diagram

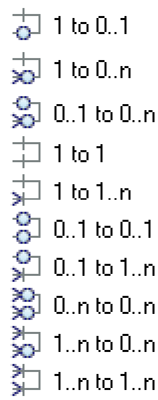


Figure 26: Relations Legend

The diagram above shows the data model used in the DHLMS. The entities are described in the following section.

3.4. Data Entities

This section describes each of the entities in the system. Each of these entities should be realized as a table in the database. For each entity, the following pieces of information are provided:

- *Attribute*: Attributes of the entity which will be columns of that entity's table in the database. The symbols (PK) and (FK = Entity.Attribute) denote primary and foreign keys of the table. For foreign keys, the entity and attribute to which the foreign key refers is included.
- *Description*: Describes the attribute and its purpose.
- *Example*: An example of a possible value from an implementation of this data model.

For each entity, a description of that entity and its relation to other entities is provided. Entity names appear in **bold** type.

District

Attribute	**Description**	**Example**
Id (PK)	Auto-generated unique identifier for the Caltrans district	1003
Name	The name of the District	District 8
Description	A brief description of the geographic area served by this District. This may include a list of county names since a District encompasses one or more whole counties.	San Bernardino and Riverside

For the sake of completeness we include the **District** entity to list the possible Caltrans districts, of which there are 12. The reason for including them is to divide entire freeways which may stretch over large areas (e.g. the entire state) into smaller **Freeway** entities which are confined to a single **District**.

Field

Attribute	Description	Example
Id (PK)	Auto-generated unique identifier	3775
Length	Number of characters this field consumes	2
Type	Describes whether the content of the field changes; the possible values being DYNAMIC (changes frequently, such as yes/no to SOHV), STATIC (never changes, such as the word "HOV") or SEMI-STATIC (usually remains constant on a single VMS, but may vary between locations, e.g. the time at which a lane is HOV only).	SEMI-STATIC
Name	A descriptive name for this field	Minimum number of occupants.

The **Field** is the smallest piece of information that is used to compose a message. An instance of a **Field** is defined by what piece of information it contains. Examples of "pieces of information" include: the word "HOV", a number of occupants per vehicle, a time of day, etc.

Field Content Dynamic

Attribute	Description	Example
State (PK) (FK=State.Id)	The Id number of the State	5238
Field (PK) (FK=Field.Id)	The Id number of the Field	5893
Value	The text value of the Field	Yes

This table stores the dynamic content which varies according to **State**. Example: “Yes” or “No” to SOHV.

Field Content Semi-Static

Attribute	**Description**	**Example**
Mask (PK) (FK=Mask.Id)	The Id number of the Mask	6952
Field (PK) (FK=Field.Id)	The Id number of the Field	5063
Value	The text value of the Field	“9:00”

This table stores the semi-static information which stays generally constant and can be applied to multiple **VMS**. Examples: The name of a freeway exit, the time at HOV only access ends.

Field Content Static

Attribute	**Description**	**Example**
Field (PK)	The Id number of the Field	8587
Value	The value of this Field which never changes and is the same in all locations	“HOV”

This table stores the value of truly static fields. The most usual case would be a basic word needed for a message, e.g. “HOV”, “HYBRIDS”, “LANE”.

Freeway

Attribute	**Description**	**Example**

Id (PK)	Auto-generated unique identifier for the Freeway.	1001
Name	The official name of the freeway, usually in the form of a short string which contains both a jurisdiction and highway number	US HWY-101
Description	A very specific description of this freeway entity.	US HWY-101 between San Jose and San Francisco
Direction	String which indicates the direction of the Freeway. It makes sense to treat the opposing travel directions of the same road segment as separate entities because their traffic conditions and HOV facilities are not related.	Northbound
District (FK=District.Id)	The Caltrans district in which this Freeway is situated. Note that there may be multiple Freeway entities in one district which share the same name. They are differentiated by the Description.	1039 (integer which is a PK in the District table, not the district name/ number)

Freeway refers to an entire freeway, which is quite large in the real world and in logical terms. Therefore, **Freeways** are divided into **Freeway Segments** which are a more manageable entity. **Freeways** are confined to a single **District**. Other background information (i.e. County) can be added as necessary.

Freeway Segment

Attribute	**Description**	**Example**

Id (PK)	Auto-generated unique identifier for the Freeway Segment	4626
Freeway (FK=Freeway.Id)	The Freeway to which this segment belongs.	1028
Length	Length in miles of this Freeway Segment	9.39
Speed Limit	Speed limit in miles per hour	65
Number of Lanes	The number of lanes on this Freeway Segment, including those which are part of an HOV facility.	4
HOV Facility (FK=HOV Facility.Id)	The HOV Facility located on this Freeway Segment. The value is null if this segment does not contain an HOV Facility.	8123, null
Geom	Geometry of the Freeway Segment	(coordinates of vertices stored as binary)

The **Freeway Segment** is the smallest road data type defined in this model. Each **Freeway Segment** may have **VMS** (Variable Message Signs), and its HOV lanes (if they exist) define an **HOV Facility**.

When the system is developed and a road vector dataset is chosen, an effort should be made to align the **Freeway Segment** definition with the features in the dataset to avoid the need for complex mapping between the two.

HOV Facility

Attribute	Description	Example
Id (PK)	Auto-generated unique identifier for the HOV Facility	1685
Number of Lanes	Number of lanes designated for HOV travel. Usually this is one.	1
Policy (FK=HOV Policy.Id)	Refers to the HOV Policy which governs this HOV Facility	8416

If a **Freeway Segment** contains HOV lanes (usually there is not more than one), then those lanes comprise an **HOV Facility**. In this manner, each **Freeway Segment** has a separate **HOV Facility**. In practice, a single **HOV Policy** will be applied across several consecutive **Freeway Segments** since controlling hybrid access for small segments of road is complicated. However, the scope of this project identifies this as a possibility.

HOV Policy

Attribute	Description	Example
Id (PK)	Auto-generated unique identifier for the HOV Policy	1685
Description	Describe this HOV policy	HOV rules for Bay Bridge

An **HOV Policy** is basically a collection of **HOV Rules** which describes the access rules for an **HOV Facility**.

HOV Rule

Attribute	Description	Example
Policy (PK) (FK=HOV	The Id of the HOV Policy to which this HOV Rule belongs	1685

Policy.Id)		
Rule Number (PK)	This value is a consecutive integer starting at 1. This permits each HOV policy to have multiple HOV Rules which comprise it.	1
Schedule (FK=Schedule.Id)	A reference to the schedule which defines a time interval when this HOV Rule applies	5098
Occupants	The minimum number of vehicle occupants required to lawfully use the HOV Facility	2
Method (FK=Method.Id)	The method for determining whether a SOHV is permitted to use the HOV Facility.	4209

An **HOV Rule** is a rule for controlling access to an **HOV Facility**. The **Schedule** defines when the rule applies and the **Method** says how SOHV access is determined. One or more **HOV Rules** forms an **HOV Policy**.

Line

Attribute	**Description**	**Example**
Id (PK)	Auto-generated unique identifier	3748
Name	Descriptive Name	One line time range
Description	Detailed description	Shows a time range on a single line

A **Line** is a single line of text displayed on a **VMS**, and one or more **Lines** together form a **Page** of a **Message**. A **Line** is composed of **Fields**.

Line_Field

Attribute	Description	Example
Line Id (PK) (FK=Line.Id)	The Id number of a Line	7837
Field Id (PK) (FK=Field.Id)	The Id number of a Field	1685
Index (PK)	The position in the Line where this Field begins	1

This table is required given the 'many to many' relationship between **Lines** and **Fields**: a **Line** has one or more **Fields**, but a **Field** is present in any number of **Lines**. The Index field is part of the primary key in case the same **Field** appears more than once on a **Line**.

Mask

Attribute	Description	Example
Id (PK)	Auto-generated unique identifier	8967
Name	Descriptive name	5 to 9 AM, 2+

A **Mask** defines the values for a set of semi-static **Fields**. If the value of any **Field** changes then a new **Mask** is used.

Method

Attribute	Description	Example
Id (PK)	Auto-generated unique identifier	3748
Live Sensor	Boolean defining whether this Method uses live speed data	True
Historical	Boolean defining whether this Method uses	False

	historical speed data	
Default	Boolean which defines the access for SOHV if Live Sensor and Historical data are not used	True
Description	Describe this method	Use live speed data, but not historical.

How each method works exactly is defined in the code, but this table explains the basic method for determining SOHV access for a given **VMS**. The three Boolean parameters mean there are only eight possible unique tuples for this table.

Page

Attribute	**Description**	**Example**
Id (PK)	Auto-generated unique identifier	9364
Name	Descriptive name	Number of occupants
Description	More detailed description and comments	This page has one line and shows the number of occupants required for HOV lane

A **Page** belongs to a **Template** and is made of **Lines.** A **Page** can be thought of as a part of a message that occupies the entire display for a certain time interval (specified in a **VMS Configuration**). For example, if a sign says "ROAD CLOSED" for 3 seconds and then "USE DETOUR" for 3 seconds, each of those statements would be a **Page**.

Page_Line

Attribute	Description	Example
Page Id (PK) (FK=Page.Id)	The Id number of a Page	3858
Line Id (PK) (FK=Line.Id)	The Id number of a Line	7837
Line Number (PK)	The position of the Line on the Page, e.g. the first line at the top of the page is 1	3

A **Page** contains one or more **Lines**, and a **Line** may appear in more than one **Page**. Line Number is part of the primary key in case the same **Line** appears more than once on a **Page**.

Schedule

Attribute	Description	Example
Id (PK)	Auto-generated unique identifier	9639
Day	This is an enumerated type which can be individual days of the week, all days, weekdays or weekend days.	TUESDAY
Start Time	Hour and minute	15:30
End Time	Hour and minute	18:30

The **HOV Rule** will apply to the **HOV Facility** on the listed day(s) during the hours specified in the other columns of the **Schedule**.

Speed

Attribute	Description	Example
Freeway Segment (PK) (FK=Freeway Segment.Id)	Auto-generated unique identifier for a Freeway Segment	9088
Current Speed	The most recent speed estimate for the Freeway Segment in miles per hour.	53.7
Six Month Average	Average speed during peak hours over last 180 days in miles per hour.	43.0

Speed information is recorded in the database by the Input module for each **Freeway Segment**.

State

Attribute	Description	Example
Id (PK)	Auto-generated unique identifier	9827
Name	Descriptive name	SOHV permitted

A **State** defines the values for a set of dynamic **Fields**. If the value of any **Field** changes then a new **State** is used.

Template

Attribute	Description	Example
Id (PK)	Auto-generated unique identifier	7852
Name	Descriptive Name	3R2P for 101 N SJ to SF

Description	Detailed description	Three rows, 2 pages for US Hwy 101 Northbound from San Jose to San Francisco

A **Template** is the highest level element of a message and is a collection of **Pages**.

Template_Page

Attribute	**Description**	**Example**
Template Id (PK) (FK=Template.Id)	The Id number of a Template	4564
Page Id (PK) (FK=Page.Id)	The Id number of a Page	3858
Page Number	This Page's place in the order of Page for the Template, i.e. the first page is 1	1

A **Template** contains one or more **Pages**, and a **Page** may appear in more than one **Template**.

VMS

Attribute	**Description**	**Example**
Id (PK)	Auto-generated unique identifier	4158
Freeway Segment (FK=Freeway Segment.Id)	The segment on which this sign is situated	2352
Configuration	The current configuration of this sign	5235

(FK=VMS Configuration.Id)		
Template (FK=Template.Id)	The template applied to this sign	6656
Mask (FK=Mask.Id)	The Mask currently applied to this sign	4789
State (FK=State.Id)	Current state applied	3958
Geom	Geometry of the VMS location, a point	(coordinates stored as binary)

The **VMS** entity describes a Variable Message Sign which is situated on **Freeway Segment**. The **VMS** has a **VMS Configuration** which describes its display capabilities. The message displayed conforms to a **Template** with dynamic content controlled by a **State.** Semi-static information is controlled by a **Mask.**

VMS Configuration

Attribute	**Description**	**Example**
Id (PK)	Auto-generated unique identifier	2304
Manufacturer	Name of the VMS manufacturer	SignCo
Model	Model of the VMS	TD-389
Pages	Number pages displayed in this configuration	2
Lines Per Page	Number of lines of text on each page	3
Characters Per Line	Number of characters displayed per line. Note that some signs can be configured to show multiple font	9

	sizes.	
Interval	Number of seconds between page flips	5

Given that there may be different models of **Variable Message Signs** employed and each of those may have different display modes, the **VMS Configuration** describes the capabilities of the sign. In the case where a single model of **VMS** has multiple display modes, there will be two tuples for that model in the table.

3.5. Functional Specifications

3.5.1. GUI

An essential feature of the DHLMS is the interface through which the operator monitors and controls the system. Given that the system deals with spatial information that changes in real time, a graphical user interface (GUI) is the ideal method. Here are the main features of the interface:

- Monitor state of VMS and freeway segments in real time: Allows the operator to see what is being displayed on the VMS, whether or not SOHV are allowed in the HOV facility of a certain freeway segment.
- System monitoring: Allows operator to verify that system components are working properly. Requires an alarm system.
- Add/delete/edit entities: For example, if the operator would like to add a new VMS, he/she can click a button, enter the information into a form and insert the new VMS into the database.
- Generate reports on system performance: View logs and reports on system events.
- Map view: Being able to view the entities on a map is suitable given the spatial nature of the information.

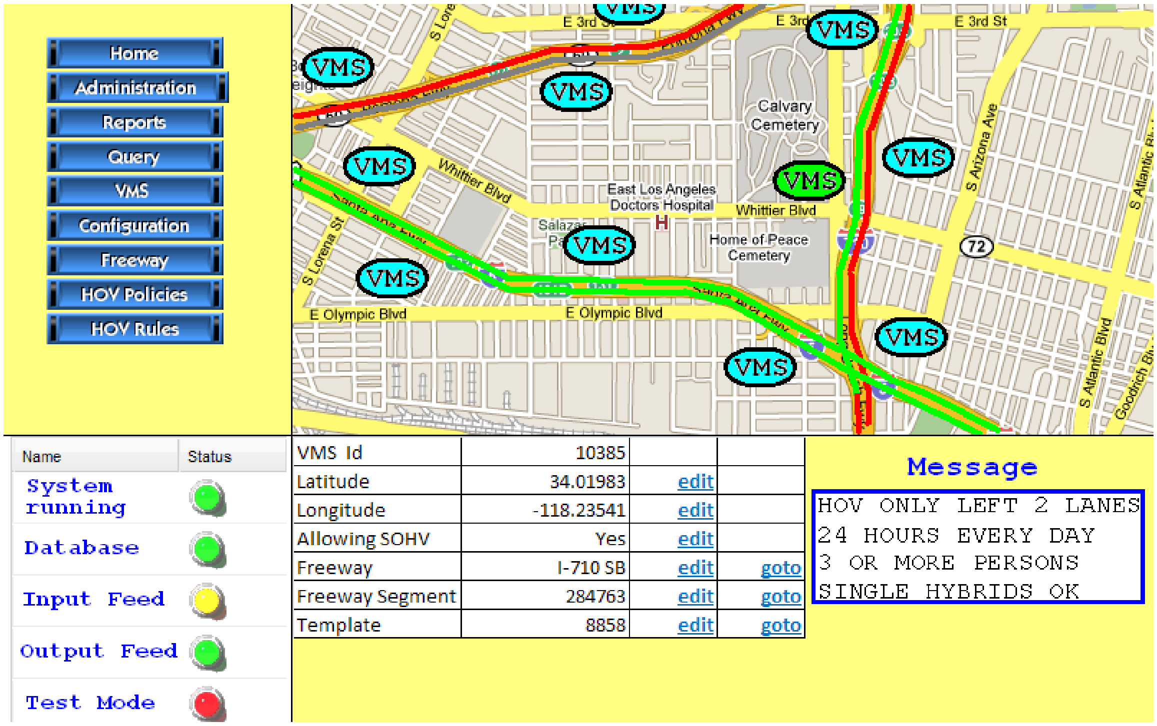


Figure 27: Mock up of GUI. In this case, the user has selected a VMS (in green) and can inspect its properties.

The figure above is a mock-up showing one view of the GUI. The top left pane contains buttons used to access different features of the interface. The bottom left pane shows current system status and the user can click on any one item to see more information. The top right pane shows a map view; the VMS and freeway segments are overlaid on a map.

The freeway links can be colored according to data values, such as red for SOHV not permitted, green for SOHV permitted and grey for N/A, or colored according to a different value such as speed. By clicking on the map, the user can inspect features more closely. In this example, the user has clicked on a VMS icon (the one colored green), and the information about that VMS is displayed in the bottom right pane where the user can edit the values.

3.5.2. Input

The system requires an Input module which is responsible for listening to data coming in to the TMC from sensors and storing it in the database. This is essential for two reasons:

- The system may use live sensor speed data in the algorithm which determines whether SOHV may use the HOV lane based on whether degradation exists.

- The system may also use historical data (e.g. a 6 month average speed for a certain road at a certain day/time) which requires that such data be collected, though perhaps not constantly.

The Input module may also contain a filtering or data quality algorithm.

3.5.3. Message Format

The message format that will be used by the DHLMS is not yet determined, and the system has been designed to accommodate various message templates and VMS types. Two possible types of signs that can be used for this project are:

Figure 28: Fully dynamic message sign

1) Fully dynamic message signs. This is the familiar light pixel sign board. All the information shown can be changed.

Figure 29: Dedicated dynamic message sign

2) Dedicated Dynamic Message Signs (DDMS) which integrate dynamic signs with traditional (static) painted/decal signs.

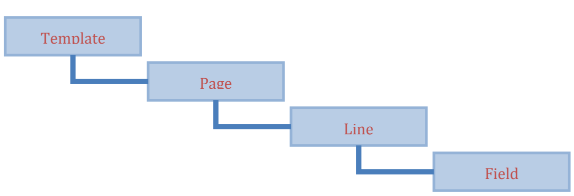


Figure 30: Message element hierarchy

In the most general sense, a message is described by a **Template** that is composed of **Pages** (e.g. the sign changes its display every few seconds) that is composed of **Lines** and **Lines** contain **Fields.** This allows for maximum flexibility in the type of message that can be displayed to be built into the system. In practice, however, it is likely that a message template might consist of a single field (and one page and one line) if a DDMS is being used.

Fields are one of three types:

1) *Static:* The value of this field never changes and is consistent in all locations, e.g. the word "LANE" would be stored in a static field since it never changes.

2) *Semi-Static:* Information in a semi-static field will change only rarely and will be consistent over a region. For example: the time an HOV lane goes into effect may vary region to region or be adjusted occasionally, so this would be stored in a semi-static field.

3) *Dynamic:* These fields store information which changes frequently. For the purposes of this project, the best example is SOHV access to HOV lanes. The value of the field would change between "OK" and "NO".

3.6. Summary

Effectively managing traffic on California's freeway system is a concern. Permitting a limited number of authorized lower emission hybrid vehicles to use HOV facilities with only a single occupant provides an incentive to promote and encourage the development of green technologies.. However, federal law mandates that SOHV must be excluded from HOV lanes if their speed performance is degraded (traffic must maintain an average speed of 45 mph during 90% of peak hours over a 180 day period).

The system design described in this document allows California to comply with this requirement by providing a way for Caltrans TMCs to determine whether or not SOHVs should be permitted in HOV facilities. In turn, they could disseminate that information through control of variable message signs that indicate to drivers which vehicles are permitted in the HOV lane.

Furthermore, this system design is presented in sufficient detail so that it may be implemented as software and a relational database. Doing so would be useful as it would allow for simulated traffic scenarios to be tested with the system. This should be the next step in the development of this system in order to refine it. The system design presented here will require changes as implementation decisions are made.

4. Challenges

The above-proposed system presents a new way to improve freeway conditions and remove congestion by redistributing the traffic flow and ensuring efficient use of HOV lane on a real-time basis. Although the implementation of the system would be a step forward for better freeway management; it could face some challenges in the real world. These challenges are:

4.1.1. Public Acceptance Challenges

Since the system proposes to remove people from the HOV lane, there could be a backlash from the public, especially from people who purchased their hybrid vehicle to take advantage of the existing rules.

Hence, before implementation, it would be better to start with a trial on a daily or seasonal basis rather than real-time basis. This would give people time to acclimatize to the new system and also allow transportation management agencies to address any issues that may arise. Also, all stakeholders should be called to take part in the initial implementation process. These stakeholders may include:

- ***Caltrans***

  Caltrans shall have the bulk of the responsibility to push this initiative as it would be the main implementer of the project. Caltrans has in the past shown motivation to implement new traffic management techniques and this would be another such endeavor. This report provides Caltrans with concise plans that it can follow for implementation.

  It should also be noted that a firm commitment is needed from the district that hosts the first pilot deployment. Like any other new system deployment, this may not be perfect at the beginning and a supportive and committed district will go a long way to ensure its success.

- ***Enforcement agencies (e.g. CHP)***

  While the proposal would reduce congestion and reduce workload of transportation management agencies, the workload for enforcement officers would increase as they would be dealing with a completely new system that would need enforcement rules to change on a real-time basis. Thus, the opinions and concerns of the officers should be taken into account while drafting the final plans. The workload could be controlled to some degree by using automatic enforcement and detection (e.g. Detection of SOHVs using cameras on the road as discussed in part 1 of this project).

- ***Public***

  The general public should be included in the planning process so that we can get a perspective of the lay person and their reaction to such a new system when deployed for the first time. Also, this would give us the opportunity to educate the public of the benefits obtained through active system management.

4.1.2. Technical Challenges

Since the proposed system, incorporates dynamic message signs to manage access to HOV lanes, technical challenges are non-trivial. It is true that no technological breakthrough is needed to achieve the goals of this system. Existing commercial off-the-shelf products are available currently to meet the technical requirements of this system. Since the whole system has never been put together, it is necessary to provide adequate time to design, test and calibrate all the components to ensure that it will meet freeway operational standards.

5. Conclusion

The work performed under this project represents a step forward to understanding various HOV restriction scenarios and their impact on HOV lane and mainline congestion. In this project, PATH studied the effects of permitting or restricting eligible single occupant hybrid vehicles (SOHV) from use of HOV facilities. The team simulated various control scenarios on a selected corridor.

Additionally, a dissemination system was designed to provide SOHV restriction messages dynamically to drivers through variable message signs. This high-level system design was presented in sufficient detail to allow implementation as software or a relational database. Implementation would allow for the simulation of traffic scenarios to be tested against real data. This should be the next step in the development of this system and allow for refinement. The system design presented here would evolve as implementation decisions are made.

The project team analyzed the effect of using various SOHV control strategies for 20 Weekdays during the month of February 2009 on a 25 mile segment of I-210E. Results showed that reduction in vehicles eligible to use HOV lane (not just SOHV but any vehicle) could reduce not only the delay experienced by HOV vehicles but also the total system delay. Removal of 1% vehicles was expected to lead 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 (it should be noted that these values are specific to the geometry and demand for the facility under consideration only. Other facilities are expected to show similar trends, but actual values may differ). This reduction could be attributed to 3 factors: (i) Reduction in HOV delays, (ii) HOV passenger-delays are weighted more than Single Occupancy Vehicles and (iii) smoothing effect of HOV lanes due to which total system delay is reduced even when the demand for MF lanes is just over capacity. Moreover, the team showed that this methodology could be used to determine the optimal operational strategies for other managed lanes like HOT lanes.