STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION
TECHNICAL REPORT DOCUMENTATION PAGE
TR0003 (REV 10/98)

ADA Notice
For individuals with sensory disabilities, this document is available in alternate formats. For information call (916) 654-6410 or TDD (916) 654-3880 or write Records and Forms Management, 1120 N Street, MS-89, Sacramento, CA 95814.

1. REPORT NUMBER
CA13-1205

2. GOVERNMENT ASSOCIATION NUMBER

3. RECIPIENT'S CATALOG NUMBER

4. TITLE AND SUBTITLE
High Occupancy Vehicle (HOV)
System Analysis Tools - District 8 HOV Facility Performance Analysis

5. REPORT DATE
November 30, 2012

6. PERFORMING ORGANIZATION CODE

7. AUTHOR
Kanok Boriboonsomsin, Guoyuan Wu, and Matthew Barth

8. PERFORMING ORGANIZATION REPORT NO.
UCR-0308

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Office of Research Affairs
University of California, Riverside
Riverside, CA. 92521

10. WORK UNIT NUMBER
3763

11. CONTRACT OR GRANT NUMBER
65A0308

12. SPONSORING AGENCY AND ADDRESS
California Department of Transportation
Division of Research and Innovation, MS-83
1227 O Street
Sacramento, CA. 95814

13. TYPE OF REPORT AND PERIOD COVERED
Final Report
December 2008 to November 2012

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
None

16. ABSTRACT
HOV facilities have been and will continue to be an integral part of the California freeway systems. Therefore, it is necessary to ensure that these HOV facilities are meeting their purposes of improving mobility, trip time reliability, and air quality. Over the last several years, there has been strong interest in comparing the performance between limited access and continuous access HOV facilities in California. The goal of this research was to develop novel methodologies for assessing operational performance of existing HOV facilities (with a focus on those in Caltrans District 8), and apply them to comparatively determine pros and cons of the two HOV lane access types. To meet this goal, five research methodologies were developed and applied: 1) corridor-level analysis, 2) statistical modeling, 3) video data analysis, 4) simulation study, and 5) before-and-after study. The collective findings from these methodologies suggest that freeway with limited access HOV facility would accommodate higher maximum throughput while freeway with continuous access HOV facility would provide higher average travel speed under mild congestion. Based on these findings, a new design of HOV lane access type that combines the advantages of the existing ones was recommended for consideration and evaluation.

17. KEY WORDS
HOV facility, HOV lane access type, operational performance, freeway throughput, travel speed, lane changing behavior,

18. DISTRIBUTION STATEMENT
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. SECURITY CLASSIFICATION *(of this report)*
Unclassified

20. NUMBER OF PAGES
200

21. COST OF REPORT CHARGED
N/A

High Occupancy Vehicle (HOV) System Analysis Tools - District 8 HOV Facility Performance Analysis

FINAL REPORT

Federal Report Number: CA12-2192

UC Riverside Report Number: UCR-0308

Prepared for:

California Department of Transportation

By:

Center for Environmental Research and Technology
University of California at Riverside

November 30, 2012

DISCLAIMER STATEMENT

Acknowledgments

The authors acknowledge the funding support from the California Department of Transportation (Caltrans). We are grateful for the assistance received from the Caltrans Project Manager, Fred Yazdan, and his assistant, Tam Nguyen. We also thank all the Caltrans Project Panel Members as well as the colleagues from the University of California (UC) Berkeley and UC Irvine for their valuable input and feedback during the course of the project.

In addition, we thank the following individuals for their assistance in this project: Manuel Jabson, Iwan Risman, Ramakrishna Tadi, Rick Chan, Fareha Zinnurayen, Thomas Tu, Terri Kasinga, and Jeff Renfro of Caltrans District 8; Steve Hague of Caltrans Division of Traffic Operations; and Yusuf Mohamedshah of Lendis Corporation.

Finally, we acknowledge Anh Vu, Alexander Vu, Oscar Garcia, Eduardo Cuevas, Jeremy Nelson, Daniel Hormozi, Yaoqiong Du, Daniel Sandez, Joseph Dean, Nicholas Jarak, Henry Chen, Qichi Yang, and Haitao Xia of the Center for Environmental Research and Technology, University of California Riverside, for their contribution.

Table of Contents

Table of Contents (continued)

Table of Contents (continued)

List of Tables

List of Figures

List of Figures (continued)

List of Figures (continued)

List of Acronyms

AMFL	Adjacent mixed-flow lane
ANOVA	Analysis of variance
API	Application programming interface
AVO	Average vehicle occupancy
FWYL	Freeway lane
GPL	General purpose lane; the same as MFL
GPS	Global Positioning System
HOT	High-occupancy tolling
HOV	High-occupancy vehicle
HOVL	High-occupancy vehicle lane
HSIS	Highway Safety Information System
ICC	Intra-class correlation
IRLS	Iterative re-weighted least squares
LMEM	Linear mixed effect model
LOS	Level of service
MARS	Multivariate adaptive regression splines
MFL	Mixed-flow lane
MLR	Multiple linear regression
PCR	Passenger carried ratio
PeMS	California Freeway Performance Measurement System
PMT	Passenger-miles traveled
REML	Restrict maximum likelihood
R-MLR	Robust multiple linear regression
RP	Recursive partitioning
SOV	Single-occupancy vehicle
TOPL	Tools for Operations Planning
VDS	Vehicle detector station
VHT	Vehicle-hours traveled
VMT	Vehicle-miles traveled

Executive Summary

Introduction

California has the most extensive high-occupancy vehicle (HOV) lane network compared to any other state in the nation. There are currently over 1,500 lane-miles of HOV facilities in California, and the California Department of Transportation (Caltrans) is on the path to implement approximately another 1,200 lane-miles through year 2030. In essence, HOV facilities have been and will continue to be an integral part of the California freeway systems. Therefore, it is necessary for Caltrans to ensure that these HOV facilities are best operated and meeting their purposes of improving mobility, trip time reliability, and air quality.

There are two general types of HOV lanes in California—limited access and continuous access (see Figure 1). Limited access HOV lanes are predominant in Southern California while continuous access HOV lanes are more common in Northern California. There has been interest from Caltrans as well as other transportation agencies in comparing the performance between the two types of HOV lanes. Two recently completed studies conducted such comparison, one with a focus on safety and the other on air quality. This research focuses the comparison on the mobility aspect. Specifically, this research attempts to address the question "which of the two HOV access types is operationally better for the overall performance of the freeway."

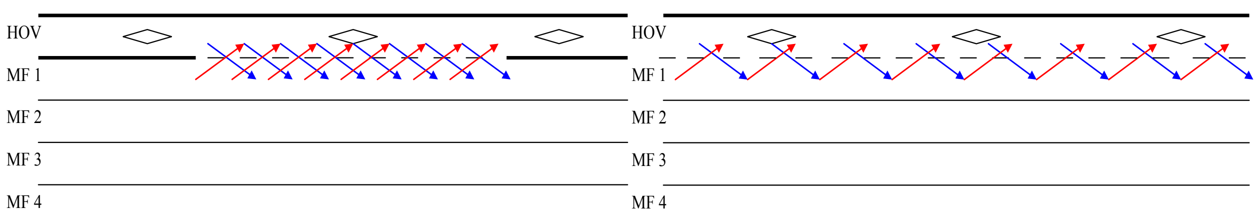


Figure 1. (Left) limited access HOV lane and (right) continuous access HOV lane

Analysis Approaches

The majority of this research was performed on HOV facilities in Caltrans District 8 (Riverside and San Bernardino Counties). Five different approaches were employed. Their pros and cons are summarized in Table 1 and briefly discussed below.

Corridor-Level Analysis

This analysis approach is aimed at evaluating the existing performance of the HOV facilities in District 8 at the corridor (or route) level. The data used for this analysis were obtained primarily from the District's HOV Monitoring Report Statistics as well as the Caltrans' Freeway Performance Measurement System (PeMS). Additionally, field data collection was conducted to supplement the existing data sources.

Table 1. Summary of pros and cons of analysis approaches used in this study

Approaches	Pros	Cons
Corridor-Level Analysis	• Implicitly account for impacts of travel demands and bottlenecks • Easy to comprehend by engineers/planners and the general public	• Results are corridor-specific. • Difficult to separate the effect of HOV lane access type from other influencing factors
Statistical Modeling	• Based on large amount of real-world data • Able to quantify the effect of HOV lane access type while controlling for other influencing factors	• Data compilation and processing is time consuming. • Currently applicable to only performance metrics measured at VDS locations
Video Data Analysis	• Provide data not measured by typical traffic data collection methods • Allow lane changing behavior to be captured and analyzed	• Difficult and costly to collect and process data • Limited data collection periods and locations
Traffic Simulation	• No any other differences besides HOV lane access type that could bias the results • Can simulate multiple what-if scenarios	• Results may be site-specific. • Underlying models in simulation tools may not capture some real-world driving behaviors
Before-and-After Study	• No other geometric differences besides HOV lane access type that could bias the results • Real-world data comparison	• Different travel demands and fleet characteristics between the before and after periods could bias the results. • Results may be site-specific.

The main advantage of this approach is that the analysis implicitly accounts for the impacts of travel demands and bottlenecks in the study corridors. Also, the results from this approach are easy to comprehend by Caltrans staff and the general public. On the other hand, the results are only applicable to the specific corridors being analyzed because there are several factors that can affect freeway operational performance at the corridor level. In this approach, no conclusion can be made with regards to the effect of HOV lane access type (i.e., limited access versus continuous access) on the operational performance of freeway as other influencing factors are not controlled for.

Statistical Modeling

In contrary to the corridor-level analysis, this approach allows for the effect of HOV lane access type on freeway operational performance to be quantified while controlling for other influencing factors. Specifically, regression techniques were used to develop relationships between freeway throughput and a number of geometric characteristics (e.g., lane width, shoulder width, distance to on-ramp and off-ramp, HOV lane access type, etc.) based on data from multiple sources including PeMS and the Highway Safety Information System (HSIS).

One advantage of this approach is that it is based on a large amount of real-world data systematically collected by PeMS. Another advantage, which is probably the most attractive one, is that the effect of HOV lane access type (i.e., limited access versus continuous access) on freeway throughput can be compared explicitly, and better yet, quantitatively. This comparison is made through an interpretation of the regression coefficient in the resulting regression models. In terms of disadvantages, this analysis approach requires a large amount of data processing time and is currently applicable to only freeway operational performance metrics measured at the locations of vehicle detector stations (VDS) in PeMS.

Video Data Analysis

This approach allows for detailed analyses of traffic operation and driving behavior on freeways with the different types of HOV lane access. It involves videotaping traffic at specific locations on freeways of interest and extracting traffic parameters from the videos. The extracted traffic parameters are the ones currently not measured by PeMS' sensors, for example, number of lane changes, gap at each lane change, etc.

The advantage of this approach is that the traffic data extracted from the videos are of high resolution in both time and space, and are not typically available from conventional traffic data collection methods. These data can be used to investigate driving behavior (such as lane-changing maneuver) on freeways with the different types of HOV lane access in detail. The results from the investigation would be a good supplement to PeMS data analysis and could be used to improve HOV behavior logics in traffic simulation models. However, video data are difficult and costly to collect and process. Therefore, only a very limited amount of data at a few locations was obtained in this research.

Traffic Simulation

Another approach that was taken in this research relies on traffic simulation. There are a variety of traffic simulation tools, from macroscopic to microscopic, that have been developed and validated over the last several decades. Some of the recent traffic simulation tools have a capability of modeling HOV lanes with both limited access and continuous access. In this research, a freeway network of State Route (SR) 91 and Interstate (I) 15 in Riverside County was simulated in Paramics traffic microsimulation software to compare the average travel speed on these freeways when implemented with limited access versus continuous access HOV lanes.

The main advantage of the simulation approach is that both types of HOV lane access can be implemented on the same freeway network with the same travel demand pattern, and the freeway operational performance can be simulated and compared directly. This means there are no other differences besides the HOV lane access type that could bias the results. This type of direct comparison would be more difficult and costly to do in real-world. Also, various what-if scenarios (e.g., different levels of traffic demand) can be simulated. However, it should be noted that the results from traffic simulation are dependent upon the ability of the underlying models to capture actual driving behaviors in real-world. Also, the results may be specific to the freeway network being simulated.

Before-and-After Study

An alternative to the traffic simulation approach is to conduct a before-and-after study in real-world. In this approach, a freeway with HOV lanes is first evaluated for its operational performance. Then, the HOV lanes are converted to the other type (i.e., from limited access to continuous access or vice versa), and the operational performance of the freeway re-evaluated.

Finally, the freeway operational performance before and after the HOV lane conversion can be compared.

Similar to the traffic simulation approach, this approach is advantageous in that both types of HOV lane access are implemented on the same freeway, so there are no other geometric differences except for HOV lane access type that could bias the results. However, the differences in travel demand patterns and fleet characteristics (e.g., the proportion of HOV-eligible vehicles, the percentage of truck traffic, etc.) between the before and after analysis periods could bias the results. In addition, while the results are based on real-world data, they may be specific to the freeway being studied.

In summary, the five analysis approaches are unique. They use different types of data and techniques and are conducted at different levels of detail. Each approach also has its own advantages and disadvantages. When taken together, their results are complementary to each other and provide a comprehensive view that can lead to a better understanding of the operational performance of freeways with different types of HOV lane access control.

Key Results and Findings

Corridor-Level Analysis

In the corridor-level analysis, the freeways in District 8 that have HOV lanes were compared with one another on several performance measures. These performance measures are either independent of the length of the study corridors or are normalized by the length of the corridors for a fair comparison. Note that I-215 N and I-215 S are unique as they have continuous access HOV lane while the other corridors all have limited access HOV lane. Key results and findings from this analysis are presented below.

According to the 2008 District 8 HOV Monitoring Report Statistics:

- The proportion of carpool vehicles in the District 8 corridors ranged from 10% to 20%. The share of carpool vehicles in HOV lane from the total carpool vehicles across all lanes was highest on I-215 S.

- The average vehicle occupancy (AVO) in mixed-flow (MF) lanes was slightly over 1.0 for all the corridors. The AVO in HOV lane was about 2.0 for most of the corridors. The HOV lane on I-210 W had the lowest AVO as it also had the highest HOV lane violation rate of 5% (see Figure 2).

- Passenger carried ratio of HOV lane to average MF lane was greater than 1 for most corridors.

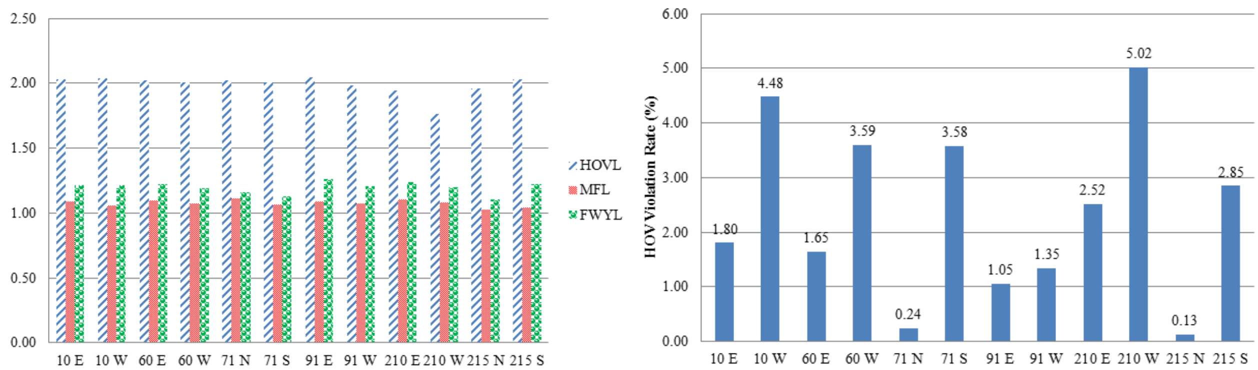


Figure 2. (Left) average vehicle occupancy and (right) HOV lane violation rate

Based on the analysis of PeMS data for the entire year of 2009:

- SR-91 was the most congested freeway in the district during peak hour. The average travel speeds (or corridor efficiencies) in both HOV and MF lanes of both SR-91 E and SR-91 W were among the lowest in the district (see Table 2).

- For I-215 N, the average travel speed was low in the MF lanes but high in the HOV lane (see Table 2). The approximately 15 mph higher average travel speed in the HOV lane would provide a significant amount of travel time savings to HOV lane-eligible vehicles.

Table 2. Average travel speed during peak hour on each corridor in District 8

Freeway	Direction	Peak Hour	HOV Lane	Avg. MF Lane	Avg. Freeway Lane
I-10	E	17:05 - 18:05	52.11	52.84	52.65
I-10	W	07:20 - 08:20	53.19	56.25	55.71
SR-60	E	17:05 - 18:05	53.47	54.09	53.95
SR-60	W	07:20 - 08:20	58.55	52.04	52.95
SR-71	N	16:55 - 17:55	57.04	63.77	61.75
SR-71	S	17:05 - 18:05	57.30	63.84	61.87
SR-91	E	15:35 - 16:35	41.18	40.17	40.37
SR-91	W	06:25 - 07:25	38.98	37.42	37.68
I-210	E	17:10 - 18:10	54.56	51.14	51.79
I-210	W	07:20 - 08:20	57.11	52.68	53.51
I-215	N	07:25 - 08:25	52.14	37.99	39.52
I-215	S	17:10 - 18:10	49.15	52.04	51.07

- Recurrent bottlenecks often occurred at the locations where there is a significant amount of traffic weaving. For corridors with limited access HOV lane such as SR-91 E (see Figure 3), the recurrent bottlenecks (spots in the plots with shade/color corresponding to low speed values in the vertical bars on the right of the plots) occurred around some ingress/egress areas , which are represented by dashed vertical lines. This resulted in shockwaves that propagated upstream. For corridors with continuous access HOV lane such as I-215 N, the recurrent bottlenecks occurred around the interchange between I-215 and SR-60 (absolute post mile 31.6 in Figure 4).

- Lastly, the travel time data collected by probe vehicle runs show that the travel time savings for HOV lanes varied significantly by corridor and time of day.

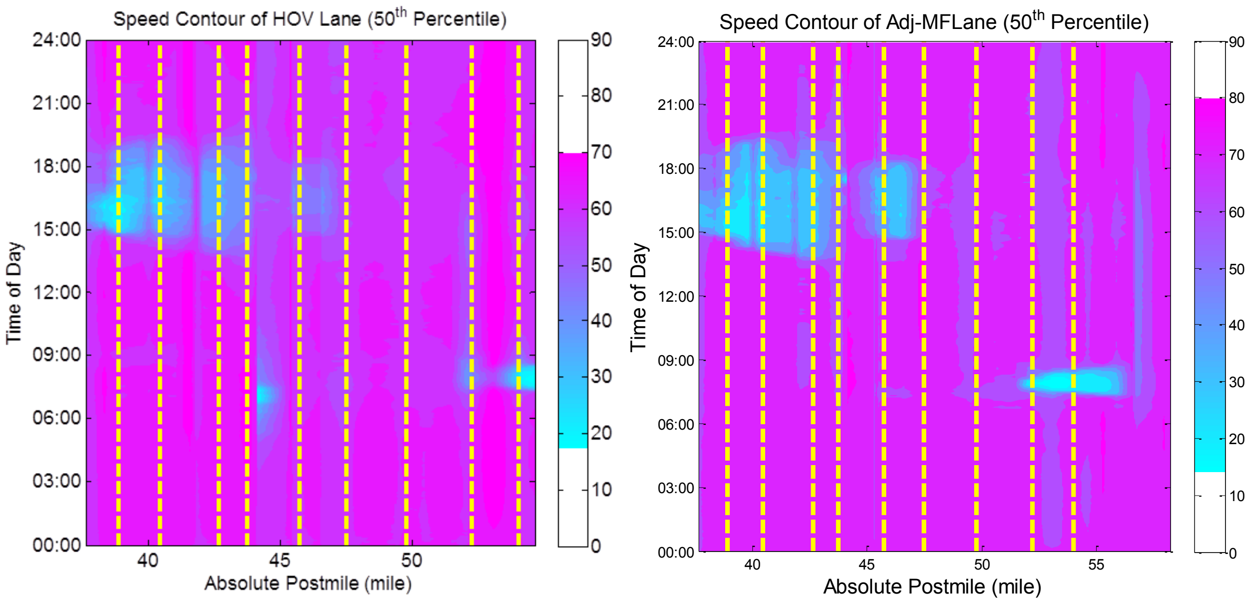


Figure 3. Speed contour plots of (left) HOV lane and (right) adjacent MF lane on SR-91 E

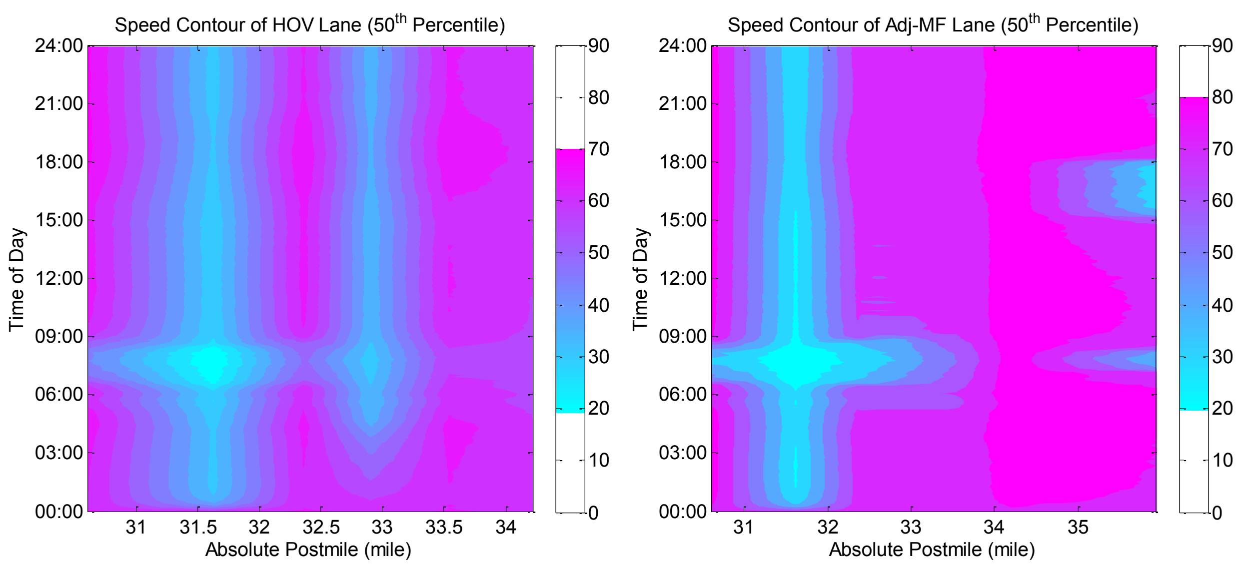


Figure 4. Speed contour plots of (left) HOV lane and (right) adjacent MF lane on I-215 N

Statistical Modeling

In this analysis, data regarding freeway throughput, geometric characteristics, and traffic measurements at the locations of PeMS' VDS on freeways with HOV facilities were gathered into a database. Freeways with HOV facilities in Districts 4, 7, and 12 were included in the analysis as the freeways with HOV facilities in District 8 alone were not able to provide sufficient data samples of continuous access HOV lanes (because there is only one freeway in the district that has continuous access HOV lane). The final database includes a total of 35 freeway corridors (listed in Table 3), which cover around 550 miles of freeway segments with HOV facilities and over 1,600 VDS in both HOV and MF lanes. Several regression techniques including multiple linear regression (MLR) and robust MLR were applied to the database to develop the models of freeway throughput as a linear function of a set of explanatory variables in the database, which include the type of HOV access (limited access versus continuous access).

Table 3. List of freeways with HOV facilities included in final database for regression analysis

HOV Type	Corridor	District	County	Absolute Post Mile		Length* (mile)	No. of VDS Covered
				Start	End		
Continuous-access	I-80 W/E	4	ALA	5.3	15.3	10.0	49
	US-101 N/S	4	SCL	367.3	401.8	34.5	114
	I-680 N/S	4	CC	31.4	43.3	11.9	66
	I-880 N	4	ALA	10.5	30.3	19.8	38
	I-215 N/S	8	RIV	29.2	37.4	8.2	23
	SR-22 W/E	12	ORA	1.5	13.5	12.0	137
	SR-55 N/S	12	ORA	12.0	18.0	6.0	41
Limited-access	SR-14 N/S	7	LA	0.0	18.5	18.5	32
	I-105 W/E	7	LA	1.2	16.9	15.7	134
	I-210 E	7	LA	24.8	39.9	15.1	43
	I-405 S	7	LA	36.7	46.0	9.3	45
	I-10 W/E	8	SBD	47.3	57.3	10.0	70
	SR-60 W/E	8	RIV/SBD	30.8	56.8	26.0	93
	SR-71 N/S	8	SBD	5.3	13.2	7.9	38
	SR-91 W/E	8	RIV	37.3	59.0	21.7	135
	I-210 W/E	8	SBD	52.5	67.4	14.9	74
	I-5N/S	12	ORA	79.2	101.2	22	183
	I-405 N/S	12	ORA	0.0	24.0	24	224
	SR-55 N	12	ORA	6.0	12.0	6	34
	SR-57 S	12	ORA	0.5	12.0	11.5	52
Total	*35*	—	—	—	—	*548.3*	*1,625*

**For each direction*

The results from the developed regression models consistently show that HOV lane access type has a statistically significant effect on the maximum freeway throughput (see Table 4). They also consistently suggest that a freeway with limited access HOV lane would have higher throughput than a freeway with continuous access HOV lane, given that everything else being equal. In addition to HOV lane access type, other statistically significant variables in the MLR models for overall freeway throughput are number of lanes, inner shoulder width, district, and lane occupancy at capacity. Whether the maximum freeway throughput is determined by the PeMS or the Max-flow methods, the effects of the statistically significant variables are qualitatively the same but quantitatively different.

Table 4. Summary of key results from regression analysis

No.	Regression Technique	Freeway Throughput Value	Freeway Throughput Determination Method	Regression Model Statistically Significant?	HOV Access Type Variable Statistically Significant?	Access Type with Higher Freeway Throughput
1	MLR	Lane Average	PeMS	Yes	Yes	Limited access
2	MLR	Lane Average	Max-flow	Yes	Yes	Limited access
3	MLR	Overall	PeMS	Yes	Yes	Limited access
4	MLR	Overall	Max-flow	Yes	Yes	Limited access
5	Robust MLR	Lane Average	PeMS	Not applicable	Yes	Limited access
6	Robust MLR	Lane Average	Max-flow	Not applicable	Yes	Limited access
7	Robust MLR	Overall	PeMS	Not applicable	Yes	Limited access
8	Robust MLR	Overall	Max-flow	Not applicable	Yes	Limited access

Video Data Analysis

In this analysis, videos of traffic at selected locations on freeways in District 8 were recorded and driving behavior-related traffic parameters were extracted. The videotaping locations include:

1. I-10 E at 6th Street
2. SR-91 W at Buchanan Street
3. I-10 E at Euclid Avenue
4. SR-91 W at La Sierra Avenue
5. I-215 S at the Humanities Building of the University of California Riverside
6. I-215 S at University Village Parking Structure

The first two locations are the ingress/egress areas of the limited access HOV lanes. The third and fourth locations are the buffered sections of the limited access HOV lanes. The last two locations are on the same corridor with continuous access HOV lane and they are adjacent to each other. The date and time periods of traffic videotaping as well as the number of lane changes between the HOV lane and the adjacent MF lane observed during each period were listed in Table 5. It is found that the numbers of lane changes at the ingress/egress areas of the limited access HOV lanes were much more than those for the continuous access HOV lane.

For each lane changing event observed in the videos, additional traffic parameters were also extracted, including the location of the lane changing event as well as gap and clearance between the vehicle making the lane change and the surrounding vehicles. Key results and findings from the analysis of these traffic parameters include:

- At the ingress/egress sections of the limited access HOV lanes on I-10 E and SR-91 W, most of the lane changes occurred early on within the first half of the sections (see the probability density plots in Figure 5). This lane-changing spatial intensity was more spread out for the continuous access HOV lane on I-215 S.

- Gaps and clearances of the vehicles changing lane from the HOV lane to the adjacent MF lane were smaller for the ingress/egress sections of the limited access HOV lanes on I-10 E and SR-91 W than for the continuous access HOV lane on I-215 S (see the probability density plots in Figure 6).

Table 5. Summary of traffic videos and the observed number of lane changes

HOV Type	Rte	Direction	Location	Date	Time	No. of Lane Changes*
Continuous	215	South	Humanities	09/09/2010	15:00 – 17:00	23
				09/10/2010	15:00 – 17:00	23
				09/13/2010	15:00 – 17:00	23
			University Village	09/09/2010	15:00 – 17:00	22
				09/10/2010	15:00 – 17:00	11
				09/13/2010	15:00 – 17:00	11
Limited	10	East	6th	09/02/2010	15:00 – 17:00	44
				09/03/2010	15:00 – 17:00	47
				09/07/2010	15:00 – 17:00	60
			Euclid	09/02/2010	15:00 – 17:00	9
				09/03/2010	15:00 – 17:00	2
				09/07/2010	15:00 – 17:00	1
	91	West	Buchanan	08/30/2010	15:00 – 17:00	277
				08/31/2010	15:00 – 17:00	121
				09/01/2010	15:00 – 17:00	103
			La Sierra	08/30/2010	15:00 – 17:00	0
				08/31/2010	15:00 – 17:00	0
				09/01/2010	15:00 – 17:00	4

**Between the HOV and the adjacent MF lanes only*

It should be noted that these results are based on a limited amount of data and the findings are specific to the study locations and time periods. Additional data and analysis will be needed before any generalization of the findings can be made.

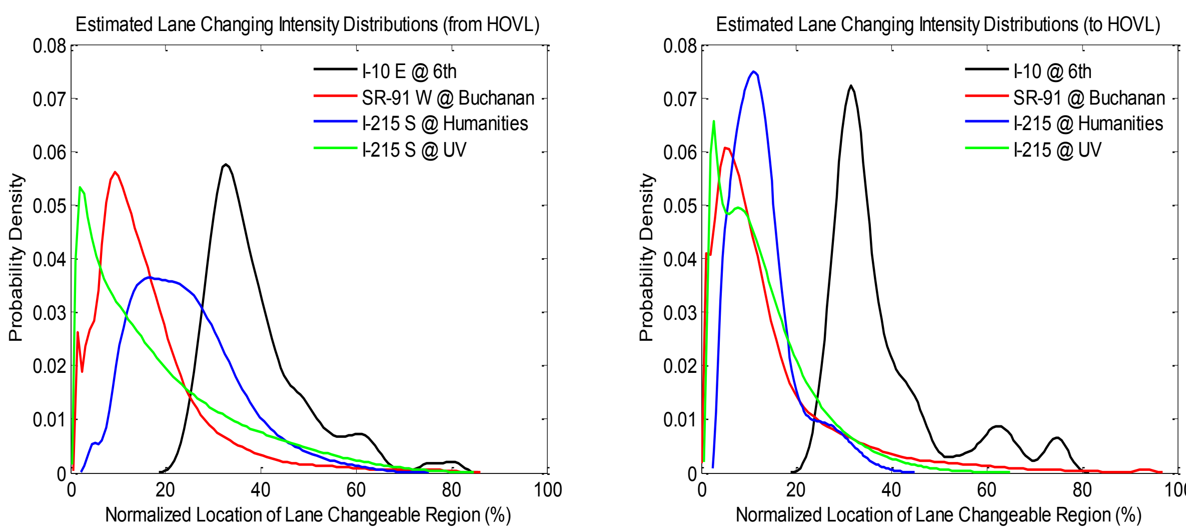


Figure 5. Estimated Intensity of lane changes (left) from HOV lane and (right) to HOV lane

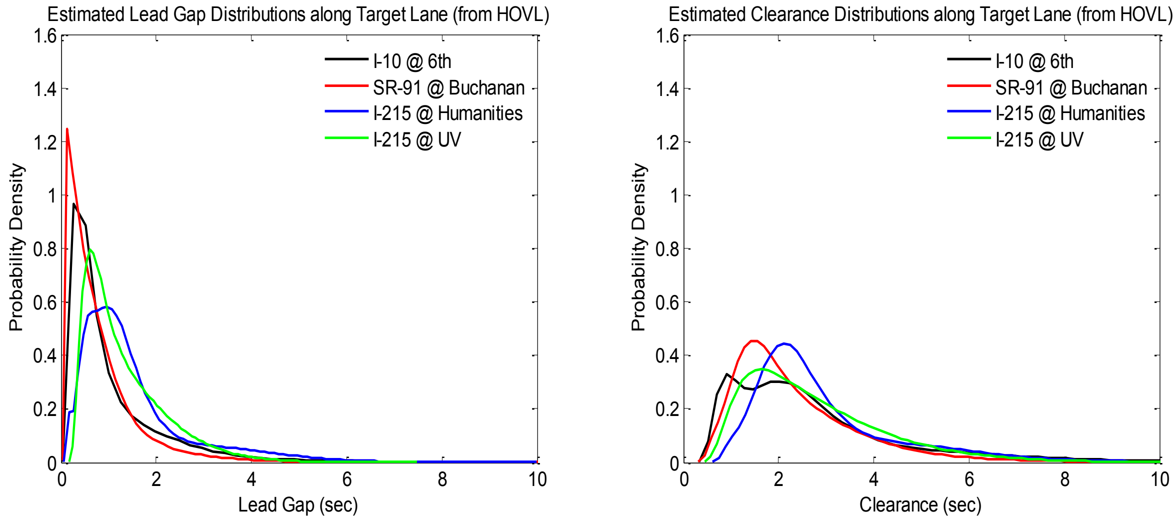


Figure 6. Probability density of (left) lead gap and (right) clearance in the target lane

Traffic Simulation

Freeway segments of 14 miles on SR-91 and 15 miles on I-15 in Riverside County that form a cross were coded in Paramics traffic microsimulation tool. The segment on SR-91 has full-time, limited access HOV lane with 2+ occupancy requirement in both directions. The simulation network was calibrated to the real-world traffic condition during the afternoon peak from 4 p.m. to 6 p.m. on August 6, 2009 (baseline scenario) based on PeMS data. During that period, both HOV and MF lanes on SR-91 E (peak direction) were not congested, with average travel speed (Q) greater than 50 mph. In addition, two more scenarios were simulated as shown in Table 6. These scenarios were created by applying common multipliers to the hourly traffic demands from all zones across the simulation network.

Table 6. Simulated scenarios as defined by traffic condition on SR-91 E

Scenario		MFL	
		35 mph < Q <= 50 mph	**Q > 50 mph**
HOVL	**35 mph < Q <= 50 mph**	Scenario I	N/A
	Q > 50 mph	Scenario II	Baseline

All the scenarios were simulated in two simulation networks – one with limited access HOV lanes on SR-91 (existing condition), and the other one with continuous access HOV lanes on SR-91. The simulation results of Q are presented in Table 7 and discussed below.

- For SR-91 E, the Q values of the network with continuous access HOV lane are much higher than those of the network with limited access HOV lane. This is true for both HOV and MF lanes and for all the scenarios. The differences in the Q values for HOV lane between the two networks range from 17% to 29% in different scenarios, which is quite significant. For MF lanes, the Q values of continuous access HOV facilities are on average 6% higher than limited access ones in all scenarios.

Table 7. Average travel speed (Q) on each route under different scenarios

Route	Lane Type	HOV Config.	Q (mph)		
			Baseline	Scenario I	Scenario II
SR-91 E	HOVL	Limited	57.99	46.85	53.65
		Continuous	68.55	60.24	63.16
		% Difference	*18.21%*	*28.58%*	*17.73%*
	MFL	Limited	53.56	45.49	45.09
		Continuous	54.91	48.23	50.02
		% Difference	*2.52%*	*6.02%*	*10.93%*
SR-91 W	HOVL	Limited	75.39	69.83	75.31
		Continuous	76.34	71.31	72.91
		% Difference	*1.26%*	*2.12%*	*-3.19%*
	MFL	Limited	62.70	54.52	55.15
		Continuous	62.68	55.50	55.01
		% Difference	*-0.03%*	*1.80%*	*-0.25%*
I-15 N	MFL	Limited	61.54	49.16	49.35
		Continuous	61.67	51.74	52.11
		% Difference	*0.21%*	*5.25%*	*5.59%*
I-15 S	MFL	Limited	60.91	50.80	55.16
		Continuous	60.76	51.49	53.15
		% Difference	*-0.25%*	*1.36%*	*-3.64%*

- For SR-91 W, the Q values of both MF lanes and HOV lane do not have obvious change (within 3%) under two types of networks, because the traffic condition (especially on HOV lanes) is not getting worse in all these scenarios.

- For I-15 N and I-15 S, the Q values for both networks are also similar, with the differences mostly negligible. This is expected as there is no HOV lane, and thus no geometric differences between the two networks, on these two routes. The variations may result from the changes in traffic condition along SR-91 (i.e., traffic flowing from/to SR-91 to/from I-15).

- Overall, it is found that when there is no congestion ($Q > 50$ mph), both networks with limited access and continuous access HOV lane tend to have similar average travel speeds (mostly less than 2 mph difference). However, as the networks get moderately congested (35 mph $< Q <=$ 50 mph), the network with continuous access HOV lane has higher average travel speeds.

Before-and-After Study

In Fall 2011, Caltrans District 8 converted the HOV lane on both directions of SR-60 in Moreno Valley, CA, from full-time limited access to part-time continuous access. A study to compare freeway operations between before and after the conversion was conducted as part of this research project. Key results and findings from the before-and-after study include:

- The eastbound direction was relatively more congested during the before analysis period, especially from 3 p.m. to 7 p.m. The westbound direction carried more traffic volumes during the after analysis period across all hours of day, which resulted in having slightly lower travel speeds for most of the day, except for the period from 12 a.m. to 3 a.m.

- The HOV violation rates after the conversion were higher. During the AM period, the HOV violation rate after the HOV conversion increased from 16.6% to 24.9%. During the PM period, the HOV violation rate after the HOV conversion more than doubled from 12.0% to 25.6%.

- After the conversion to continuous access, the number of lane changes per mile traveled into and out of the HOV lane increased. However, these lane changes generally occurred at a larger clearance.

- After the conversion to continuous access, the number of collisions decreased, especially at the ingress/egress section at the Heacock St interchange in eastbound direction.

Conclusions and Recommendations

Conclusions

This research was aimed at addressing the question "which of the two HOV access types (limited access versus continuous access) is operationally better for the overall performance of the freeway." It has been successfully carried out using four different but complementary analysis approaches. Based on the research results and findings, the following conclusions are made:

- The operational performance of the HOV facilities in District 8 was varied by corridor due to several factors. But in general, all of them maintained average travel speeds greater than 45 mph even during their peak hours, except for the ones on SR-91. The HOV lanes on SR-91 experienced significant delays in the westbound during the morning peak and in the eastbound during the afternoon peak. Part of these delays was due to recurrent bottlenecks around the ingress/egress areas along the corridors.

- Based on statistical analyses of the statewide HOV database consisting of freeways with HOV facilities in Districts 4, 7, 8, and 12, it was found that a freeway with limited access HOV lane would have higher maximum throughput than a freeway with continuous access HOV lane (by 90 vehicles/hour/lane for the PeMS method and 180 vehicles/hour/lane for the Max method), given that everything else such as other geometric characteristics, traffic demand, truck proportion, etc. being equal.

- Collecting and analyzing videos of traffic was demonstrated to be a useful approach for examining vehicle weaving behavior along HOV lanes. The limited amount of lane changing data collected in this research suggested that lane changing between HOV lane and the adjacent MF lane was smoother for continuous access HOV lane. Vehicles changing lane from the HOV lane to the adjacent MF lane in the ingress/egress areas of limited access HOV lane had smaller gaps and clearances than in the case of continuous access HOV lane.

- Based on traffic simulation, it was found that when there is no congestion, freeways with limited access and continuous access HOV lane tend to have similar average travel speeds (mostly less than 2 mph difference). As traffic gets moderately congested, the freeway with continuous access HOV lane has higher average travel speeds.

- After converting the HOV lane on a segment of SR-60 from full-time limited access operation to part-time continuous access, the HOV violation rate increased but the number of collision decreased, especially at one location on the eastbound where it was an ingress/egress section.

It is interesting to find that limited access HOV lanes would result in the freeways having higher maximum throughput while continuous access HOV lanes would provide higher average travel speed along the corridors under moderate congestion. Thus, there is a tradeoff between throughput and average travel speed when comparing the operational performance of the two HOV access types. One of the Caltrans' Strategic Goals is "Mobility", which aims to "maximize transportation system performance and accessibility". In this context, a higher freeway throughput means more accessibility to travelers (i.e., allowing more travelers to access activities in the same amount of time) while a higher average travel speed means better system performance in terms of productivity (i.e., providing travelers more miles in the same amount of time).

Recommendations

Based on the synthesis of the results and findings from this research, the following recommendations are made for consideration:

- It is desirable to continue to monitor the performance of HOV facilities in District 8 on a periodic basis. Particular attention should be paid to the HOV lanes on SR-91 in both directions as they experience significant delays during peak hours. Increasing the HOV eligibility requirement during the peak periods may help alleviate congestion in the SR-91 HOV lanes.

- Both limited access and continuous access HOV lanes have their own unique advantages. The buffered sections of limited access HOV lanes are found to be good at separating traffic flows between HOV and MF lanes, thus resulting in higher freeway throughput. The continuous access HOV lanes are found to be good at spreading out lane changing maneuvers, thus reducing major traffic perturbations that can cause significant delays. It is possible to design new types of HOV access that incorporate these advantages together. Specifically, an HOV lane can be designed to be continuous access to achieve relatively higher travel speed along the corridor, but have buffers strategically placed at critical freeway segments (e.g., around non-HOV-related bottlenecks and ramp merges) to facilitate relatively higher throughput on those segments.

- In exploring the alternative designs of HOV access, additional research should be undertaken to collect new data and develop new tools/methods that can help determine the locations of buffer placement.

This page is intentionally left blank.

1. Introduction

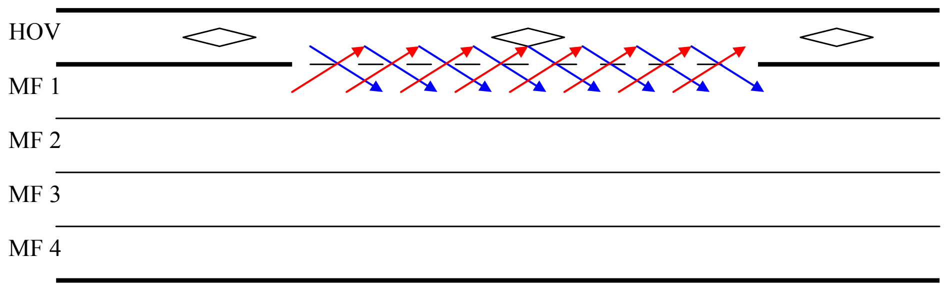
1.1. Background

California has the most extensive high-occupancy vehicle (HOV) lane network compared to any other state in the nation. There are currently over 1,500 lane-miles of HOV facilities in California, and the California Department of Transportation (Caltrans) is on the path to implement approximately another 1,200 lane-miles through year 2030. In essence, HOV facilities have been and will continue to be an integral part of the California freeway systems. Therefore, it is necessary for Caltrans to ensure that these HOV facilities are best operated and meeting their purposes of improving mobility, trip time reliability, and air quality. In addition, it is desired to potentially evolve some of the HOV lanes to other types of managed lanes including High Occupancy Toll (HOT) lanes.

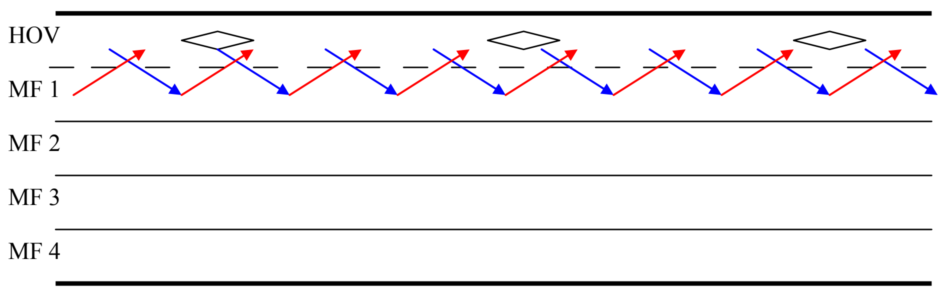
Caltrans' Division of Traffic Operations has developed guidelines for planning, design, and operations of HOV facilities [Caltrans, 2003a]. The guidelines indicate that the operation of an HOV facility is closely linked to the design of the facility, the traffic demand in the freeway corridor, and the geographic distribution development as well as the associated travel patterns in the region. In areas that experience regular periods of congestion for many hours of the day, full-time HOV operations with restricted access is favored to maximize opportunities for HOV utilization and travel time savings, thereby providing incentives to rideshare and relieve the rate of congestion.

Conversely, in areas where commute patterns generally consist of short definable peak periods and clear directional flows, part-time, peak period HOV operations are preferred. With part-time operations, the HOV lanes ideally should look like general purpose lanes to minimize the potential for motorist confusion when they are open to general-purpose traffic. Accordingly, it is preferred that access into and out of HOV lanes that operate part time not be restricted. Figure 1-1 shows the two configurations of HOV lanes in California. The limited access HOV lane is commonly found in Southern California while the continuous access HOV lane is dominant in Northern California.

In addition to the two conventional types of HOV lanes, toll or value-priced lanes also exist in California. The most well-known one is probably the State Route 91 (SR-91) Express lanes in Orange County, which are owned and operated by the Orange County Transportation Authority. Thorough studies were conducted in the late 1990s' to evaluate the impacts of the lanes on various aspects [Sullivan, 1998; Sullivan, 2000]. The lanes are now operated as high-occupancy toll (HOT) lanes with variable toll schedules depending on time of day and day of week. The SR-91 Express lanes have been a critical component of the Orange-Riverside Counties transportation corridor.



(a) Limited access HOV lane



(b) Continuous access HOV lane

Figure 1-1. HOV lane configurations in California

1.2. Objectives

In 2006, the College of Engineering–Center for Environmental Research and Technology (CE-CERT) at the University of California, Riverside, completed a research project for Caltrans (Caltrans Project PS-06) to evaluate the effectiveness of HOV lanes in California at improving air quality [Boriboonsomsin and Barth, 2006]. In that project, an evaluation of environmental performance of different HOV types in California was conducted. However, there has been very little amount of research to evaluate the operational performance of HOV/HOT lanes in California. Therefore, there is a need to investigate and compare the operational characteristics and benefits of the various types of HOV/HOT lanes in California. This research project is aimed at addressing such need. The project focuses primarily on the HOV facilities in operation in Riverside and San Bernardino Counties (i.e., Caltrans District 8) as well as the SR91 Express lanes. The HOV System map for Caltrans District 8 is shown in Figure 1-2.

The specific objectives of this project are to develop a research methodology, gather and analyze data from the Riverside/San Bernardino Counties various types of HOV lane configurations, including the HOT lanes on SR91, and assess the operational performance of each type of HOV/HOT facilities on the overall corridor. This is performed at various levels of demand, including those projected into the future, to determine the facility's operational performance across the full spectrum of possible vehicle demand. The outcome of this project is to provide Caltrans with adequate operational data and analysis on the pros and cons of the different types of HOV facilities.

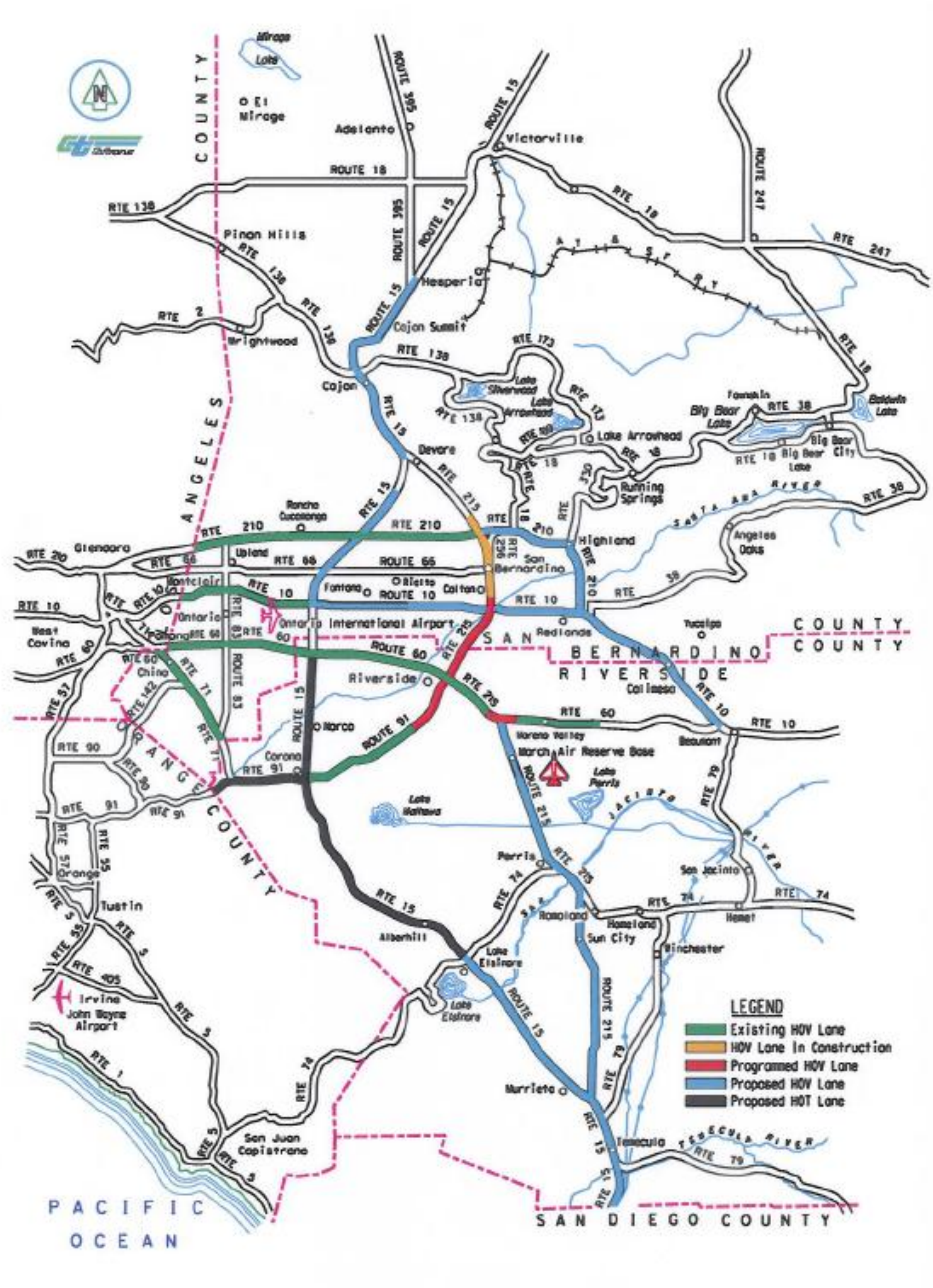


Figure 1-2. District 8 HOV System map

1.3. Past Relevant Studies

Many studies have been conducted that evaluate the effectiveness or impact of HOV facilities in California. However, only a small fraction of those studies has focused on a comparative assessment of the HOV configuration and other related operation policy components. Three studies have been identified as mostly related to such assessment. They are discussed briefly below:

1.3.1. Orange County HOV Operations Policy Study

In this study, various criteria including cost, effectiveness, safety, operation, violation, and enforcement of differing policy alternatives were evaluated and discussed. In particular, the study was focused on the advantages and disadvantages of: 1) full-time versus part-time HOV operation and 2) limited access versus continuous access HOV lane.

The evaluation and discussion relied on available data and reports to provide the basis for developing pros and cons for each approach to HOV design and operation. In some cases, the available data was either incomplete or inconclusive, and the investigation team applied their collective experience and perspectives in providing a response to each policy in question. The study concluded by recommending that more studies be conducted to examine, in detail, HOV lane performance characteristics, location-specific operational and safety issues, design exceptions, environmental considerations, enforcement needs, and associated costs of these operation policy components. For more details about this study, please refer to [Orange County Transportation Authority, 2002].

1.3.2. HOV Lane Configuration and Collision Distribution on Freeway Lanes

This study investigated the relationship between HOV lane configuration and collision distribution on freeway lanes. In this study, it was hypothesized that the operation of HOV lanes might result in traffic interactions that affect safety performance. Therefore, historical accident data from a number of freeway corridors in California were used to illustrate the distribution of collisions in different lanes of the freeways. Peak-hour traffic data, when compared to those during non-peak hours, indicated that more interactions due to traffic weaving near the HOV lanes might lead to a greater concentration of collision on the inside lanes of the corridors. This was found to be true for all the corridors studied.

In addition, a comparison of corridors with continuous access HOV lanes versus those with limited access HOV lanes implied that the restricted entrance and exit of the HOV lanes could cause more intense and challenging lane-changing actions; and subsequently, a greater proportion of collisions near the HOV lanes. It should be noted that this study did not attempt to draw a relationship between collision and traffic conditions (e.g. speed, density). As the frequency of collision usually increases with the increasing traffic density, it may be the case that the safety issues discussed in this study are mostly attributable to certain traffic conditions (e.g. high volume, high speed differential between HOV lanes and the adjacent mixed-flow (MF) lanes). For more details about this study, please refer to [Chung et al., 2007].

1.3.3. Modeling the Effectiveness of HOV Lanes at Improving Air Quality

This study was aimed at evaluating the air quality benefits of existing HOV lanes in California and develop modeling tools that can be used to provide reliable estimates of the air quality impacts of HOV lanes. The study consisted of three major components. The first component was the evaluation of air quality benefits of HOV lanes in California based on sampled vehicle trajectory data collected in real-world. Key findings from this evaluation were that [Boriboonsomsin and Barth, 2007]: 1) the HOV lanes on the study freeways produced less pollutant emissions per lane as compared to the adjacent MF lanes, mainly due to the better flow of traffic in the lanes; and 2) these HOV lanes were also found to produce far less emissions per person. These findings are applicable to both HOV lanes in Southern California and HOV lanes in Northern California when they are in operation.

The second component of this study was to make improvements to the emission calculation process for HOV lanes. Based on the real-world data collected in this study, it was found that the model years of vehicles in HOV and MF lanes on the same freeways were relatively the same. However, the driving patterns of vehicles in HOV and MF lanes (in terms of second-by-second speed and acceleration) were significantly different from each other, which could result in very different emission factors. Therefore, lane-specific emission correction factors for HOV lanes were developed that allow modelers to adjust the emission rates for HOV lanes to properly reflect the acceleration/deceleration characteristics of HOV lane operation under different traffic conditions [Boriboonsomsin et al., 2009a].

The last component of this study was to demonstrate the deployment of an integrated Paramics microscopic traffic simulation and Comprehensive Modal Emissions Modeling (CMEM) tool to evaluate air quality impacts of HOV lane at a corridor level. Using State Route 91 freeway in Riverside County, California, as a case study, the emission impacts of having the innermost lane of the freeway as a limited access HOV lane, a continuous access HOV lane, and a standard MF lane were modeled and compared. It was found that the limited access HOV lane would result in more pollutant emissions than the continuous access HOV lane due in large part to the highly concentrated lane changing activities over the limited length of the designated ingress/egress sections [Boriboonsomsin and Barth, 2008].

For more details about this study, please refer to [Boriboonsomsin, K. and Barth, M., 2006].

1.4. Analysis Approaches

In this research, a variety of approaches were employed to address the research question at hand. These approaches utilized both real-world data collected by various techniques and simulated data generated by traffic simulation. The overview of the different approaches as well as pros and cons are discussed below.

1.4.1. Corridor-Level Analysis

This analysis approach is aimed at evaluating the existing performance of the HOV facilities in District 8 at the corridor (or route) level. The data used for this analysis were obtained primarily from the District's HOV Monitoring Report Statistics as well as the Caltrans' Freeway Performance Measurement System (PeMS). Additionally, field data collection was conducted to supplement the readily available data.

In this corridor-level analysis, the freeways in District 8 that have HOV lanes are compared with one another based on several performance measures. These performance measures are either independent of the length of the study corridors or are normalized by the length of the corridors for a fair comparison. Examples include speed-flow joint probability distribution, HOV travel time savings, etc.

The main advantage of this approach is that the analysis implicitly accounts for the impact of vehicle demand and bottlenecks in the study corridors. Also, the analysis results from this approach are easy to comprehend by Caltrans staff and the general public. On the other hand, the individual results from this approach are only applicable to the specific corridors that are analyzed because there are several factors that can affect the freeway operational performance at the corridor level. In this approach, no conclusion can be made with regards to the effect of HOV lane configuration (i.e., limited access vs. continuous access) on the freeway operational performance as other influencing factors are not controlled for.

1.4.2. Statistical Modeling

This approach is based on the fact that PeMS data (e.g., flow, speed, etc.) are collected at discrete locations of vehicle detector stations (VDS) along freeways. Therefore, HOV and MF data from PeMS represent lane operational performance at the cross sections where the VDS are situated. The freeway throughput at these cross sections can be influenced by several geometric characteristics, for instance, lane width, shoulder width, road grade, HOV lane configuration, etc. In addition, whether there are nearby on-ramp and off-ramp and how far these ramps are from the VDS also plays a role as they could induce weaving maneuvers that affect freeway throughput.

The data of these geometric characteristics were gathered and compiled into a database along with freeway throughput data. Then, this database was used to conduct regression analysis where the maximum freeway throughput is written as:

$$C = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \beta_{n+1} Type_{HOV} \tag{1-1}$$

where C is maximum freeway throughput; x_i are geometric characteristics affecting freeway throughput, β_i are regression constant and coefficients; and $Type_{HOV}$ is a dummy variable representing the type of HOV lane configuration (e.g. continuous access = 0 and limited access = 1). Setting continuous access to 0 means it is used as a baseline for comparison with limited access.

Once the regression equation above has been developed using the real-world data from PeMS, the regression coefficient β_{n+1} can be evaluated to see if it is statistically significant or not. If no, then it can be inferred that there is no statistically significant difference in the operation performance between the two lane configurations. If yes, then the algebraic sign of the coefficient will imply which of the two types of HOV lane configuration is operationally better. If the coefficient is negative, then the limited access will be considered to result in lower throughput as compared to the continuous access, and vice versa, all other factors being equal.

The advantage of this approach is that it ties directly to PeMS data at VDS so the data are a true representation of freeway lane operational performance at the locations of VDS. Also, we will be able to create a very large database for use in the regression analysis since there are numerous VDS throughout the state although the compilation of database takes a significant amount of time and effort. This helps improve the robustness of the results. In addition, the regression analysis results will not only reveal whether the two HOV lane configurations are operationally different or not, but also indicate the effect of other geometric characteristics on the operational performance of freeways with HOV facilities.

1.4.3. Video Data Analysis

This approach involves videotaping traffic at the locations of interest. The collected videos of traffic were used to extract several traffic parameters that are not measured by PeMS' sensors, for example, number of lane changes, gap at each lane change, etc. In addition, vehicle trajectories in terms of second-by-second vehicle speed profile can be extracted and used to improve HOV behavior logics in traffic simulation models.

The advantage of this approach is that the traffic parameters obtained through videos are not easy to come by in real-world. The high resolution of these traffic parameters, in both space and time, can provide new perspectives to freeway performance analysis. This can lead to a better understanding of the impact of HOV lane configuration on the operational performance of freeways with HOV facilities. However, the video data is difficult and costly to collect and process. Therefore, only a very limited number of data sets at selected locations can be obtained in this project.

1.4.4. Traffic Simulation

Another approach relies on traffic simulation. There are a variety of traffic simulation tools, from macroscopic to microscopic, that have been developed and validated over the last several decades. Many of these simulation tools have a capability of modeling HOV lanes for both limited access and continuous access configurations.

The main advantage of the simulation approach is that both types of HOV lane access can be implemented on the same freeway network with the same travel demand pattern, and the freeway operational performance can be simulated and compared directly. This means there are no other differences besides the HOV lane access type that could bias the results. This type of direct comparison would be more difficult and costly to do in real-world. Also, various what-if scenarios (e.g., different levels of traffic demand) can be simulated. However, it should be noted that the results from traffic simulation are dependent upon the ability of the underlying models to capture actual driving behaviors in real-world. Also, the results may be specific to the freeway network being simulated.

1.4.5. Before-and-After Study

An alternative to the traffic simulation approach is to conduct a before-and-after study in real-world. In this approach, a freeway with HOV lanes is first evaluated for its operational performance. Then, the HOV lanes are converted to the other type (i.e., from limited access to continuous access or vice versa), and the operational performance of the freeway re-evaluated. Finally, the freeway operational performance before and after the HOV lane conversion can be compared.

Similar to the traffic simulation approach, this approach is advantageous in that both types of HOV lane access are implemented on the same freeway, so there are no other geometric differences except for HOV lane access type that could bias the results. However, the differences in travel demand patterns and fleet characteristics (e.g., the proportion of HOV-eligible vehicles, the percentage of truck traffic, etc.) between the before and after analysis periods could bias the results. In addition, while the results are based on real-world data, they may be specific to the freeway being studied.

In summary, the five analysis approaches are unique. They use different types of data and techniques and are conducted at different levels of detail. Each approach also has its own advantages and disadvantages. When taken together, their results are complementary to each other and provide a comprehensive view that can lead to a better understanding of the operational performance of freeways with different types of HOV lane access control.

1.5. Organization of the Report

This report is organized into seven chapters as follows:

1. Chapter 1 introduces the background on the topics being addressed in this project. The research objectives are given and the relevant studies in the past are reviewed. In addition, the research approaches taken in this project are briefly discussed.

2. Chapter 2 presents the data, methods, and results of the corridor-level analysis. This chapter is divided into three sections based on the data used, which include the Caltrans District 8's HOV Monitoring Report statistics, PeMS data, and field data.

3. Chapter 3 presents the data, methods, and results of the statistical modeling. Two databases—District 8 and statewide—were created and regression analyses were performed separately using each database.

4. Chapter 4 describes the collection and processing of videos of traffic at selected locations in District 8. It also discusses the analysis of traffic parameters extracted from the videos.

5. Chapter 5 describes the creation and calibration of traffic microsimulation network for use in comparing the performance of the two HOV lane access types. It also discusses the simulation results under different scenarios.

6. Chapter 6 presents the before-and-after study of HOV conversion on SR-60 in Moreno Valley, CA, from full-time limited access operation to part-time continuous access.

7. Chapter 7 provides conclusion and recommendations from this research.

8. Chapter 8 lists the references cited in this report.

The last chapter is followed by a series of appendices that show detailed results from the various analyses in this report.

2. Corridor-Level Analysis

2.1. Overview

This analysis is aimed at evaluating the existing performance of the HOV facilities in District 8 at the corridor (or route) level. The data used for this analysis were obtained primarily from the District's HOV Monitoring Report Statistics as well as the Caltrans' Freeway Performance Measurement System (PeMS). Additionally, field data collection was conducted to supplement the readily available data.

In this corridor-level analysis, the freeways in District 8 that have HOV lanes were compared with one another based on several performance measures. These performance measures were either independent of the length of the study corridors or were normalized by the length of the corridors for a fair comparison. Examples include speed-flow joint probability distribution, HOV travel time savings, etc.

The main advantage of this approach is that the analysis implicitly accounts for the impact of vehicle demand and bottlenecks in the study corridors. Also, the analysis results from this approach are easy to comprehend by Caltrans staff and the general public. On the other hand, the individual results from this approach are only applicable to the specific corridors that are analyzed because there are several factors that can affect the freeway operational performance at the corridor level. In this approach, no conclusion can be made with regards to the effect of HOV lane configuration (i.e., limited access vs. continuous access) on the freeway operational performance as other influencing factors are not controlled for.

2.2. Analysis of District 8 HOV Monitoring Report Statistics

2.2.1. Data Description

Based on a multiple-weekday survey, D8 HOV Monitoring Report provides traffic information, including traffic counts, vehicle occupancy, and vehicle classification for both HOV lane and mixed flow (MF) lane, along I-10, SR-60, SR-71, SR-91, I-210 and I-215 in the Fall 2008. Table 2-1 lists the corresponding monitoring locations. At each location, 3-hour data were collected during the peak period.

Table 2-1. D8 HOV Monitoring Locations

Location		AM Dir.	PM Dir.	# of MFL	# of HOVL
I-10	Haven Ave O/C	W	E	4	1
	San Antonio Ave. O/C	W	E	4	1
SR-60	Haven Ave. O/C	W	E	4	1
	Monte Vista Ave. O/C	W	E	4	1
	La Rue St. O/C	W	E	3	1
	Indian Ave. O/C	W	E	2	1
SR-71	Pine Ave. O/C	S	N	2	1
SR-91	Promenade Ave. O/C	W	E	4	1
	Jackson St. O/C	W	E	4	1
	Smith Ave. O/C	W	E	4	1
I-210	Baseline Rd. O/C	W	E	3	1
	Etiwanda Ave. O/C	W	E	3	1
	Riverside Ave. O/C	W	E	3	1
I-215	Blaine St. O/C	N	S	4	1

2.2.2. Data Analysis

Due to the very limited sample size, only the average value of mid-hour data over different study sites has been used as the representative traffic information. The following results have been extracted and compared across different HOV facilities:

- Average vehicle occupancy (AVO) on each lane type (HOVL, MFL, and FWYL)
- HOV violation rate (%)
- Passenger carried ratio (HOVL vs. avg. MFL)
- Proportion of carpool on each lane type (HOVL, MFL and FWYL)
- Share of HOVL carpool

Average Vehicle Occupancy (AVO)

The average vehicle occupancy (AVO), is calculated for HOVL, MFL and FWYL, respectively, as follows:

$$AVO_{HOVL} = \#\ of\ people\ using\ HOVL / \#\ of\ vehicles\ along\ HOVL \tag{2-1}$$

$$AVO_{MFL} = \#\ of\ people\ using\ MFLs / \#\ of\ vehicles\ along\ MFLs \tag{2-2}$$

$$AVO_{FWYL} = \frac{\#of\ people\ using\ HOVL + \#\ of\ people\ using\ MFLs}{\#of\ vehicles\ using\ HOVL + \#\ of\ vehicles\ using\ MFLs} \tag{2-3}$$

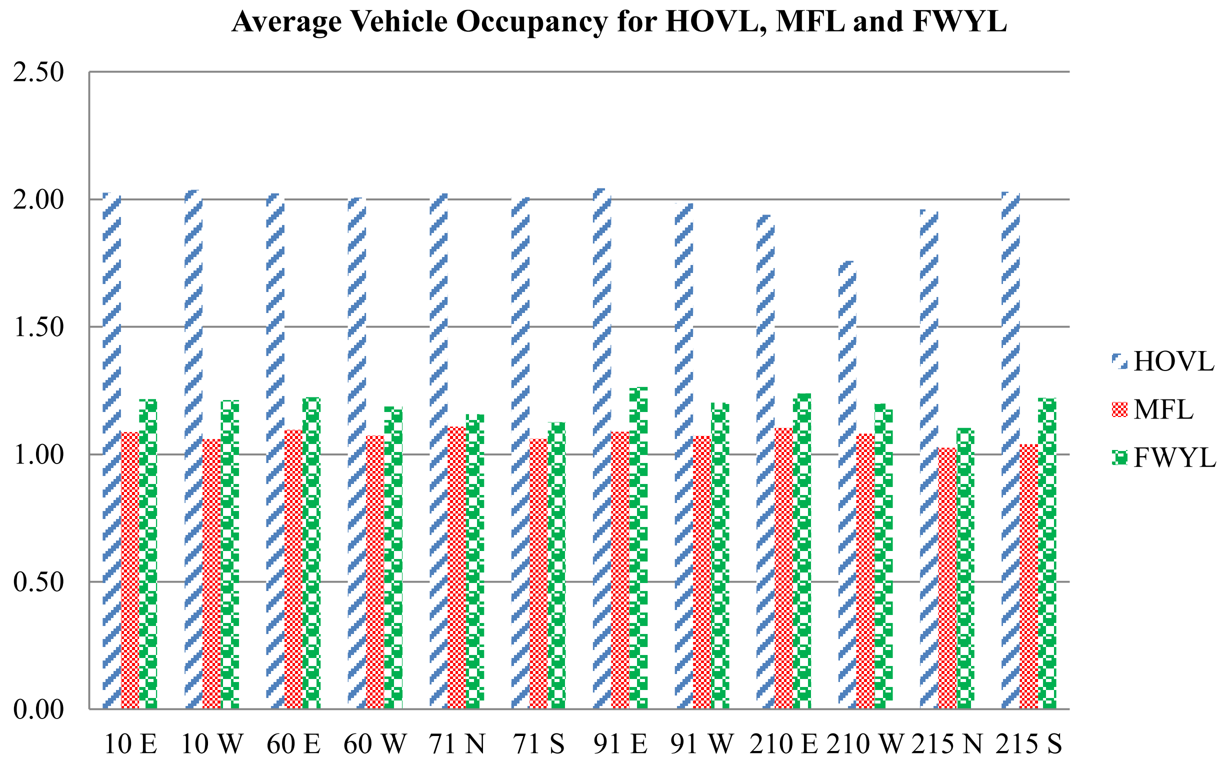


Figure 2-1. Average Vehicle Occupancy of D8 HOV Facilities

As shown in Figure 2-1, compared with the other HOVL, I-210 (both Eastbound and Westbound) has lower average vehicle occupancy. All D8 facilities are comparable in the AVO along mixed-flow lanes and freeway lanes.

HOV Violation Rate (%)

Figure 2-2 presents the surveyed HOV violation (in occupancy requirement only) rate for all D8 HOV facilities. Of all study routes, I-210 W has the highest HOV violation rate, which is consistent with the results of AVO shown in Figure 2-1.

Passenger Carried Ratio

The passenger carried ratio (PCR) of HOV lane to the average MF lane is

$$PCR = \frac{\#\ of\ people\ carried\ per\ HOVL}{\#\ of\ people\ carried\ per\ MFL} \qquad (2\text{-}4)$$

This measure is used to evaluate the people utilization of HOV facilities (HOVL vs. MFL). Figure 2-3 presents the PCR for all D8 HOV facilities. It can be observed that:

- The PCR for most D8 HOV facilities is greater than 1, i.e. on average, one HOVL carries more passenger than one MFL;
- The PCR is much smaller than the AVO shown in Figure 2-1 for most D8 HOV facilities, which means that the vehicle volume per MFL is much higher than that per HOVL.

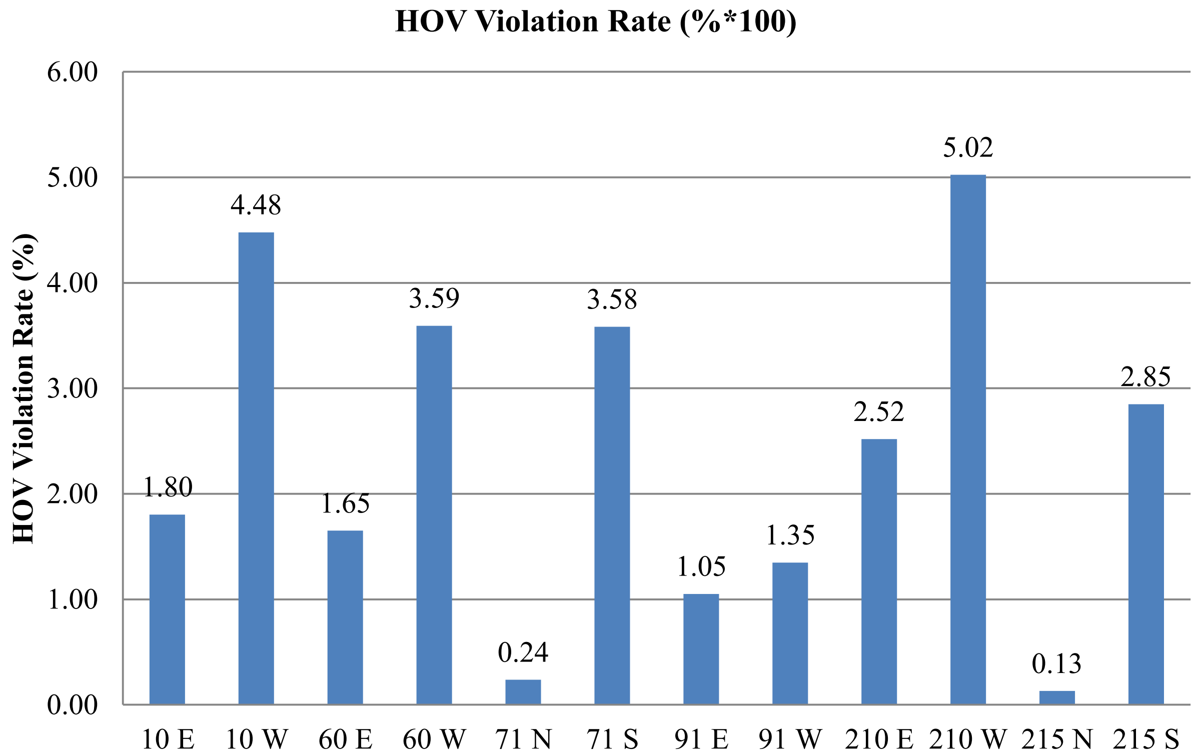


Figure 2-2. HOV Violation Rate of D8 HOV Facilities

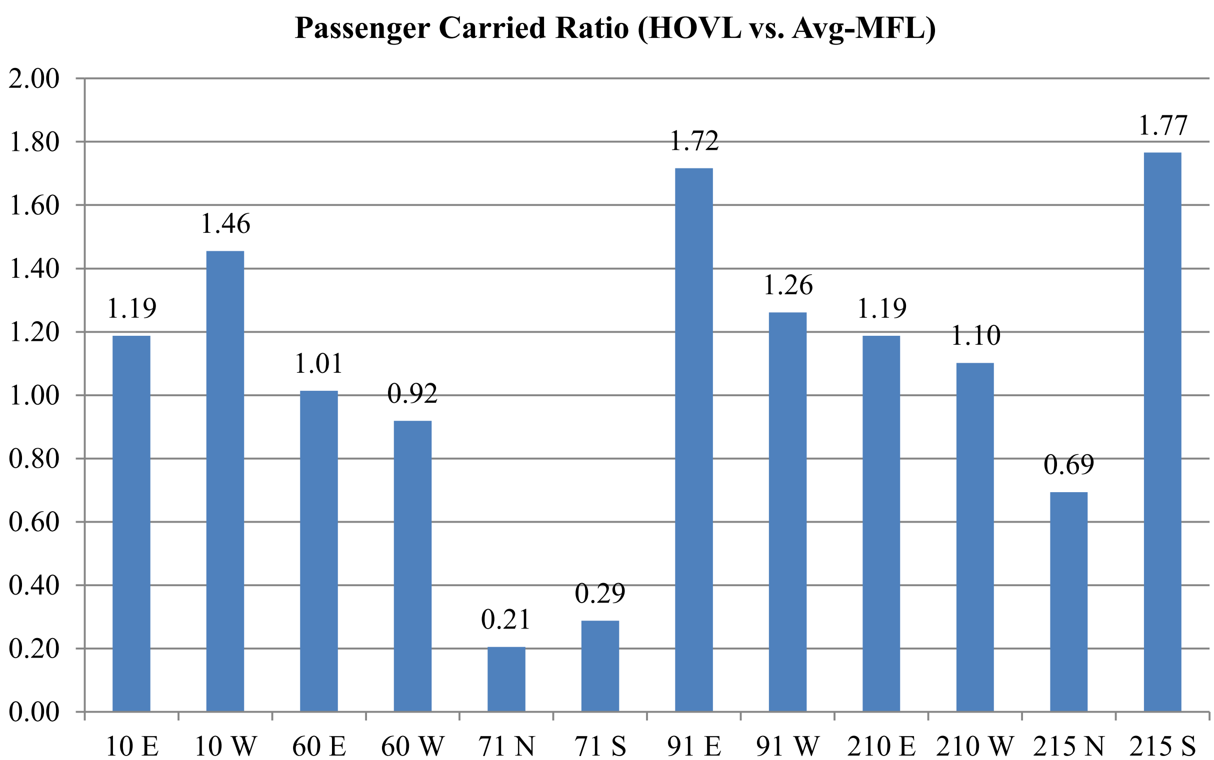


Figure 2-3. Passenger Carried Ratio of D8 HOV Facilities

Proportion of Carpool Vehicle on Each Lane Type

The proportion of carpool represents how much the carpool vehicles account for all types of vehicles along HOVL, mixed-flow lane and overall freeway lane. Figure 2-4 presents this proportion for all D8 HOV facilities. It is interesting to find out that in I-215 (continuous access) the carpool vehicle proportion is higher in HOVL but lower in MFL than any other routes.

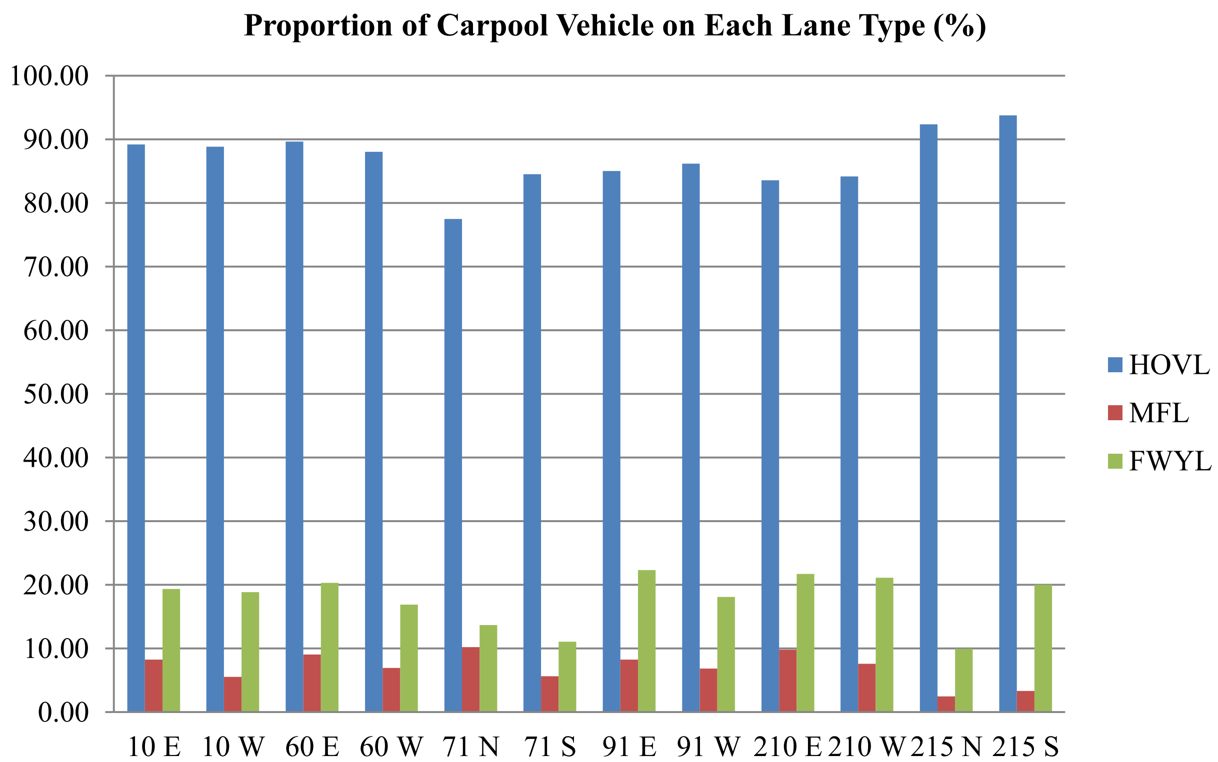


Figure 2-4. Carpool Vehicle Proportion along Each Lane Type of D8 HOV Facilities

Share of HOV Lane Carpool Vehicles

The share of HOV lane carpool vehicle is defined as:

$$S_{HOVL} = \frac{\#\ of\ Carpool\ vehicles\ in\ HOVL}{\#\ of\ Carpool\ vehicles\ in\ all\ lanes} \tag{2-5}$$

Figure 2-5 presents this value for all D8 HOV facilities. It is noted that the measure is higher for I-215 than any other routes in D8, which means that carpoolers utilize HOVL more along I-215. Combined with the findings from Figure 2-4, a potential reason is that it is more convenient for carpool to merge in or out of HOV lane for continuous-access facilities. As for SR-71, there is little stimulus for carpoolers to use HOVL due to the light traffic condition along MFL. Even worse, the flexibility of changing lane is restricted to some extent for this limited-access facility.

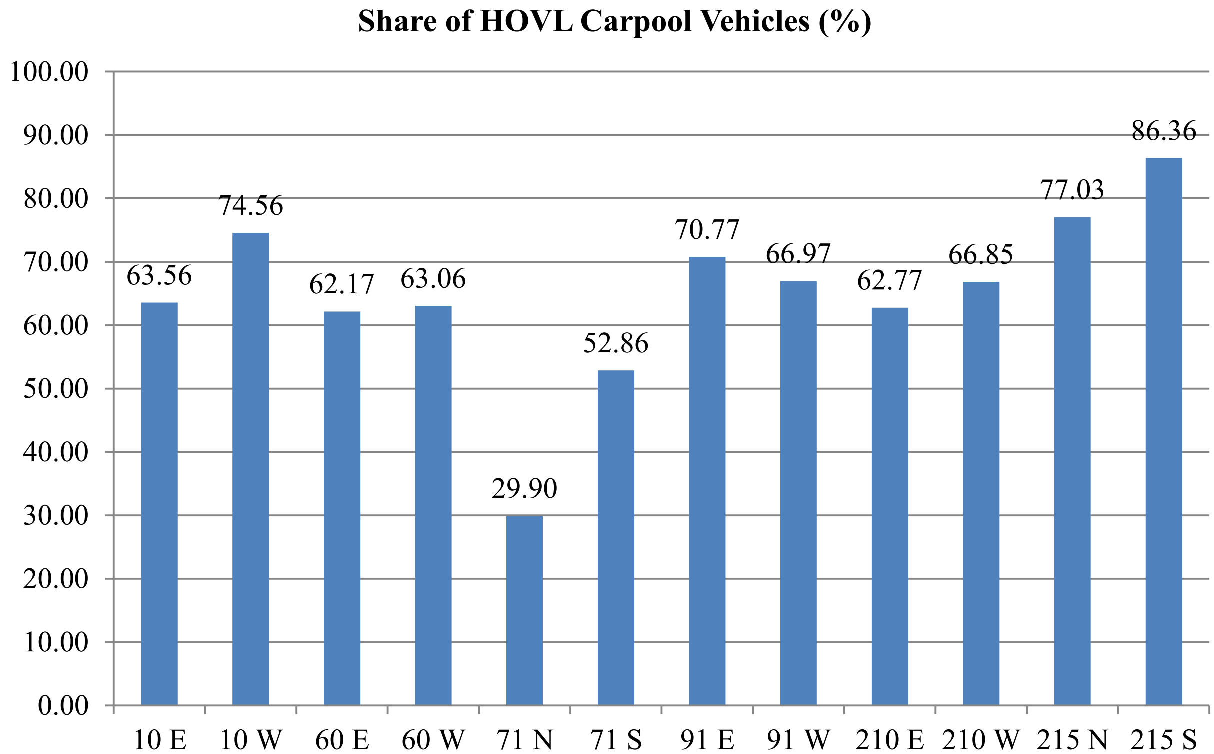


Figure 2-5. Share of HOVL Carpool Vehicles of D8 HOV Facilities

2.3. PeMS Data Analysis

To obtain further insight into the performance of HOV facilities with continuous-access and limited-access, real-world loop detector data archived in the Caltrans Performance Measurement System (PeMS) have been extensively processed and the results have been analyzed accordingly.

2.3.1. Scope of the Study

The scope of this study includes totally 12 corridors (listed in Table 2-2), which cover around 150 miles of freeway segments with HOV facilities throughout District 8. Five-minute aggregated traffic data, including count and loop occupancy for each lane during the typical weekdays (Tuesdays, Wednesdays and Thursdays) throughout the Year 2009 were used to evaluate the performance of each HOV facility. In addition, estimated speeds using the *g*-factor algorithm [Jia et al., 2001] served as another statistic for comparison across both HOV lanes and MF lanes of HOV facilities with different access control. The density used in the following analysis is computed from the flow and speed by using the fundamental relation, i.e. flow equals speed times density. Please note that the temporal range of examined data may vary with different types of analysis in the following sections due to the issue of computational efficiency. The temporal coverage of data samples will be specified again for each analysis.

Table 2-2. D8 HOV facilities in the scope of this study

<table>
<tr><th rowspan="2">HOV Type</th><th rowspan="2">Rte.</th><th rowspan="2">Dir.</th><th rowspan="2">County</th><th colspan="2">Study Boundary (CA PM)</th><th colspan="2">Study Boundary (Abs. PM)</th></tr>
<tr><th>Start</th><th>End</th><th>Start</th><th>End</th></tr>
<tr><td rowspan="2">Full-time, continuous</td><td rowspan="2">I-215</td><td>N</td><td>RIV</td><td>R37.6</td><td>43.97</td><td>29.27</td><td>35.94</td></tr>
<tr><td>S</td><td>RIV</td><td>R38.77</td><td>41.45</td><td>30.44</td><td>33.42</td></tr>
<tr><td rowspan="10">Full-time, buffered</td><td rowspan="2">I-10</td><td>E</td><td>SBD</td><td>0.59</td><td>10.53</td><td>47.36</td><td>57.30</td></tr>
<tr><td>W</td><td>SBD</td><td>0.72</td><td>10.53</td><td>47.49</td><td>57.30</td></tr>
<tr><td rowspan="2">SR-60</td><td>E</td><td>RIV/SBD</td><td>R1.17</td><td>16.20</td><td>31.77</td><td>56.32</td></tr>
<tr><td>W</td><td>RIV/SBD</td><td>0.28</td><td>16.60</td><td>30.88</td><td>56.72</td></tr>
<tr><td rowspan="2">SR-71</td><td>N</td><td>SBD</td><td>R0.86</td><td>R8.03</td><td>5.81</td><td>12.98</td></tr>
<tr><td>S</td><td>SBD</td><td>R0.38</td><td>R8.21</td><td>5.33</td><td>13.16</td></tr>
<tr><td rowspan="2">SR-91</td><td>E</td><td>RIV</td><td>R0.05</td><td>21.48</td><td>37.28</td><td>58.71</td></tr>
<tr><td>W</td><td>RIV</td><td>R0.40</td><td>20.86</td><td>37.72</td><td>58.18</td></tr>
<tr><td rowspan="2">I-210</td><td>E</td><td>SBD</td><td>1.40</td><td>14.90</td><td>53.84</td><td>67.34</td></tr>
<tr><td>W</td><td>SBD</td><td>0.10</td><td>14.88</td><td>52.54</td><td>67.32</td></tr>
</table>

Based on the statement in the white paper "Summary of Refined Methodologies for Evaluating Operational Performance of Freeways with HOV facilities in California", two types of analysis have been conducted on the traffic data collected from loop detectors: a) Corridor level analysis; b) VDS (vehicle detector station) level analysis. Before detailing each type of analysis, it should be pointed out that two selection criteria have been followed to guarantee the fidelity of loop detector data.

- Data samples come from those loop detectors with indicator of "good" health condition;
- The percentage of observed samples is above 80%.

However, verifying the validity of PeMS data is a fundamental issue, which is beyond the scope of this study. Readers if interested may refer to [Kwon et al., 2007] for further information.

2.3.2. Analysis Results

This document focuses on the corridor level analysis. In this analysis, the performance measures have been calculated and compared with one another route-by-route. For fair comparison, the selected performance measures should be independent of the length of study corridors. In this report, the following types of analysis have been conducted for each study corridors.

- Recurrent bottlenecks
- Space mean speed and identification of peak hour
- VMT and PMT ratio during peak hour
- HOVL-MFL joint LOS matrix during peak hour
- Percentile-based speed difference vs. density
- Speed-flow joint probability distribution

Recurrent Bottlenecks

To identify the recurrent bottleneck(s) along each corridor, traffic data within the 6-month period (May 2009 through October 2009) from PeMS database have been extensively investigated. Unlike conventional bottleneck identification methods based on the speed contour of a single-day data, a percentile-based speed contour is plotted by integrating traffic information collected from multiple days (e.g. 6 months).

The p-th percentile speed over D days at the i-th loop detector station during the t-th discrete time interval (e.g. every 5 minutes) is denoted by $\mathrm{v}^{\mathrm{p}}(\mathrm{i},\mathrm{t})$, and the probability of observing speed at detector i at time t on the d-th day, $v_d(i,t)$, lower than $v^p(i,t)$ can be defined as

$$P\big(v_d(i,t) \le v^p(i,t)\big) \ge p \quad \forall d = 1, 2, \cdots, D \tag{2-6}$$

where $\mathrm{P}(\cdot)$ represents the probability operator.

Instead of plotting one speed contour for each day over a long period (e.g. 6 months), one "representative" speed contour is plotted against speed data sample which is selected based on the user-defined percentile (e.g. 50th percentile or median) for each individual detector during each time interval over multiple days [Brownstone et al., 2008]. Such method is more flexible and robust than choosing an average speed, which may be biased by "outliers" that may arise due to abnormal traffic conditions such as incidents, special events, and road construction. Therefore, recurrent bottleneck(s) of a study route can be identified more easily. It should be noted that the lower the percentile value is selected, the more bottlenecks with less recurrence will be identified.

The 50th percentile speed contour plots of HOV lane and adjacent MF lane for SR-91 E are shown in Figure 2-6, where the color-bars represent the range of speed (in mph). The similar speed contour plots for all D8 HOV facilities are given in Appendix A. Observations from these percentile-based speed contour plots are made as follows:

- For limited-access HOV facilities (e.g., SR-91 E), all HOV lane bottlenecks (speed below 45 mph) in the peak hours occur around the ingress/egress areas and they are highly related to the adjacent MF lane bottlenecks (speed below 35 mph). A hypothesis of this phenomenon is that the relatively more concentrated lane changing maneuvers around the ingress/egress areas may generate shockwaves which propagated upstream along HOV lanes. In addition, the downstream congestion along adjacent MF lanes may deteriorate the upstream congestion along HOV lanes due to the slowing down effect on HOVs which attempt to move out from HOV lanes;

- For continuous-access HOV facilities (e.g., I-215 N), bottlenecks along HOV lanes and adjacent MFL may be caused by the lane merging of interchange between I-215 and SR-60.

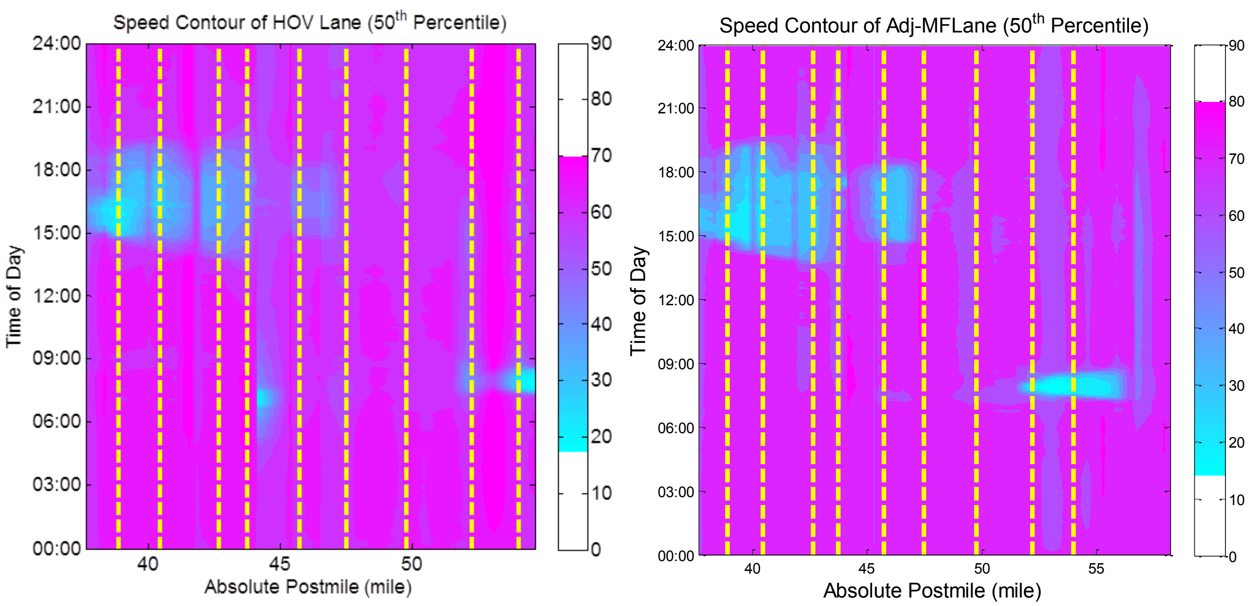


Figure 2-6. 50th Percentile Speed Contours for SR-91 E

Space Mean Speed

To evaluate the operational performance of each corridor during the peak hour (the most congested 1-hour period during a day), corridor space mean speed or corridor efficiency Q has been investigated, which is the ratio of the output, VMT (vehicle-mile-traveled), to the input of a freeway system, VHT (vehicle-hour-traveled), or

$$Q = \frac{VMT}{VHT} \tag{2-7}$$

The higher the Q is, the better the freeway segment performs (PeMS 2011). The Q value can also be thought of as an average travel speed along a corridor. Accordingly, the Q values for HOV lane, average mixed-flow lane (MFL) and average freeway lane (FWYL) can be described as

$$Q_{HOVL} = \frac{VMT_{HOVL}}{VHT_{HOVL}} \tag{2-8}$$

$$Q_{Avg-MFL} = \frac{VMT_{Avg-MFL}}{VHT_{Avg-MFL}} \tag{2-9}$$

$$Q_{Avg-FWYL} = \frac{VMT_{Avg-FWYL}}{VHT_{Avg-FWYL}} \tag{2-10}$$

Vehicle-miles traveled (VMT) and vehicle-hours traveled (VHT) for the segment at the *i*-th lane over a predetermined period, e.g. the peak period, can be computed as

$$VMT_i = \sum_j \sum_t q_i(x_j, t) \cdot L_j \tag{2-11}$$

$$VHT_i = \sum_j \sum_t q_i(x_j, t) \cdot \frac{L_j}{v_i(x_j, t)} \tag{2-12}$$

where, x_j is the location (in post-mile) of the *j*-th VDS within the segment. $q_i(x_j,\ t)$ and $v_i(x_j,\ t)$ are the total flow and average speed on lane i at x_j during time interval t. L_j is the effective length of the *j*-th VDS [Kwon and Varaiya, 2008].

According the above equations, *Q*, therefore, can be also viewed as the weighted harmonic mean of estimated speed at each VDS and the weighting factor for *j*-th VDS is

$$\omega_j = \sum_t q_i(x_j, t) \cdot L_j / \sum_j \sum_t q_i(x_j, t) \cdot L_j \tag{2-13}$$

One of the heuristic methods to determine the peak hour of a corridor during a typical weekday is to search for the 1-hour period (e.g. 16:00 – 17:00) with the lowest corridor efficiency over a sampled weekday (e.g. Wednesday). However, the results may be biased due to non-recurrent traffic conditions, such as an accident or a special event. To overcome this shortfall, 5-minute aggregate traffic data from PeMS over typical weekdays (i.e. Tuesdays, Wednesdays, and Thursdays) throughout the Year 2009 are used to calculate the corridor VMT and VHT for each study route. Due to the additive property of both VMT and VHT, the *i*-th corridor efficiency between the time of day t_1 and t_2 (e.g. 16:00 – 17:00) over *n* days can be written as

$$Q_i(t_1, t_2) = \sum_{k=1}^{n} VMT_{i,k}(t_1, t_2) / \sum_{k=1}^{n} VHT_{i,k}(t_1, t_2) \tag{2-14}$$

where k is the index of day. By following the procedure shown below, the peak hour for each individual route can then be identified. It should be pointed out that the obtained peak hour using this method may not necessarily be on the hour. In addition, the identified peak hours for HOV lane, average MF lane and average freeway lane may be different because the time interval when Q values reach minima may not coincide among HOV lane, average MF lane and average freeway lane.

```
Peak-Hour Finding Procedure:

Δ = 01:00:00;
FOR EACH    Route i;
   Q_i^min = 90 mph;
   t_{i,1}^min = 00:00:00;
   t_{i,2}^min = t_1^min + Δ;
   FOR EACH    t_1 = 00:00:00 to 23:55:00 with an increment of 00:05:00;
      t_2 = t_1 + Δ;
      IF    t_2 ≥ 24:00:00
         t_2 ← t_2 – 24:00:00;
      END IF
      Calculate   VMT_{i,k}, ∀k     using Equation (2-11);
      Calculate   VHT_{i,k}, ∀k     using Equation (2-12);
      Calculate   Q_i(t_1, t_2)     using Equation (2-14);
      IF    Q_i(t_1, t_2) < Q^min
         Q^min ← Q_i(t_1, t_2);
         t_{i,1}^min ← t_1;
         t_{i,2}^min ← t_2;
      END IF
   END FOR
END FOR
```

Table 2-3 presents the results on peak hours for each route. Based on the observations, some remarks can be made as follows:

- Except for SR-71, directional peaks can be clearly observed for all study routes for HOV lanes, average MF lanes, and average freeway lanes. That is, for the same route, if there is a peak in traffic volume along one direction in the morning, then there will be another peak along the opposite direction in the afternoon. Compared to other routes, the Q values of SR-71 are relatively higher due to having less traffic demand.

- For some of the limited access HOV facilities, the corridor efficiency along HOV lane is slightly worse than that along average MF lane during the peak hour. For I-215 N which has continuous access HOV lane, the HOV lane operates much better than average MF lane or average freeway lane in the morning peak. A hypothesis of this phenomenon is that the proportion of HOV in the traffic mix may be imbalance with the capacity ratio of HOV lane to overall freeway.

Based on the previous results, the statistics of Q value during peak hour over the Year 2009 for each route can then be compared to one another. Figure 2-7 through Figure 2-9 present the box plots of Q values for HOV lane, average MF lane, and average freeway lane along each route, respectively. The statistical elements of a box plot are also illustrated in Figure 2-7. It can be observed that the corridor efficiency along HOV lane of SR-91 (for both directions) is much lower than any other routes during the peak hour. The average MF lane and average freeway lane of I-215 N perform unsatisfactorily in the morning peak. It needs to be pointed out that not only specific geometric feature but also traffic demand is responsible for the Q values.

Table 2-3. Summary of peak hour for each study route

Route	Direction	Avg. FWYL Peak Hour	Q_{HOVL}	$Q_{Avg\text{-}MFL}$	$Q_{Avg\text{-}FWYL}$
I-10	E	17:05 - 18:05	52.11	52.84	52.65
I-10	W	07:20 - 08:20	53.19	56.25	55.71
SR-60	E	17:05 - 18:05	53.47	54.09	53.95
SR-60	W	07:20 - 08:20	58.55	52.04	52.95
SR-71	N	16:55 - 17:55	57.04	63.77	61.75
SR-71	S	17:05 - 18:05	57.30	63.84	61.87
SR-91	E	15:35 - 16:35	41.18	40.17	40.37
SR-91	W	06:25 - 07:25	38.98	37.42	37.68
I-210	E	17:10 - 18:10	54.56	51.14	51.79
I-210	W	07:20 - 08:20	57.11	52.68	53.51
I-215	N	07:25 - 08:25	52.14	37.99	39.52
I-215	S	17:10 - 18:10	49.15	52.04	51.07

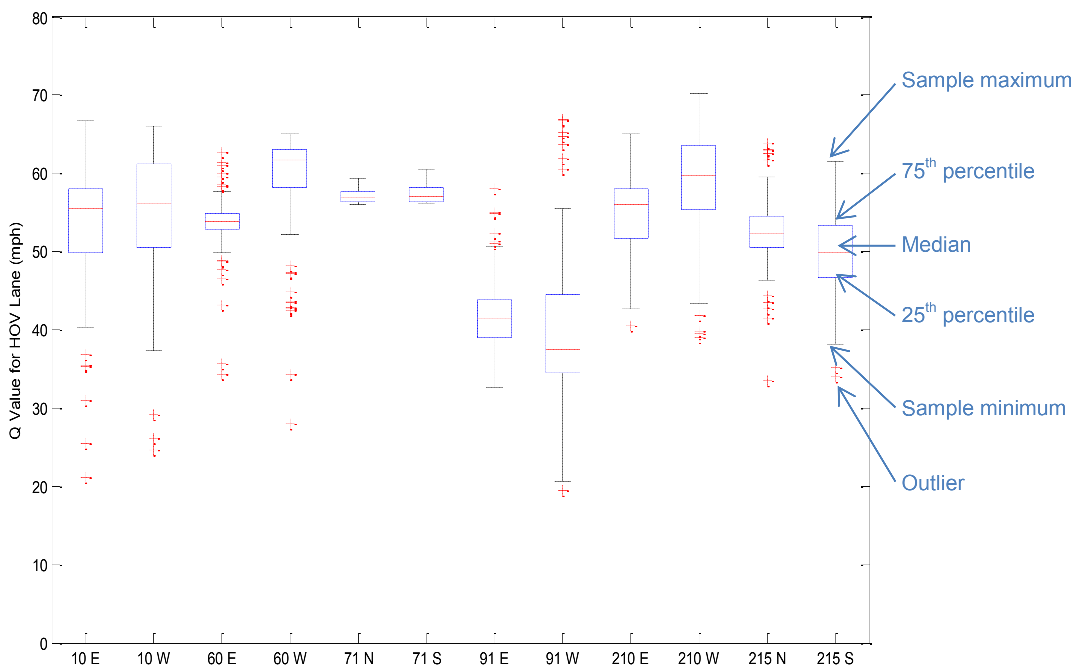


Figure 2-7. Q of HOVL during HOVL Peak Hour for Each Study Route in D8

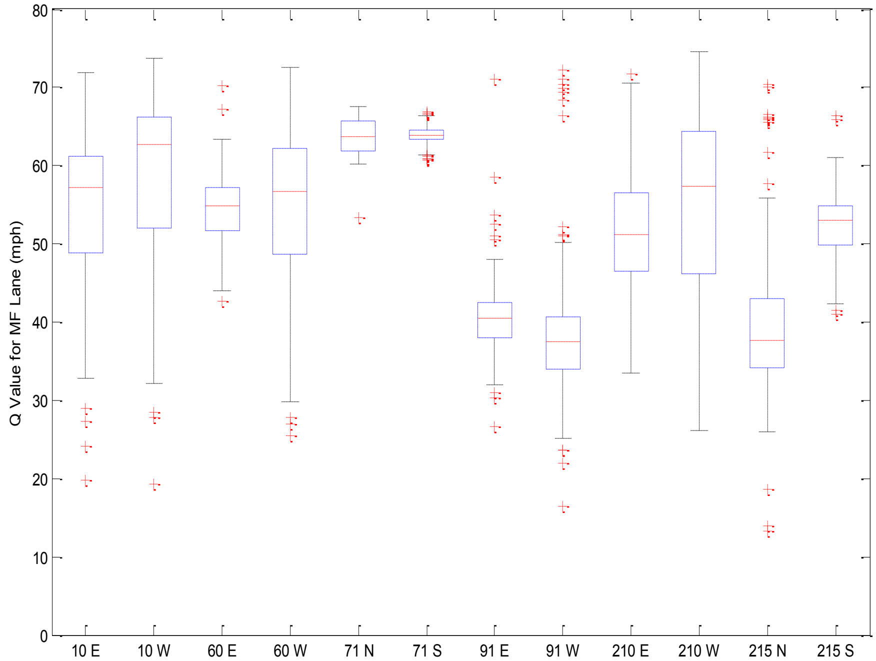


Figure 2-8. Q of Average MFL during Average MFL Peak Hour for Each Study Route in D8

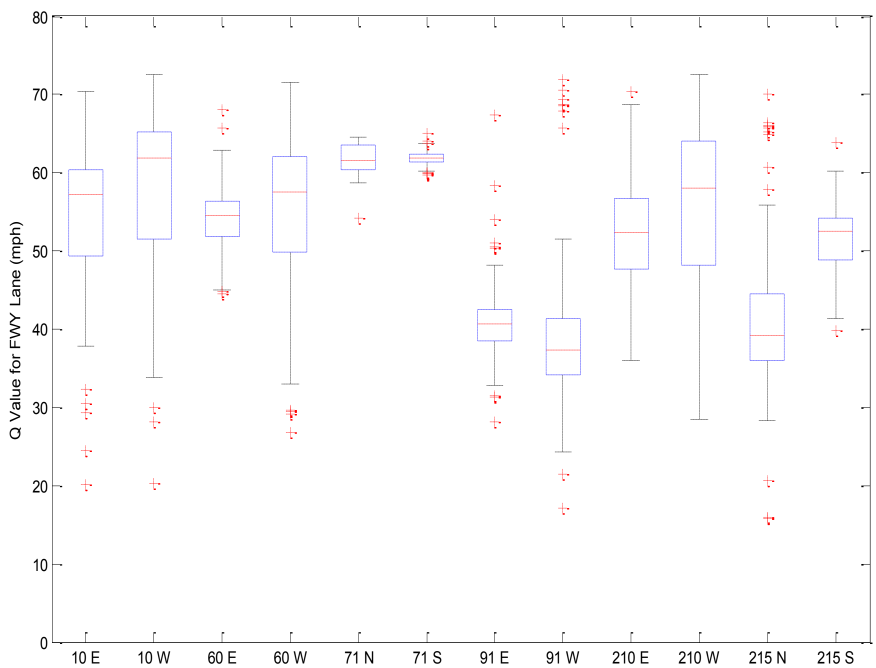


Figure 2-9. Q of Average FWYL during Average FWYL Peak Hour for Each Study Route in D8

VMT and PMT Ratio

Based on the same peak hour data for all D8 HOV facilities, the vehicle-mile-traveled (VMT) ratio of HOV lane vs. average MF lane at the route level has been obtained and presented in Figure 2-10. On the other hand, due to the limited availability of vehicle occupancy count data, statistics from *D8 HOV Monitoring Report* (Fall 2008) were used to estimate person-mile-traveled (PMT) ratio between HOV lane and MF lane for each route. It is simply assumed that the vehicle occupancy on a route basis is a constant and is the average of multiple field observations from the same route. The result is shown in Figure 2-11.
It can be observed that:

- For most samples from I-10 E, SR-71 and I-215 S, the peak hour VMT ratio of HOVL vs. average MFL, or the ratio of weighted traffic flow, is higher than 1, where the weight is defined as

$$\bar{\omega}_j = L_j / \sum_j L_j \tag{2-15}$$

  while HOV lanes of the other routes experience less VMT than the associated average MFL.

- However, except for SR-91 E, the person-mile-traveled along HOV lanes of all D8 HOV facilities in most cases are higher than those of average mixed-flow lanes during the peak hour.

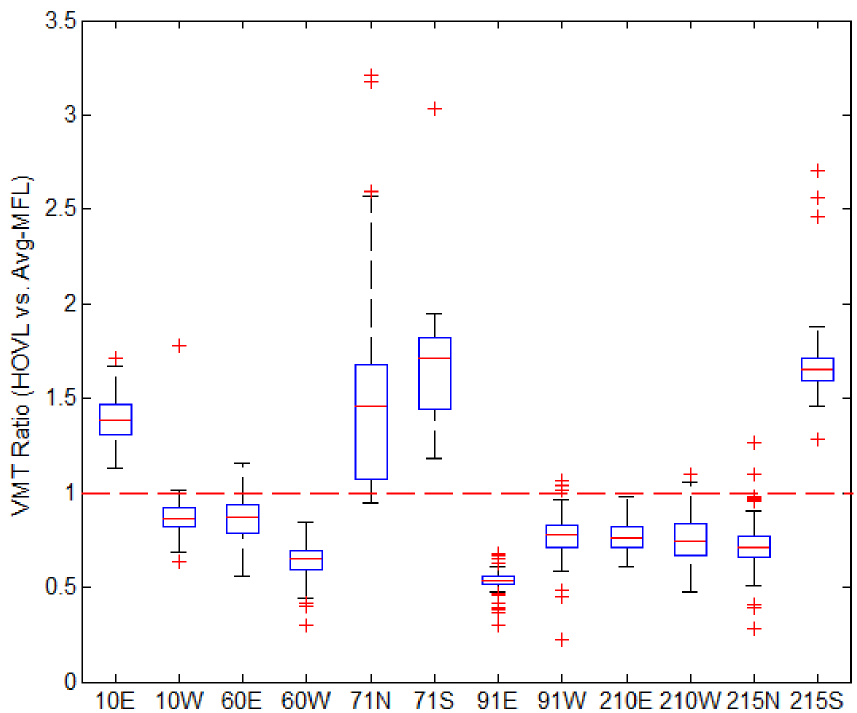


Figure 2-10. VMT Ratio of HOV Lane vs. Average MF Lane during Peak Hour

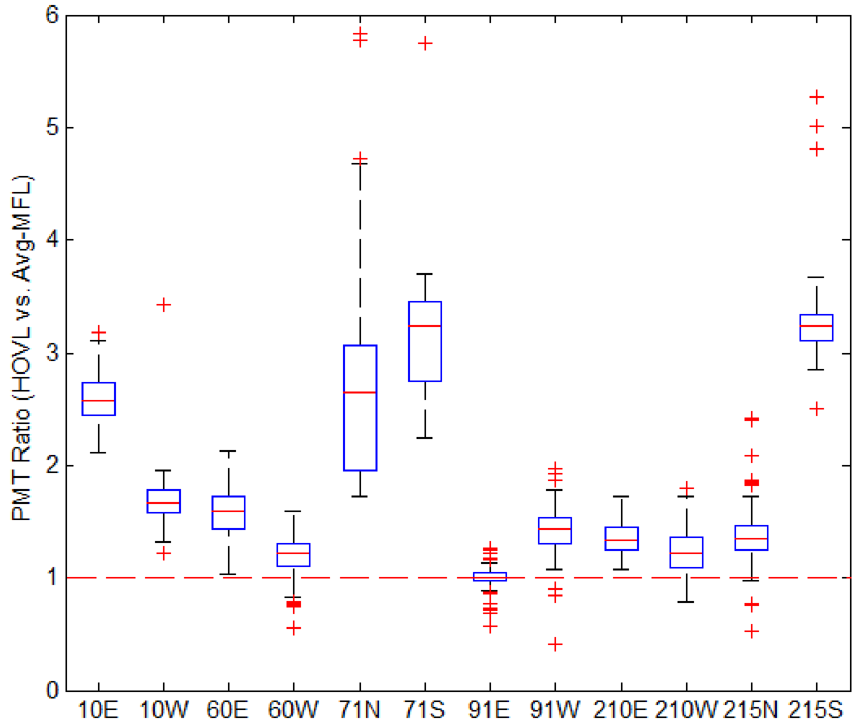


Figure 2-11. PMT Ratio of HOV Lane vs. Average MF Lane during Peak Hour

HOVL-MFL LOS Matrix

Density is useful in identifying the states of traffic conditions along freeways. To determine the representative traffic states during the peak hour, the HOVL-MFL density joint distributions have been plotted for all D8 HOV facilities based on PeMS data in year 2009. Figure 2-12 illustrates the result for SR-91 E during the peak hour (either morning or afternoon). The results for all other routes in District 8 are given in Appendix B. The colored vertical bar on the right of these plots shows the range of probability for each HOVL-MFL joint LOS cell, and the sum of the probability for all the cells in the plot is 1.0. For example, in Figure 2-12 the probability of both HOVL and MFL having LOS F at the same time (the most upper right cell in the plot) is 0.09. In other words, during the peak hour of SR-91 E, both HOVL and MFL would have LOS F at the same time for 9% of the time. According to these figures, the representative (i.e. the most frequent occurrence) traffic state, or the mode of density ranges for both HOV lane and average MF lanes, can be obtained and summarized in Table 2-4.

In addition, the level of service (LOS) is specified in the same table based on the referenced density ranges provided by *Highway Capacity Manual 2000* [Transportation Research Board, 2000]. It should be noted that, HCM 2000 does not provide any suggestion on HOV facilities performance. In this document, it is assumed that the density-based LOS definition for basic freeway segment also applies to HOVL. It turns out that for most D8 HOV facilities (except for SR-71) the level-of-service of HOVL is better than that of average MFL during the peak hour. For SR-71, the HOVL experience LOS B while the LOS of average MFL is A. This may be due to having a slow vehicle in the limited access HOVL, which blocks and slows down the following vehicles in the lane (referred to "snail effect") [Kwon and Varaiya, 2008].

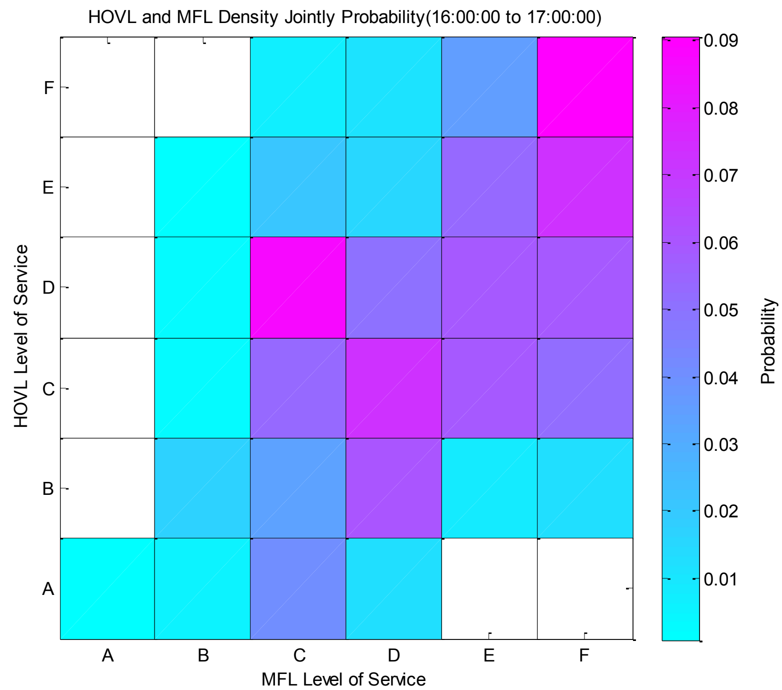


Figure 2-12. HOVL-MFL Joint LOS Matrix during Peak Hour for SR-91 E

Table 2-4. Summary of Representative HOVL-MFL Joint Density for D8 HOV Facilities

Rte.	Dir.	Peak Hour*	Traffic Density (vehicle per mile per lane)		LOS	
			HOVL	MFL	HOVL	MFL
I-10	E	17:00 – 18:00	11 ~ 18	18 ~ 26	B	C
	W	07:00 – 08:00	11 ~ 18	18 ~ 26	B	C
SR-60	E	17:00 – 18:00	11 ~ 18	18 ~ 26	B	C
	W	07:00 – 08:00	0 ~ 11	18 ~ 26	A	C
SR-71	N	17:00 – 18:00	11 ~ 18	0 ~ 11	B	A
	S	17:00 – 18:00	11 ~ 18	0 ~ 11	B	A
SR-91	E	16:00 – 17:00	> 45	> 45	F	F
	W	06:00 – 07:00	0 ~ 11	18 ~ 26	A	C
I-210	E	17:00 – 18:00	18 ~ 26	26 ~ 35	C	D
	W	07:00 – 08:00	0 ~ 11	18 ~ 26	A	C
I-215	N	07:00 – 08:00	11 ~ 18	35 ~ 45	B	E
	S	17:00 – 18:00	18 ~ 26	26 ~ 35	C	D

** Peak hour for each route is determined on the hour which is closest to the results from Table 2-3*

Percentile-based Speed Difference vs. Density

As for HOV facilities, densities of HOV lanes and adjacent MF lanes and the associated speed differences may also provide stimuli for drivers to change lanes across the access. To further explore the relationship between the speed differential ($v_{HOVL} - v_{Adj-MFL}$) and traffic states, percentile-based speed difference vs. vehicular densities of HOV lanes and adjacent MF lanes for all D8 HOV facilities were plotted. The plot for SR-91 E is shown in Figure 2-13 and the rest are provided in Appendix C. In these figures, each data point represents the median (50^{th} percentile) speed difference with respect to each combination of vehicular densities along both lanes. The colored vertical bar on the right of these plots shows the range of speed differences between HOVL and the adjacent MFL. Positive values mean the speed in HOVL is higher and vice versa. It should be noted that PeMS data of typical weekdays (all day long) between May 2009 and October 2009 were used in this analysis and the results were aggregated with a resolution of 2 veh/mile in density. In addition, data records where HOVL speed was lower than adjacent MFL speed by more than 40 mph were removed as they are unreasonable and may be caused by loop detector errors.

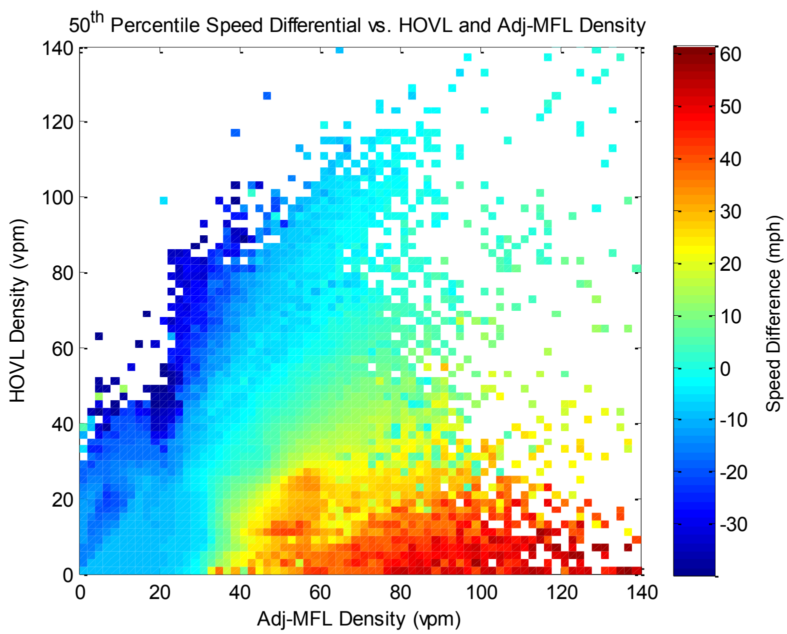


Figure 2-13. 50th Percentile Speed Difference vs. Density of HOVL and Adj-MFL for SR-91 E

It can be observed that compared with limited-access HOV facilities, there are much less data samples where the HOVL density is much higher than that of adjacent MFL for continuous-access HOV facilities in District 8 (i.e., I-215). Hence, a hypothesis for this phenomenon is that lane-change maneuvers are more restrictive in limited-access HOV facilities than in continuous-access ones. This results in a more concentrated occurrence of congested states in HOV lane traffic even though the density of HOV lane is much higher than that of adjacent MF lane.

Speed-Flow Joint Probability Distribution

To evaluate the operational performance of different access types of HOV facilities when the traffic demand is high, the 3-hour data samples for either morning peak (6-9 a.m.) or afternoon peak (3-6 p.m.) of typical weekdays (Tuesdays, Wednesdays, and Thursdays) between May 2009 and October 2009 were used to create speed-flow joint probability distributions for both HOV lane and adjacent MF lane of each individual route in D8. Figure 2-14 illustrates the result for SR-91 E. The results of other routes are given in Appendix D. The colored vertical bar on the right of these plots shows the range of probability density (not cumulative) for each cell in the figures. The sum of probability densities for all these cells is 1.0.This type of probability histogram has been used in [Kwon and Varaiya, 2008] to evaluate the utilization and capacity of HOV lanes.

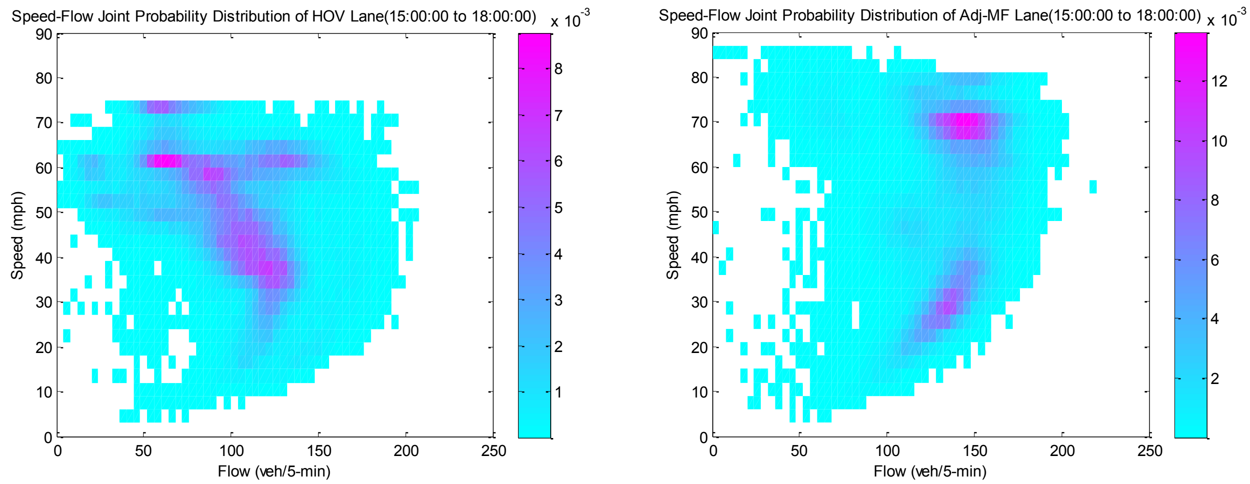


Figure 2-14. Speed-Flow Joint Probability Distributions for SR-91 E (p.m.)

The followings can be observed from these figures:

- Except for I-215 S, the modes of the joint probability distributions (representing the highest probability) for both continuous and limited access HOV facilities during peak periods occur at speeds around 60 mph and flows below 100 veh/5-min or 1,200 veh/hr. This suggests that most HOV facilities in D8 are typically not congested. On the other hand, the HOVL on I-215 S is very congested during the afternoon peak with the mode of speed being as low as 30 mph. This implies that this HOV lane may be over-utilized.

- The modes of the joint probability distributions of the adjacent MF lanes on these freeways during peak periods occur at speeds around 70 mph and flows around 150 veh/5-min or 1,800 veh/hr, except for SR-71 (both directions) and I-215 S. The former experiences very light traffic throughout while the latter is very congested in the afternoon.

2.4. Field Data Collection and Analysis

To supplement the HOV Monitoring Report Statistics and PeMS data, a limited amount of field data was collected mainly to analyze HOV travel time savings. Tach runs were conducted in December 2009 to measure travel time on all freeways in D8 that have HOV lane. The tach runs were conducted using two GPS-instrumented vehicles, one running in the HOV lane and the other one in the second leftmost lane of the MF lanes (not the adjacent MF lane). Figure 2-15 shows an example of vehicle trajectory collected by the GPS-instrumented vehicles. Using the logged vehicle position and time stamp, travel times were calculated for each of the 10 segments labeled A-J in Figure 2-16. The travel time results are summarized in Table 2-5.

Since this set of tach runs were conducted close to the holiday season and after some schools and colleges in the area (e.g., UC Riverside) had already begun the winter break, it was felt that the travel time data might not reflect the typical traffic condition in the area. Therefore, another set of tach runs were conducted on the same 10 segments in November 2010. The travel time results of this set of tach runs are summarized in Table 2-6. Then, the travel time results from both sets of tach runs are compared in Table 2-7.

Several observations can be made with regards to the travel time results:

- Based on the tach run data collected in November 2010, HOV drivers could save travel time during the peak periods by using HOV lane instead of MF lanes on most of the freeways in D8.

- Based on the tach run data collected in November 2010, the travel time savings varied by route and peak period (morning or afternoon). For example, in the morning peak, the travel time for the HOV driver using HOVL on SR-60 W between I-215 interchange and Redlands Blvd was 61.4% less than that for the SOV driver using MFL. On the other hand, both drivers experienced similar travel times on the same segment of SR-60 E in the morning.

- By comparing the tach run data collected in December 2009 and November 2010, it is observed that, for most HOV facilities, the amount of travel time saving was similar while a few HOV facilities experienced considerably different amount of travel time saving.

- It should be noted that due to the limited sample size of travel time collected on each segment of D8 HOV facilities, the results could be biased due to atypical circumstance, e.g., accident or lane closure. Statistical tests could be performed to test the significance of the results if a larger sample size was available.

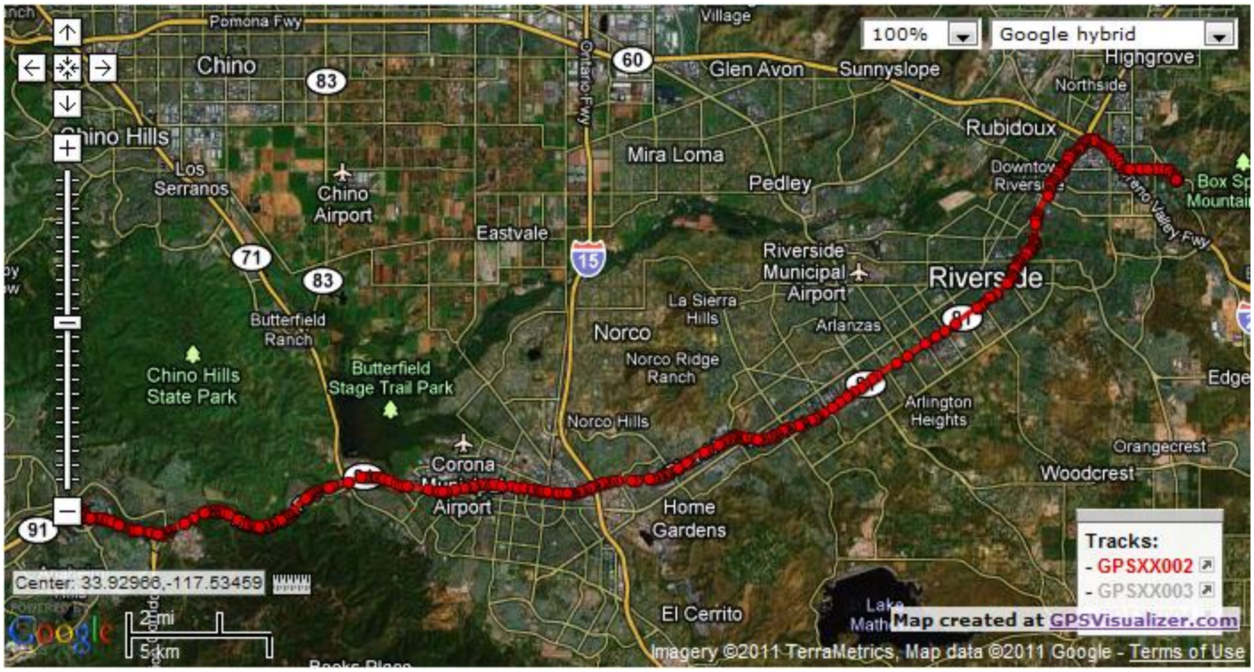


Figure 2-15. Vehicle trajectory of an HOV run on Nov. 15th, 2010 (a.m.) along SR-91 W

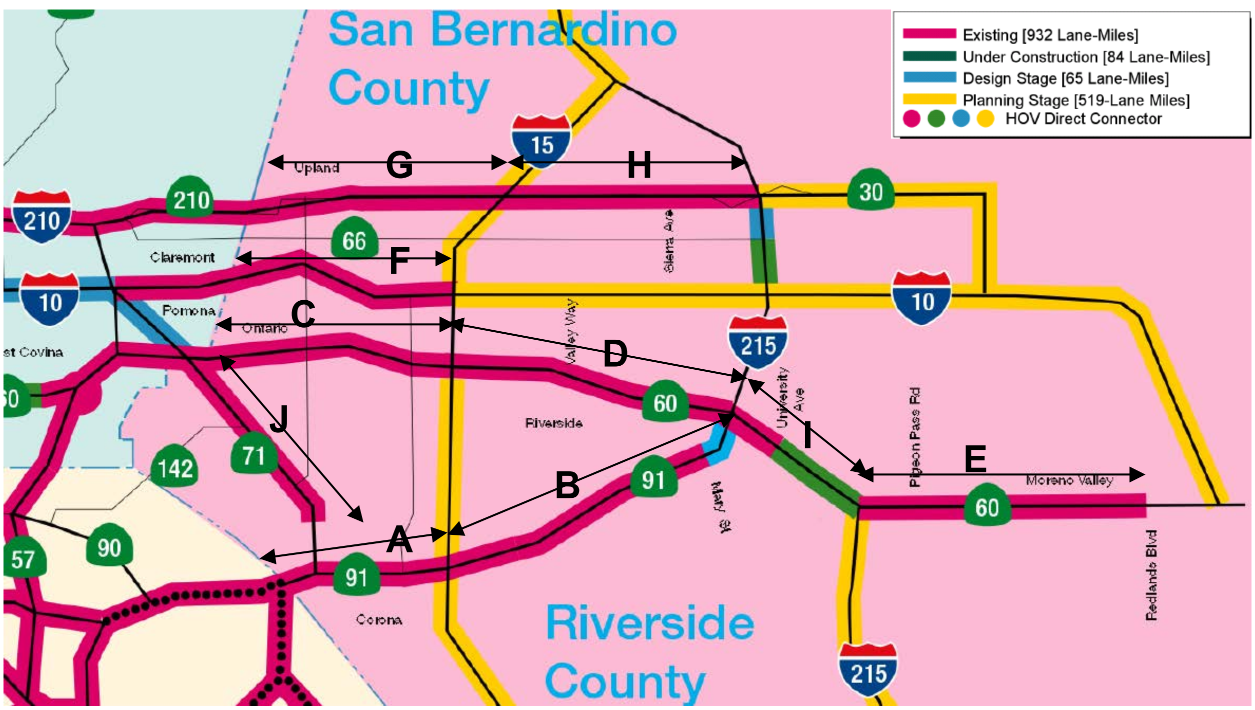


Figure 2-16. Segments of HOV facilities in D8 for travel time analysis

Table 2-5. Results of tach runs in December 2009

Fwy	Dir	Period	Hour	Segment	Description	Length	Travel Time (mins)		Avg Speed (mph)		HOV Travel Time Saving		
						(mi)	MF	HOV	MF	HOV	(mins)	(%)	(sec/mile)
91	E	AM	8-9	A	Green River Rd to I-15	6.2	5.6	5.2	66.0	71.1	0.4	7.1	3.9
			8-9	B	I-15 to Riverside	9.3	8.9	7.7	62.5	72.9	1.3	14.4	8.3
		PM	4-5	A	Green River Rd to I-15	6.2	13.5	8.9	27.6	41.8	4.6	33.9	44.2
			4-5	B	I-15 to Riverside	9.3	12.0	9.2	46.4	60.4	2.8	23.3	18.1
	W	AM	8-9	B	Riverside to I-15	9.3	8.0	8.0	69.6	70.0	0.1	0.6	0.3
			8-9	A	I-15 to Green River Rd	6.2	7.9	6.0	47.3	62.5	1.9	24.4	18.5
		PM	4-5	B	Riverside to I-15	9.3	12.5	9.2	44.7	60.7	3.3	26.3	21.2
			4-5	A	I-15 to Green River Rd	6.2	5.8	5.5	64.5	67.2	0.2	4.0	2.3
60	E	AM	8-9	C	County Line to I-15	10.2	8.7	8.9	70.2	69.2	-0.1	-1.5	-0.8
			8-9	D	I-15 to I-215/SR-60/SR-91	11.4	10.2	10.3	66.8	66.4	-0.1	-0.7	-0.4
			8-9	E	I-215/SR-60 to Redlands Blvd	7.7	7.5	6.7	61.5	69.0	0.8	10.9	6.4
		PM	5-6	C	County Line to I-15	10.2	13.4	9.8	45.8	62.2	3.5	26.3	20.7
			5-6	D	I-15 to I-215/SR-60/SR-91	11.4	15.6	12.0	43.8	57.0	3.6	23.1	18.9
			5-6	E	I-215/SR-60 to Redlands Blvd	7.7	9.5	7.5	48.8	61.9	2.0	21.1	15.6
	W	AM	8-9	E	Redlands Blvd to I-215/SR-60	7.7	8.6	7.3	53.5	63.1	1.3	15.3	10.3
			8-9	D	I-215/SR-60/SR-91 to I-15	11.4	10.0	9.8	68.5	70.0	0.2	2.2	1.1
			8-9	C	I-15 to County Line	10.2	13.4	9.5	45.8	64.6	3.9	29.1	22.8
		PM	5-6	E	Redlands Blvd to I-215/SR-60	7.7	7.0	6.9	65.8	66.6	0.1	1.2	0.6
			5-6	D	I-215/SR-60/SR-91 to I-15	11.4	10.3	10.3	66.5	66.6	0.0	0.2	0.1
			5-6	C	I-15 to County Line	10.2	9.4	9.4	65.2	65.2	0.0	0.0	0.0
10	E	AM	8-9	F	County Line to I-15	9.4	8.2	7.5	68.9	75.0	0.7	8.1	4.3
		PM	5-6	F	County Line to I-15	9.4	15.5	10.2	36.4	55.4	5.3	34.3	33.9
	W	AM	9-10	F	I-15 to County Line	9.3	8.3	7.4	67.2	75.1	0.9	10.4	5.6
		PM	6-7	F	I-15 to County Line	9.3	9.4	8.8	59.2	63.3	0.6	6.5	4.0
210	E	AM	9-10	G	County Line to I-15	10.4	9.0	8.3	69.2	75.3	0.7	8.1	4.2
			9-10	H	I-15 to I-215	7.5	6.4	5.8	70.1	77.4	0.6	9.4	4.8
		PM	5-6	G	County Line to I-15	10.4	18.3	11.9	34.2	52.3	6.3	34.6	36.4
			5-6	H	I-15 to I-215	7.5	7.3	6.2	61.4	72.6	1.1	15.5	9.1
	W	AM	9-10	H	I-215 to I-15	8.8	7.8	7.1	67.4	74.2	0.7	9.1	4.9
			9-10	G	I-15 to County Line	11.5	10.0	9.5	68.9	73.0	0.6	5.7	3.0
		PM	5-6	H	I-215 to I-15	8.8	8.1	7.1	65.2	74.4	1.0	12.3	6.8
			5-6	G	I-15 to County Line	11.5	10.7	9.8	64.3	70.3	0.9	8.5	4.8
215	N	AM	8-9	I	I-215/SR-60 to I-215/SR-60/SR-91	5.2	8.3	5.6	37.8	55.9	2.7	32.3	30.8
		PM	5-6	I	I-215/SR-60 to I-215/SR-60/SR-91	5.2	5.3	4.8	58.9	65.7	0.6	10.4	6.3
	S	AM	8-9	I	I-215/SR-60/SR-91 to I-215/SR-60	5.2	4.8	4.9	65.0	63.5	-0.1	-2.4	-1.3
		PM	5-6	I	I-215/SR-60/SR-91 to I-215/SR-60	5.2	14.7	8.4	21.2	37.1	6.3	42.9	72.9
71	N	AM	8-9	J	SR-91 to SR-60	8.5	7.5	7.2	68.5	70.8	0.3	3.4	1.8
		PM	5-6	J	SR-91 to SR-60	8.5	7.8	7.3	65.8	69.5	0.4	5.4	2.9
	S	AM	10-11	J	SR-60 to SR-91	8.5	7.0	6.6	73.4	77.7	0.4	5.5	2.7
		PM	6-7	J	SR-60 to SR-91	8.5	7.9	7.3	64.3	69.7	0.6	7.8	4.4

Table 2-6. Results of tach runs in November 2010

Fwy	Dir	Period	Hour	Segment	Description	Length	Travel Time (mins)		Avg Speed (mph)		HOV Travel Time Saving		
						(mi)	MF	HOV	MF	HOV	(mins)	(%)	(sec/mile)
91	E	AM	9-10	A	Green River Rd to I-15	7.6	6.4	6.2	71.8	73.5	0.2	2.4	1.2
			9-10	B	I-15 to Riverside	8.6	6.9	6.9	74.4	74.2	0.0	-0.2	-0.1
		PM	6-7	A	Green River Rd to I-15	7.6	14.8	12.2	30.9	37.5	2.6	17.6	20.5
			6-7	B	I-15 to Riverside	8.6	9.0	7.5	57.4	68.6	1.5	16.3	10.2
	W	AM	7-8	B	Riverside to I-15	10	14.8	8.4	40.7	71.6	6.4	43.2	38.2
			7-8	A	I-15 to Green River Rd	7.6	21.8	14.4	20.9	31.8	7.4	34.1	58.6
		PM	4-5	B	Riverside to I-15	10	11.1	9.1	54.1	65.9	2.0	18.0	12.0
			4-5	A	I-15 to Green River Rd	7.6	6.8	6.4	67.4	70.9	0.3	4.9	2.6
60	E	AM	8-9	C	County Line to I-15	10.4	8.8	8.3	70.8	74.9	0.5	5.5	2.8
			9-10	D	I-15 to I-215/SR-60/SR-91	11.4	9.6	9.4	70.9	72.5	0.2	2.2	1.1
			7-8	E	I-215/SR-60 to Redlands Blvd	6.7	5.3	5.4	75.6	74.0	-0.1	-2.2	-1.0
		PM	6-7	C	County Line to I-15	10.4	13.0	10.7	48.1	58.4	2.3	17.6	13.2
			6-7	D	I-15 to I-215/SR-60/SR-91	11.4	12.0	12.2	57.2	56.1	-0.2	-1.9	-1.2
			4-5	E	I-215/SR-60 to Redlands Blvd	6.7	7.7	6.3	51.9	64.1	1.5	19.1	13.3
	W	AM	7-8	E	Redlands Blvd to I-215/SR-60	6.9	16.6	6.4	25.0	64.7	10.2	61.4	88.4
			7-8	D	I-215/SR-60/SR-91 to I-15	11	9.4	9.3	69.8	71.0	0.1	1.6	0.8
			7-8	C	I-15 to County Line	10.4	10.3	9.1	60.6	68.8	1.2	12.0	7.1
		PM	5-6	E	Redlands Blvd to I-215/SR-60	6.9	6.3	6.2	65.2	67.0	0.2	2.6	1.4
			3-4	D	I-215/SR-60/SR-91 to I-15	11	9.8	8.6	67.3	76.9	1.2	12.4	6.6
			4-5	C	I-15 to County Line	10.4	9.7	8.9	64.7	69.7	0.7	7.3	4.0
10	E	AM	7-8	F	County Line to I-15	8.3	8.0	7.5	62.4	66.7	0.5	6.5	3.7
		PM	4-5	F	County Line to I-15	8.3	8.9	7.8	55.6	63.7	1.1	12.7	8.2
	W	AM	8-9	F	I-15 to County Line	8.6	7.3	7.3	70.7	71.0	0.0	0.5	0.2
		PM	5-6	F	I-15 to County Line	8.6	8.7	7.5	59.1	68.5	1.2	13.7	8.4
210	E	AM	7-8	G	County Line to I-15	11.5	9.9	10.0	69.6	69.0	-0.1	-0.8	-0.4
			8-9	H	I-15 to I-215	9.8	8.3	7.5	71.0	78.1	0.8	9.1	4.6
		PM	4-5	G	County Line to I-15	11.5	10.4	9.9	66.7	69.9	0.5	4.7	2.5
			4-5	H	I-15 to I-215	9.8	8.2	7.9	72.0	74.3	0.2	3.1	1.5
	W	AM	7-8	H	I-215 to I-15	9.9	8.6	8.2	68.9	72.9	0.5	5.4	2.8
			7-8	G	I-15 to County Line	11.5	10.8	9.8	63.7	70.5	1.1	9.7	5.5
		PM	4-5	H	I-215 to I-15	9.9	8.3	8.0	72.0	74.4	0.3	3.2	1.6
			4-5	G	I-15 to County Line	11.5	9.9	9.5	69.7	72.5	0.4	3.9	2.0
215	N	AM	7-8	I	I-215/SR-60 to I-215/SR-60/SR-91	3.9	7.2	3.6	32.4	65.3	3.7	50.5	56.2
		PM	5-6	I	I-215/SR-60 to I-215/SR-60/SR-91	3.9	4.4	3.5	53.2	65.9	0.8	19.3	13.1
	S	AM	7-8	I	I-215/SR-60/SR-91 to I-215/SR-60	3.8	3.2	3.2	70.5	72.0	0.1	2.1	1.1
		PM	4-5	I	I-215/SR-60/SR-91 to I-215/SR-60	3.8	7.5	5.9	30.4	38.5	1.6	21.1	25.0
71	N	AM	8-9	J	SR-91 to SR-60	7.3	6.0	6.0	73.2	73.2	0.0	0.0	0.0
		PM	5-6	J	SR-91 to SR-60	7.3	7.0	6.1	62.7	72.0	0.9	12.9	7.4
	S	AM	8-9	J	SR-60 to SR-91	7.1	5.8	5.8	74.1	73.7	0.0	-0.6	-0.3
		PM	5-6	J	SR-60 to SR-91	7.1	6.2	5.5	69.3	77.0	0.6	10.0	5.2

Table 2-7. Comparison of tach runs results between Year 2009 and Year 2010

Fwy	Dir	Period	Segment	Description	2009 Travel Time Per Mile (sec/mile)			2010 Travel Time Per Mile (sec/mile)		
					MF	HOV	HOV Savings	MF	HOV	HOV Savings
91	E	AM	A	Green River Rd to I-15	54.5	50.6	3.9	50.1	48.9	1.2
			B	I-15 to Riverside	57.6	49.4	8.3	48.4	48.5	-0.1
		PM	A	Green River Rd to I-15	130.3	86.1	44.2	116.6	96.1	20.5
			B	I-15 to Riverside	77.6	59.6	18.1	62.7	52.4	10.2
	W	AM	B	Riverside to I-15	51.7	51.4	0.3	88.5	50.3	38.2
			A	I-15 to Green River Rd	76.1	57.6	18.5	171.8	113.3	58.6
		PM	B	Riverside to I-15	80.5	59.4	21.2	66.6	54.6	12.0
			A	I-15 to Green River Rd	55.8	53.5	2.3	53.4	50.8	2.6
60	E	AM	C	County Line to I-15	51.3	52.1	-0.8	50.9	48.1	2.8
			D	I-15 to I-215/SR-60/SR-91	53.9	54.2	-0.4	50.8	49.6	1.1
			E	I-215/SR-60 to Redlands Blvd	58.6	52.2	6.4	47.6	48.7	-1.0
		PM	C	County Line to I-15	78.5	57.8	20.7	74.8	61.6	13.2
			D	I-15 to I-215/SR-60/SR-91	82.1	63.2	18.9	63.0	64.2	-1.2
			E	I-215/SR-60 to Redlands Blvd	73.8	58.2	15.6	69.4	56.1	13.3
	W	AM	E	Redlands Blvd to I-215/SR-60	67.3	57.0	10.3	144.1	55.7	88.4
			D	I-215/SR-60/SR-91 to I-15	52.5	51.4	1.1	51.5	50.7	0.8
			C	I-15 to County Line	78.5	55.7	22.8	59.4	52.3	7.1
		PM	E	Redlands Blvd to I-215/SR-60	54.7	54.0	0.6	55.2	53.8	1.4
			D	I-215/SR-60/SR-91 to I-15	54.1	54.0	0.1	53.5	46.8	6.6
			C	I-15 to County Line	55.2	55.2	0.0	55.7	51.6	4.0
10	E	AM	F	County Line to I-15	52.2	48.0	4.3	57.7	54.0	3.7
		PM	F	County Line to I-15	98.9	65.0	33.9	64.7	56.5	8.2
	W	AM	F	I-15 to County Line	53.5	48.0	5.6	50.9	50.7	0.2
		PM	F	I-15 to County Line	60.9	56.9	4.0	60.9	52.6	8.4
210	E	AM	G	County Line to I-15	52.0	47.8	4.2	51.7	52.2	-0.4
			H	I-15 to I-215	51.3	46.5	4.8	50.7	46.1	4.6
		PM	G	County Line to I-15	105.3	68.8	36.4	54.0	51.5	2.5
			H	I-15 to I-215	58.7	49.6	9.1	50.0	48.5	1.5
	W	AM	H	I-215 to I-15	53.4	48.5	4.9	52.2	49.4	2.8
			G	I-15 to County Line	52.3	49.3	3.0	56.5	51.0	5.5
		PM	H	I-215 to I-15	55.2	48.4	6.8	50.0	48.4	1.6
			G	I-15 to County Line	56.0	51.2	4.8	51.7	49.7	2.0
215	N	AM	I	I-215/SR-60 to I-215/SR-60/SR-91	95.2	64.4	30.8	111.3	55.1	56.2
		PM	I	I-215/SR-60 to I-215/SR-60/SR-91	61.2	54.8	6.3	67.7	54.6	13.1
	S	AM	I	I-215/SR-60/SR-91 to I-215/SR-60	55.4	56.7	-1.3	51.1	50.0	1.1
		PM	I	I-215/SR-60/SR-91 to I-215/SR-60	169.8	96.9	72.9	118.4	93.4	25.0
71	N	AM	J	SR-91 to SR-60	52.6	50.8	1.8	49.2	49.2	0.0
		PM	J	SR-91 to SR-60	54.7	51.8	2.9	57.4	50.0	7.4
	S	AM	J	SR-60 to SR-91	49.1	46.4	2.7	48.6	48.9	-0.3
		PM	J	SR-60 to SR-91	56.0	51.6	4.4	52.0	46.8	5.2

3. Statistical Modeling

3.1. Overview

This analysis is based on the fact that PeMS data (e.g. flow, speed, etc.) are collected at discrete locations of vehicle detector stations (VDS) along freeways. Therefore, HOV and MF data from PeMS represent lane operational performance at the cross sections where the VDS are situated. The freeway throughput at these cross sections can be influenced by several geometric characteristics, for instance, lane width, shoulder width, road grade, HOV lane configuration, etc. In addition, whether there are nearby on-ramp and off-ramp and how far these ramps are from the VDS also plays a role as they could induce weaving maneuvers that affect freeway throughput (see Figure 3-1).

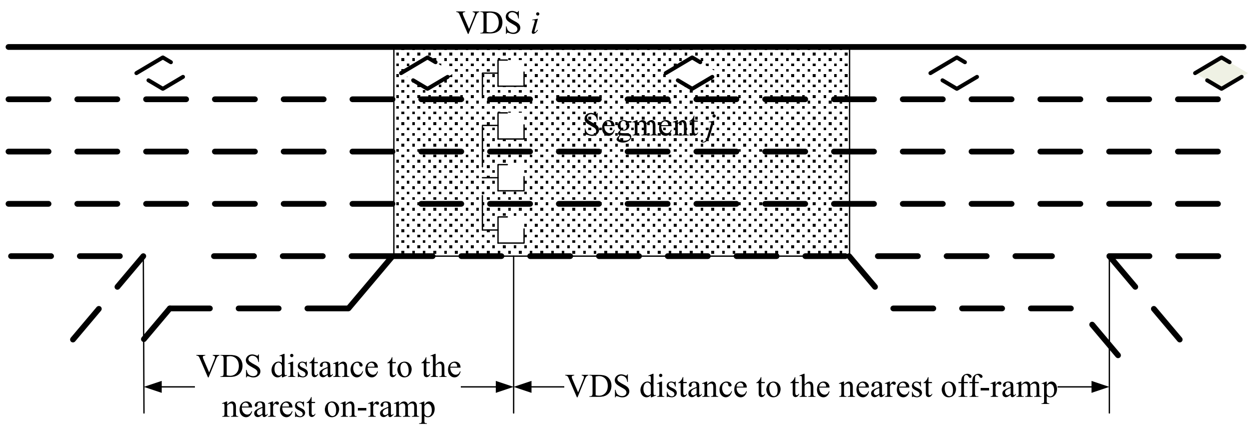


Figure 3-1. VDS level analysis for a corridor with continuous-access HOV lane

The data of these geometric characteristics can be gathered and compiled into a database along with freeway throughput data. Then, this database can be used in a regression analysis where the maximum freeway throughput is written as:

$$C = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \beta_{n+1} Type_{HOV} \qquad (3\text{-}1)$$

where C is maximum freeway throughput; x_i are geometric characteristics affecting freeway throughput, β_i are regression constant and coefficients; and $Type_{HOV}$ is a dummy variable representing the type of HOV lane configuration (e.g. continuous access = 0 and limited access = 1). Setting continuous access to 0 means it is used as a baseline for comparison with limited access.

Once the regression equation above has been developed using the real-world data from PeMS, we can evaluate the regression coefficient β_{n+1} to see if it is statistically significant or not. If no, then it can be inferred that there is no statistically significant difference in the operation performance between the two lane configurations. If yes, then the algebraic sign of the coefficient will imply which of the two types of HOV lane configuration is operationally better.

If the coefficient is negative, then the limited access will be considered to result in lower throughput as compared to the continuous access, and vice versa, all other factors being equal.

The advantage of this approach is that it ties directly to PeMS data at VDS so the data are a true representation of freeway lane operational performance at the locations of VDS. Also, we will be able to create a very large database for use in the regression analysis since there are numerous VDS throughout the state although the compilation of database takes a significant amount of time and effort. This helps improve the robustness of the results. In addition, the regression analysis results will not only reveal whether the two HOV lane configurations are operationally different or not, but also indicate the effect of other geometric characteristics on the operational performance of freeways with HOV facilities.

3.2. Data

The data used for this study are obtained mainly from two major sources:

- The California Freeway Performance Measurement System (PeMS)
- The Highway Safety Information System (HSIS)

Other data sources include Google Earth, Caltrans Photolog, and miscellaneous documents (e.g., as-built maps) from Caltrans, which are used to determine the ingress/egress location. In addition, road grade data for freeways in Districts 7, 8, and 12 are obtained from a previous study by the research team [Boriboonsomsin et al., 2009b]. However, road grade information is not available for freeways in District 4.

3.2.1. Freeway Maximum Throughput Estimation

Similar to previous analysis, 5-minute aggregated traffic data from PeMS, including overall traffic count and estimated speed for each lane during the typical weekdays (Tuesdays, Wednesdays and Thursdays) throughout the Year 2009 are used to determine the observed maximum throughput at each individual VDS. To account for the factors impacting freeway throughput, occupancy and truck volume are also extracted from the database.

As one of fundamental performance metrics, capacity (maximum throughput at bottleneck) has been widely used to evaluate the operational effectiveness of a freeway facility. Numerous studies have been focused on the estimation of freeway capacity. Most of recent studies have examined the stochastic nature of capacity along a freeway segment [Evans et al., 2001; Zhang, 2005; Brilon, 2005] and compared with the conventional deterministic definition [Lorenz and Elefteriadou, 2001]. Nevertheless, capacity estimation using stochastic methods involve heavy computation and may not be applied to an extensive study for the statewide HOV facilities. Therefore, deterministic methods are used in this report to estimate capacity values.

A couple of deterministic methods have been proposed to estimate the observed capacity of a roadway segment based on empirical data. Highway Capacity Manual 2000 [Transportation Research Board, 2000] defines that “the capacity of a facility is the maximum hourly rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, traffic, and control conditions.” Therefore, it provides a base capacity for each type of roadway under the prevailing condition, and the associated adjustment factors for specific conditions. Such method is good for the purpose of planning but not for operation.

PeMS estimates the capacity of freeway at each VDS as the maximum 5-minute sustainable flow over 15-minute period [PeMS, 2011]. To compute this value, a few weeks of weekday, peak period (both AM and PM), 5-minute observed flow data are aggregated across all lanes, and the maximum value for any 15-minute period is identified. Then, the minimum 5-minute flow of that 15-minute maximum is taken as the observed capacity at that VDS location. It is noted that only data with more than 50% of observations are used for the capacity estimation. However, the PeMS method does not take into account the fact that some VDS may never experience congestion and the estimated value will be much lower than the actual capacity.

Another heuristic method is proposed by [Dervisoglu et al. 2009], which has been implemented in TOPL (Tools for Operations Planning) to automatically calibrate the observed capacity of a freeway segment based on the fundamental diagram analysis. The capacity was defined as the maximum value of flow across the section among all observed days with aggregated data over an interval of 5 minutes. It is self-evident that such observed capacity may not be sustainable for a longer period due to either random noise or transition in traffic condition.

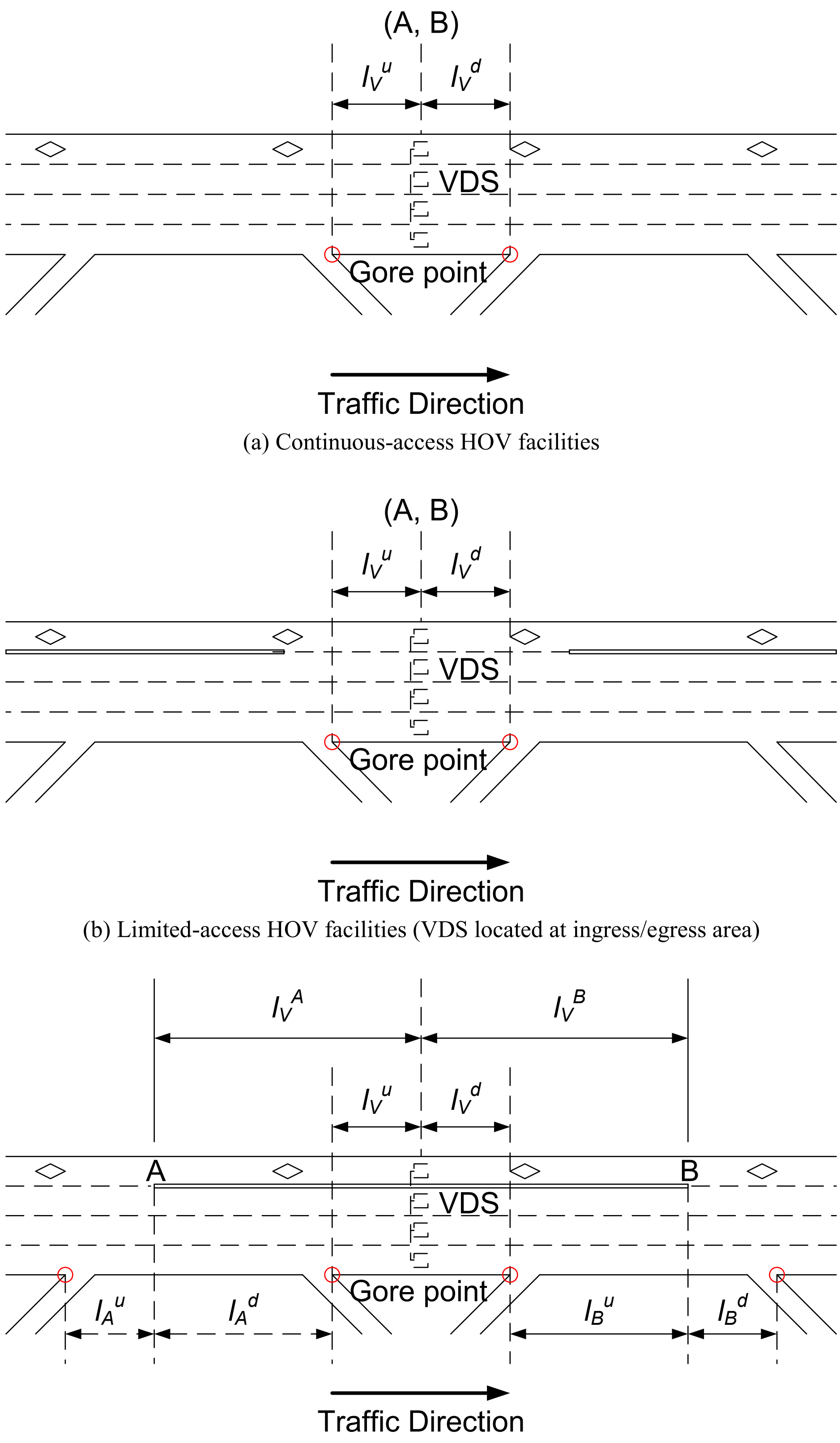
In this report, for the purpose of comparison, both the PeMS method [PeMS, 2011] and the Max-flow method [Dervisoglu et al., 2009] have been applied to the empirical data for freeway throughput estimation. As pointed out, there may be some VDS within the scope of study which never get congested and reach their maximum throughput throughout the year 2009. Thus, a screening was conducted to first drop out these unqualified VDS based on Caltrans's definition of congestion, which states "Congestion is defined as a condition where the average speed drops below 35 mph for 15 minutes or more on a typical weekday" [Caltrans, 2003b].

Such congestion may be caused by excess demand or non-recurrent incidents. As for HOV lane, however, there is no such rule of thumb. Based on the suggestion in [Transportation Research Board, 1998] on desirable operating conditions of HOV facilities, 45 mph was selected as the criterion for HOV lane congestion. With these two methods, different values of observed maximum throughput were obtained for each candidate VDS, including HOV lane throughput, adjacent mixed-flow lane throughput, average/overall mixed-flow lane throughput, and average/overall freeway lane throughput. Among others, HOV lane throughput and overall freeway lane throughput are of particular interest to practitioners and researchers. In the following, regression analysis is focused on these two types of observed throughput values.

3.2.2. HSIS and Geometric Information

The Highway Safety Information System (HSIS) is a multistate (including California) database which documents safety-related information for highways [Highway Safety Information System, 2011]. It provides not only accident inventory but also detailed information about the geometrics and other characteristics of roadways, interchange ramps and intersections, such as the number of lanes, outer/inner shoulder width, average lane width, median width and type, design speed limit and ramp's location in terms of the state post-mile.

By fusing the VDS configuration files from PeMS and the California "Roadlog File" and "Interchange Ramp File" (Year 2008) from HSIS database, the distance between a VDS and the associated nearest down/up-stream ramp including its type (i. e. on-ramp or off-ramp), and other VDS-related geometric feature can be determined. Figure 3-2 illustrates an example of relative locations between a VDS and the nearest ramps or ingress/egress areas. For example, l_V^A represents the distance between the VDS and A, the nearest upstream lane changeable point. l_V^d denotes the distance between the VDS and the gore point of the nearest downstream ramp. It is noted that the location information of ingress/egress areas cannot be retrieved from the HSIS database but other archived documents from Caltrans, such as photo-logs or as-built maps, and Google Earth. There might be measurement errors for these geometric characteristics, but the associated error structure is not available. Therefore, it is simply assumed in the following analysis that all these independent variables have been measured or observed without errors.



(a) Continuous-access HOV facilities

(b) Limited-access HOV facilities (VDS located at ingress/egress area)

(c) Limited-access HOV facilities (VDS located at buffered area)

Figure 3-2. Geometric Data Related to VDS Location

3.2.3. Integrated Database for Regression Analysis

As aforementioned, a new database for regression analysis on observed maximum throughput at the VDS level has been obtained by integrating different data sources. Figure 3-3 presents the system architecture on how to implement such data fusion. Table 3-1 provides a full list of all factors stored in the integrated database and to be considered in the following regression analysis.

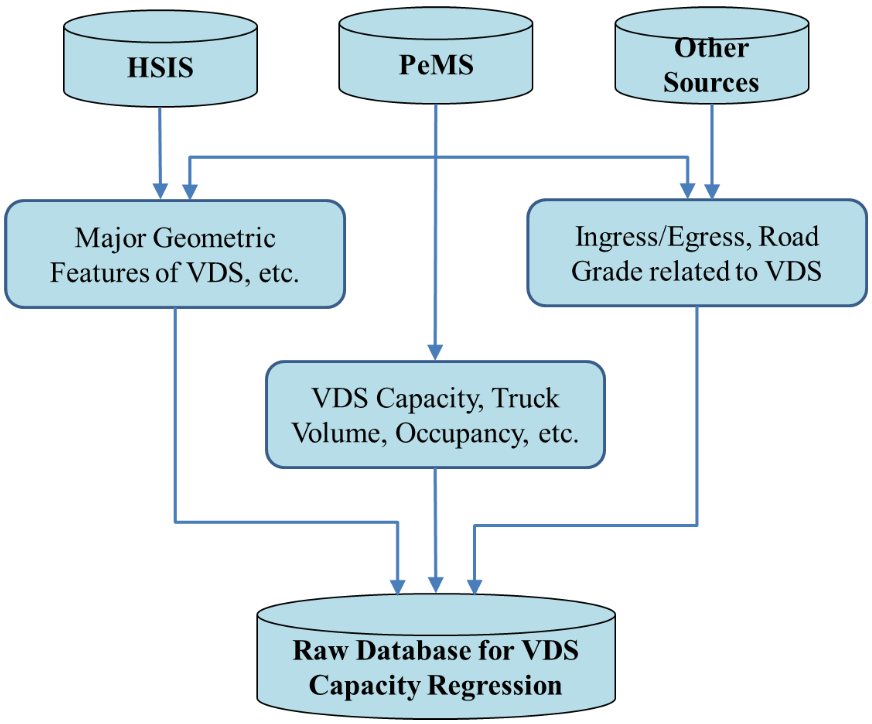


Figure 3-3. System Architecture on Data Integration for Regression Analysis

Table 3-1. List of Independent Variables for Regression Analysis

Category	Description	Unit
General Characteristics	District indicator	
	Route indicator	
	Direction indicator	
Geometric Characteristics	HOV access type indicator (0 – continuous, 1 – limited)	
	VDS location indicator (0 – lane changeable, 1 – otherwise)	
	No. of lanes	
	Outer shoulder width	ft
	Lane width	ft
	Inner shoulder width	ft
	Median width	ft
	Design speed	mph
	Roadway grade	degree
	Distance to Point A	mi
	Distance to Point B	mi
	Type of the closest upstream ramp (with respect to. VDS)	
	Distance to the closest upstream ramp (with respect to. VDS)	mi
	Type of the closest downstream ramp (with respect to. VDS)	
	Distance to the closest downstream ramp (with respect to. VDS)	mi
	Type of the closest upstream ramp (with respect to. Point A)	
	Distance to the closest upstream ramp (with respect to. Point A)	mi
	Type of the closest downstream ramp (with respect to. Point A)	
	Distance to the closest downstream ramp (with respect to. Point A)	mi
	Type of the closest upstream ramp (with respect to. Point B)	
	Distance to the closest upstream ramp (with respect to. Point B)	mi
	Type of the closest downstream ramp (with respect to. Point B)	
	Distance to the closest downstream ramp (with respect to. Point B)	mi
	Terrain type	
	Roadway type indicator	
	Road-bed feature indicator	
	Median type indicator	
	Median barrier type	
Traffic Characteristics	5-minute aggregate loop occupancy at capacity	
	5-minute truck volume at capacity	veh/5-min

3.3. Preliminary District 8 Analysis and Results

Initially, the regression analysis was applied to HOV facilities in District 8 only. Table 3-2 lists the HOV facilities included in this analysis. Note that I-215 is the only freeway in District 8 with continuous-access HOV lane. Therefore, in this initial database, the sample size for continuous-access HOV lanes after screening is 5 and the sample size for limited-access HOV lanes is 95.

Table 3-2. List of HOV facilities for the District 8 analysis

HOV Type	Corridor	District	County	Study Boundary*		Length** (mile)
				Start	End	
Continuous-access	I-215 N/S	8	RIV	29.2	37.4	8.2
Limited-access	I-10 W/E	8	SBD	47.3	57.3	10.0
	SR-60 W/E	8	RIV/SBD	30.8	56.8	26.0
	SR-71 N/S	8	SBD	5.3	13.2	7.9
	SR-91 W/E	8	RIV	37.3	59.0	21.7
	I-210 W/E	8	SBD	52.5	67.4	14.9

* *Absolute post-mile*
** *For each direction*

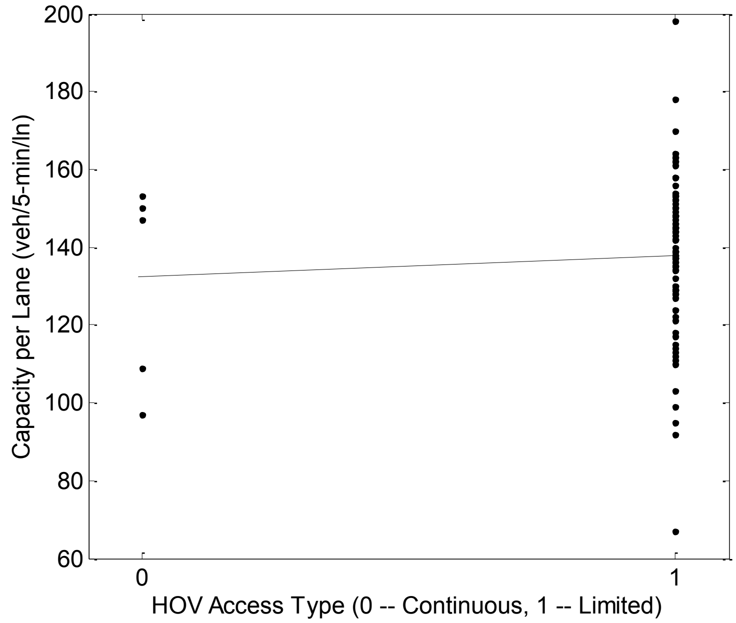
Figure 3-4 shows the scatter plots of average freeway lane throughput versus HOV access type. On average, the limited access HOV facilities in District 8 have higher throughput as determined by PeMS method than the continuous access ones. This is opposite for the throughput as determined by the Max-Flow method. However, these plots cannot reveal the influence of other characteristics on the maximum throughput values. That is why multiple regression analysis is needed.

The regression result of the District 8 dataset is in the form of the equation below, and the corresponding regression coefficients are given in Table 3-3. Each regression coefficient reflects the amount of change to the average freeway lane throughput (y) when the corresponding variable (x_i) increases or decreases by one unit.

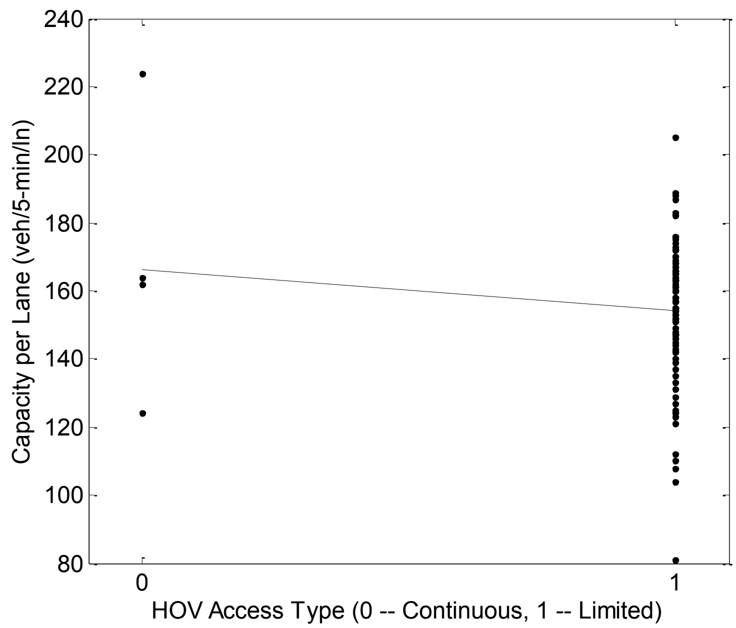
$$y = \beta_0 + \beta_1 \cdot x_1 + \beta_2 \cdot x_2 + \beta_3 \cdot x_3 + \beta_4 \cdot x_4 + \beta_5 \cdot x_5 + \beta_6 \cdot x_6 \\ + \beta_7 \cdot x_7 + \beta_8 \cdot x_8 + \beta_9 \cdot x_9 + \beta_{10} \cdot x_{10} \quad (3\text{-}2)$$

According to Table 3-3, the HOV type would not cause a significant difference in the average freeway lane throughput as determined by the PeMS method. However, it would cause a significant difference in the average freeway lane throughput as determined by the Max-Flow method where the limited-access HOV would result in a lower average freeway lane throughput by about 5 vehicles/lane/5 min.

It should be noted that these results are based on data from District 8 only, and thus the findings may not be applicable to other districts. Also, the sample size for continuous-access HOV facilities is very small, which could bias the results.



(a) PeMS method



(b) Max-Flow method

Figure 3-4. Average freeway lane throughput versus HOV access type

Table 3-3. Regression results for District 8 dataset

i	x_i	β_i (PeMS method)	β_i (Max-Flow method)
0	-	126.76*	141.23*
1	HOV access type; 0 – continuous, 1 – limited	8.26	-4.94*
2	VDS location indicator; 0 – in ingress/egress section, and 1 – in barrier-separated section	-4.43	-3.24*
3	Number of lanes	-4.35	-9.81
4	Total roadway width for one direction (ft)	-0.07*	0.12*
5	Road grade (%)	-0.35	-0.59*
6	Distance from the VDS to the nearest upstream ramp (mile)	1.24*	3.24*
7	Distance from the VDS to the nearest downstream ramp (mile)	-2.07*	-2.96*
8	Type of the nearest downstream ramp (with respect to VDS); 0 – off-ramp, 1 – on-ramp	-6.38	-6.82
9	Average truck volume per lane within the time window at capacity (veh/5-min)	0.66	0.71
10	Average loop occupancy per lane within the time window at capacity	250.90*	424.60*
	R-quared	*0.31*	*0.65*
	Adjusted R-quared	*0.19*	*0.59*

**significant at 5% alpha level*

3.4. Statewide Analysis and Results

In order to address the sample size issue, HOV facilities in other Districts (i.e., D4, D7, and D12) were added to the integrated database for regression analysis. Essentially, this became a statewide analysis. It is noted that the raw database obtained from the integration is still very noisy. Therefore, it needs to be pre-processed before conducting the regression analysis. The major objectives of such data pre-processing are three-fold:

- Delete samples with missing information for one or multiple factors;
- Identify potentially erroneous data, especially the response (observed throughput);
- Create a proper set of regressors which potentially are the most critical for the regression model, through data transformation or factor combination.

3.4.1. Database Preparation

Row-wise Deletion

By integrating different data sources, information of one or more factors may be incomplete in the raw database. For example, the roadway grade is not available for VDS in District 4 as aforementioned. For another instance, the type or freeway direction of some ramps in HSIS database are not clear or unavailable. Although there are a number of ways to deal with missing data, the list-wise deletion, i.e. to simply omit those samples where there is any incomplete information for any of independent variables, has been used in this study. After the deletion, the size of samples with complete information for HOV lane and average freeway lane are 589 and 556, respectively, which is large enough for regression analysis.

Distribution of Observed Maximum Throughput

To identify the potential errors in the response data, distributions of observed throughput values by HOV access type, by district, and by route were plotted for HOV lane and average freeway lane based on both the PeMS method and Max-flow method. The plots are provided in Appendix E. It can be observed that:

- The estimated maximum throughput data are very noisy and the values span over a long range. Some of them are as low as 30 veh/5-min/ln, while others reach up to 400 veh/5-min/ln. Samples with these extreme values are potential outliers which are handled later.

- The variation of observed throughput values for average freeway lane is much less than that for HOV lane. The variation resulting from the PeMS method is also less than that from the Max-flow one.

- For distributions by HOV access type, there are a significant portion of "low" observed throughput values (< 70 veh/5-min/ln) from the continuous-access HOV facilities.

- For distributions by district, the observed throughput values for average FWY lane of District 12 are much higher than those from any other districts. On the other hand, all HOV facilities in D4 are continuous-access and its data set contains a significant portion of "low" throughput values which is consistent with the observations from the distributions by HOV access type. Furthermore, the distributions (both the PeMS and

Max-flow methods) of HOV lane throughput in District 8 exhibits “dual mode”, i.e., two peak values. These observations may provide some hints in regression analysis that the district indicator can be one of the regressors or there might be a hierarchical structure in the regression model due to the district effect.

- For distributions by route, the observed HOVL/FWYL throughput values of I-80 E (D4, continuous-access), I-80 W (D4, continuous-access), and SR-71 N (D8, limited-access) are much lower than others. Therefore, these data samples were removed in the following analysis. It should be noted that there is no sample from SR-71 S (D8, limited-access) which did not satisfy the congestion screening criterion. After the removal of these questionable data, the sample sizes for HOV lane and average FWY lane further reduced to 560 and 530, respectively.

To further verify the equality of the data sample distributions from HOV facilities with different lane configuration, the two sample Kolmogorov-Smirnov test was conducted. The null hypothesis, H_0, is that the true distribution function of continuous-access throughput is equal to the distribution function of limited-access throughput at the 5% significance level. As is shown in Table 3-4, the test results reveal that all the null hypotheses should be rejected, which means that the observed maximum throughput distributions (using the PeMS or Max-flow method) of HOV lane or average freeway lane for different access types are not equal in the statistical sense.

Table 3-4. Kolmogorov-Smirnov test results for HOVL and FWYL throughput distributions

	Method	Statistics D	P-value	Reject H_0
HOV Lane	PeMS	0.239	1.251e-07	Yes
	Max	0.288	6.727e-11	Yes
FWY Lane	PeMS	0.197	3.323e-05	Yes
	Max	0.253	2.457e-08	Yes

Handling the Outliers

Even though the routes with abnormal observed maximum throughput values have been identified and removed from the dataset, there are still some outliers whose values are much lower or higher than the average. It is well known that outliers can have deleterious effects on statistical analysis. Potentially, there are at least two types of strategies to deal with the outlier issue. The first one is outlier-exclusion. For example, based on user-defined percentile thresholds for both lower and upper bounds (e.g. 5^{th} and 95^{th} percentile), only samples within the acceptable range will be reserved for further analysis. Another alternative and commonly-used approach may be to only exclude points which exhibit a large degree of influence on the parameters using a measure such as Cook’s Distance [Cook, 1977], which indicates data points that are particularly worth checking for validity.

It is self-evident that the outlier-exclusion method is somewhat subjective. The second strategy is outlier-retention, which means that all outliers will be retained in the analysis but a more robust method needs to be applied to reduce the influence of outlying data points. In this study, the illegitimacy of the remaining outliers is difficult to justify, so the robust version of multiple linear regression modeling technique has been also investigated.

3.4.2. Correlation Analysis

The potential influential factors include both numerical variables (e.g. average lane width and distance to the nearest ramp) and categorical variables such as HOV access type and ramp type. To evaluate the correlation (or association) between these variables, different methods need to be applied accordingly (see Table 3-5). However, it is noted that for a bi-level categorical variable (e.g. HOV access type), dummy binary 0 and 1 can be used to define its levels and the method for numerical variable is still valid for checking the correlation. Therefore, the Pearson product-moment correlation coefficient is calculated to examine the linear dependence between any two factors. Figure 3-5 presents an example of the correlation matrix for the dataset of average freeway lane using the PeMS method.

Table 3-5. Methods used to check the strength of relationship between different types of variables

	Numerical (Interval)	Categorical (Nominal)
Numerical (Interval)	Pearson correlation	Analysis of Variance (ANOVA)
Categorical (Nominal)	Analysis of Variance (ANOVA)	Contingency table (Cramer's V)

As is shown in Figure 3-5, the HOV access type and VDS location indicator are highly correlated because the VDS location indicator is always 0 for continuous-access HOV facilities and very likely to be 1 for limited-access HOV facilities. This may cause the collinearity issue and therefore the VDS location indicator has been removed for regression analysis. It also turns out that, for example, the distance of the nearest down/up-stream ramp to a VDS is highly correlated ($\rho > 0.5$) with the distance between Point A or Point B and the associated nearest down/up-stream ramp. Similar trend can be expected for the ramp type. This may be due to the coincidence of the VDS with Point A and B, when the VDS is located at a continuous HOV facility or an ingress/egress area of a limited HOV facility. In addition, the ramp distance and type with respect to VDS has higher dependence on the response than those with respect to. Point A and Point B. Therefore, the ramp distance and type with respect to. Point A and Point B will not be taken into account in the following regression models.

It should be pointed out that even though the linear correlation is trivial, it is possible that variables may have strong non-linear correlation. This is out of the scope of current study but can be a potential research topic in the future.

Uni-variate Relationship

To better understand the impact of each factor on the maximum throughput as well as to select a more proper set of explanatory variables for regression models, the uni-variate relationship between individual factor and the response has been investigated. Figure 3-6 and Figure 3-7 provide some examples on such relationship by plotting the No. of lanes and distance from VDS to the nearest downstream ramp vs. average freeway lane throughput (using the PeMS method), respectively. As is shown in Figure 3-6, the medians of freeway lane capacities are around 150 (veh/5-min/ln) and do not vary significantly for HOV facilities with different number of lanes. It is interesting to observe from Figure 3-7 that the fitted line has a positive slope, which means that the longer the distance from VDS to the nearest downstream ramp, the higher the observed throughput would be. A possible explanation for this is the impact of throughput drop due to lane changing maneuver may be mitigated as the VDS distance to ramp increases.

	Type	Loc	V2A	V2B	Lanes	OShld	LnWid	IShld	VuRT	VuRD	VdRT	VdRD	AuRT	AuRD	AdRT	AdRD	BuRT	BuRD	BdRT	BdRD	Occ	Tr_Vol	Cap
Type	1.000	0.777	0.512	0.532	0.415	0.272	0.004	0.001	0.171	0.094	-0.099	0.104	0.153	0.092	-0.088	0.107	0.124	0.104	-0.105	0.106	0.115	0.055	0.296
Loc	0.777	1.000	0.659	0.685	0.328	0.223	-0.015	0.003	0.128	0.073	-0.076	0.090	0.107	0.070	-0.062	0.094	0.073	0.087	-0.084	0.094	0.091	0.032	0.201
V2A	0.512	0.659	1.000	0.295	0.126	0.125	0.064	0.049	0.092	-0.007	-0.077	-0.001	0.008	-0.003	-0.040	-0.011	0.126	0.005	-0.102	0.007	0.069	-0.075	0.056
V2B	0.532	0.685	0.295	1.000	0.111	0.165	0.043	0.017	0.084	-0.017	-0.067	-0.005	0.000	-0.023	0.008	0.000	0.053	-0.004	-0.058	0.020	0.142	0.072	0.138
Lanes	0.415	0.328	0.126	0.111	1.000	0.090	-0.231	-0.147	0.199	0.137	-0.072	0.082	0.169	0.106	-0.031	0.069	0.097	0.099	-0.077	0.115	-0.197	0.090	0.074
OShld	0.272	0.223	0.125	0.165	0.090	1.000	-0.151	0.249	0.091	-0.055	0.027	-0.019	0.098	-0.055	0.007	-0.018	0.101	-0.033	-0.008	-0.023	0.132	0.005	0.036
LnWid	0.004	-0.015	0.064	0.043	-0.231	-0.151	1.000	0.210	-0.108	-0.110	0.084	-0.045	-0.094	-0.096	0.018	-0.058	-0.076	-0.078	0.092	-0.047	-0.035	-0.051	0.063
IShld	0.001	0.003	0.049	0.017	-0.147	0.249	0.210	1.000	-0.117	-0.248	0.166	-0.248	-0.109	-0.263	0.121	-0.246	-0.177	-0.292	0.164	-0.206	0.045	-0.025	-0.065
VuRT	0.171	0.128	0.092	0.084	0.199	0.091	-0.108	-0.117	1.000	0.177	-0.325	0.134	0.690	0.133	-0.199	0.121	0.557	0.160	-0.206	0.084	0.098	0.008	0.052
VuRD	0.094	0.073	-0.007	-0.017	0.137	-0.055	-0.110	-0.248	0.177	1.000	-0.259	0.376	0.176	0.897	-0.247	0.462	0.120	0.906	-0.224	0.303	-0.048	0.063	0.194
VdRT	-0.099	-0.076	-0.077	-0.067	-0.072	0.027	0.084	0.166	-0.325	-0.259	1.000	-0.289	-0.268	-0.194	0.688	-0.262	-0.164	-0.257	0.652	-0.217	0.004	-0.058	-0.094
VdRD	0.104	0.090	-0.001	-0.005	0.082	-0.019	-0.045	-0.248	0.134	0.376	-0.289	1.000	0.149	0.316	-0.243	0.921	0.120	0.469	-0.265	0.869	-0.037	0.051	0.221
AuRT	0.153	0.107	0.008	0.000	0.169	0.098	-0.094	-0.109	0.690	0.176	-0.268	0.149	1.000	0.187	-0.400	0.148	0.486	0.156	-0.150	0.119	0.085	0.000	0.089
AuRD	0.092	0.070	-0.003	-0.023	0.106	-0.055	-0.096	-0.263	0.133	0.897	-0.194	0.316	0.187	1.000	-0.250	0.380	0.125	0.829	-0.237	0.250	-0.043	0.040	0.189
AdRT	-0.088	-0.062	-0.040	0.008	-0.031	0.007	0.018	0.121	-0.199	-0.247	0.688	-0.243	-0.400	-0.250	1.000	-0.288	-0.084	-0.246	0.593	-0.229	0.004	-0.048	-0.073
AdRD	0.107	0.094	-0.011	0.000	0.069	-0.018	-0.058	-0.246	0.121	0.462	-0.262	0.921	0.148	0.380	-0.288	1.000	0.100	0.521	-0.243	0.822	-0.045	0.060	0.214
BuRT	0.124	0.073	0.126	0.053	0.097	0.101	-0.076	-0.177	0.557	0.120	-0.164	0.120	0.486	0.125	-0.084	0.100	1.000	0.206	-0.368	0.121	0.118	-0.048	-0.010
BuRD	0.104	0.087	0.005	-0.004	0.099	-0.033	-0.078	-0.292	0.160	0.906	-0.257	0.469	0.156	0.829	-0.246	0.521	0.206	1.000	-0.282	0.363	-0.048	0.051	0.186
BdRT	-0.105	-0.084	-0.102	-0.058	-0.077	-0.008	0.092	0.164	-0.206	-0.224	0.652	-0.265	-0.150	-0.237	0.593	-0.243	-0.368	-0.282	1.000	-0.273	-0.023	0.001	-0.066
BdRD	0.106	0.094	0.007	0.020	0.115	-0.023	-0.047	-0.206	0.084	0.303	-0.217	0.869	0.119	0.250	-0.229	0.822	0.121	0.363	-0.273	1.000	-0.062	0.098	0.213
Occ	0.115	0.091	0.069	0.142	-0.197	0.132	-0.035	0.045	0.098	-0.048	0.004	-0.037	0.085	-0.043	0.004	-0.045	0.118	-0.048	-0.023	-0.062	1.000	0.052	0.124
Tr_Vol	0.055	0.032	-0.075	0.072	0.090	0.005	-0.051	-0.025	0.008	0.063	-0.058	0.051	0.000	0.040	-0.048	0.060	-0.048	0.051	0.001	0.098	0.052	1.000	0.199
Cap	0.296	0.201	0.056	0.138	0.074	0.036	0.063	-0.065	0.052	0.194	-0.094	0.221	0.089	0.189	-0.073	0.214	-0.010	0.186	-0.066	0.213	0.124	0.199	1.000

Type – HOV access type (0 – continuous, 1 – limited)
Loc – VDS location indicator (0 – open, 1 – barrier)
V2A – Distance between VDS and Point A (mile)
V2B – Distance between VDS and Point B (mile)
Lanes – No. of lanes
OShld – Outer shoulder width (ft)
LnWid – Average lane width (ft)
IShld – Inner shoulder width (ft)
VuRT – Type of upstream ramp with respect to (w.r.t.) VDS
VuRD – Distance to upstream ramp w.r.t. VDS (mile)
VdRT – Type of downstream ramp w.r.t. VDS
VdRD – Distance to downstream ramp w.r.t. VDS (mile)
AuRT – Type of upstream ramp w.r.t. Point A
AuRD – Distance to upstream ramp w.r.t. Point A (mile)
AdRT – Type of downstream ramp w.r.t. Point A
AdRD – Distance to downstream ramp w.r.t. Point A (mile)
BuRT – Type of upstream ramp w.r.t. Point B
BuRD – Distance to upstream ramp w.r.t. Point B (mile)
BdRT – Type of downstream ramp w.r.t. Point B
BdRD – Distance to downstream ramp w.r.t. Point B (mile)
Occ – Aggregate loop occupancy at capacity
Tr_Vol – Aggregate truck volume at capacity (veh/5-min)
Cap – Lane capacity (veh/5-min/ln)

Figure 3-5. Correlation matrix for the statewide dataset of average freeway lane throughput using PeMS method

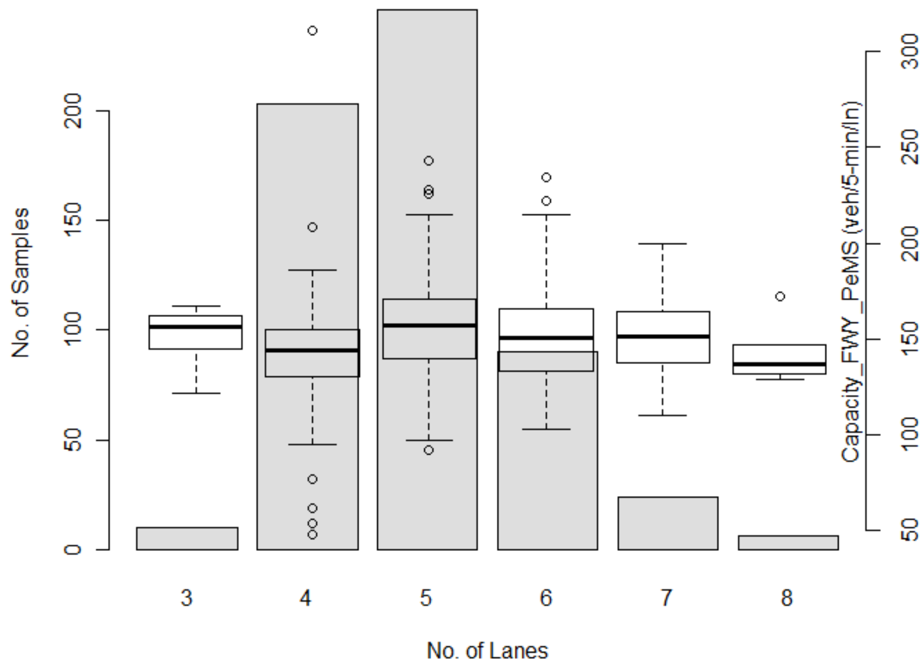


Figure 3-6. Histogram and box-plot of No. of lanes vs. freeway lane throughput

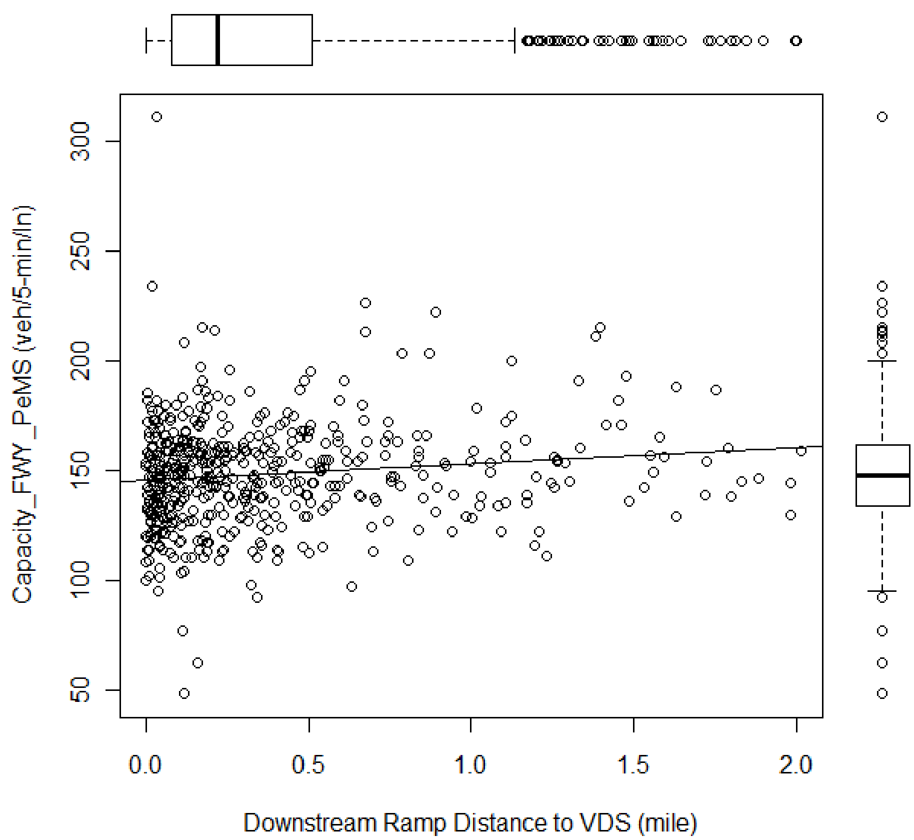


Figure 3-7. Scatter-plot and box-plot of downstream ramp distance to VDS vs. freeway lane throughput

Explanatory Variables and Response

The major purpose of this analysis is to evaluate the dependence of HOV facilities' capacities on various explanatory variables, particularly HOV lane access type. For all the available data, correlation and (multi-)colinearity analysis between pairs of explanatory variables as well as uni-variate relationship analysis between the regressors and the response were conducted. Based on the results of these analyses, a set of explanatory variables were selected for regression modeling. These include variables related to the lane configuration and VDS's geometric attributes as well as VDS occupancy at capacity and truck proportion at capacity.

As to the response, the observed HOV lane throughput, observed average and overall freeway lane capacities are of much interest in this study. Table 3-6 presents a full list of explanatory variables of regression models for HOV lane and FWY lane, respectively. It should be noted that the inclusion of variables for HOV lane and FWY lane analysis may be different due to the fact that some variables do not provide any useful information for estimating the HOV lane throughput. For example, the number of HOV lane is almost 1 within the scope of this study and the outer shoulder width should not impact the HOV lane throughput since the HOV lane lies in the innermost in California. For another instance, no truck is allowed along the HOV lane.

Table 3-6. List of independent variables in regression

i	x_i	*HOV Lane*	*FWY Lane*
0	Intercept	√	√
1	HOV access type	√	√
2	Distance between VDS and Point A	√	√
3	Distance between VDS and Point B	√	√
4	Number of Lanes		√
5	Outer shoulder width		√
6	Average width per lane	√	√
7	Inner shoulder width	√	√
8	On-ramp indicator of upstream ramp with respect to. VDS	√	√
9	Distance to upstream ramp with respect to. VDS	√	√
10	On-ramp indicator of downstream ramp with respect to. VDS	√	√
11	Distance to downstream ramp with respect to. VDS	√	√
12	District indicator of District 7	√	√
13	District indicator of District 8	√	√
14	District indicator of District 12	√	√
15	Truck proportion at capacity		√
16	VDS occupancy at capacity	√	√

Before the detailed presentation of regression models and results analysis, there are still a couple of comments on the selection of explanatory variables as follows:

- The design speed is available and may also affect the observed maximum throughput. However, all investigated locations have design speed of 70 mph except that very few of them have 65 mph or 60 mph. To prevent singularity, design speed is not included as a factor in the regression model.

- Further analysis reveals that the information of Median, roadway type and road-bed feature is of little dependence on the observed maximum throughput. Therefore, these factors have not been considered in the following regression analysis.

- As is shown in previous sections, the maximum throughput distributions from different District are different. Hence, a nominal variable is used in the regression model to account for the District effect. The District indicator of District 4 is not used as an explicit explanatory variable, but its impact will be included in the intercept term. It should be noted that the effect at the route level is not considered because the sample size is limited for each individual route.

- Truck proportion instead of absolute volume at capacity is used as one of predictor variables for the purpose of normalization and better interpretation of analysis results.

- To reduce the skewedness of some predictor variables and improve the linearity between regressors and the response, data transformation on those explanatory variables can be further applied. For example, the square root transformation can be employed to those distance-related variables. Due to the fact that the values of these variables may be 0, two other commonly used transformation techniques, logarithm and reciprocal, may not be appropriate. To avoid confusion, no data transformation on distance-related regressors has been performed in this study.

- Combining multiple factors into a composite variable and/or including interaction term are a bit subjective but widely-used techniques in regression analysis. Trial and error is required for successful implementation and this can be another potential research topic in the future.

3.4.3. Regression Models and Results

No regression method is best for all situations. In this study, the following regression models have been applied to the same dataset:

- Multiple linear regression (MLR) model
- Robust multiple linear regression (R-MLR) model
- Linear mixed effect model
- Multivariate adaptive regression splines (MARS)

The R statistical package ver. 2.13.0 [R Development Core Team, 2011] was used to develop these regression models. Each model is useful for addressing one or more issues from the data. In this section, only the MLR model, which is the simplest model, is discussed. The presentation and discussion of the other models are given in Appendix F for those who are interested in more advanced statistical techniques.

Multiple Linear Regression (MLR) Model

The simplest multivariate regression method is the multiple linear regression (MLR) which models the linear dependence of selected explanatory variables on the observed maximum throughput of HOV facilities. Two key assumptions are common to linear regression models:

- The design matrix must have full column rank, i.e. no multi-collinearity exists in the regressors. This issue has been addressed in the previous section.

- The regressors are assumed to be error-free, that is, they are not contaminated with measurement errors. As is aforementioned, the assumption may not be satisfied in this study. However, it is difficult to obtain the structure of these measurement errors. Although not realistic in many settings, dropping this assumption leads to significantly more difficult error-in-variables models.

The multiple linear regression model, in general, can be written as

$$y_i = \beta_0 + \sum_k \beta_k \cdot x_{i,k} + \varepsilon_i \tag{3-3}$$

where y_i represents the i-th response, i. e. either observed maximum throughput of HOV lane or overall freeway lane at VDS i; $x_{i,k}$ denotes the k-th explanatory variable as listed in Table 3-6 in the i-th data sample; β_0 is the intercept; β_k is the estimated coefficient associated with $x_{i,k}$; and ε_i is the independent normally distributed random error with zero mean and constant variance. The interpretation of β_k is the expected change in y_i for a one-unit change in $x_{i,k}$ when the other covariates are held fixed. Care must be taken when interpreting regression results, as some of the regressors may not allow for marginal changes (such as dummy variables, or the intercept term), while others cannot be held fixed.

It should be noted that besides the assumptions mentioned above, other strict assumptions may be applied to the MLR model for validation. However, linear regression modeling requires less computation effort than non-linear one. In addition, without comprehensive understanding of the functional relationship between response (i.e. observed maximum throughput in this study) and independent variables, a pre-mature non-linear model may not necessarily outperform a linear one in data fitting. Results of the multiple linear regression model have been shown in Table 3-7 and Table 3-8 for HOV lane and FWY lane, respectively. The stepwise deletion method can also be used to derive a more simplified model with only a small subset of explanatory variables, most of which are statistically significant (at 5% α-level). However, the results have not been presented in this report because no too much value can be added on the top of the full-size model.

As is shown in Table 3-7, for both the PeMS and Max-flow methods, the HOV access type is statistically significant at 5% α-level response and the associated estimate of coefficient is positive. This means that the limited-access HOV facilities may induce higher maximum throughput than the continuous-access ones based on these models' prediction. In addition, there is no obvious District effect for the HOV lane observed maximum throughput using the PeMS method but it is not the case for the model using the Max-flow method. However, both multiple and adjusted R^2 values are very small for HOV lane regression, which indicates that the proposed models may not be good for the estimation of observed HOV lane throughput (either the PeMS or Max-flow methods) because the percentage of response variation can only be accounted for from 12 to 26 by the regressors in these models. More response variation can be explained in the model using the Max-flow method than PeMS one.

Table 3-7. List of regression coefficients of MLR models for HOVL

Independent Variables	PeMS Method		Max-flow Method	
	β_i	P-Value	β_i	P-Value
Intercept	126.38*	2.2E-09	103.20*	2.4E-04
HOV access type	18.96*	0.001	35.86*	2.7E-06
Distance between VDS and Point A	-2.32	0.404	-4.98	0.180
Distance between VDS and Point B	5.55	0.051	10.78*	0.005
Number of Lanes	—	—	—	—
Outer shoulder width	—	—	—	—
Average width per lane	-0.80	0.794	3.11	0.447
Inner shoulder width	-0.45	0.289	-0.89	0.116
On-ramp indicator of upstream ramp with respect to. VDS	-2.99	0.396	-0.02	0.996
Distance to upstream ramp with respect to. VDS	-0.14	0.909	-0.96	0.568
On-ramp indicator of downstream ramp with respect to. VDS	-1.00	0.774	0.15	0.975
Distance to downstream ramp with respect to. VDS	1.96	0.086	2.52	0.099
District indicator of District 7	-11.86	0.119	-35.59*	5.0E-04
District indicator of District 8	-10.47	0.134	-32.77*	4.6E-04
District indicator of District 12	-8.42	0.158	1.46	0.854
Truck proportion at capacity	—	—	—	—
VDS occupancy at capacity	121.80*	1.2E-10	296.43*	< 2.2E-16
Degree of Freedom	546		546	
Residual SE**	35.42		47.39	
Multiple R-Squared	0.143		0.279	
Adjusted R-Squared	0.122		0.262	
F-Statistic P-Value	1.3E-12		< 2.2E-16	

* *Significant at 5% α-level*
** *Standard error*

As shown in Table 3-8, the variable of our interest, HOV lane access type, is statistically significant and the associated estimate of coefficient is positive in all models, which is similar to the result for HOV lane. Also, the district indicator for District 12 is significant at 5% α-level for the PeMS method while all district indicators are statistically significant for the Max-flow method. This matches the observations from Appendix E. The estimated coefficient for District 12 is positive but those for District 7 and 8 are negative, which means that the estimated response may vary a lot with Caltrans District.

An interesting finding is that the number of lanes is statistically significant for all models. However, the estimated coefficient is negative for average freeway lane case but positive for overall freeway lane model. A potential explanation is that the more the number of lanes there is, the higher the maximum throughput of overall freeway segment, but the more intensive the lane changing maneuvers would occur, which may cause throughput drop for each lane. Another interesting observation is that the inner shoulder width is statistically significant with negative coefficient, which means the wider the inner shoulder width is, the lower the freeway lane throughput, and vice versa. This may be because for some freeways with limited right of way, a new lane was added by partially reducing the width of the shoulders. Therefore, the overall throughput on those freeways increases while the inner shoulder width decreases.

Table 3-8. List of regression coefficients of MLR models for FWYL

Independent Variables	**Average FWYL**				**Overall FWYL**			
	PeMS Method		**Max-flow Method**		**PeMS Method**		**Max-flow Method**	
	$\boldsymbol{\beta_i}$	**P-Value**	$\boldsymbol{\beta_i}$	**P-Value**	$\boldsymbol{\beta_i}$	**P-Value**	$\boldsymbol{\beta_i}$	**P-Value**
Intercept	**136.08**	2.4E-12	**127.94**	5.6E-07	-49.31	0.594	**-271.50**	0.039
HOV access type	**7.45**	0.047	**15.12**	0.003	**48.58**	0.008	**94.69**	3.0E-04
Distance between VDS and Point A	0.30	0.868	0.16	0.946	1.89	0.829	0.85	0.946
Distance between VDS and Point B	2.44	0.186	4.30	0.083	7.26	0.420	16.77	0.192
Number of Lanes	**-5.13**	1.6E-04	**-4.64**	0.011	**121.32**	< 2E-16	**162.86**	< 2E-16
Outer shoulder width	0.58	0.473	**2.19**	0.044	3.10	0.431	11.01	0.051
Average width per lane	0.45	0.652	-0.14	0.917	2.97	0.542	0.52	0.940
Inner shoulder width	**-0.63**	0.021	**-0.75**	0.042	**-3.68**	0.006	**-3.90**	0.040
On-ramp indicator of upstream ramp with respect to. VDS	0.34	0.874	3.33	0.249	-0.68	0.949	15.22	0.310
Distance to upstream ramp with respect to. VDS	0.04	0.952	-0.49	0.616	0.78	0.827	-2.38	0.638
On-ramp indicator of downstream ramp with respect to. VDS	-3.20	0.121	-0.93	0.736	-15.79	0.117	-6.14	0.669
Distance to downstream ramp with respect to. VDS	0.73	0.277	0.72	0.425	3.27	0.318	1.69	0.718
District indicator of District 7	-2.72	0.568	**-16.46**	0.011	-30.15	0.195	**-114.99**	6.0E-04
District indicator of District 8	-6.93	0.133	**-15.94**	0.010	**-49.59**	0.028	**-111.78**	5.3E-04
District indicator of District 12	**24.40**	7.1E-11	**61.01**	< 2E-16	**110.46**	1.3E-09	**280.96**	< 2E-16
Truck proportion at capacity	-13.56	0.601	-39.73	0.253	-96.67	0.445	-161.51	0.370
VDS occupancy at capacity	**148.23**	3.7E-10	**251.62**	5.5E-14	**710.14**	7.6E-10	**1177.38**	9.2E-12
Degree of Freedom	513		513		513		513	
Residual SE	20.94		28.13		102.2		145.8	
Multiple R-Squared	0.319		0.578		0.725		0.790	
Adjusted R-Squared	0.297		0.565		0.717		0.784	
F-Statistic P-Value	< 2.2E-16		< 2.2E-16		< 2.2E-16		< 2.2E-16	

Variables in bold-face are statistically significant at 5% α-level

Additional and more advanced regression analyses can be found in Appendix F.

4. Video Data Analysis

4.1. Overview

This approach involves videotaping traffic at the locations of interest. The collected videos of traffic were used to extract several traffic parameters that are not measured by PeMS' sensors, for example, number of lane changes, gap at each lane change, etc. In addition, vehicle trajectories in terms of second-by-second vehicle speed profile can be extracted and used to improve HOV behavior logics in traffic simulation models.

The advantage of this approach is that the traffic parameters obtained through videos are not easy to come by in real-world. The high resolution of these traffic parameters, in both space and time, can provide new perspectives to freeway performance analysis. This can lead to a better understanding of the impact of HOV lane configuration on the operational performance of freeways with HOV facilities. However, the video data is difficult and costly to collect and process. Therefore, only a very limited number of data sets at selected locations can be obtained in this project.

4.2. Data

4.2.1. Video Data Collection

To obtain further insight into the difference in traffic operation and driver behavior across different HOV access type, video data were collected for six study sites from late August to early September, 2010. For every site, there are three collection periods, which last 2 hours each. Table 4-1 presents a summary of video footages. Figure 4-3 through Figure 4-2 show a snapshot from the video at each of the six study sites. Please note that for Euclid along I-10 East and La Sierra along SR-91 West, no ingress/egress fall into the visible range from video shot.

Table 4-1. Summary of Video Footage and Lane Changing Data Samples

HOV Type	Rte	Direction	Location	Date	Time	Sample Size**
Continuous	215	South	Humanities	09/09/2010	15:00 – 17:00	23
				09/10/2010	15:00 – 17:00	23
				09/13/2010	15:00 – 17:00	23
			University Village	09/09/2010	15:00 – 17:00	22
				09/10/2010	15:00 – 17:00	11
				09/13/2010	15:00 – 17:00	11
Limited	10	East	6th Ave	09/02/2010	15:00 – 17:00	44
				09/03/2010	15:00 – 17:00	47
				09/07/2010	15:00 – 17:00	60
			Euclid*	09/02/2010	15:00 – 17:00	9
				09/03/2010	15:00 – 17:00	2
				09/07/2010	15:00 – 17:00	1
	91	West	Buchanan	08/30/2010	15:00 – 17:00	277
				08/31/2010	15:00 – 17:00	121
				09/01/2010	15:00 – 17:00	103
			La Sierra*	08/30/2010	15:00 – 17:00	0
				08/31/2010	15:00 – 17:00	0
				09/01/2010	15:00 – 17:00	4

**HOV segment within buffered area*
***For lane changing from and to HOV lane only*

Figure 4-1. Snapshot from video on I-215 S from UCR's Humanities building (continuous access)

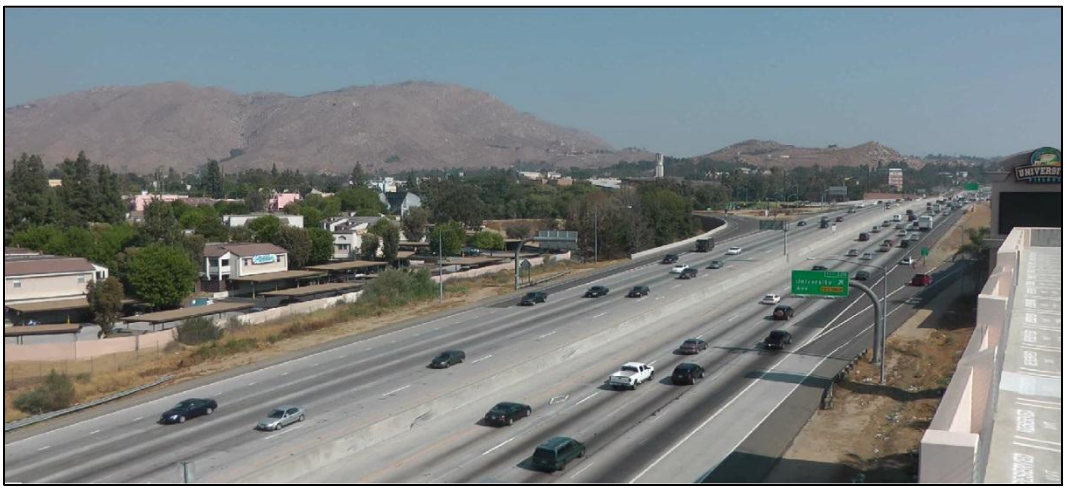


Figure 4-2. Snapshot from video on I-215 S from UV parking structure (continuous access)

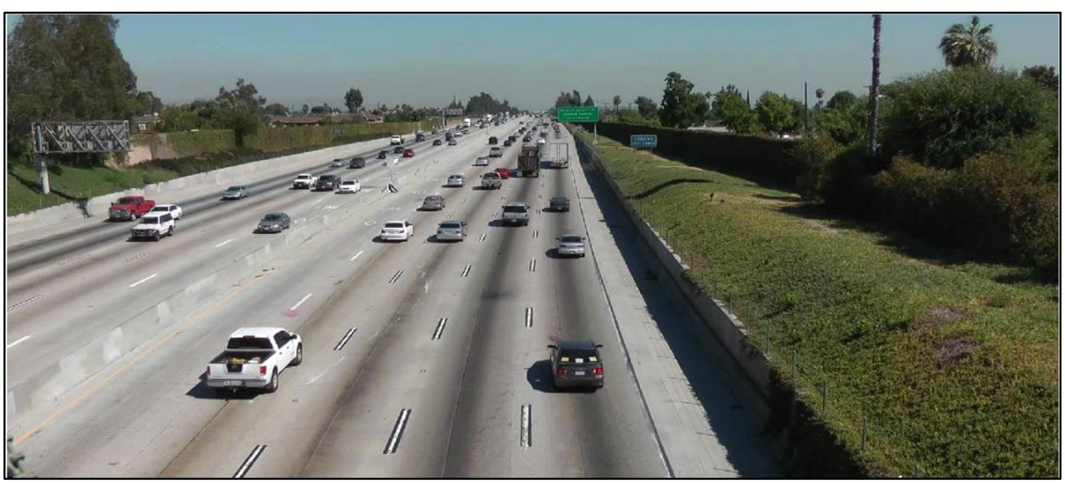


Figure 4-3. Snapshot from video at I-10 E and 6th St (limited access – ingress/egress section)

Figure 4-4. Snapshot from video at I-10 E and Euclid Ave (limited access – buffered section)

Figure 4-5. Snapshot from video at SR-91 W and Buchanan St (limited access – ingress/egress section)

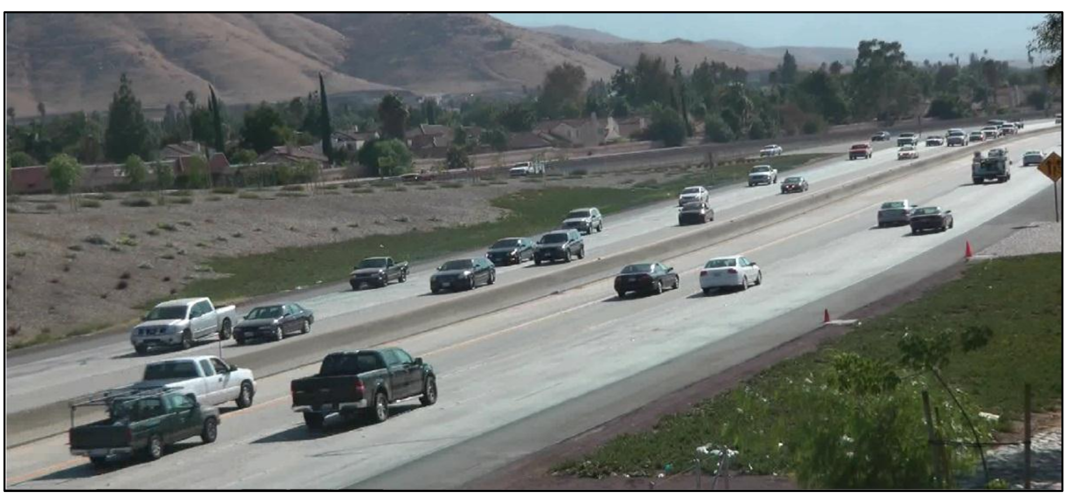


Figure 4-6. Snapshot from video at SR-91 W and La Sierra Ave (limited access – buffered section)

4.2.2. Video Data Processing

The video footages of HOV lane operation data were first processed to extract the data related to each lane changing maneuver. The data were extracted manually using the computer-aided vehicle tracking software developed earlier in the project, as shown in Figure 4-7.

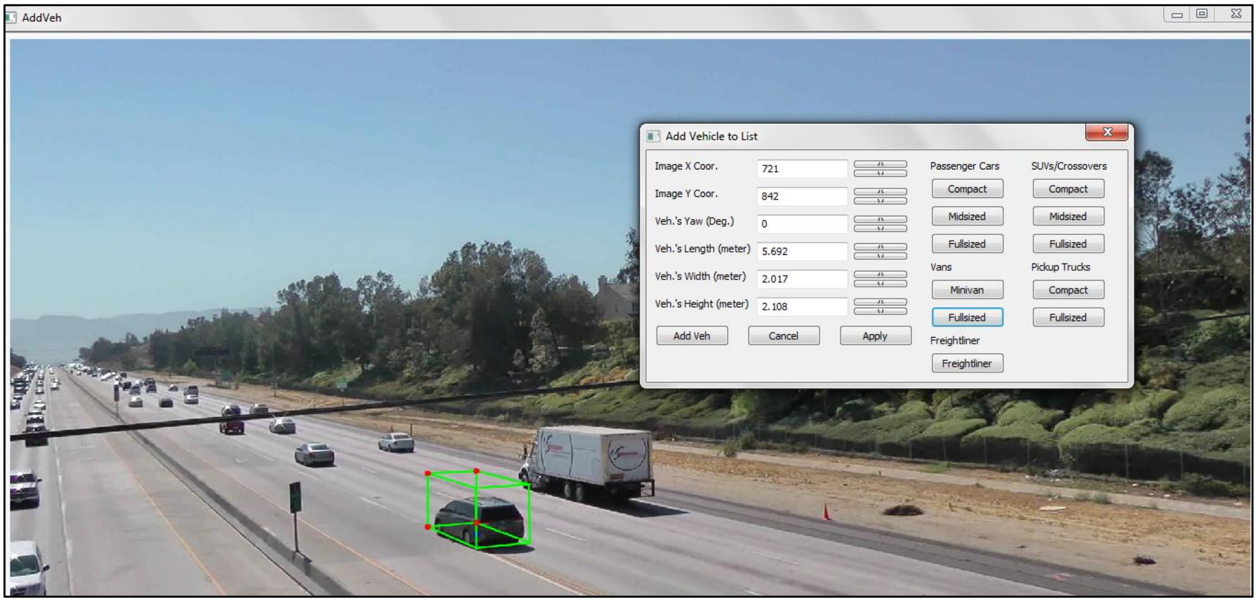


Figure 4-7. Snapshot from the developed computer-aided vehicle tracking software

To assist the manual processing, a "lane-changing moment" is defined as the time point when the front bumper of the subject vehicle hits the lane separation line (dashed line) for the first time. Figure 4-8 presents a snapshot of such event. Based on the recorded location and time information, the following quantities can be identified.

1. *Lag gap along the target lane (G1)* – The time difference between the lane changing moment and the time point when the front bumper of the lag vehicle (Vehicle D) on the target lane (lane 1 in Figure 4-8) hits x_{sub} for the first time;
2. *Lead gap along the target lane (G2)* – The time difference between the lane changing moment and the time point when the front bumper of the subject vehicle hits x_{lead}^{t} for the first time;

3. *Lead gap along the pre-changing lane (G3)* – The time difference between the lane changing moment and the time point when the front bumper of the subject vehicle hits x_{lead}^{p} for the first time;

4. *Clearance for lane-changing (G4)* – The time difference between the lane changing moment and the time point when the front bumper of the lag vehicle (Vehicle D) on the target lane hits x_{lead}^{t} for the first time.

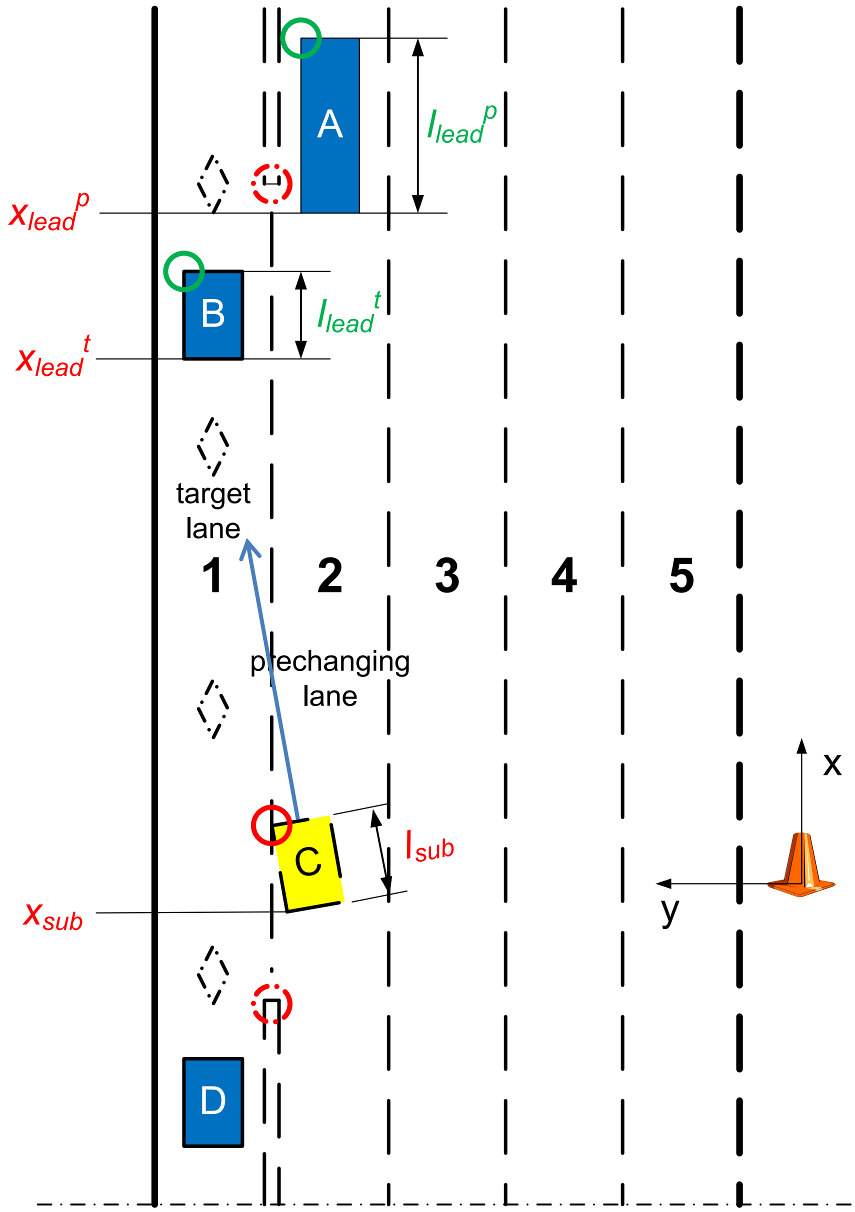
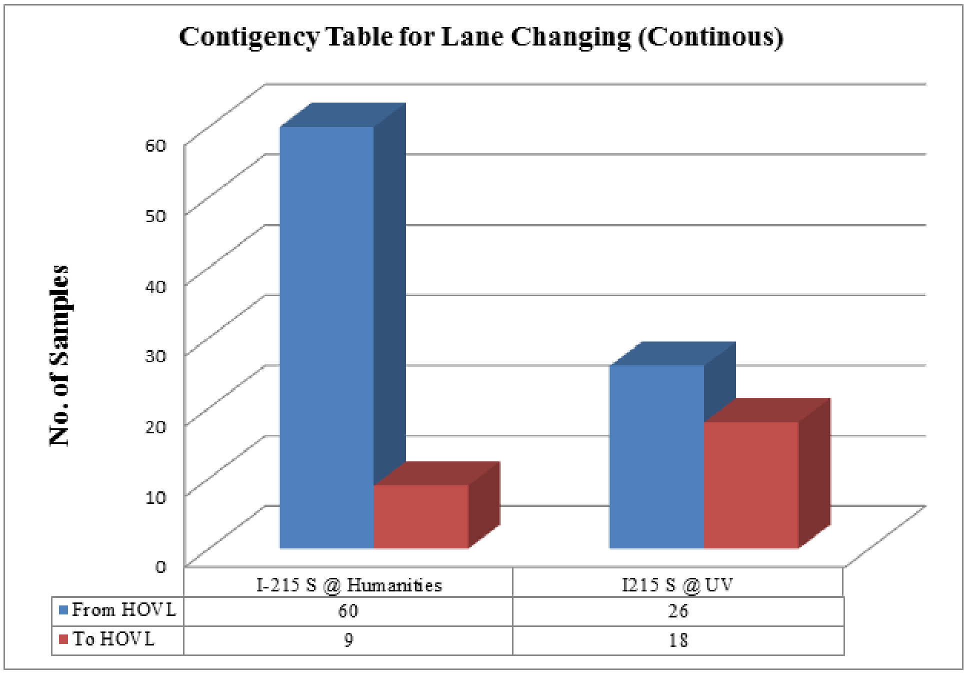
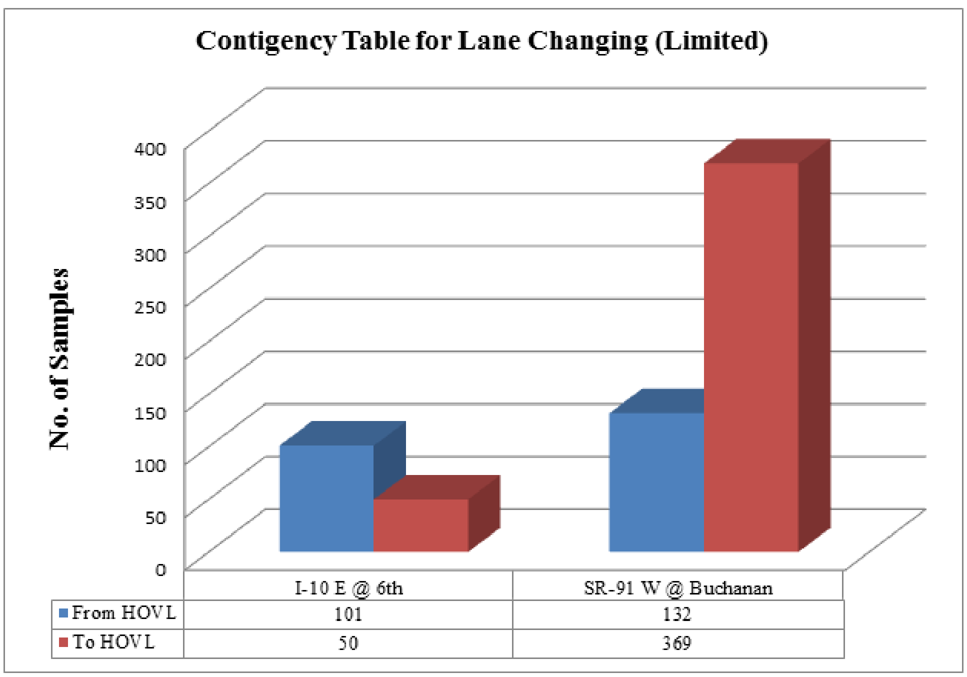


Figure 4-8. Illustration of the lane changing moment for manual processing of video footages

After the quantities above are available, preliminary analysis has been conducted on the processed data for both continuous-access and limited-access HOV facilities. To compare the HOV lane operation difference due to the HOV access type and/or study location, the analyses are focused on lane changing maneuvers between the HOV and adjacent mixed-flow lanes. The sample size of lane changing from and to HOV lane only is also listed in Table 4-1 for each study site. Please note that those very limited samples at Euclid along I-10 East and La Sierra along SR-91 West may result from drivers' violation by traversing the double yellow solid lines. In the following analysis, data samples from these two sites have been removed. A contingency table for data samples of lane changing from and to HOVL is illustrated in Figure 4-9 for each data collection site.



(a) Continuous HOV facilities



(b) Limited HOV facilities

Figure 4-9. Cross-tabulation for data samples of lane changing from and to HOV lane by location

4.3. Analysis and Results

Two types of analyses have been conducted in this report.

1. Estimated lane changing intensity with respect to location
2. Distributions of lane changing acceptance gaps

The analysis is still preliminary at the current stage. More comprehensive data analysis can be conducted due to the availability of other extracted information, such as vehicle type which may also potentially affect the gap statistics. This could be a future step for data analysis.

4.3.1. Estimated Lane-Changing Intensity with respect to. Location

Based on the observed data samples, a kernel density estimator is used to estimate the intensity of lane-changings over location. Kernel density estimation is a method for inferring the probability density function of the population of a random variable based on a finite number of data samples. Figure 4-10 and Figure 4-11 present the estimation results along both HOV and adjacent mixed-flow lane. Please note that for comparison, the locations have been normalized by the percentage of overall length of lane-changeable range at each site, i.e.

$$\bar{l}_{i,j} = \frac{l_{i,j} - s_i}{L_i} \times 100\% \tag{4-1}$$

where $\bar{l}_{i,j}$ is the normalized location for the j-th data sample from the i-th data set (e.g. I-10 @ 6th Ave on Sep. 2nd, 2010); $l_{i,j}$ is the associated measured location; s_i and L_i are the starting point location and overall length of the lane-changeable region, respectively. In this study, for limited access HOV facilities, the starting point is the place where ingress/egress begins and the overall length is the length of ingress/egress area. For continuous access HOV facilities, s_i represents the starting point of the segment covered by the video footage while L_i is the length of visible region.

It can be observed from Figure 4-10 and Figure 4-11 that distributions for different sites vary significantly. All the distributions exhibit a single peak, which skews towards the left. This may be due to the limitation on visible region in manual processing and some samples of lane changing occurring far-side are not able to capture. As shown in Figure 4-10, compared with limited-access HOV facilities (I-10 @ 6th Ave and SR-91 @ Buchanan), the intensity distributions (from HOVL to AMFL) of continuous facility (I-215 S) get more spread out, which may be explained by the fact that there is more flexibility in lane changing maneuver along continuous access HOV facilities than limited ones. However, no similar trend can be seen for the lane changing from AMF lane to HOV lane (see Figure 4-11).

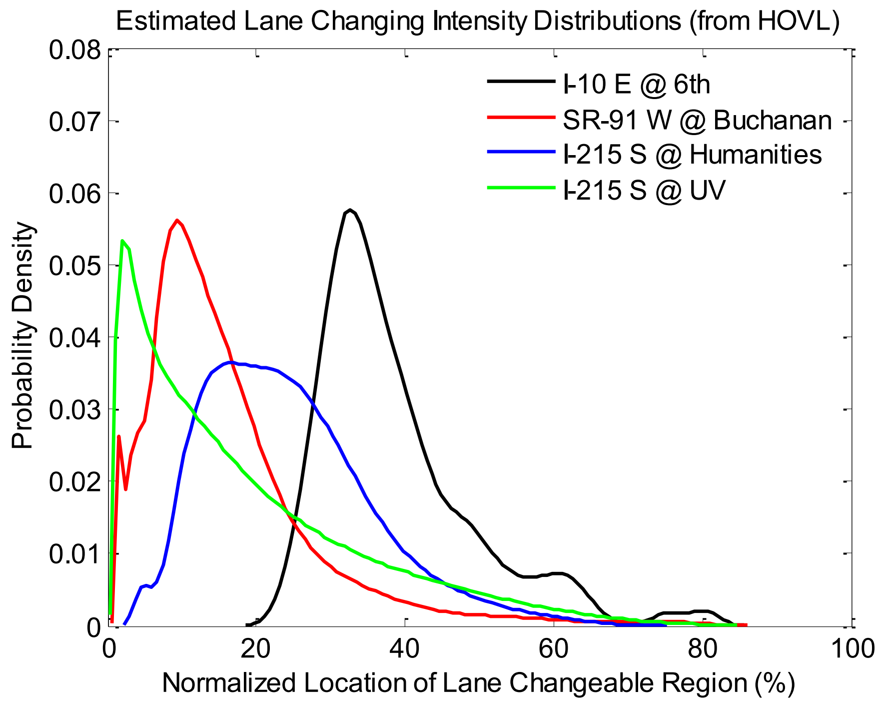


Figure 4-10. Estimated Lane-Changing Intensity vs. Normalized Location (from HOV Lane)

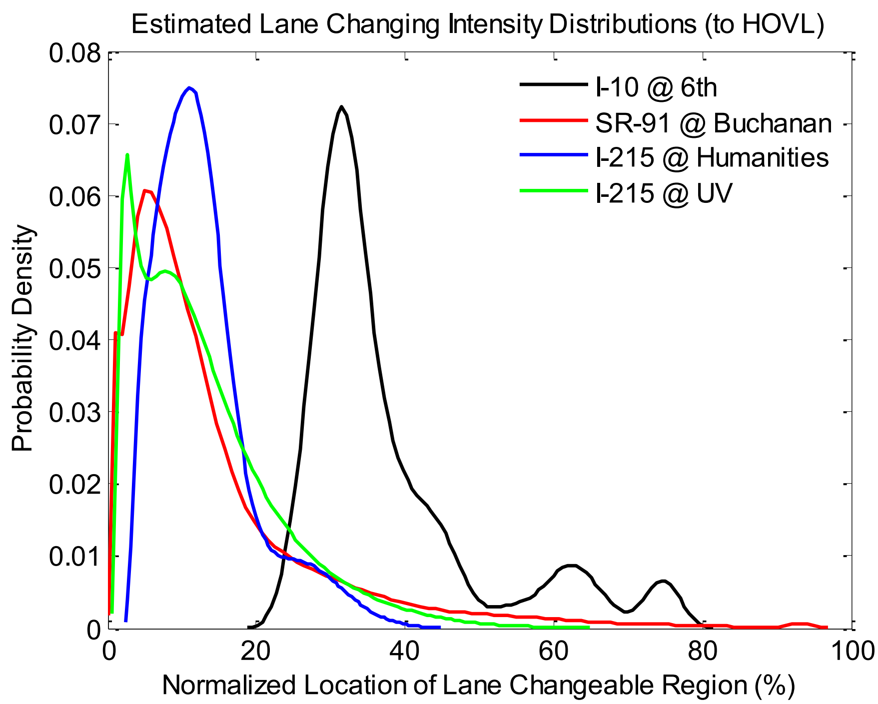


Figure 4-11. Estimated Lane-Changing Intensity vs. Normalized Location (to HOV Lane)

4.3.2. Lane-Changing Gap Distributions

Figure 4-12 through Figure 4-19 provide results for different gap quantities as defined previously, including lead/lag gap along target lane, lead gap along pre-changing lane and clearance along target lane. These distributions are also estimated by applying kernel density estimator (using Normal function) to data samples.

As shown in Figure 4-13, lag gaps along adjacent MF lanes for all sites are smaller than those along HOV lanes shown in Figure 4-12. This may result from AMFL being more congestion than HOVL during the afternoon peak hours.

An interesting finding from Figure 4-14 is that the distributions of lead gap along adjacent MF lanes for continuous-access HOV facilities (I-215 S) are more spread out than those of limited access ones. One of potential explanations is that less restriction has been cast on lane changing location for continuous-access HOV facilities. However, no similar pattern can be observed for the HOV lanes (see Figure 4-15).

As to lead gap distributions along the pre-change lanes (from HOVL to AMFL), there is not obvious difference in the mode among different types of HOV facilities (see Figure 4-16). But as illustrated in Figure 4-17, such gaps become larger for lane changing maneuvers from AMFL to HOVL along continuous-access HOV facilities. Further investigation on the vehicle type (e.g. sedan or trucks) may provide deeper insight, which can be a topic for future research.

As shown in Figure 4-18and Figure 4-19, the clearance along HOVL or AMFL for continuous-access HOV facilities is slightly higher than that of limited ones. This may be expected because drivers along continuous-access HOV facilities have more room to conduct a safer lane changing maneuver without restriction on the location.

It has to be pointed out that the kernel density estimate actually is very sensitive to the outliers. However, errors may occur in the procedure of manually video processing. To obtain more robust conclusions, considerable efforts are critical for data preprocessing and cleaning. Rather than these estimated density distributions, more statistical tests can be conducted to identify the disparity between two types of HOV facilities. In addition, most of the distributions are highly correlated to the travel pattern and demand around individual study site (e.g. location of the nearest on-/off-ramp). Therefore, more reliable explanations can be obtained by combining other information, such as traffic flow and geometric characteristics.

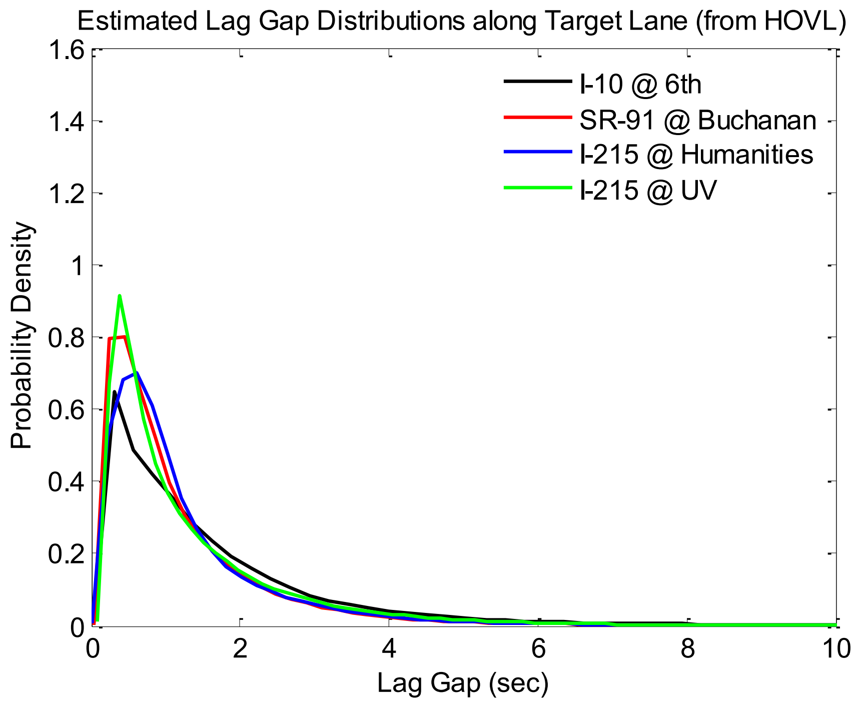


Figure 4-12. Estimated Distributions of Lag Gap along Target Lane (from HOVL)

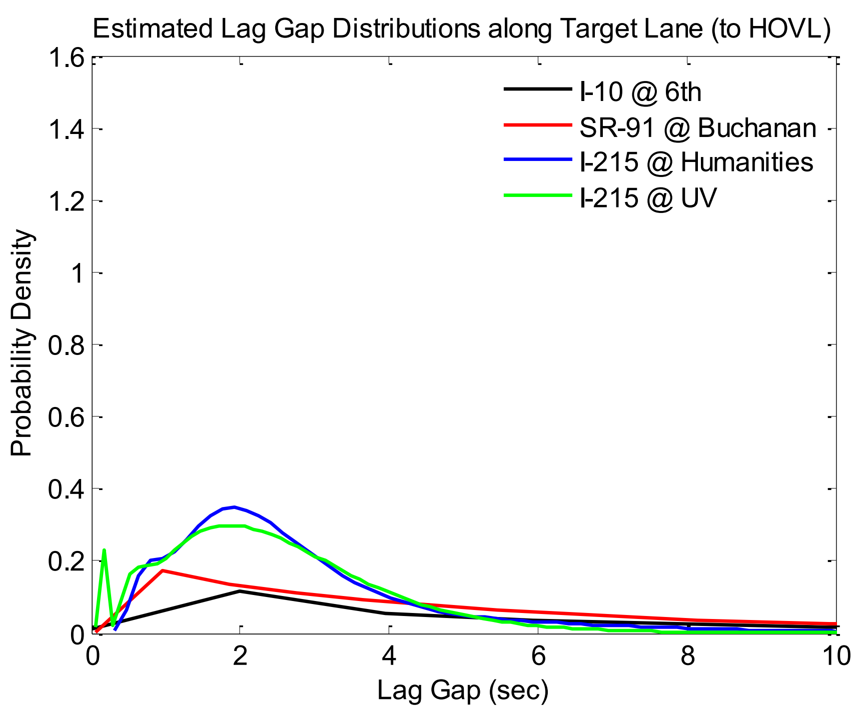


Figure 4-13. Estimated Distributions of Lag Gap along Target Lane (to HOVL)

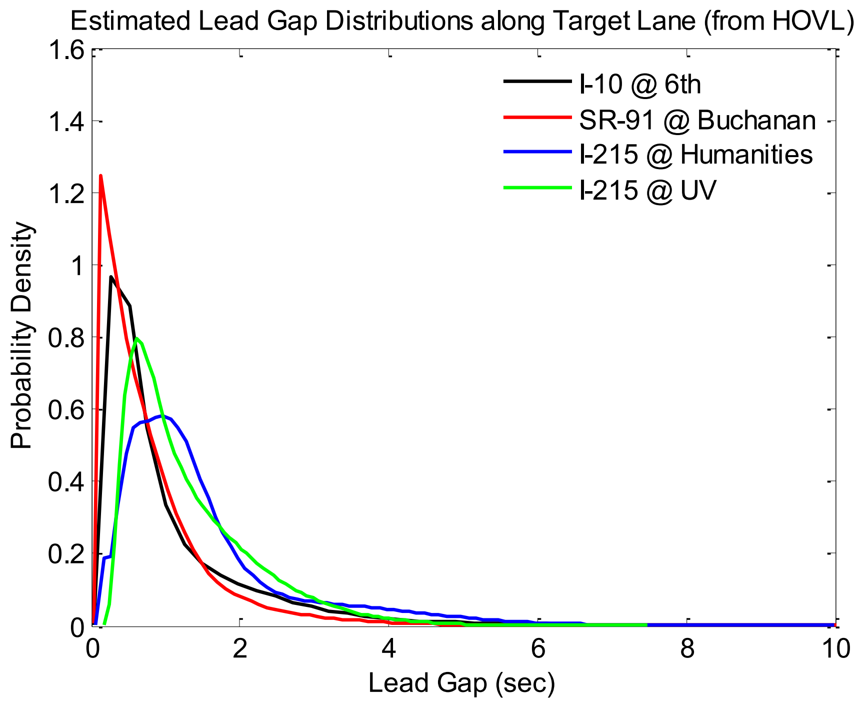


Figure 4-14. Estimated Distributions of Lead Gap along Target Lane (from HOVL)

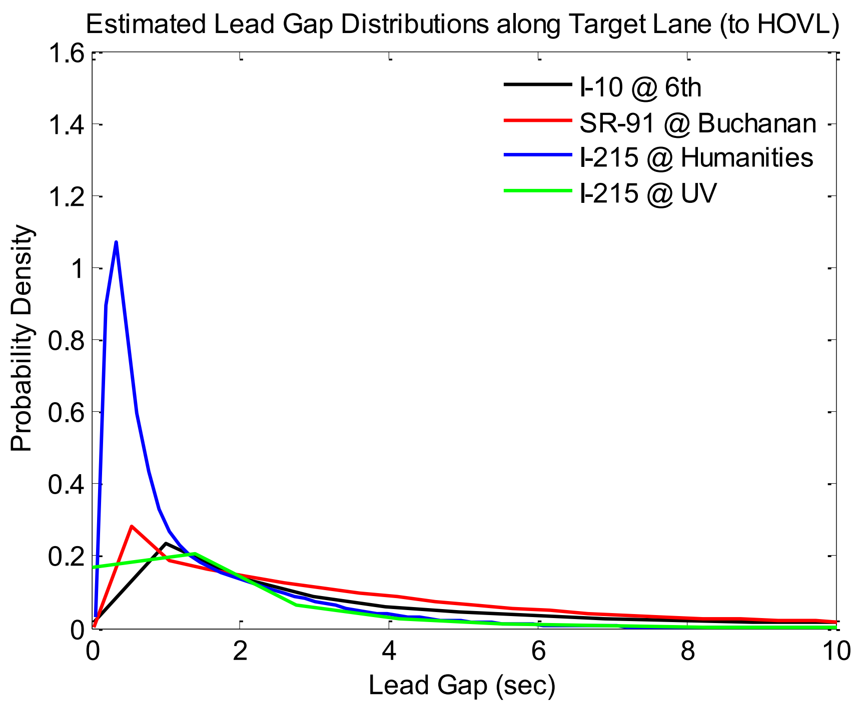


Figure 4-15. Estimated Distributions of Lead Gap along Target Lane (to HOVL)

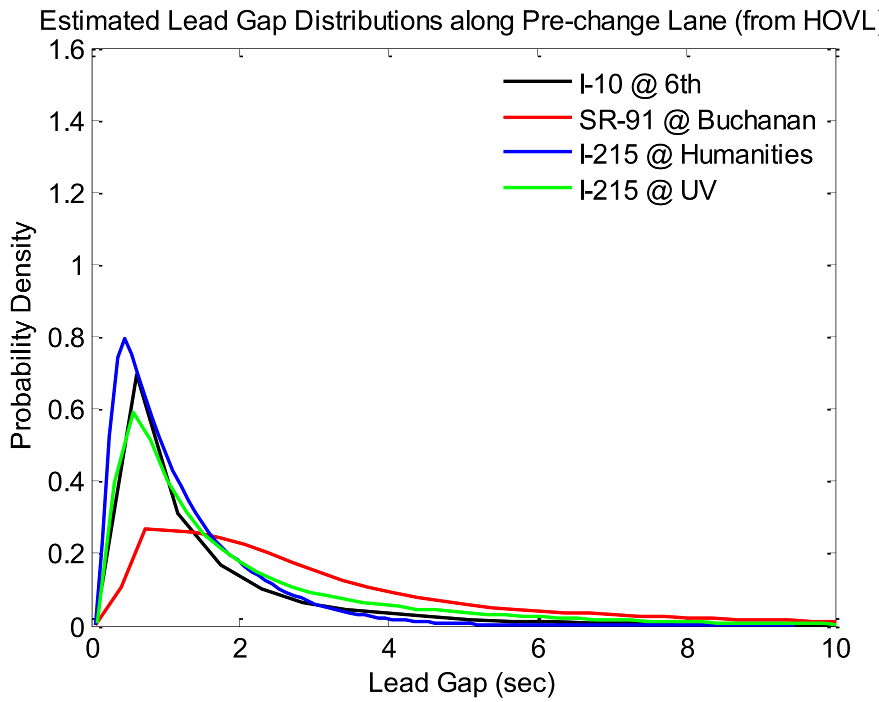


Figure 4-16. Estimated Distributions of Lead Gap along Pre-change Lane (from HOVL)

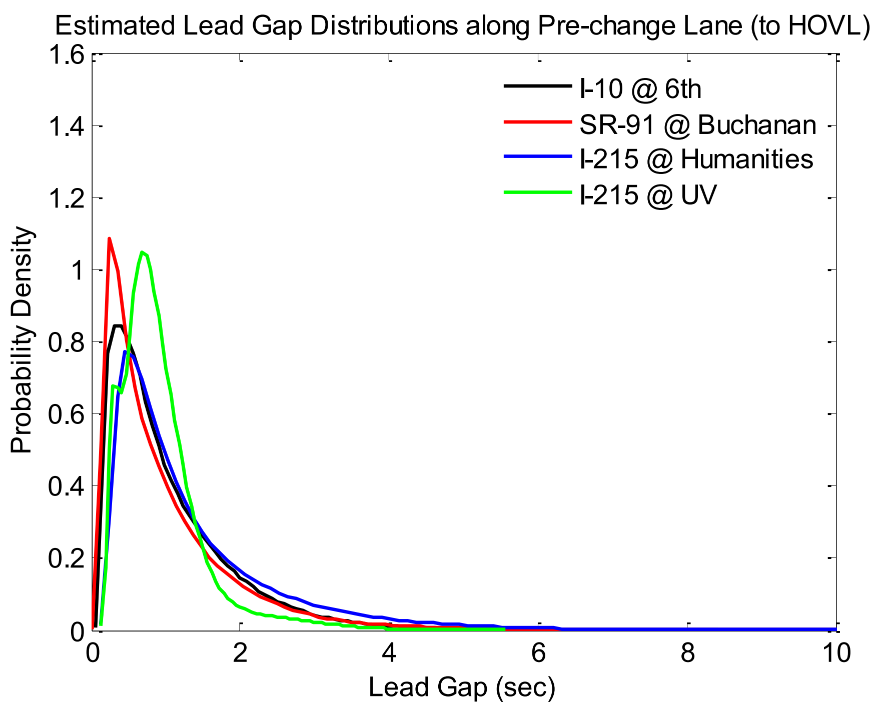


Figure 4-17. Estimated Distributions of Lead Gap along Pre-change Lane (to HOVL)

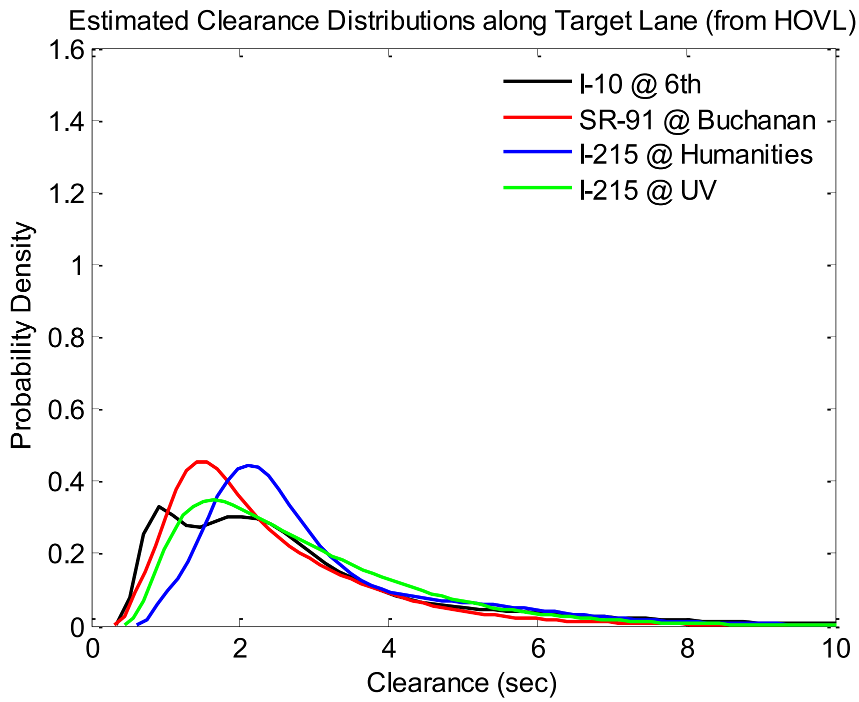


Figure 4-18. Estimated Distributions of Clearance along Target Lane (from HOVL)

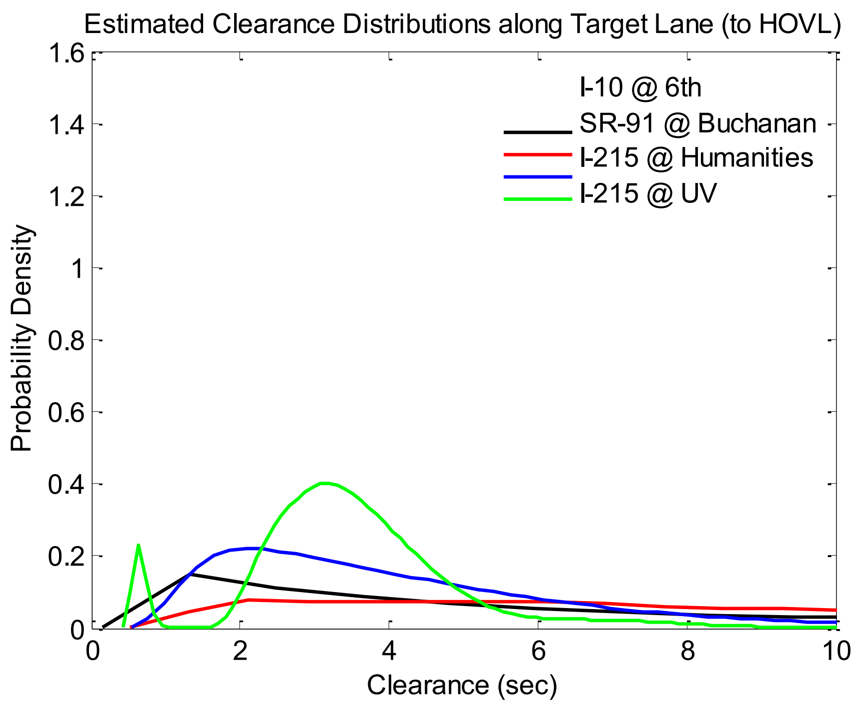


Figure 4-19. Estimated Distributions of Clearance along Target Lane (to HOVL)

5. Traffic Simulation

5.1. Overview

In addition to the approaches that are based on real-world data, a study of HOV lanes' operational performance can be conducted through traffic simulation modeling. There are a variety of traffic simulation tools, from macroscopic to microscopic, that have been developed and validated over the last several decades. Many of these simulation tools have a capability of modeling HOV lanes for both limited access and continuous access configurations.

The advantage of the simulation approach is that both types of HOV lane configuration can be implemented on the same freeway network and its operational performance can be simulated and compared directly. There are no other geometric differences besides the HOV lane configuration that could bias the results. This type of direct comparison would be more difficult and costly to do so in real-world. Also, in the simulation the overall traffic demand and mode split between HOVs and SOVs can be set to be the same for both types of HOV lane configuration. In addition, the simulation network can be created for any freeway segments or corridors, and a variety of scenarios can be tested.

This chapter presents a traffic simulation modeling study to evaluate and compare the network-wide operational performance between limited access and continuous access HOV facilities under various traffic demand and HOV proportion.

5.2. Simulation Network

5.2.1. Study Site

Two major intersecting freeways in D8 were simulated in this study: SR-91 and I-15 (see Figure 5-1 for the map and Table 5-1 for the network boundary). The SR-91 section is a 14-mile stretch from west of the interchange with SR-241 to east of Tyler Street. The I-15 section is from Temescal Canyon Road. to Limonite Avenue. There are 21 on-ramps and off-ramps along SR-91 and 18 on-ramps and off-ramps along I-15 in both directions. The HOV lane on SR-91 is limited access with 2+ occupancy requirement and full-time enforcement. There are 12 ingress/egress locations. The SR-91 section is well covered by PeMS vehicle detector stations (VDS)–37 in HOV lanes and 37 in MF lanes (both directions combined). The I-15 section has no HOV lane and is covered by 36 VDSs (both directions combined).

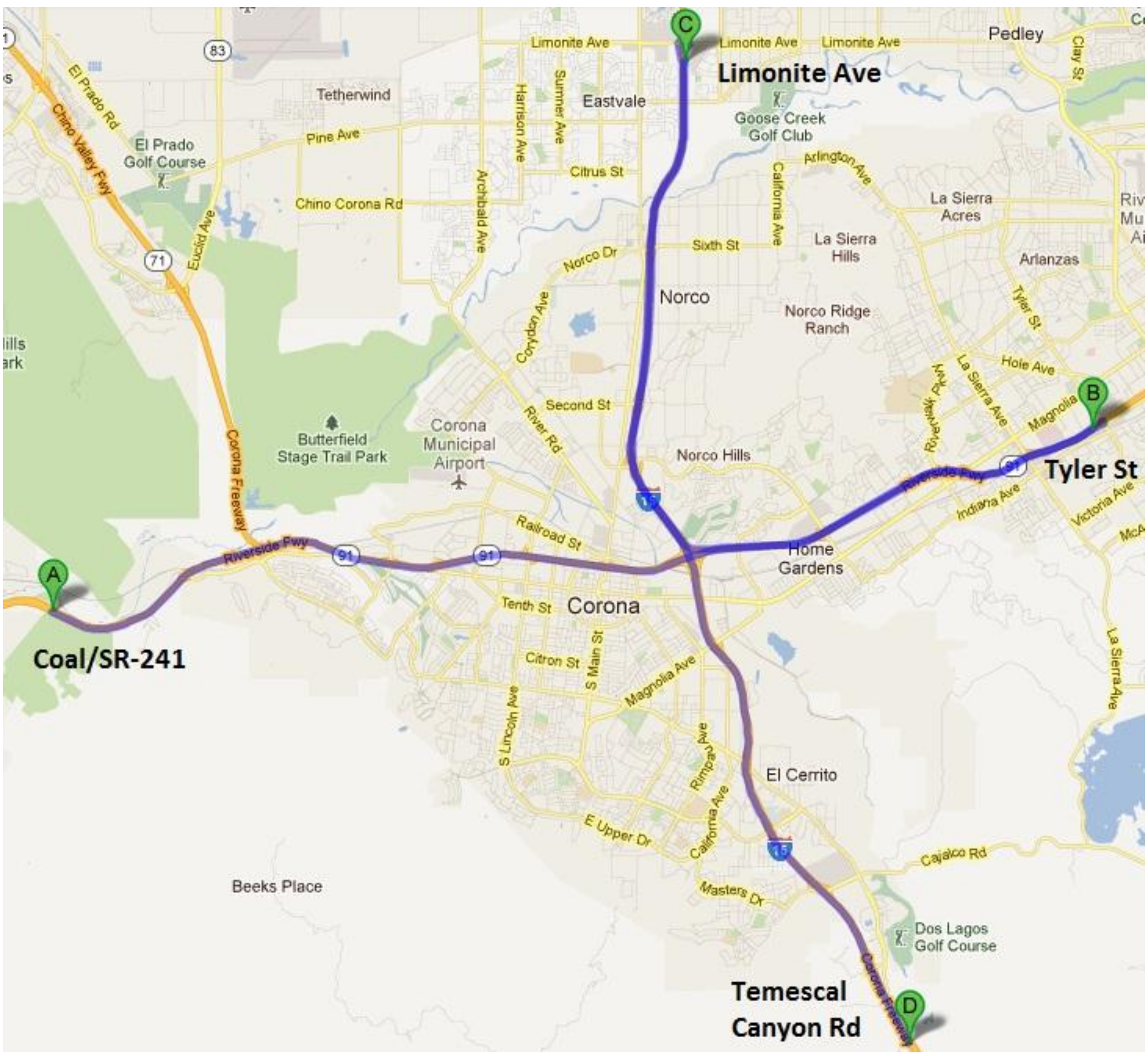


Figure 5-1. Study site of the simulation modeling

Table 5-1. Boundary of the simulation network

Route	Dir	Starting Point			Ending Point			Length (miles)
		Location	CA_PM	Abs_PM	Location	CA_PM	Abs_PM	
SR-91	E	Coal	R17.9	36.2	Tyler	12.9	50.2	14
	W	Tyler	12.9	50.2	Coal	R17.9	36.2	14
I-15	N	Temescal Canyon	33.5	88.0	Limonite	48.6	103.1	15.1
	S	Limonite	48.6	103.1	Temescal Canyon	33.5	88.0	15.1

The simulation network was built in PARAMICS traffic micro-simulation software suite version 6.7.2. The software suite consists of several modules—Modeler, Processer, Analyzer, Programmer, Monitor, and Estimator—that can be used to model behavior of individual vehicle and interaction between vehicles in a stochastic way. Simulation network setup, model configuration, and traffic demand coding, among others, are performed in the Modeler module. The inputs to PARAMICS include network geometry, vehicle dynamics, traffic control settings, and traffic demand information, while the typical outputs include statistics at the network level (e.g., overall travel time, total travel distance, and average speed), on a link basis (e.g., flow, queue length, delay, speed, and density), or at specific locations (instantaneous detector-type information). With a user-defined software plug-in developed though application programming interface (API), statistics can also be reported on a time-step or event basis. For more detailed information about PARAMICS, please refer to http://www.paramics-online.com/.

5.2.2. Network Coding

The high resolution satellite images from Google Map (as of November 2009) were used to guide the digitization of the simulation network. They were imported into PARAMICS as background images and used to guide the detailed coding of geometry of each node and link, for example, degree of curvature of curves, locations of ramp merge and diverge, etc. However, the resolution of these images may not always be high enough for proper determination of the number of lanes as well as the exact locations of HOV lane ingress/egress sections. Thus, this detailed information was obtained from other sources, such as as-built maps. The accuracy of geometric feature is critical to the simulation results since they can have significant impacts on how vehicles interact with the roadway and with each other. Therefore, great care was exercised throughout the network coding to ensure that the geometry of the simulation network was as close as possible to the real world. Figure 5-2 shows the entire simulation network coded in PARAMICS and Figure 5-3 zooms in to the SR-91 and I-15 interchange.

In the case of network with limited-access HOV lanes, HOV and MF lanes were coded as separate links along the sections where there are barriers between the HOV and MF lanes. They were coded as being on the same links along the ingress/egress sections. In the case of network with continuous-access HOV lanes, both HOV and MF lanes were coded on the same links throughout the simulation network. The HOV lane enforcement was coded using the "restriction" feature in PARAMICS, i.e., only HOVs were allowed to use HOV lanes. For more details on network coding of limited-access and continuous-access HOV facilities in PARAMICS, please refer to [Boriboonsomsin and Barth, 2006].

It should be pointed out that virtual loop detectors were also coded in the simulation network to represent the PeMS VDSs. They were coded at the same locations as in the real world. Traffic data collected from these virtual loop detectors in the simulation were used to calibrate the model against the real-world traffic condition, and later used to measure the operational performance of the simulation network.

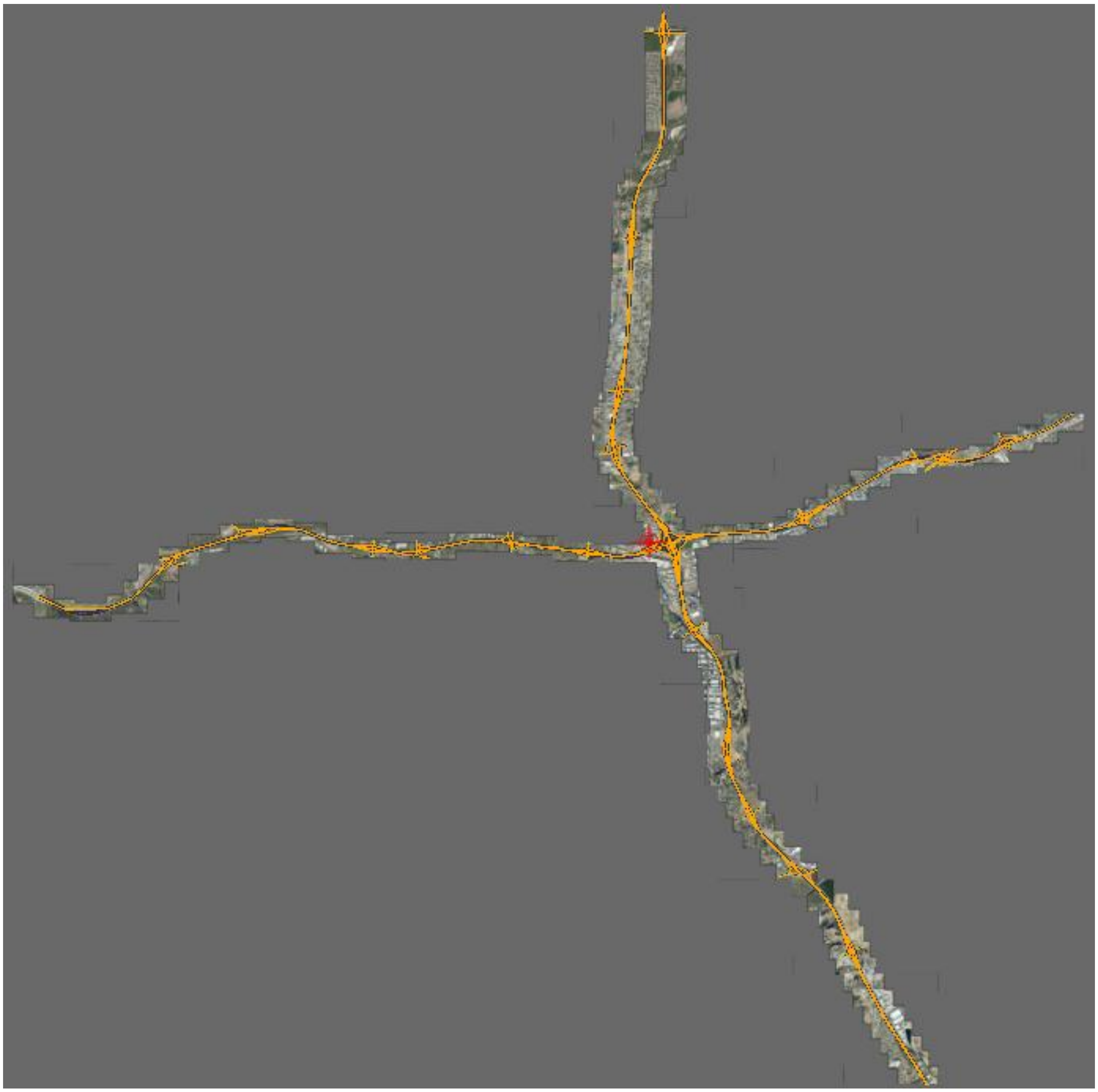


Figure 5-2. The entire simulation network

Figure 5-3. Zoom in of the simulation network at the SR-91 and I-15 interchange

5.3. Network Verification and Calibration

To verify the simulation network, error checking was conducted on several simulation components including link attributes (e.g., number of lanes, free-flow speed, etc.), lane restriction, traffic zones, and trip matrices for both single-occupant vehicles (SOVs) and HOVs. In addition, partial demands were loaded onto the network and vehicle behaviors were observed as the simulated vehicles moved through the network. This was to check for improper network connectivity, unrealistic congestion that might show up at low demand levels, hidden bottlenecks, as well as unexpected braking and lane changing of the vehicles [Dowling et al., 2002].

The purpose of network calibration is to replicate the real-world traffic characteristics in the simulation network by adjusting various parameters to achieve (both qualitative and quantitative) consistency between the simulation and the field data. The maximum throughput of the network was calibrated by adjusting global parameters including mean target headway and mean driver's reaction time and by fine-tuning local parameters (e.g., signposting distance and signposting range). For ramps, parameters such as slip lane length, ramp aware distance, and minimum ramp time were also calibrated.

5.3.1. Baseline Traffic Condition

The real-world data for baseline traffic condition were obtained from PeMS. After carefully examining the health and data quality of PeMS detectors (including those for MF lanes, HOV lanes, and on-ramps) along the study sites during the period from May 1 to October 31, 2009, the traffic data on Thursday, August 6, 2009 were selected. They were used to calibrate the O-D matrices and traffic condition. The detectors' health is summarized in Table 5-2, and the data fidelity (i.e., percentage of data points observed) ranges from 85% to 93% for both SR-91 and I-15. The simulation period was selected to be the afternoon peak (2-hour duration) from 15:00 to 17:00. Compared to other periods in the same day, the traffic volume was relatively high and stable. The hourly plots of vehicle miles traveled (VMT) and network productivity (Q), defined as VMT divided by vehicle hours traveled (VHT), for each corridor are given in Figure 5-4 through Figure 5-7.

Table 5-2. Detector health on August 6, 2009

Corridor	Good	Line Down	Ctlr Down	No Data	Insufficient Data	Card Off	High Val	Inter-mittent	Constant	Feed Unstable
SR91-E	93.8	0	3.1	0.5	0	2.6	0	0	0	0
SR91-W	93	0	3.8	0.6	0	1.9	0	0.6	0	0
I15-N	92	0	2.8	0	1.2	2.8	1.2	0	0	0
I15-S	89.1	0	4.1	1	0	5.7	0	0	0	0

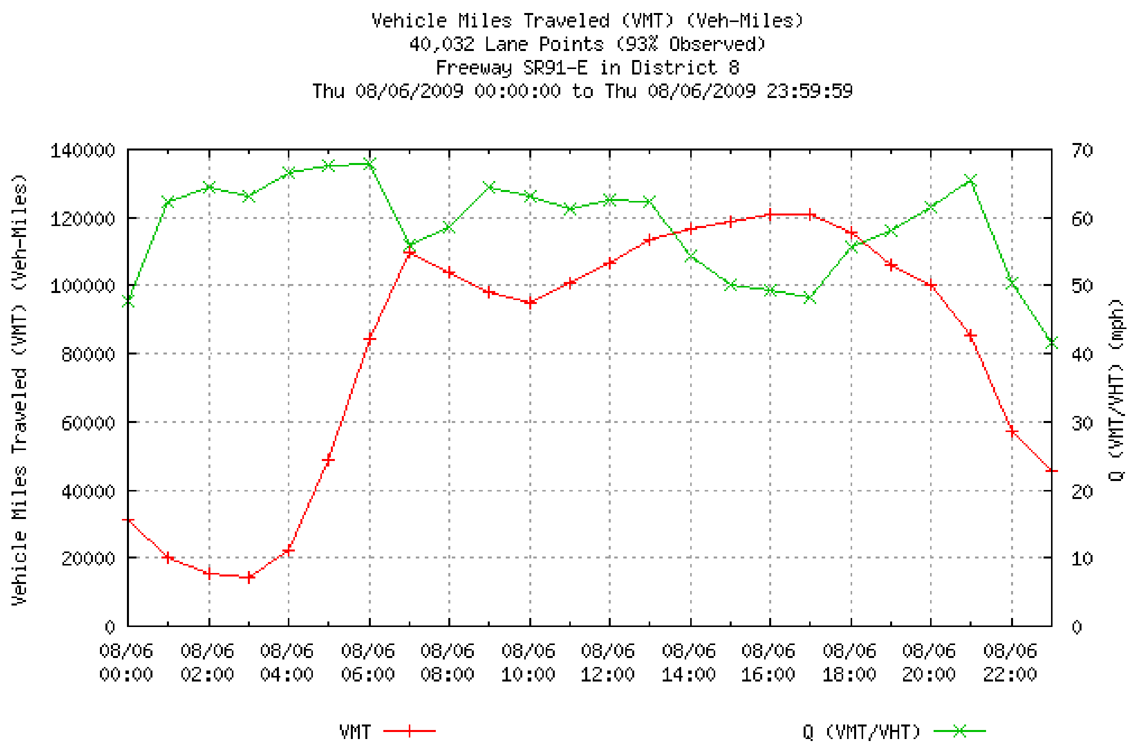


Figure 5-4. Hourly VMT and Q (VMT/VHT) for SR-91 E on August 6, 2009

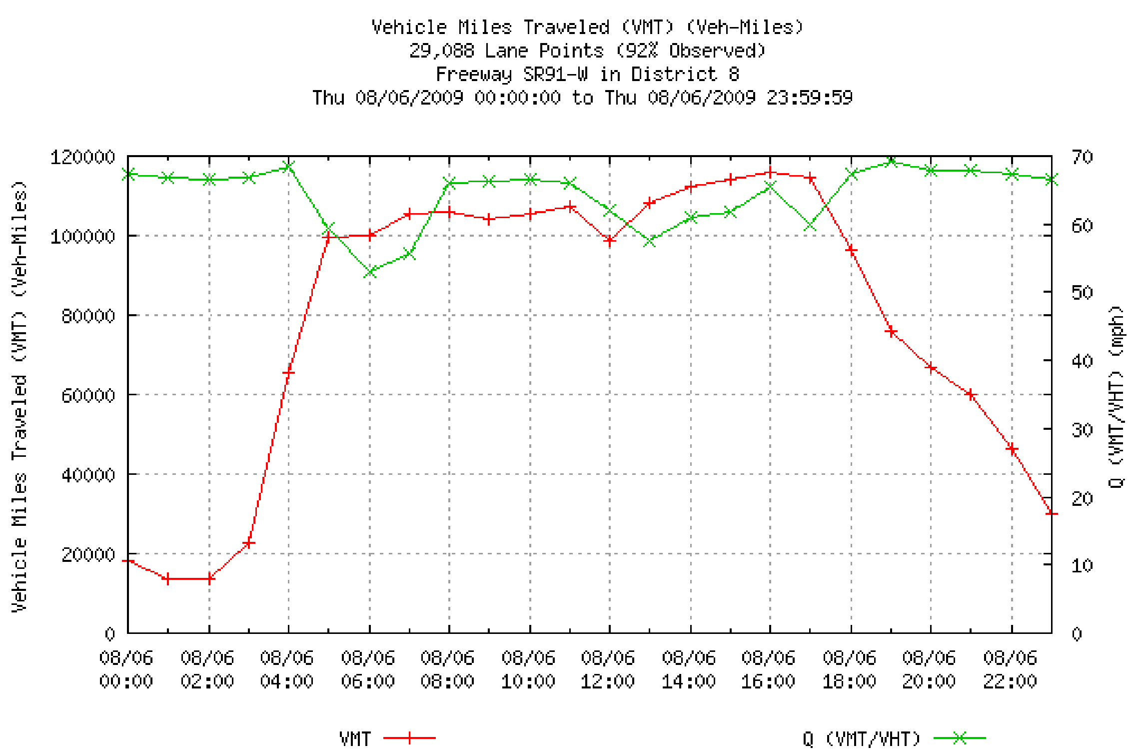


Figure 5-5. Hourly VMT and Q (VMT/VHT) for SR-91 W on August 6, 2009

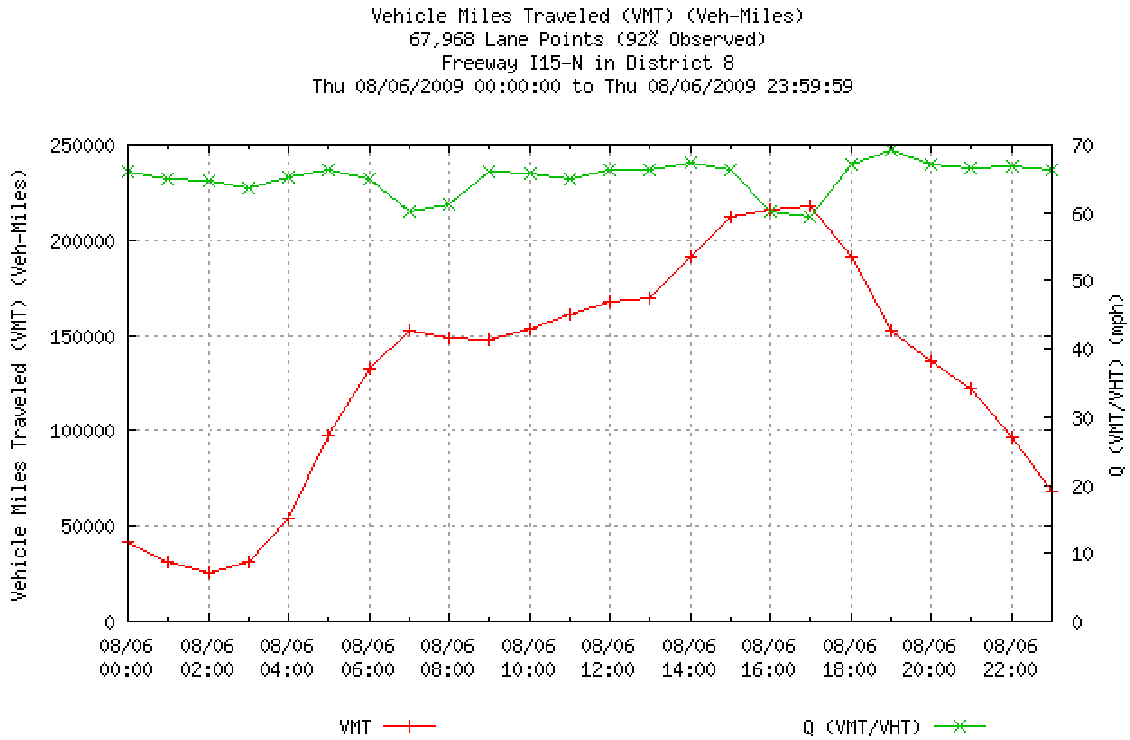


Figure 5-6. Hourly VMT and Q (VMT/VHT) for I-15 N on August 6, 2009

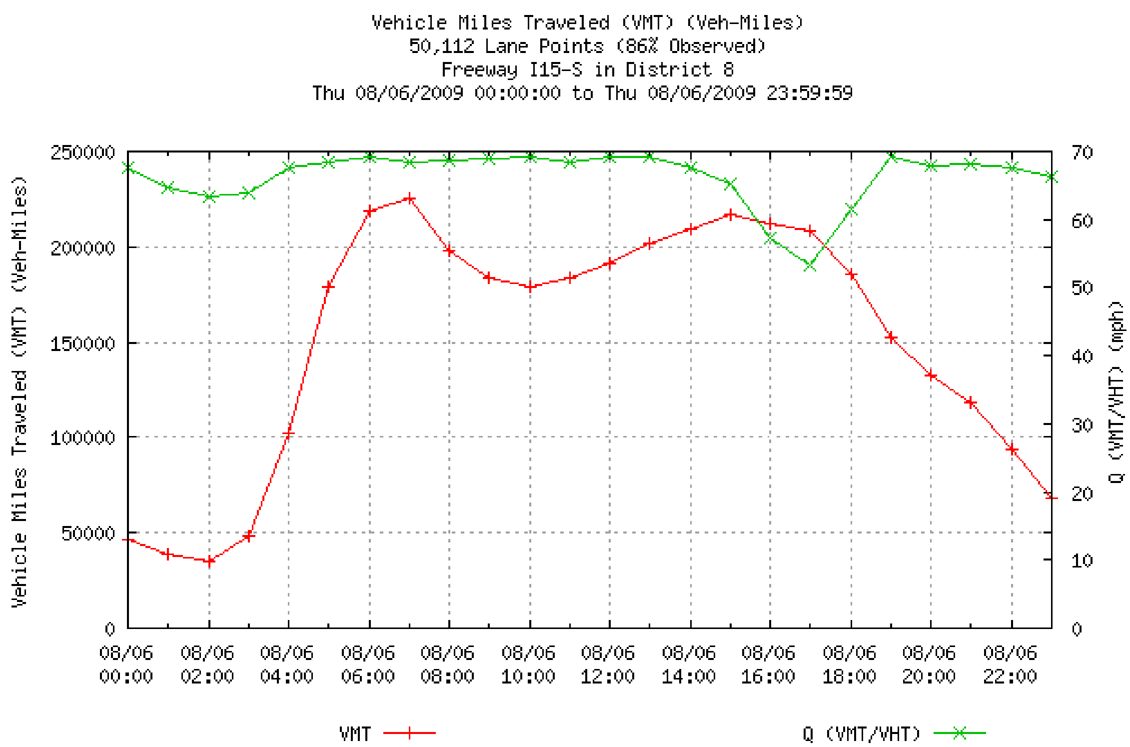


Figure 5-7. Hourly VMT and Q (VMT/VHT) for I-15 S on August 6, 2009

If smaller interval (e.g., 5 minutes) is examined, then it can be observed that the traffic condition along the whole simulation network is rather stable during the afternoon peak hour (with respect to SR-91E). Figure 5-8 and Figure 5-9 show the 5-minute VMT along SR-91 E and the whole network, respectively, from 16:00 to 17:00 on August 6th, 2009.

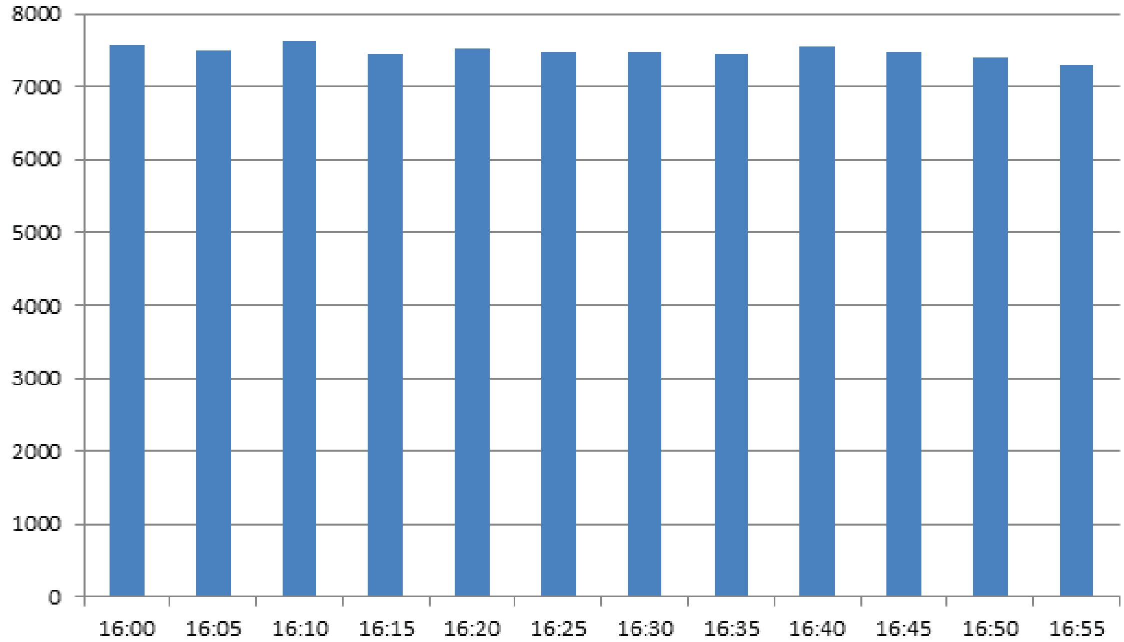


Figure 5-8. 5-minute VMT for SR-91 E from 16:00 to 17:00 on August 6, 2009

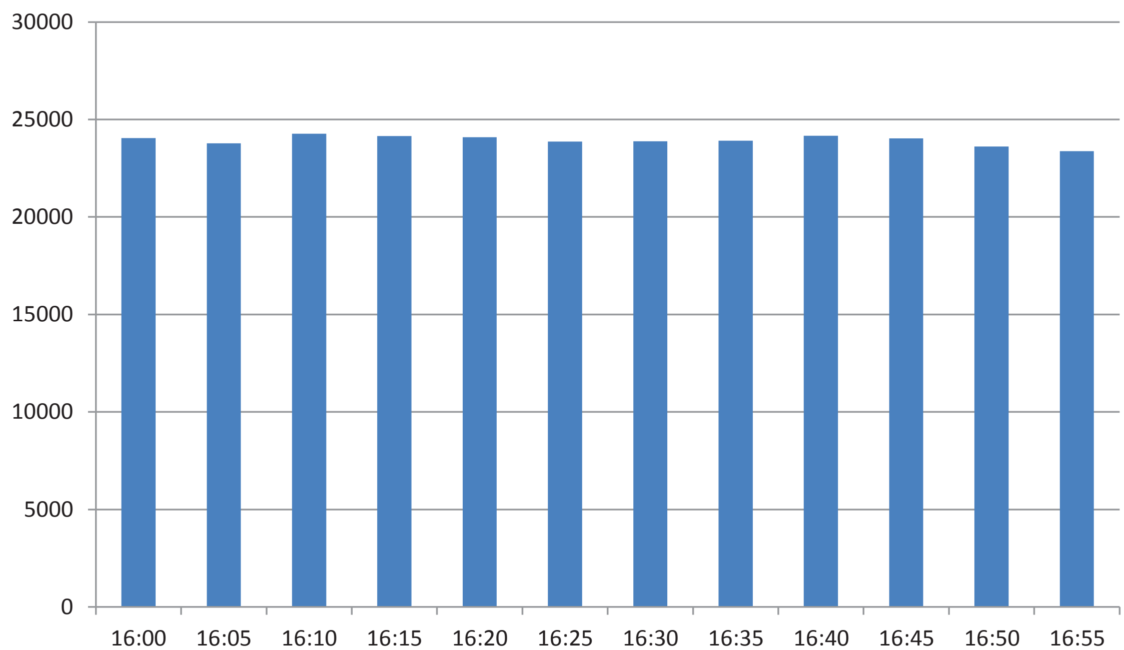


Figure 5-9. 5-minute VMT for the simulation network from 16:00 to 17:00 on August 6, 2009

5.3.2. HOV Lane Choice

To calibrate traffic flows in the HOV and MF lanes separately, one must consider how many HOVs choose to use the HOV lane for all or part of their trips. This highly depends on the traffic condition along the MF lanes, the traffic condition along the HOV lanes, and some other casual factors. This complex behavior is usually modeled as a route choice (or lane choice) behavior in the traffic assignment process. In PARAMICS, the travel costs (in the context of this simulation network, travel time) for each vehicle are updated and vehicles select the route with the lowest costs. There are many parameters that may have impact on the travel cost calculation, for example, category cost factor, link cost factor, and cost perturbation factor. For the modeling of HOV lanes, these parameters need to be calibrated so that the simulated HOVs replicate the actual HOVs in their route choice decision. In the case of network with the limited access HOV lanes, the stochastic route choice model with dynamic feedback traffic assignment technique was employed. For more detailed procedures of HOV lane choice calibration, please refer to [Boriboonsomsin and Barth, 2006].

5.3.3. Calibration Results for Limited Access HOV Facilities

The calibration criteria and acceptable targets used in the study are based on the guidelines by Caltrans [Dowling et al., 2002]. For hourly flow, the set criteria are based on the link flow and the GEH statistic. The GEH statistics is computed as:

$$GEH = \sqrt{\frac{(q_m - q_o)^2}{(q_m + q_o)/2}} \tag{5-1}$$

where q_m is the modeled hourly volume at a location, and q_o is the observed hourly volume at the same location. The detailed results for both demand calibration and route choice calibration are given in Table 5-3 and Table 5-4, respectively. The observed flows presented in these tables were extracted from the reports by PeMS. Note that a small portion of VDSs were excluded because the observed data were below 75% or no data were recorded at those locations. In these two tables, the observed data include flows on mixed flow (MF) lanes, HOV lane, and on-ramp (ONR) lanes. Table 5-5 provides a summary of the overall calibration targets and the corresponding results for the network with limited-access HOV lanes. It shows that the simulated network has been well calibrated to match the existing traffic condition in the real world. Only the GEH of all MFL links is slightly higher than the threshold of 4. A potential reason is that the flows of along SR-91E are a bit hard to model under congested condition, due to some unrealistic HOV driver behaviors, such as stopping for acceptable gap thus causing blockage at ingress/egress area (see Figure 5-10). In addition, Appendix A also list the speed contours of all study routes (i.e., SR-91 E/W, I-15 N/S) for both observed data and simulated data.

Table 5-3. Demand calibration results of hourly flow

Rte.	Lane Type	VDS ID	Station Name	No. of Lanes	Obs. Flow	Mod. Flow	Mod. - Obs.	GEH
91-E	MF/HOV	801415	.41 E/O CO LINE	4	8870	8900	30	0.32
		801428	.45 W/O RTE 71	5	8690	8837	147	1.57
		801435	RTE 71	4	7208	6990	-218	2.59
		811309	M 1.7 E/O GREEN RIV.	5	8522	8024	-498	5.48
		801442	.66 W/O SERFAS CL	4	7278	6874	-404	4.80
		801449	SERFAS CLUB	4	7790	7454	-336	3.85
		801457	MAPLE	4	7256	7170	-86	1.01
		801464	.02 E/O SMITH	4	7828	7417	-411	4.71
		801473	LINCOLN	4	7527	6975	-552	6.48
		801488	.09 E/O EAST GRAND	4	6846	6432	-414	5.08
		811325	M .1 E/O E GRAND BL	5	7794	7599	-195	2.22
		817544	.1 W/O PROMENADE	4	7434	7385	-49	0.57
		817546	.2 E/O PROMENADE	4	7424	7261	-163	1.90
		806674	MCKINLEY LOOP ON	3	5997	5803	-194	2.53
		801493	MCKINLEY	3	5992	5886	-106	1.38
		811389	M .2 W/O BUCHANAN ST	3	6715	6536	-179	2.20
		801502	MAGNOLIA	3	5922	5985	63	0.82
	On-Ramp	801425	GREEN RIVER	2	222	236	14	0.93
		801452	SERFAS CLUB	2	498	514	16	0.71
		801460	MAPLE	2	538	536	-2	0.09
		801487	MAIN	3	1188	1176	-12	0.35
		801504	MAGNOLIA	1	735	693	-42	1.57
91-W	MF/HOV	801418	GREEN RIVER	5	6903	7310	407	4.83
		801445	SERFAS CLUB	4	6868	7430	562	6.65
		814351	M .75 E/O LINCOLN	4	7801	7794	-7	0.08
		801469	LINCOLN	4	7270	7418	148	1.73
		801477	GRAND	4	7281	7589	308	3.57
		801481	MAIN	4	7057	7011	-46	0.55
		811332	M .1 E/O E GRAND BL	5	7211	7336	125	1.47
		801490	MCKINLEY	3	5631	5598	-33	0.44
		810678	M .2 W/O BUCHANAN ST	3	6168	6184	16	0.20
		801496	PIERCE	3	5749	5527	-222	2.96
		801499	MAGNOLIA	3	5429	5157	-272	3.74
		811404	M .5 W/O TYLER ST	3	5736	5961	225	2.94
	On-Ramp	801421	GREEN RIVER	3	339	318	-21	1.16
		801448	SERFAS CLUB	3	489	489	0	0.00
		801456	MAPLE	2	496	492	-4	0.18
		801472	LINCOLN	3	477	502	25	1.13
		801480	GRAND	1	320	304	-16	0.91
		801492	MCKINLEY	3	1401	1384	-17	0.46
		801498	PIERCE	2	808	753	-55	1.97
		801501	MAGNOLIA	1	347	367	20	1.06
15-N	MF	801290	ONTARIO	4	3904	3851	-53	0.85
		806176	.01 N/O TEMESCAL OC	4	4972	4638	-334	4.82
		806191	.25 N/O Old TEMESCAL	4	4804	4633	-171	2.49
		811077	M 1.27 N/O ORLANDO	4	4456	4629	173	2.57
		801301	MAGNOLIA	3	3852	3932	80	1.28
		806212	.5 N/O MAGNOLIA	4	5520	5216	-304	4.15
		806218	100 FT S/O CORONA OC	4	5636	5213	-423	5.74

Table 5-3 (continued). Demand calibration results of hourly flow

Rte.	Lane Type	VDS ID	Station Name	No. of Lanes	Obs. Flow	Mod. Flow	Mod. - Obs.	GEH
		806224	.19 S/O JCT 15/91	3	2364	2357	-7	0.14
		808622	500' S/O PARKRIDGE	4	3656	3919	263	4.27
		801327	N/O 2ND ST	3	4314	4473	159	2.40
		801329	0.3 N/O 2ND	3	4608	4870	262	3.81
		811087	M .4 N/O 2ND STREET	3	4929	4869	-60	0.86
		801331	.08 N/O 3RD ST	3	4983	4875	-108	1.54
		811095	M .18 N/O FIFTH ST	3	4794	4902	108	1.55
		808210	6TH ST NB ONR	3	4122	4322	200	3.08
		807790	.25 N/O 6TH ST	3	4617	4913	296	4.29
		807804	.75 S/O LIMEONITE	3	4803	4862	59	0.85
		811278	M .28 S/O LIMEONITE	3	3225	3889	664	11.13
		808109	LIMEONITE NB ON	3	3888	3889	1	0.02
	On-Ramp	801292	ONTARIO	2	876	812	-64	2.20
		801323	HIDDEN VALLEY	2	704	690	-14	0.53
		814417	2ND ST ONR	1	421	410	-11	0.54
		814425	6TH ST NB ONR	1	643	612	-31	1.24
		814432	LIMEONITE NB ON	1	304	308	4	0.23
15-S	MF	808808	0.4 N/O ONTARIO AVE	4	6108	6117	9	0.12
		808670	N/O OLD TEMESCAL	4	6216	6116	-100	1.27
		808690	OLD TEMESCAL RD	4	6100	6134	34	0.43
		811082	M 1.27 N/O ORLANDO	4	6060	6135	75	0.96
		808354	.5 N/O MAGNOLIA	4	5744	5642	-102	1.35
		808616	JCT 15/91	3	3141	3339	198	3.48
		808631	PARKRIDGE OC	4	5176	4554	-622	8.92
		801320	YUMA	4	4992	5264	272	3.80
		801324	2ND	4	5060	5094	34	0.48
		811100	M .4 N/O 2ND STREET	4	5228	5106	-122	1.70
		808191	6 TH ST SB	3	4668	4531	-137	2.02
		807897	SB LIMEONITE ONR	3	4650	4570	-80	1.18
	On-Ramp	801321	HIDDEN VALLEY	2	592	567	-25	1.04
		814438	6TH ST SB	1	653	628	-25	0.99
		807898	SB LIMEONITE ONR	2	834	792	-42	1.47
	Total				363672	361280	-2392	3.97

Table 5-4. Route choice calibration results of hourly flow

Lane Type	Rte.	VDS ID	Station Name	No. of Lanes	Obs. Flow	Mod. Flow	Mod. - Obs.	GEH
MF	91-E	801415	.41 E/O CO LINE	4	8870	8900	30	0.32
		801428	.45 W/O RTE 71	5	8690	8837	147	1.57
		801435	RTE 71	4	7208	6990	-218	2.59
		811309	M 1.7 E/O GREEN RIV.	5	8522	8024	-498	5.48
		801442	.66 W/O SERFAS CL	4	7278	6874	-404	4.80
		801449	SERFAS CLUB	4	7790	7454	-336	3.85
		801457	MAPLE	4	7256	7170	-86	1.01
		801464	.02 E/O SMITH	4	7828	7417	-411	4.71
		801473	LINCOLN	4	7527	6975	-552	6.48
		801488	.09 E/O EAST GRAND	4	6846	6432	-414	5.08
		811325	M .1 E/O E GRAND BL	5	7794	7599	-195	2.22
		817544	.1 W/O PROMENADE	4	7434	7385	-49	0.57
		817546	.2 E/O PROMENADE	4	7424	7261	-163	1.90
		806674	MCKINLEY LOOP ON	3	5997	5803	-194	2.53
		801493	MCKINLEY	3	5992	5886	-106	1.38
		811389	M .2 W/O BUCHANAN ST	3	6715	6536	-179	2.20
		801502	MAGNOLIA	3	5922	5985	63	0.82
	91-W	801418	GREEN RIVER	5	6903	7310	407	4.83
		801445	SERFAS CLUB	4	6868	7430	562	6.65
		814351	M .75 E/O LINCOLN	4	7801	7794	-7	0.08
		801469	LINCOLN	4	7270	7418	148	1.73
		801477	GRAND	4	7281	7589	308	3.57
		801481	MAIN	4	7057	7011	-46	0.55
		811332	M .1 E/O E GRAND BL	5	7211	7336	125	1.47
		801490	MCKINLEY	3	5631	5598	-33	0.44
		810678	M .2 W/O BUCHANAN ST	3	6168	6184	16	0.20
		801496	PIERCE	3	5749	5527	-222	2.96
		801499	MAGNOLIA	3	5429	5157	-272	3.74
		811404	M .5 W/O TYLER ST	3	5736	5961	225	2.94
	15-N	801290	ONTARIO	4	3904	3851	-53	0.85
		806176	.01 N/O TEMESCAL OC	4	4972	4638	-334	4.82
		806191	.25 N/O Old TEMESCAL	4	4804	4633	-171	2.49
		811077	M 1.27 N/O ORLANDO	4	4456	4629	173	2.57
		801301	MAGNOLIA	3	3852	3932	80	1.28
		806212	.5 N/O MAGNOLIA	4	5520	5216	-304	4.15
		806218	100 FT S/O CORONA OC	4	5636	5213	-423	5.74
		806224	.19 S/O JCT 15/91	3	2364	2357	-7	0.14
		808622	500' S/O PARKRIDGE	4	3656	3919	263	4.27
		801327	N/O 2ND ST	3	4314	4473	159	2.40
		801329	0.3 N/O 2ND	3	4608	4870	262	3.81
		811087	M .4 N/O 2ND STREET	3	4929	4869	-60	0.86
		801331	.08 N/O 3RD ST	3	4983	4875	-108	1.54
		811095	M .18 N/O FIFTH ST	3	4794	4902	108	1.55
		808210	6TH ST NB ONR	3	4122	4322	200	3.08
		807790	.25 N/O 6TH ST	3	4617	4913	296	4.29
		807804	.75 S/O LIMEONITE	3	4803	4862	59	0.85
		811278	M .28 S/O LIMEONITE	3	3225	3889	664	11.13
		808109	LIMEONITE NB ON	3	3888	3889	1	0.02
	15-S	808808	0.4 N/O ONTARIO AVE	4	6108	6117	9	0.12

Table 5-4 (continued). Route choice calibration results of hourly flow

Lane Type	Rte.	VDS ID	Station Name	No. of Lanes	Obs. Flow	Mod. Flow	Mod. - Obs.	GEH
		808670	N/O OLD TEMESCAL	4	6216	6116	-100	1.27
		808690	OLD TEMESCAL RD	4	6100	6134	34	0.43
		811082	M 1.27 N/O ORLANDO	4	6060	6135	75	0.96
		808354	.5 N/O MAGNOLIA	4	5744	5642	-102	1.35
		808616	JCT 15/91	3	3141	3339	198	3.48
		808631	PARKRIDGE OC	4	5176	4554	-622	8.92
		801320	YUMA	4	4992	5264	272	3.80
		801324	2ND	4	5060	5094	34	0.48
		811100	M .4 N/O 2ND STREET	4	5228	5106	-122	1.70
		808191	6 TH ST SB	3	4668	4531	-137	2.02
		807897	SB LIMEONITE ONR	3	4650	4570	-80	1.18
Total					318477	315835	-2642	4.69
HOV	91-E	801416	2180' E/O CO LINE	1	1506	1796	-290	7.14
		801429	2400' W/O RTE 71	1	1100	1074	26	0.79
		801436	RTE 71	1	1144	1169	-25	0.74
		811316	M 1.7 E/O GREEN RIV.	1	1182	1143	39	1.14
		801443	3500' W/O SERFAS CL	1	1438	1133	305	8.51
		801450	SERFAS CLUB	1	1546	1404	142	3.70
		801458	MAPLE	1	1500	1365	135	3.57
		801465	100' E/O SMITH	1	1408	1331	77	2.08
		801474	LINCOLN	1	1327	1316	11	0.30
		801489	500'E/O EAST GRAND	1	1118	1283	-165	4.76
		811334	M .1 E/O E GRAND BL	1	1239	1282	-43	1.21
		817545	.1 W/O PROMENADE	1	1222	1274	-52	1.47
		817547	.2 E/O PROMENADE	1	1404	1263	141	3.86
		806676	MCKINLEY LOOP ON	1	1443	1470	-27	0.71
		807246	MCKINLEY	1	1438	1447	-9	0.24
		811352	M .2 W/O BUCHANAN ST	1	1306	1410	-104	2.82
		801503	MAGNOLIA	1	1209	1419	-210	5.79
	91-W	813443	GREEN RIVER	1	948	1030	-82	2.61
		801446	SERFAS CLUB	1	1084	1131	-47	1.41
		810854	M .75 E/O LINCOLN	1	977	1136	-159	4.89
		801470	LINCOLN	1	1086	1153	-67	2.00
		801478	GRAND	1	701	828	-127	4.59
		801482	MAIN	1	761	664	97	3.63
		811336	M .1 E/O E GRAND BL	1	641	672	-31	1.21
		801491	MCKINLEY	1	792	703	89	3.26
		811354	M .2 W/O BUCHANAN ST	1	903	699	204	7.21
		801497	PIERCE	1	718	766	-48	1.76
		801500	MAGNOLIA	1	701	762	-61	2.26
		811396	M .5 W/O TYLER ST	1	468	739	-271	11.03
Total					32310	32862	-552	3.06
ONR	91-E	801425	GREEN RIVER	2	222	236	-14	0.93
		801452	SERFAS CLUB	2	498	514	-16	0.71
		801460	MAPLE	2	538	536	2	0.09
		801487	MAIN	3	1188	1176	12	0.35
		801504	MAGNOLIA	1	735	693	42	1.57
	91-W	801421	GREEN RIVER	3	339	318	21	1.16
		801448	SERFAS CLUB	3	489	489	0	0.00

Table 5-4 (continued). Route choice calibration results of hourly flow

Lane Type	Rte.	VDS ID	Station Name	No. of Lanes	Obs. Flow	Mod. Flow	Mod. - Obs.	GEH
		801456	MAPLE	2	496	492	4	0.18
		801472	LINCOLN	3	477	502	-25	1.13
		801480	GRAND	1	320	304	16	0.91
		801492	MCKINLEY	3	1401	1384	17	0.46
		801498	PIERCE	2	808	753	55	1.97
		801501	MAGNOLIA	1	347	367	-20	1.06
	15-N	801292	ONTARIO	2	876	812	64	2.20
		801323	HIDDEN VALLEY	2	704	690	14	0.53
		814417	2ND ST ONR	1	421	410	11	0.54
		814425	6TH ST NB ONR	1	643	612	31	1.24
		814432	LIMEONITE NB ON	1	304	308	-4	0.23
	15-S	801321	HIDDEN VALLEY	2	592	567	25	1.04
		814438	6 TH ST SB	1	653	628	25	0.99
		807898	SB LIMEONITE ONR	2	834	792	42	1.47
Total					12885	12583	302	2.68

Table 5-5. Summary of calibration targets and results

Criteria & Measures	Acceptability Targets	Calibration Results
Hourly Flows: Modeled versus Observed		
Individual link flows Within 100 vph, for flow < 700vph Within 15%, for 700 vph < flow < 2700 vph Within 400 vph, for flow > 2700 vph	 > 85% of all cases > 85% of all cases > 85% of all cases	**Yes.** 93.75% of 16 cases 85.71% Of 35 cases 88.14% of 59 cases
Total link flows Within 5%	 All accepting links	**Yes.** MFL = -0.83% HOVL = 1.71% ONR = -2.34% Total = -0.66%
GEH statistics – individual link flows GEH < 5	 > 85% of all cases	**Yes.** 89.09% of 110 cases
GEH statistics – total link flows GEH < 4	 All accepting links	MFL = 4.69 (**No**) HOVL = 3.06 (**Yes**) ONR = 2.68 (**Yes**) Total = 3.97 (**Yes**)
Visual Audits		
Individual link speeds Visually acceptable speed-flow relationship Bottlenecks Visually acceptable queuing	 To analyst's satisfaction To analyst's satisfaction	 Satisfied Satisfied

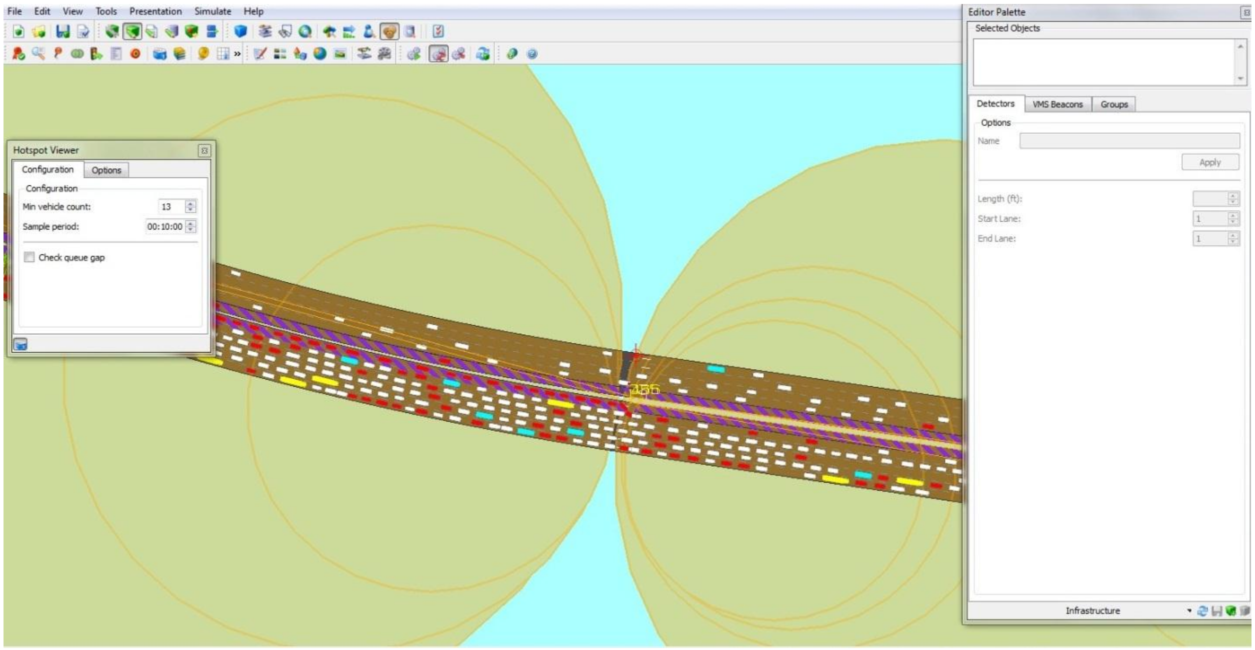


Figure 5-10. Snapshot of simulation showing blockage due to unrealistic driver behavior

5.3.4. Continuous Access HOV Network

Unlike the network with limited access HOV lanes, there is no route choice for HOVs in the network with continuous access HOV lanes since both HOV and MF lanes were coded on the same link. In this case, the behavior of HOVs was modeled using the "HOV behavior" plug-in supplied by PARAMICS. This plug-in was found to provide satisfactory basis for modeling continuous access HOV lanes in an earlier study [Gardes et al., 2003]. However, it was shown by [Oh and Chu, 2004] that this plug-in: 1) is not sensitive to MF lane speed, and 2) underestimate HOV lane volume in the application that they tested.

There are multiple behavioral parameters associated with this plug-in, for instance, lane change accept time, lane change reset time, patients, and overtake time. Based on the calibration results in a previous study [Boriboonsomsin and Barth, 2006], these parameters were set as follows:

- Patients = 10 seconds
- Overtake time = 15 seconds
- Lane change accept time = 5 seconds
- Lane change reset time = 10 seconds

5.4. Operational Performance Comparison

After the network calibration was performed to satisfaction, the simulation networks with both limited access and continuous access HOV facilities were simulated and their operational performance was measured. The key performance measure that was used for comparison between the two networks was Q or network productivity. It can also be viewed as network-wide average speed as it has the unit of miles per hour.

Multiple scenarios with different levels of congestion on SR-91 E were simulated, as shown in Table 5-6. The levels of congestion were based on Q values and were categorized as heavy congestion (0-35 mph), mild congestion (35-50 mph), and no congestion (>50 mph). SR-91 E was used as the benchmark because it was the peak traffic direction for the simulation period (PM peak). Despite of that, the Q values for both HOV and MF lanes on SR-91 E in the baseline scenario (i.e., August 6, 2009, 4-6 p.m.) were still greater than 50 mph, as shown in Table 5-7. This is true for both networks with limited access and continuous access HOV lanes. In addition, the corresponding Q values for SR-91 W, I-15 N, and I-15 S for the same scenario were calculated and reported in Table 5-7. As expected, the Q values for SR-91 W for both HOV and MF lanes were much higher than those for SR-91 E. As for I-15 N and I-15 S, there were no clear directional differences.

It is shown in Table 5-6 that there are a total of nine possible scenarios. The baseline scenario represents one that has no congestion in both HOV and MF lanes (both lane types have Q greater than 50 mph). To achieve other hypothetical scenarios, common multipliers were applied to the hourly traffic demands from all zones for the same type of vehicles. For example, to make the MF lanes along SR-91 E more congested, the SOV demand was increased by the same level for all zones including those on SR-91 W, I-15 N, and I-15 S. Specifically, in Scenario I the baseline demands for both SOVs and HOVs were doubled, while in Scenario II only the SOV demand was doubled but the HOV demand kept the same.

It is noted that it was difficult to construct a scenario in the simulation network where the Q value became lower than 35 mph. In one of the attempts, both SOV and HOV demands were quadrupled in the network with limited access HOV lane, and the Q values for HOV and MF lanes along SR-91 E were still above 35 mph. By carefully examining the simulation network, it was found that many vehicles were blocked and not released from some zones that were already congested. Therefore, the three possible scenarios where Q values would be lower than 35 mph were not simulated. In addition, the other three scenarios where the Q value of HOV lane would be lower than that of MF lanes were also not simulated as they were counter-intuitive.

Table 5-6. Definition of simulation scenarios based on traffic condition on SR-91 E

Q value (mph)		MFL		
		0 - 35	35 - 50	>50
HOVL	0 - 35	N/A	Counter-intuitive	Counter-intuitive
	35 - 50	N/A	Scenario I	Counter-intuitive
	>50	N/A	Scenario II	Baseline

Table 5-7. Q value (mph) for each route under different scenarios

Route	Lane Type	HOV Config.	Q (mph)		
			Baseline	Scenario I	Scenario II
SR-91 E	HOVL	Limited	57.99	46.85	53.65
		Continuous	68.55	60.24	63.16
		% Difference	*18.21%*	*28.58%*	*17.73%*
	MFL	Limited	53.56	45.49	45.09
		Continuous	54.91	48.23	50.02
		% Difference	*2.52%*	*6.02%*	*10.93%*
SR-91 W	HOVL	Limited	75.39	69.83	75.31
		Continuous	76.34	71.31	72.91
		% Difference	*1.26%*	*2.12%*	*-3.19%*
	MFL	Limited	62.70	54.52	55.15
		Continuous	62.68	55.50	55.01
		% Difference	*-0.03%*	*1.80%*	*-0.25%*
I-15 N	MFL	Limited	61.54	49.16	49.35
		Continuous	61.67	51.74	52.11
		% Difference	*0.21%*	*5.25%*	*5.59%*
I-15 S	MFL	Limited	60.91	50.80	55.16
		Continuous	60.76	51.49	53.15
		% Difference	*-0.25%*	*1.36%*	*-3.64%*

The following observations are made based on the results in Table 5-7:

- For SR-91 E, the Q values of the network with continuous access HOV lane are much higher than those of the network with limited access HOV lane. This is true for both HOV and MF lanes and for all the scenarios. The differences in the Q values for HOV lane between the two networks range from 17% to 29% in different scenarios, which is quite significant. For MF lanes, the Q values of continuous access HOV facilities are on average 6% higher than limited access ones in all scenarios.

- For SR-91 W, the Q values of both MF lanes and HOV lane do not have obvious change (within 3%) under two types of networks, because the traffic condition (especially on HOV lanes) is not getting worse in all these scenarios.

- For I-15 N and I-15 S, the Q values for both networks are also similar, with the differences mostly negligible. This is expected as there is no HOV lane, and thus no geometric differences between the two networks, on these two routes. The variations may result from the changes in traffic condition along SR-91 (i.e., traffic flowing from/to SR-91 to/from I-15).

Overall, it is found that when travel demand is low and there is no congestion (Q > 50 mph), both networks with limited access and continuous access HOV lane have similar average travel speeds (mostly less than 2 mph difference). However, as the traffic demand increases and the networks get moderately congested (35 mph < Q <= 50 mph), the network with continuous access HOV performs better operationally, especially in the HOV lane. These findings are consistent with those in the previous study [Boriboonsomsin and Barth, 2006].

The underlying reason for these findings are partly because in the network with limited HOV lane, HOVs are limited to change lane between the HOV and MF lanes only at ingress/egress locations. Therefore, the lane changing activities are concentrated over the limited length of the weaving section. This is not an issue when the traffic demand is low as the HOVs can still make lane changes comfortably. As the traffic demand increases, lane changing becomes more difficult and the HOVs sometime have to conduct unnatural driving behaviors such as slowing down to wait for an acceptable gap in the adjacent lane, accelerating aggressively in order to take the gap ahead of them, or making a forceful merge into the adjacent lane. These behaviors cause perturbation in the traffic stream which may result in speed drop for a brief period, or even a breakdown of the traffic stream. In addition, the aforementioned deficiency in the PARAMICS model of driver behavior in limited access HOV network also contributes to the results shown in Table 5-7.

6. Before-and-After Study

6.1. Overview

In Fall 2011, Caltrans District 8 converted the HOV lane on both directions of SR-60 in Moreno Valley, CA, from full-time limited access to part-time continuous access. The District 8 Traffic Operations Division requested that UC Riverside conducted a study to compare freeway operations between before and after the conversion, as part of this District 8 HOV Facility Performance Analysis project.

The segment of the HOV conversion on SR-60 is between CA PM 13.1 and 21.1 from Day Street to Redlands Boulevard through the City of Moreno Valley in Riverside County, as shown in Figure 6-1. Prior to the conversion, this HOV facility was buffer-separated (with limited access) and operated as full-time HOV lane. Caltrans District 8 requested and received approval from the U.S. Environmental Protection Agency, the California Air Resources Board, and the Southern California Association of Governments to convert this HOV facility to part-time continuous access operation. After the conversion, the HOV facility has operated as a HOV only from 6 a.m. to 10 a.m. and from 3 p.m. to 7 p.m., Monday through Friday. It is open to SOV for the rest of the hours.

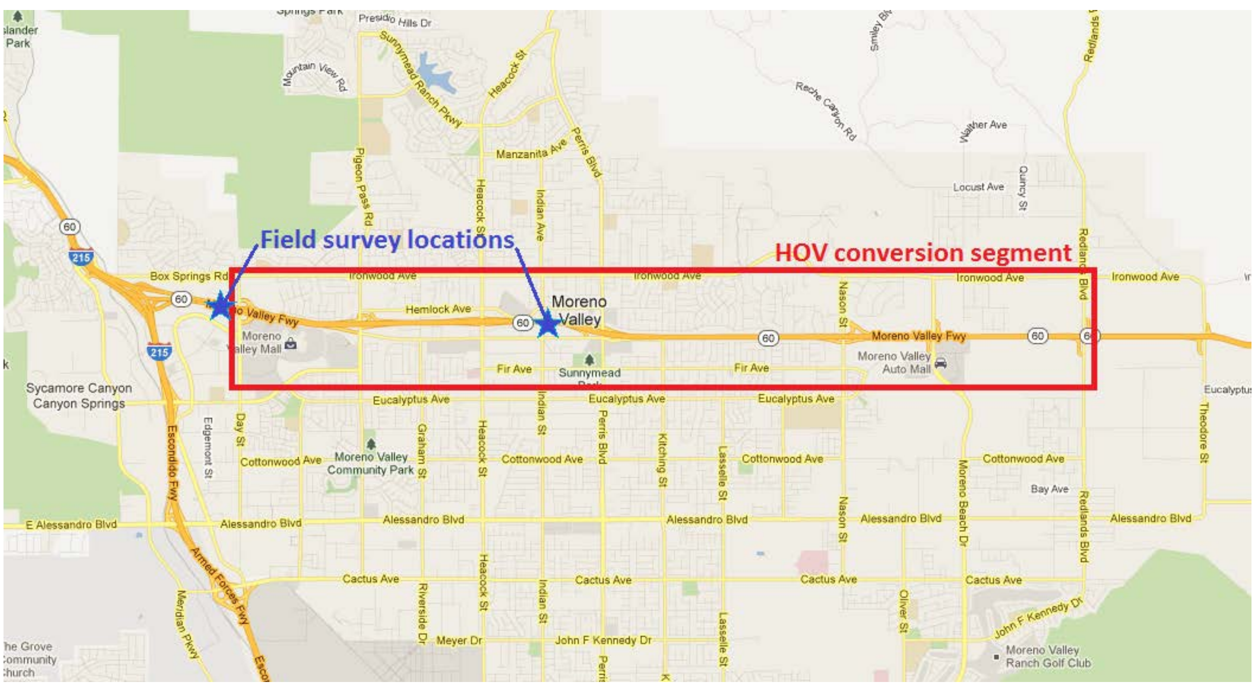


Figure 6-1. Segment of HOV conversion on SR-60 in Moreno Valley, CA

6.2. Data

In this before-and-after study, data were collected from various sources, including PeMS, field survey, aerial survey, and Caltrans's records. The collection and processing of each dataset are described in the following sections.

6.2.1. PeMS

PeMS data were used to compare traffic performance (speed, flow, and density) before and after the HOV conversion. The analysis periods for retrieving PeMS data for the "before" and "after" cases are defined in Figure 6-2. The construction period of the HOV conversion was from August 2, 2011 to November 21, 2011. It was desirable to leave at least one-month gap before the construction began and after the construction was completed as traffic during those periods might still be affected by the construction. Also, it was desirable that data for both analysis periods are for the same months so that there is no seasonal bias. Therefore, the "before" analysis period was selected to be from January 1, 2011 to June 30, 2011 while the "after" analysis period was selected to be from January 1, 2012 to June 30, 2012. In addition to the traffic performance data, the data regarding number of accidents from the California Highway Patrol (CHP) for the same analysis periods were also retrieved from PeMS and compared.

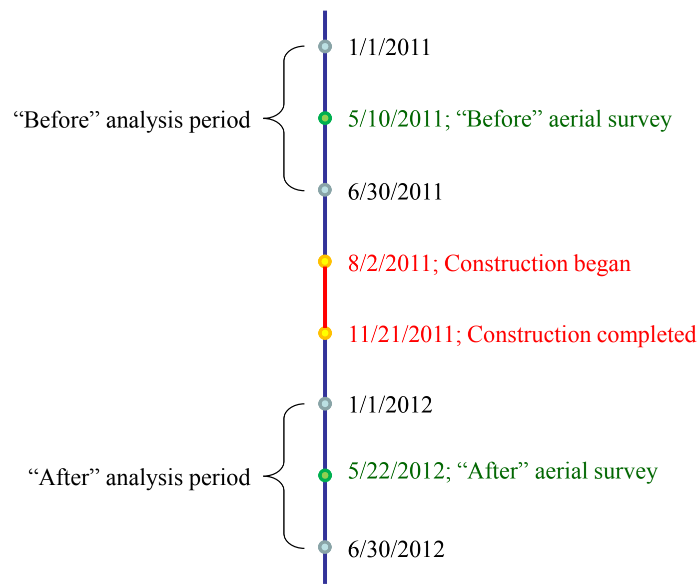


Figure 6-2. Timeline of the construction and the analysis periods

There is a different number of PeMS VDS in each direction of the HOV conversion segment. In this study, only the VDS listed in Table 6-1 were included so that the study segment on both directions of the freeway has a similar length. This means that the absolute postmile range of 53-57 was specified when querying data from PeMS. This postmile range covers the area where congestion most occurs on this segment of the freeway in both directions.

Table 6-1. PeMS VDS included in the study

Fwy	District	County	City	CA PM	Abs PM	ID	Name
SR60-E	8	Riverside	Riverside	13.447	53.57	801167	DAY ST E/B ON
SR60-E	8	Riverside	Moreno Valley	14.509	54.63	801170	PIGEON PASS
SR60-E	8	Riverside	Moreno Valley	15.495	55.62	801172	HEACOCK
SR60-E	8	Riverside	Moreno Valley	16.602	56.72	810305	PERRIS EB ONR
SR60-W	8	Riverside	Riverside	13.392	53.51	801166	DAY
SR60-W	8	Riverside	Riverside	14.168	54.29	801168	PIGEON PASS
SR60-W	8	Riverside	Moreno Valley	14.412	54.53	801169	PIGEON PASS LOOP
SR60-W	8	Riverside	Moreno Valley	15.166	55.29	801171	HEACOCK
SR60-W	8	Riverside	Moreno Valley	16.195	56.32	801173	PERRIS WB ON

6.2.2. Field Survey

The field survey consisted of: 1) vehicle occupancy count for determining HOV violation rates, and 2) vehicle license plate survey for measuring travel times. The field survey was conducted over three sessions for both "before" and "after" cases during the dates and times shown in Table 6-2. For each session, the vehicle license plate survey was performed for the full two hours while the vehicle occupancy count was performed during the middle hour.

Table 6-2. Dates and times of field survey

Session	Direction	Before Conversion	After Conversion
AM (6:30-8:30 a.m.)	Westbound	Thursday 5/12/2011	Thursday 5/24/2012
Midday (1-3 p.m.)	Eastbound	Wednesday 5/11/2011	Wednesday 5/23/2012
PM (4:30-6:30 p.m.)	Eastbound	Wednesday 5/11/2011	Wednesday 5/23/2012

The vehicle occupancy count was conducted manually. The crews stood on the Indian Avenue overpass (the east field survey location in Figure 6-1) and counted the number of persons in each vehicle passing under. This is the same location at which Caltrans District 8 performed vehicle occupancy count in previous years. In the vehicle occupancy count, the vehicles were also classified as auto, bus, motorcycle, truck, van, or hybrid. Hybrid vehicles were determined based on the crews' judgment. Some hybrid vehicles such as Toyota Prius are easy to recognize as they have a unique look. However, many hybrid vehicles such as Toyota Camry Hybrid, Honda Civic Hybrid, Nissan Altima Hybrid, etc. have the same look as their non-hybrid counterparts. In this study, vehicles were classified as hybrid only if the crews were confident that they were hybrid vehicles. Similarly, vehicles were determined to have more than one person only if the crews were able to see the passengers.

The vehicle license plate survey was conducted by videotaping license plate numbers of vehicles on the freeway segment at the locations shown in Figure 6-1. These locations were chosen so that the crews could set up video cameras safely. The location on the west is between the SR-60/I-215 interchange and Day Street. The location on the east is the Indian Avenue overpass, which is also the location for the vehicle occupancy count. At each location, two video cameras were set up as shown in Figure 6-3. One of them recorded license plate numbers of the vehicles in HOV lane; the other recorded license plate number of the vehicles in the adjacent MF lane. The videos were replayed and vehicle license plate numbers along with their timestamp were entered in a spreadsheet.

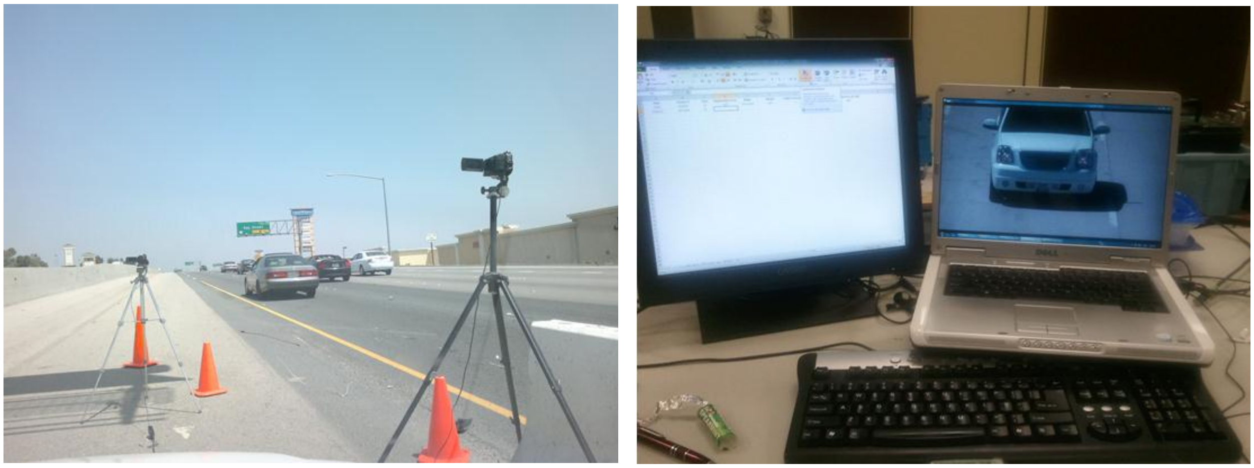


Figure 6-3. Videotaping and extracting vehicle license plate numbers

6.2.3. Aerial Survey

In this study, UC Riverside also contracted Skycomp, Inc. to conduct aerial survey of SR-60 both before and after the HOV conversion. The dates and times of the survey are shown in Table 6-3. In the before conversion survey, Skycomp personnel flew a plane over the study site in circular and took photos of site every second using a high-resolution digital camera. The survey was conducted over two adjacent freeway segments shown in Figure 6-4. Each segment is about 1 mile long, and was surveyed for 30 minutes for a total survey time of 60 minutes.

In the after conversion survey, Skycomp used a newly developed technique where its personnel flew a helicopter instead of a plane. This technique provided an orthogonal view of the study site, which would make the photos easier to process later. It also allowed a larger spatial coverage to be captured in each photo. The after conversion survey was conducted for a total of 40 minutes where both survey segments were captured in the same photos.

Table 6-3. Dates and times of aerial survey

Segment	Before Conversion (Tuesday 5/10/2011)		After Conversion (Tuesday 5/22/2012)	
	Images Recorded	Images Processed	Images Recorded	Images Processed
1	4:35 – 5:05 p.m.	4:45 – 5:05 p.m.	4:45 – 5:25 p.m.	4:50 – 5:20 p.m.
2	5:10 – 5:40 p.m.	5:10 – 5:30 p.m.	4:45 – 5:25 p.m.	4:50 – 5:20 p.m.

The aerial photos were processed to extract the second-by-second trajectory (i.e., speed and position) of each vehicle on the survey segments during the survey periods. Due to the limited resources, only a subset of the images recorded could be processed as summarized in Table 6-3. The processing (i.e., vehicle tracking) was performed by UC Riverside personnel with the aid of Skycomp's SkyTracker 2 software shown in Figure 6-5. The vehicle tracking involved manually clicking on individual vehicles in the successive aerial photos to record their pixels in the photo plane. Then, using three reference points in the ground plane, the Cartesian coordinates of the vehicles in the ground plane can be calculated. For each vehicle, the linear distance between two consecutive coordinates (which are one second apart) is assumed to be the distance traveled by that vehicle. Then, the vehicle speed is calculated based on this distance.

Only vehicles on eastbound were tracked as eastbound is the peak direction during the aerial survey periods. Across the aerial survey segments, there are two MF lanes and one HOV lane.

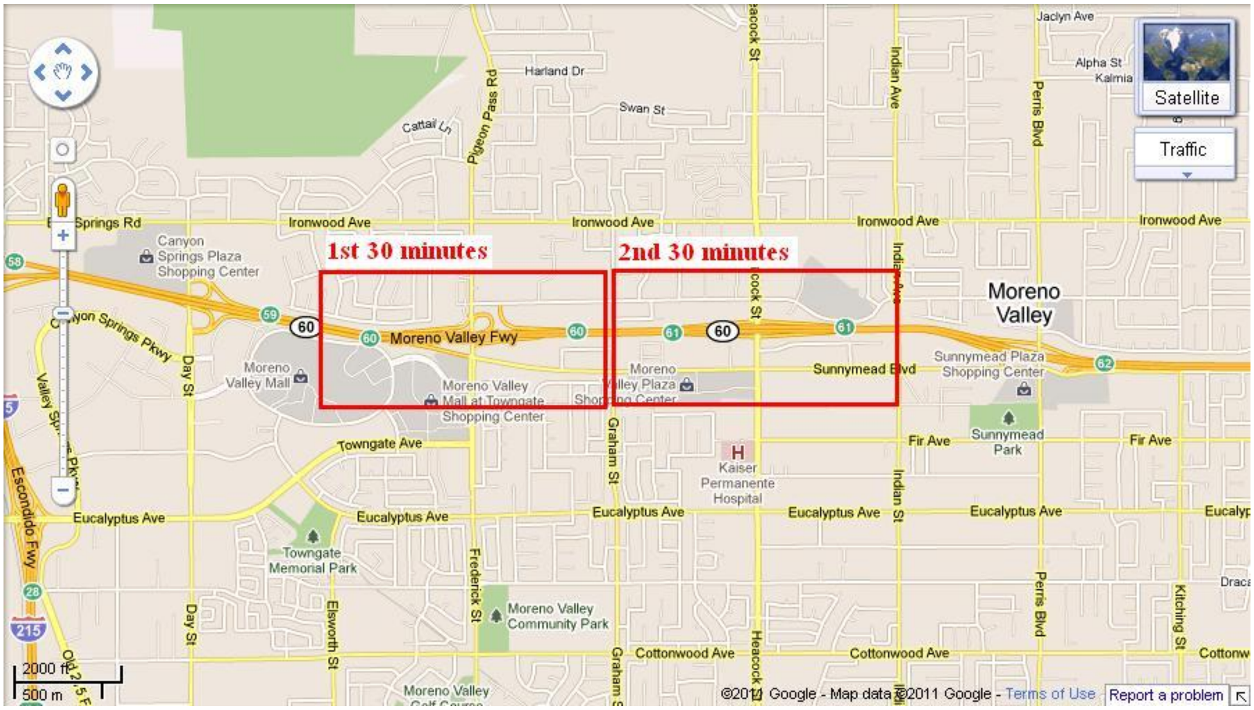


Figure 6-4. Aerial survey segments

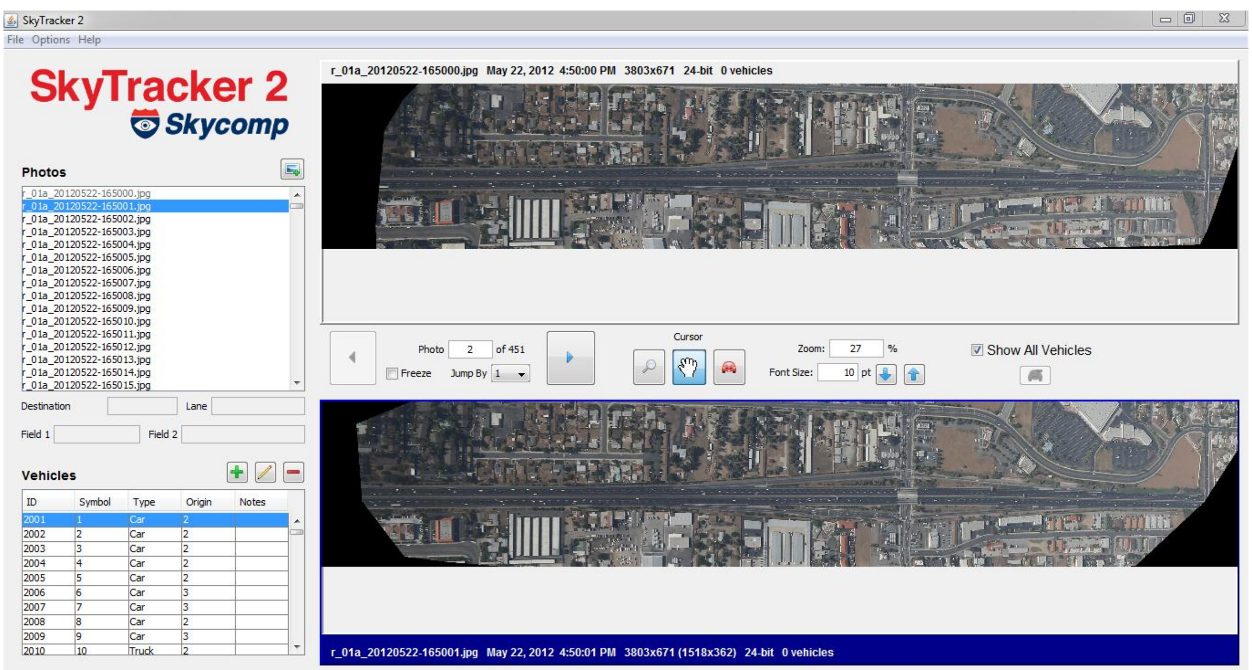


Figure 6-5. Aerial photos loaded into SkyTracker 2 software

Due to human errors as well as certain issues with some aerial photos (e.g., the camera was shielded by cloud for a few seconds), the raw second-by-second vehicle trajectory data were filtered using the following procedures.

- *Removal of erroneous data points* – Data points with unrealistically high or low values of distance, speed, or acceleration/deceleration were removed.

- *Data gap filling* – After the erroneous data points were removed, linear interpolation was applied to the distance values of the neighboring data points. Then, the speed and acceleration/deceleration of the data points were recalculated.

- *Data correction* – After all the data gaps were filled, a 5-point moving average filter was applied to data points with yet unrealistic speed and acceleration/deceleration values. Then, the distance values of those data points were recalculated.

6.2.4. Caltrans' Records

In addition to all of the above data items, data regarding maintenance effort as well as number of complaints, public concerns, or customer satisfaction were requested from Caltrans District 8.

6.3. Analysis and Results

6.3.1. Speed, Volume, and Density across All Lanes

Data from PeMS were used to compare traffic performance before and after the HOV conversion. As there are multiple PeMS VDS on the study segment as shown in Table 6-1, the network efficiency, Q, was used as a representative of travel speed across the segment. Similarly, VMT was used to represent traffic volume, and level of service (LOS) was used as a surrogate for density. Figure 6-6 and Figure 6-7 show the comparison of median travel speed and median VMT on eastbound by time of day between before and after analysis periods.

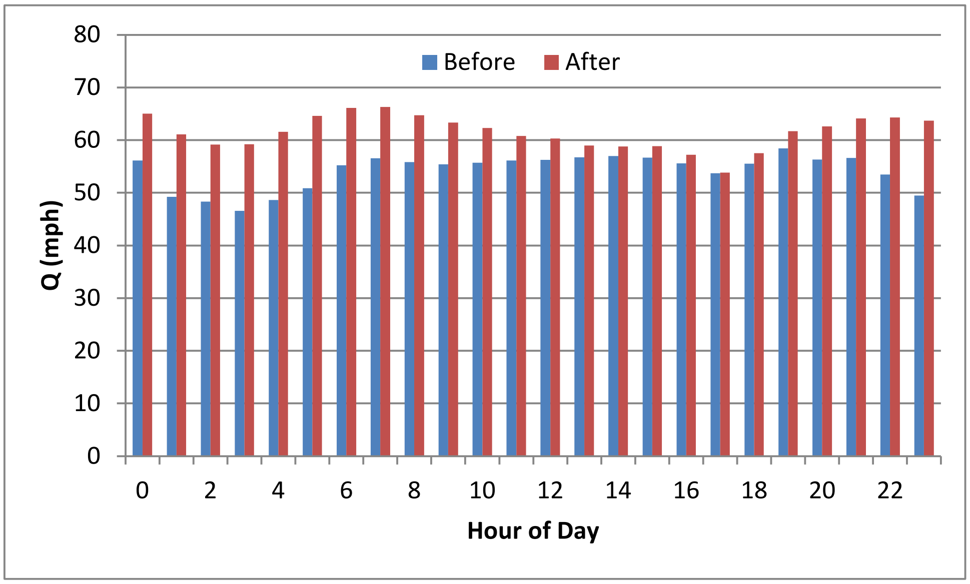


Figure 6-6. Median travel speed on eastbound during before and after analysis periods

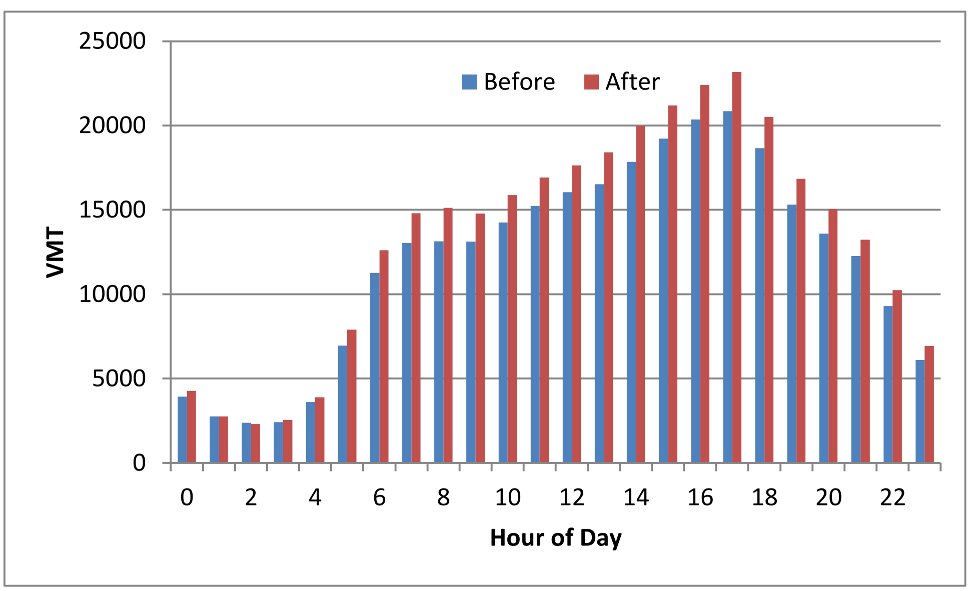


Figure 6-7. Median VMT on eastbound during before and after analysis periods

The data in Figure 6-6 show an unexpected trend where the travel speeds for the before analysis period were lower than 60 mph across all hours of day. In addition, the travel speeds from 1 a.m. to 5 a.m. were lowest despite having the least VMT. This may be due to construction activities during nighttime during parts of that period.

Figure 6-8 shows the percent time the eastbound segment operated in each LOS during the before analysis period. Figure 6-9 show a similar plot for the after analysis period. According to these two figures, the eastbound direction was relatively more congested during the before analysis period, especially from 3 p.m. to 7 p.m.

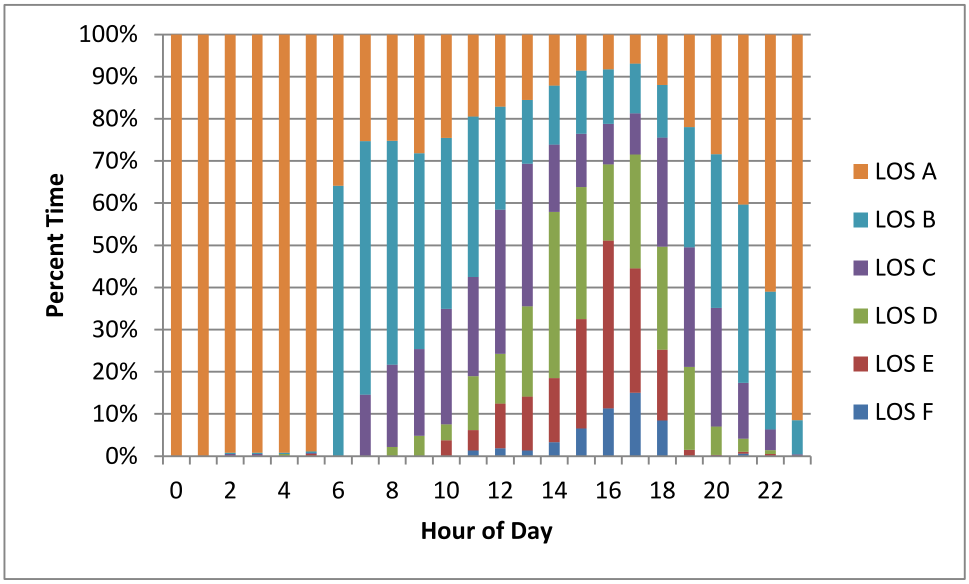


Figure 6-8. Percent time in each LOS for eastbound during before analysis period

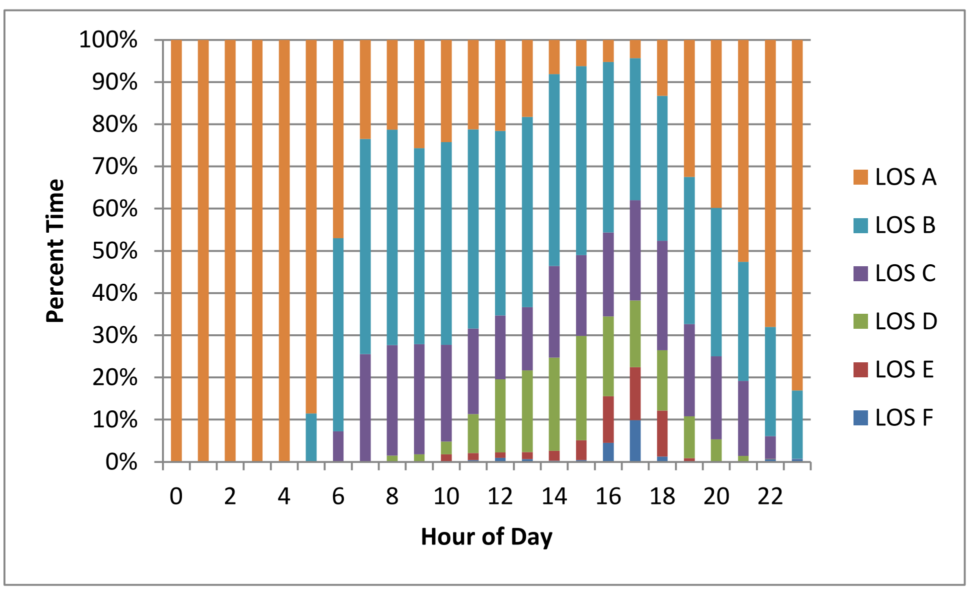


Figure 6-9. Percent time in each LOS for eastbound during after analysis period

Figure 6-10 and Figure 6-11 show the comparison of median travel speed and median VMT on westbound by time of day between before and after analysis periods. According to these two figures, the westbound direction carried more traffic volumes during the after analysis period across all hours of day, which resulted in having slightly lower travel speeds.

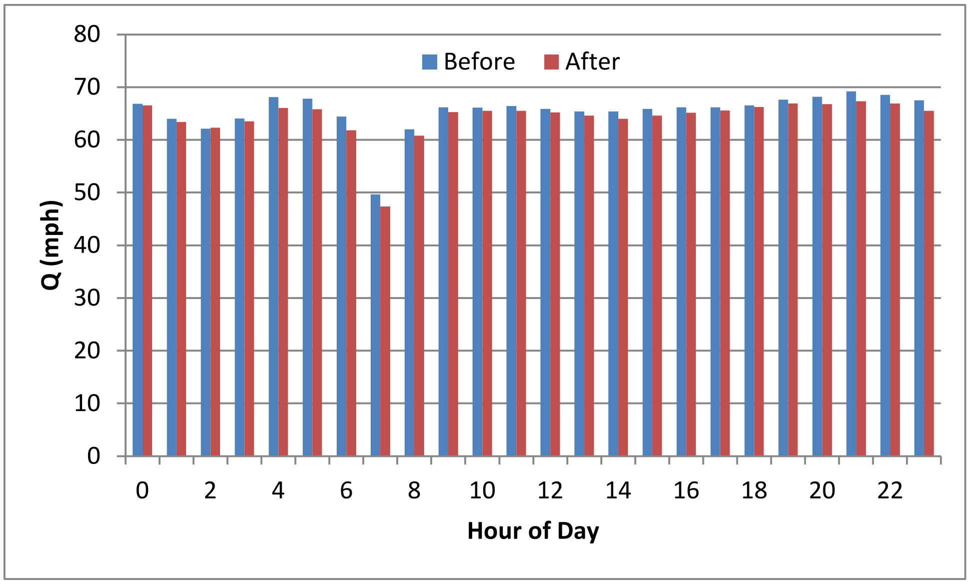


Figure 6-10. Median travel speed on westbound during before and after analysis periods

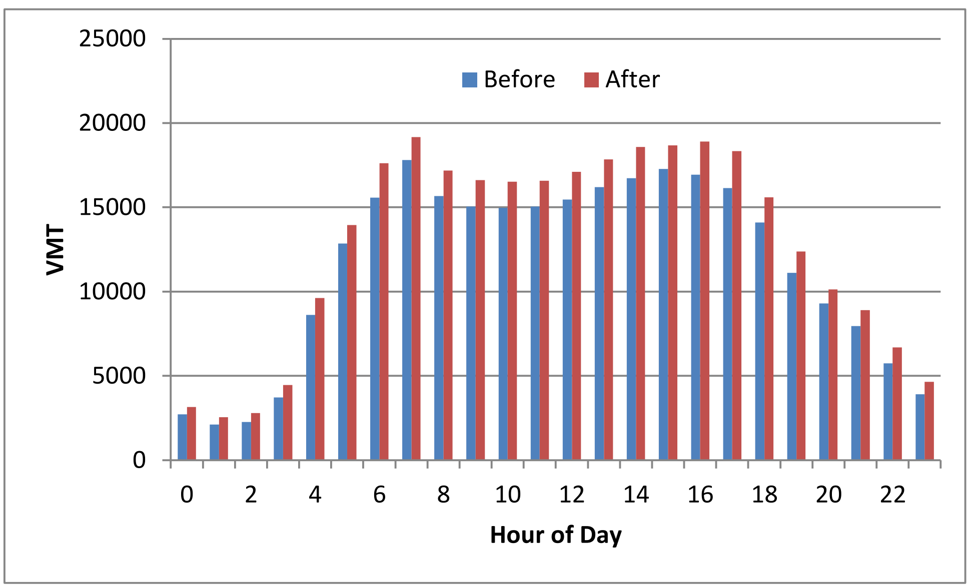


Figure 6-11. Median VMT on westbound during before and after analysis periods

Figure 6-12 shows the percent time the westbound segment operated in each LOS during the before analysis period. Figure 6-13 show a similar plot for the after analysis period. According to these two figures, the westbound segment experienced severe congestion (LOS E and F) relatively more often during the after analysis period while it experienced moderate congestion (LOS C and D) relatively more often during the before analysis period.

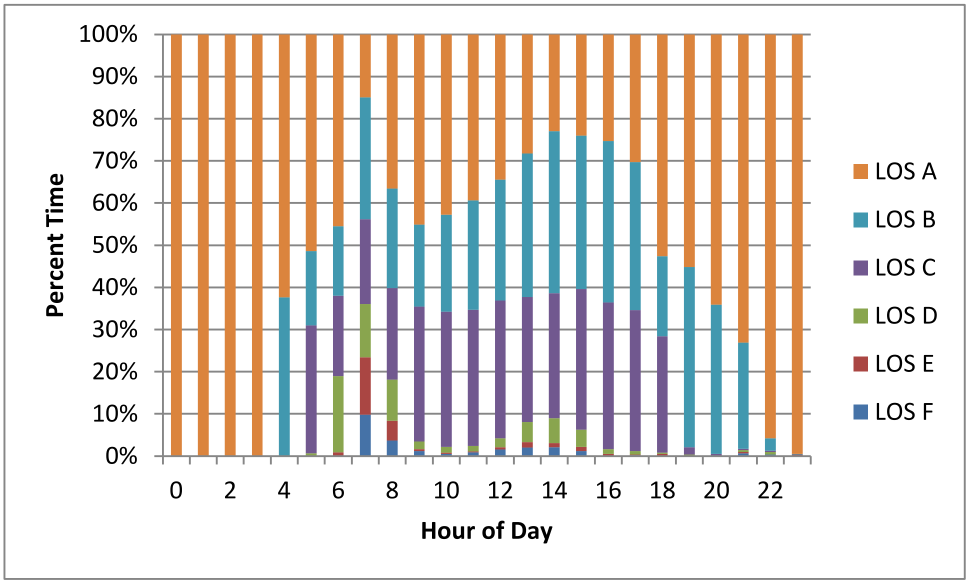


Figure 6-12. Percent time in each LOS for westbound during before analysis period

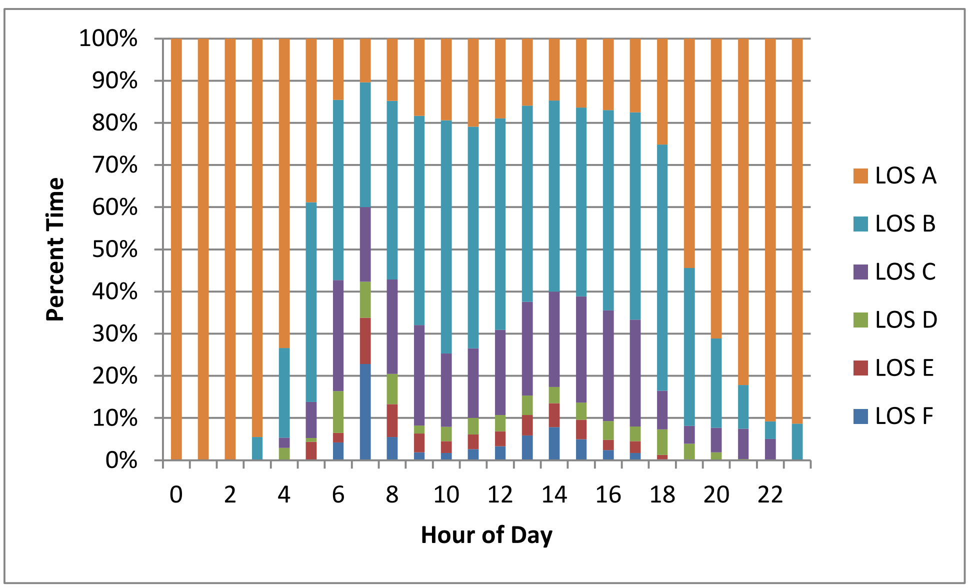


Figure 6-13. Percent time in each LOS for westbound during after analysis period

6.3.2. HOV Violation Rates

The vehicle occupancy count data for HOV lane are presented in Table 6-4 through Table 6-6. Before the HOV conversion, the HOV violation rate was lowest during the midday period. This is expected as the HOV lane was likely to provide little travel time saving during off-peak hours.

After the conversion, the HOV policy was not enforced during the midday period. Thus, there was no HOV violation although 23% of the vehicles traveling in this lane had only one person.

When comparing between before and after the conversion, it was found that the HOV violation rates after the conversion were higher. During the AM period, the HOV violation rate after the HOV conversion increased from 16.6% to 24.9%. During the PM period, the HOV violation rate after the HOV conversion more than doubled from 12.0% to 25.6%.

Table 6-4. Vehicle occupancy count data for HOV lane during AM period

	Before Conversion, 5/12/2011, 7-8 a.m.				**After Conversion, 5/24/2012, 7-8 a.m.**			
	1 person	**2 persons**	**3+ persons**	***Total***	**1 person**	**2 persons**	**3+ persons**	***Total***
Auto	81	386	4	*471*	137	339	5	*481*
Bus	0	0	0	*0*	1	0	0	*1*
Motorcycle	19	0	0	*19*	21	0	0	*21*
Truck	0	1	0	*1*	0	0	0	*0*
Van	4	52	7	*63*	14	92	0	*106*
Hybrid	9	3	0	*12*	3	7	0	*10*
Total	*113*	*442*	*11*	*566*	*176*	*438*	*5*	*619*
% Total	*20.0*	*78.1*	*1.9*	*100.0*	*28.4*	*70.8*	*0.8*	*100.0*
% Violation	**16.6**				**24.9**			

Table 6-5. Vehicle occupancy count data for HOV lane during midday period

	Before Conversion, 5/11/2011, 1:30-2:30 p.m.				**After Conversion, 5/23/2012, 1:30-2:30 p.m.**			
	1 person	**2 persons**	**3+ persons**	***Total***	**1 person**	**2 persons**	**3+ persons**	***Total***
Auto	14	296	24	*334*	96	382	9	*487*
Bus	0	0	5	*5*	3	0	0	*3*
Motorcycle	4	0	0	*4*	12	0	0	*12*
Truck	0	10	0	*10*	0	2	0	*2*
Van	6	18	7	*31*	11	15	0	*26*
Hybrid	1	6	0	*7*	0	0	0	*0*
Total	*25*	*330*	*36*	*391*	*122*	*399*	*9*	*530*
% Total	*6.4*	*84.4*	*9.2*	*100.0*	*23.0*	*75.3*	*1.7*	*100.0*
% Violation	**5.4**				**n/a**			

Table 6-6. Vehicle occupancy count data for HOV lane during PM period

	Before Conversion, 5/11/2011, 5-6 p.m.				**After Conversion, 5/23/2012, 5-6 p.m.**			
	1 person	**2 persons**	**3+ persons**	***Total***	**1 person**	**2 persons**	**3+ persons**	***Total***
Auto	42	431	2	*475*	188	462	53	*703*
Bus	0	0	3	*3*	9	0	0	*9*
Motorcycle	17	0	0	*17*	36	0	0	*36*
Truck	9	24	0	*33*	0	0	0	*0*
Van	4	24	1	*29*	6	8	0	*14*
Hybrid	14	4	0	*18*	4	8	0	*12*
Total	*86*	*483*	*6*	*575*	*243*	*478*	*53*	*774*
% Total	*15.0*	*84.0*	*1.0*	*100.0*	*31.4*	*61.8*	*6.8*	*100.0*
% Violation	**12.0**				**25.6**			

6.3.3. Traffic Dynamics

Traffic dynamics before and after the HOV conversion were compared based on the number of lane changes and the clearance during lane changes.

Normalized Segment Lane Changing Rate

For a fair comparison between before and after the conversion, the numbers of lane changes in each case were normalized by VMT. The so-called normalized segment lane changing rate, R_{ij}^{LC}, is defined as:

$$R_{ij}^{LC} = \frac{\text{No. of lane changes from lane } i \text{ to } j}{\text{VMT across all lanes on the segment}}$$

Figure 6-14 compares the normalized segment lane changing rates between before and after the HOV conversion. It shows that the lane changing rates between MF lanes (MFL1 and MFL2) are much higher than those between HOV lane (HOVL) and the adjacent MF lane (MFL1) for both before and after the HOV conversion. After the conversion from limited access to continuous access HOV lane, the normalized segment lane changing rate increased in the cases of both merging into and out of the HOV lane. A potential explanation is that there were more discretionary lane changing maneuvers in the case of continuous access HOV lane as this HOV type has no lane change restrictions.

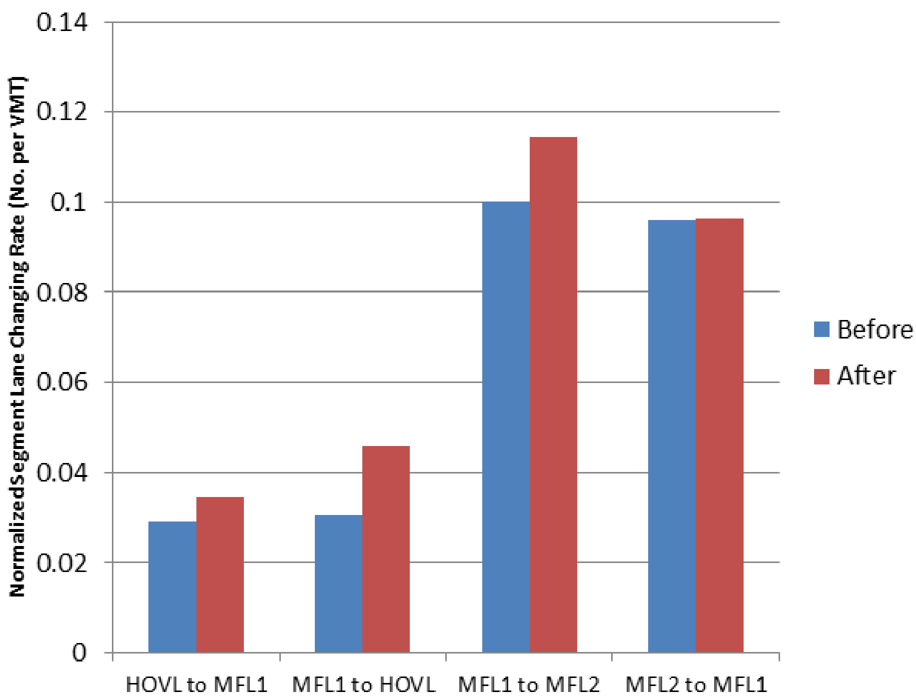


Figure 6-14. Normalized segment lane changing rate for before and after study

Clearance distribution

Clearance (or time gap) when changing lane is an important measure for describing driver behavior. Figure 6-15 through Figure 6-17 present the distributions of clearance during lane changes for both before and after cases. According to Figure 6-15 and Figure 6-16, the distributions of the after case are more spread out, which indicates that the lane changes between the HOV lane and the adjacent MF lane in the case of continuous access HOV lane were generally less aggressive than those in the case of limited access HOV lane. However, according to Figure 6-17, there was no significant difference between the distributions of clearance for lane changes between the two MF lanes. This implies that the differences observed in Figure 6-15 and Figure 6-16 are not likely due to individual drivers' aggressiveness, and more likely due to the geometry of the HOV access type.

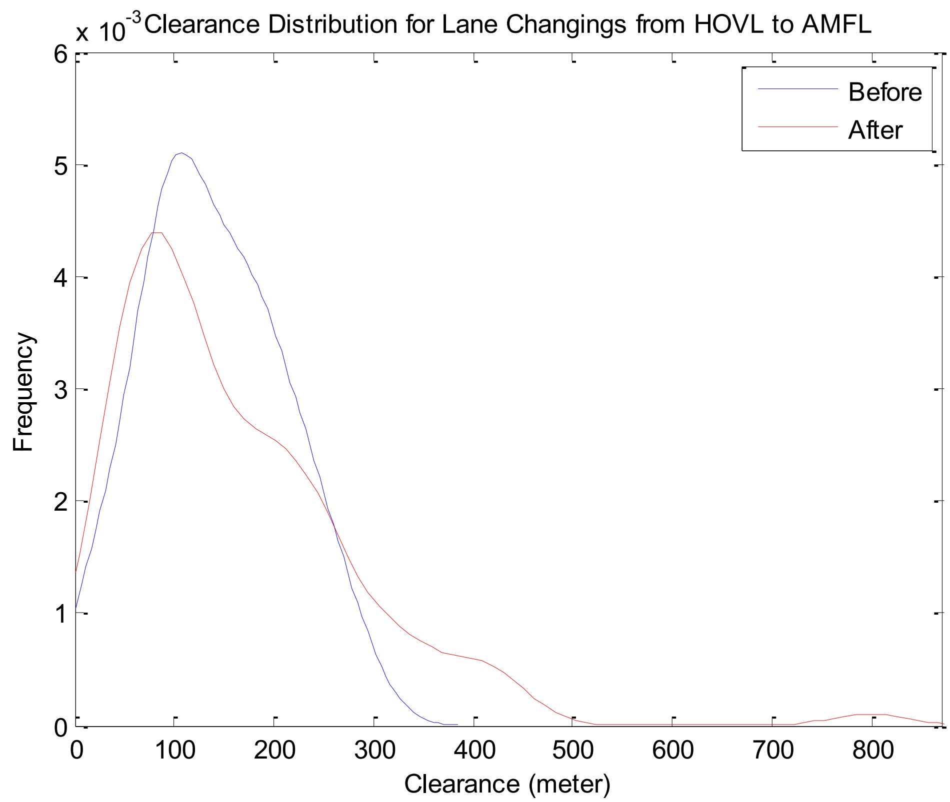


Figure 6-15. Distributions of clearance for lane changes from HOVL to AMFL

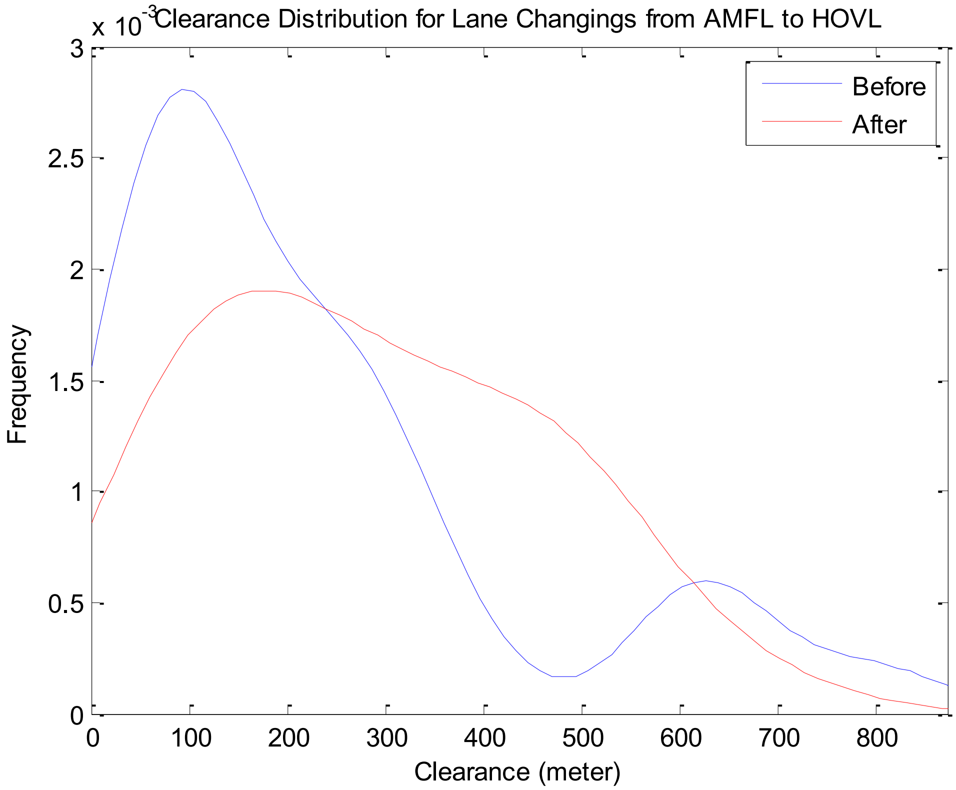


Figure 6-16. Distributions of clearance for lane changes from AMFL to HOVL

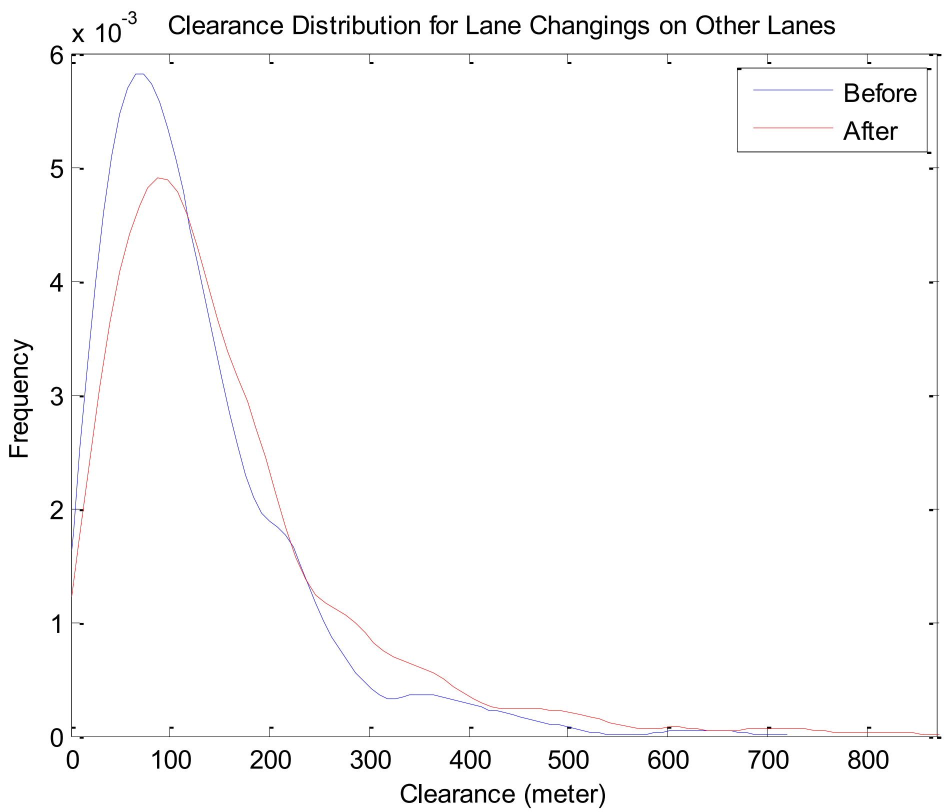


Figure 6-17. Distributions of clearance for lane changes between MFLs

6.3.4. Maintenance Effort

Table 6-7 shows records of maintenance effort on the project segment from CA PM 13.1 (Day St) to 21.1 (Redlands Boulevard) for the period from January 1, 2011 to June 30, 2011 (i.e., before conversion analysis period). Table 6-8 shows records of maintenance effort for the period from January 1, 2012 to June 30, 2012 (i.e., after conversion analysis period). During the before conversion analysis period, there were 14 work orders while there were 24 work orders during the before conversion analysis period.

Table 6-7. Records of maintenance effort between January 1, 2011 and June 30, 2011

Wono	Crew	Activity	Activity Description	From Mile	To Mile	Comments	Work Date
2368232	08661	M10003	NIGHT INSPECT STRIPING	0.000	30.047	NITE INSPECTS STRIPING 08-RIV-060 1/5/11 0.0-10 NOT COMPLETE. 1/5/11 10-30 COMPLETE.	05-JAN-2011
2374017	08721	M40010	REPAIR/REPLACE SIGNS	1.000	20.866	01/04/11- repair/replace signs rte.60, P.M. 12.2 - 21.3 01/24/11- repair/replace signs rte.60, P.M. 1.0 - 12.2 01/27/11- repair/replace signs rte.60, P.M. 1.0 - 13.3	04-JAN-2011
							24-JAN-2011
							27-JAN-2011
2376400	08663	M40010	REPAIR/REPLACE SIGNS	19.566	23.566	08-RIV-060 REPAIR KNOCKDOWNS	06-JAN-2011
							07-JAN-2011
2396391	08721	M40010	REPAIR/REPLACE SIGNS	1.000	20.866	02/01/11- repair signs rte.60, P.M.12.2 - 21.3 02/02/11- repair signd rte.60, P.M. 1.0 - 12.2	01-FEB-2011
							02-FEB-2011
2427904	08721	M40010	REPAIR/REPLACE SIGNS	0.000	21.300	03-14-11 remove graffiti from signs and replace if needed, Rte 60 various locations. 03-17-11 Replace old faded signs with new laminated signs. Rte. 60 variuos locations.	14-MAR-2011
							17-MAR-2011
							30-MAR-2011
2428197	08663	M40010	REPAIR/REPLACE SIGNS	14.200	14.200	08-RIV-060 REPAIR POST E/B @ FREDRICKS REMOVE CARPOOL SIGNS 08-RIV-215 @ N/B MLK ON RAMP	16-MAR-2011
2457780	08721	M10001	INSPECTION M FAMILY	12.906	12.906	08-RIV-060 WB 013.340 .6 MI W OF DAY ST; SIGN SEVERED AT BASE, 40' FENCE DAMAGE0 04/26/11 721 crew Inspected PM location unable to locate down sign 10-98	26-APR-2011
2468036	08663	M40010	REPAIR/REPLACE SIGNS	14.324	14.324	08-RIV-060 REPAIR KNOCKDOWN E/B FREDRICK ST OFF RAMP	03-MAY-2011
2470821	08721	M10001	INSPECTION M FAMILY	12.873	16.168	05/09/10/11 Restriping operation by contractor (Cal-stripe) Day St. ramps rained out. 05/10/11 Restriping operation by contractor (Cal-stripe) Day St.,Heacock ramps .	09-MAY-2011
							10-MAY-2011
							11-MAY-2011
2475011	08721	M10002	COMPLAINT INVESTIG. M FAMILY	17.830	17.830	05/12/11 Inspected PM location unable to locate	12-MAY-2011
2475796	08721	M40010	REPAIR/REPLACE SIGNS	1.080	20.935	05/16/11 1-G84 AND 4X6 Post checked, adjusted and replaced hardware on signs in area. 05/17/11 1-R1 and 4x4 post , R10 and 4x4 post ,1-R11 4x6 post checked and adjusted signs replaced hardware in area. 05/23/11 replaced 1- R5-1 and 4x6 post @ Moreno Beach off E/B.	16-MAY-2011
							17-MAY-2011
							23-MAY-2011
2495925	08663	M40010	REPAIR/REPLACE SIGNS	14.300	21.300	08-RIV-060 INSTALL 2 EA. POPULATION SIGNS FOR CITY OF MORENO VALLEY	14-JUN-2011
2502789	08721	M40010	REPAIR/REPLACE SIGNS	1.008	20.935	08-RIV-060 EB 001.507 PM EB 60 ON VAN BUREN OFR, EXIT SIGN DOWN IN GOREPOINT, CAD 780, LFT MSG 8721 SAM HERNANDEZ 06/27/11 721 crew repaired down exit sign 1098	27-JUN-2011
2502824	08721	M40010	REPAIR/REPLACE SIGNS	1.080	20.501	06/27/11 721 crew repaired Pedestrian sign @ Frederick E/B on ramp	27-JUN-2011
							28-JUN-2011

Table 6-8. Records of maintenance effort between January 1, 2012 and June 30, 2012

Wono	Crew	Activity	Activity Description	From Mile	To Mile	Comments	Work Date
2648575	08721	M40010	REPAIR/REPLACE SIGNS	16.093	20.934	01/03/12 Replaced 1-2-G50 , 1-R11 , 1-R1 ,1-Type N W/B PM 020.472-021.368 per night INSP 01/30/12 Repaired down 1-G84 W/B Pyrite off ramp	03-JAN-2012
							30-JAN-2012
2652275	08664	M10002	COMPLAINT INVESTIG. M FAMILY	14.366	14.366	01/06/12 Called by 8721 in reguards to damaged rail that his crew removed but left exposed rail. I checked rail and temporary repaired by installing J-terminal to end.	06-JAN-2012
2657001	08721	M10002	COMPLAINT INVESTIG. M FAMILY	18.190	18.190	08-RIV-060 EB 018.264 PM EB SR60 AT NASON ST, CEMENT DIVIDER NEEDS TO BE MOVED, DIRECTLY SPOKE WITH 8-721 SAM HERNANDEZ ON CELL, LOG #122 01/17/12 Responded to TMC call K-rail damage it appeared that contractor had moved the K-rail to the present location neg. hazard	17-JAN-2012
2657871	08721	M40010	REPAIR/REPLACE SIGNS	0.985	20.935	01/17/2012 repaired and replaced 2 exit signs (G-84) W/B 60 at Market off ramp and Main st off ramp.	17-JAN-2012
2666560	08721	M10002	COMPLAINT INVESTIG. M FAMILY	12.923	12.923	08-RIV-060 WB 013.357 50' E OF DAY ST; CENTER DIVIDER SIGN BENT OVER 01/30/12 721 crew inspected PM location Contractor sign on tri-pod 1098	30-JAN-2012
2666566	08721	M10002	COMPLAINT INVESTIG. M FAMILY	19.766	19.766	08-RIV-060 W/B 1600' EAST OF REDLANDS BLVD; KNOCKED DOWN CAR POOL LANE SIGN 01/30/12 721 crew inspected PM location unable to locate 1098	30-JAN-2012
2676646	08721	M40010	REPAIR/REPLACE SIGNS	1.080	20.935	02/06/12 Repaired 1-W59 E/B Valley Way on ramp adjusted and tightend sign hardware in area 02/28/12 Repaired 1-W-59 and post W/B Fredrick on ramp	06-FEB-2012
							28-FEB-2012
2681003	08721	M10002	COMPLAINT INVESTIG. M FAMILY	12.705	12.705	08-RIV-060 EB 013.139 PM EB SR60 JWO DAY ST, 10 FEET OF GUARDRAIL DAMAGE FOR CALTRANS, DIRECTLY SPOKE WITH 8-721 SAM HERNANDEZ ON CELL TO ADVISE, LOG #69 02/14/12 721 responded removed damaged rail from fogline placed cones 1- SRT	14-FEB-2012
2683458	08721	M40010	REPAIR/REPLACE SIGNS	18.683	18.683	08-RIV-060 WB 015.116 PM WB SR60 JEO HEACOCK ST, GARAGE DOOR ON THE RIGHT HAND SHOULDER, LOG #76 02/16/12 721 crew removed debris checked area 1098	16-FEB-2012
2689590	08721	M10002	COMPLAINT INVESTIG. M FAMILY	18.683	18.743	08-RIV-060 WB 019.117 PM WB SR60 ON MORENO BEACH DR OFR, "SHOULD WORK AHEAD SIGN" KNOCKED DOWN, ALSO 30 FEET OF GUARDRAIL DAMAGE IN THE AREA, DIRECTLY SPOKE WITH 8-721 SAM HERNANDEZ ON CELL TO ADVISE, LOG #1551 02/28/12 721 Inspected damage place cone NCIC# 9840 Officer ID 19594 1- ET 2000 NOTE:SHOULD WORK AHEAD SIGN" KNOCKED DOWN belongs to Construction	28-FEB-2012
							29-FEB-2012
2695711	08721	M40010	REPAIR/REPLACE SIGNS	15.707	15.707	08-RIV-060 WB 016.141 PM WB SR60 AT PERRIS BLVD, EXIT SIGN IS DOWN 4X4 WOODEN POST FOR CALTRANS, NOTIFIED 8-721 SAM HERNANDEZ AT OFFICE LEFT MESSAGE TO ADVISE, LOG #1662 02/28/12 721 crew repaired down G-84 and post 1098	28-FEB-2012
2697517	08721	M40010	REPAIR/REPLACE SIGNS	1.080	20.935	03/02/12 repaired/replaced 1-G28-1 @ Pedly on ramp , 1-G28-2 Day St. on ramp 03/20/12 Repaired 2-R11 , 2-11A , 4-R10 W/B off ramp 03/21/12 1-W59 W/B Market on , 1-W59 W/B Pedley On ,1-W59 W/B Country Village ,1-W59 E/B Etiwanda on , 1-W59 E/B Pedley on , 1-G84 Pyrite off. 03/28/12 W/B Etiwanda off 1-W41 , 1-R11 , 1-R11A , Etiwanda on E/B	02-MAR-2012
							20-MAR-2012
							21-MAR-2012
							28-MAR-2012

Table 6-8 (continued). Records of maintenance effort between January 1, 2012 and June 30, 2012

Wono	Crew	Activity	Activity Description	From Mile	To Mile	Comments	Work Date
							30-MAR-2012
2702859	08721	M10002	COMPLAINT INVESTIG. M FAMILY	14.692	14.692	08-RIV-060 EB 015.126 PM 060 EB ON HEACOCK ST, "LANE DIRECTIONAL SIGN", POST NEEDS TO BE REPLACED, 8721 SAM HERNANDEZ DIRECTLY ON CELL, CAD 384 03/08/12 721 crew inspected PM location large two post sign, reasign to District 08 sign crew.	08-MAR-2012
2707961	08721	M40010	REPAIR/REPLACE SIGNS	15.707	15.707	08-RIV-060 WB 016.141 PM WB 60 AT DAY, EXIT SIGN TAKEN OUT, CAD 1233, DIRECT CONTACT 8721 SAM HERNANDEZ 03/18/12 721 crew repaired down G-84 1098	18-MAR-2012
2727186	08711	M40010	REPAIR/REPLACE SIGNS	20.566	20.566		04-APR-2012
							12-APR-2012
2728442	08663	M40010	REPAIR/REPLACE SIGNS	14.766	14.766	08-RIV-060 REPAIR HANGING W4-14 E/B 60 TO N/B 215 CONNECTOR	09-APR-2012
							10-APR-2012
2728456	08663	M40010	REPAIR/REPLACE SIGNS	14.097	14.097	08-RIV-060 REPAIR KNOCKDOWN R-61 E/B HEACOCK OFF RAMP	09-APR-2012
							10-APR-2012
2728783	08721	M40020	DAY LABOR SIGNS	13.890	13.890	04/09/12 Repaired and replaced (1) W4-2 AND A 4X6 post at Frederick street in C/M.	09-APR-2012
2737686	08664	M10001	INSPECTION M FAMILY	0.010	29.552	04-23-12 write ups on Hwy 60	19-APR-2012
							23-APR-2012
							26-APR-2012
2740153	08721	M40010	REPAIR/REPLACE SIGNS	1.080	20.935	04/26/12 W/B Day st off. 1-R5-109 and post , W/B Perris off 1-G70-4 and post , W/B off Country Village 1-G 70-4 and post	26-APR-2012
2740793	08664	M10001	INSPECTION M FAMILY	0.010	30.042		27-APR-2012
2779395	08661	M10010	REPAIR/REPLACE STRIPING	9.500	16.500	Striping 6-16-2012...Installed all lines W/B Perris off. Installed all lines W/B Rubidoux on.	16-JUN-2012
2780741	08664	M10001	INSPECTION M FAMILY	2.000	27.552		19-JUN-2012
							21-JUN-2012
2781227	08663	M40020	DAY LABOR SIGNS	13.890	20.036	08-RIV-060 TRAFFIC JOBS I.O. 11591 INSTALL 1EA. W4-4P W/B OFF RAMP TO REDLANDS BLVD. COMP. I.O. 11646 RAISE R9-3A TO 7' VERTICAL CLEARANCE E/B FREDRICK ST/ PIGEON PASS RD ON RAMP	19-JUN-2012

6.3.5. Number of Collisions

Figure 6-18 shows the comparison of number of collisions between the before conversion and the after conversion analysis periods based on CHP data retrieved from PeMS. The number of collisions after the HOV conversion dropped by 24% (from 79 to 60) in eastbound direction and by 20% (from 125 to 100) in westbound direction.

Figure 6-19 and Figure 6-20 show the distributions of collisions by absolute postmile on eastbound before and after the HOV conversion, respectively. It is observed that the number of collisions between absolute postmile 54.7 and 55.5 dropped significantly after the conversion. This postmile range coincides with the ingress/egress section at the Heacock St interchange. This is the last ingress/egress section before the freeway off-ramp at Perris Boulevard where a large portion of traffic in this direction gets off the freeway during the afternoon peak period.

Figure 6-21 and Figure 6-22 show the distributions of collisions by absolute postmile on westbound before and after the HOV conversion, respectively. There was no significant change in the shape of the distribution after the conversion as compared to that before the conversion.

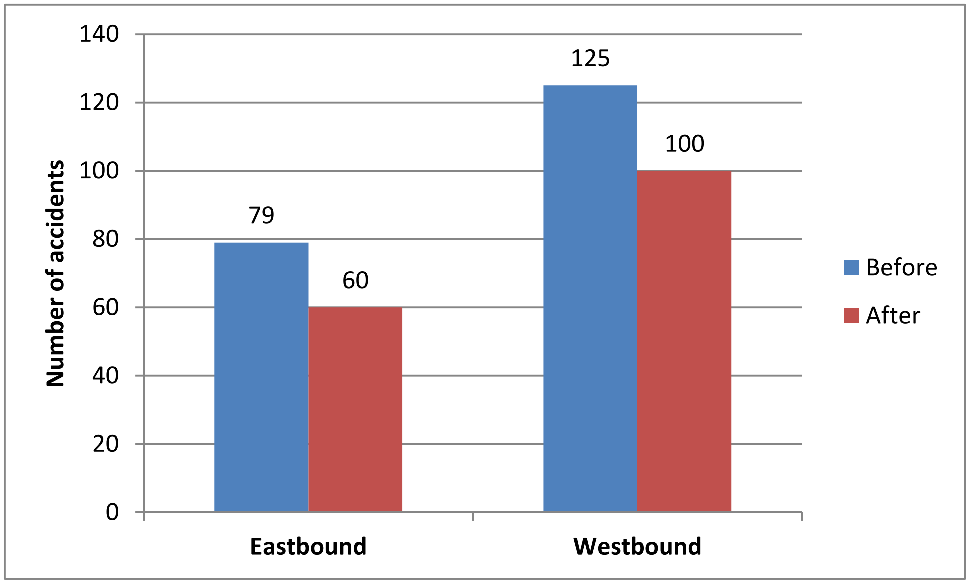


Figure 6-18. Number of accidents between absolute PM 53 and 57

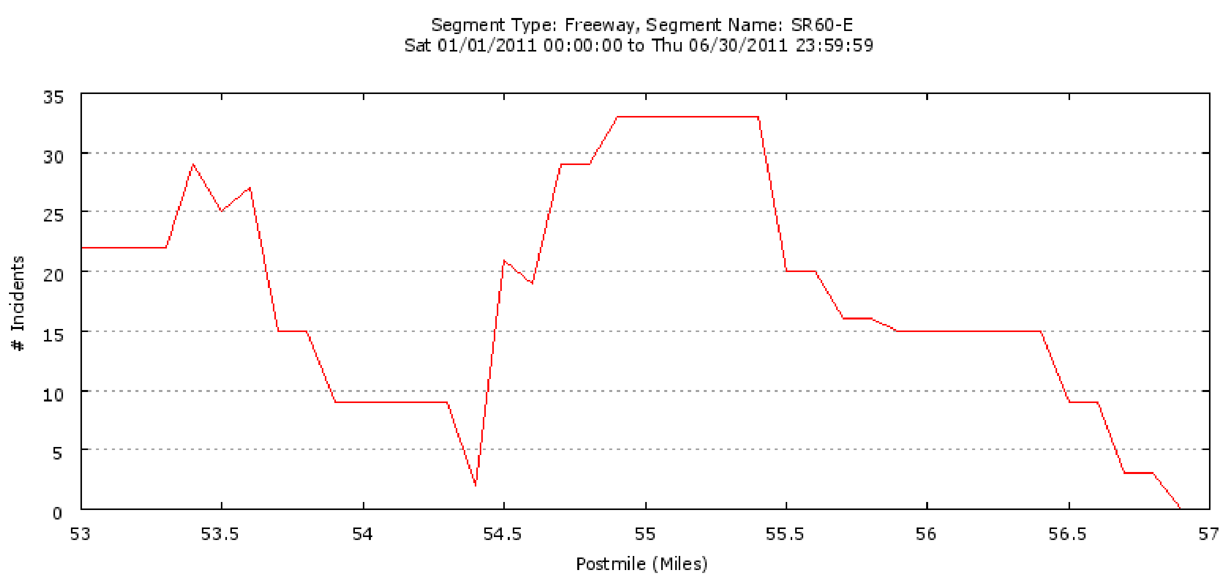


Figure 6-19. Number of accidents by postmile on eastbound before the HOV conversion

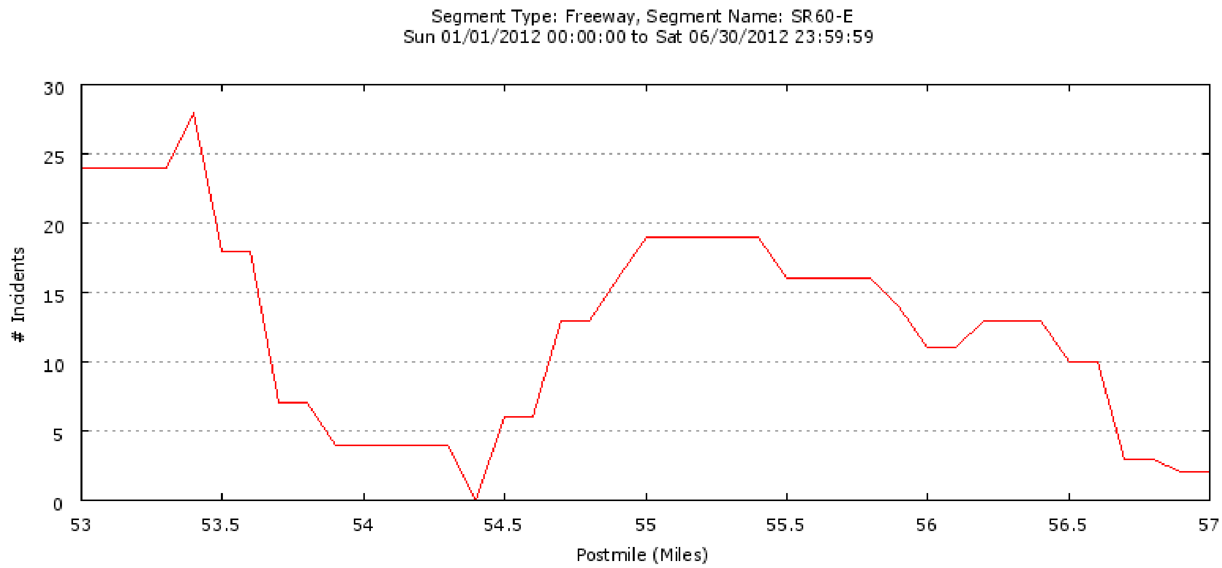


Figure 6-20. Number of accidents by postmile on eastbound after the HOV conversion

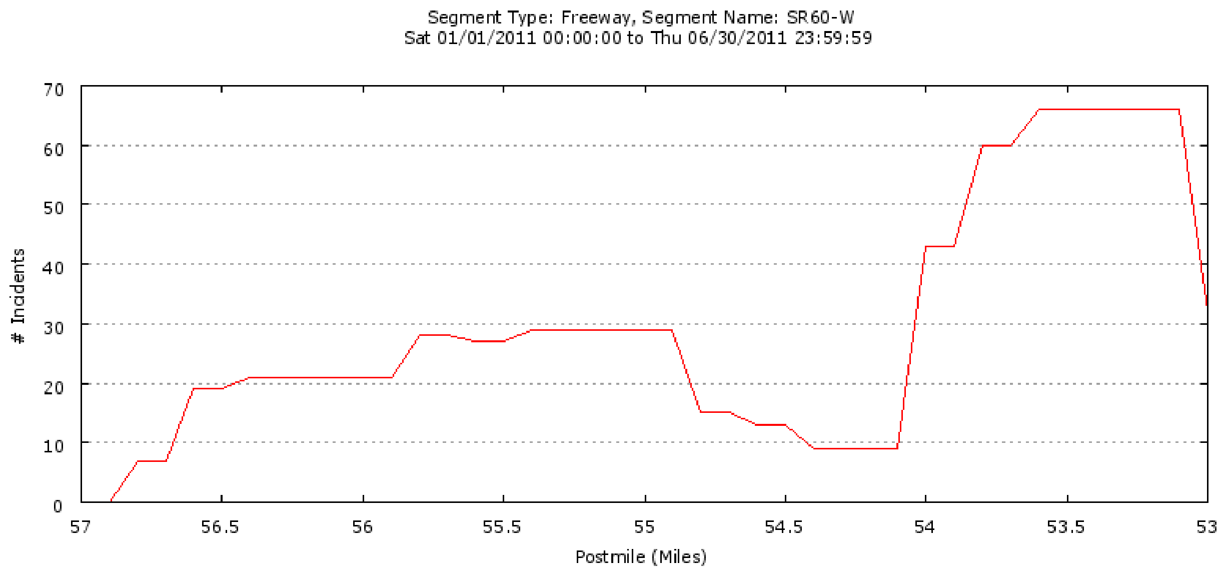


Figure 6-21. Number of accidents by postmile on westbound before the HOV conversion

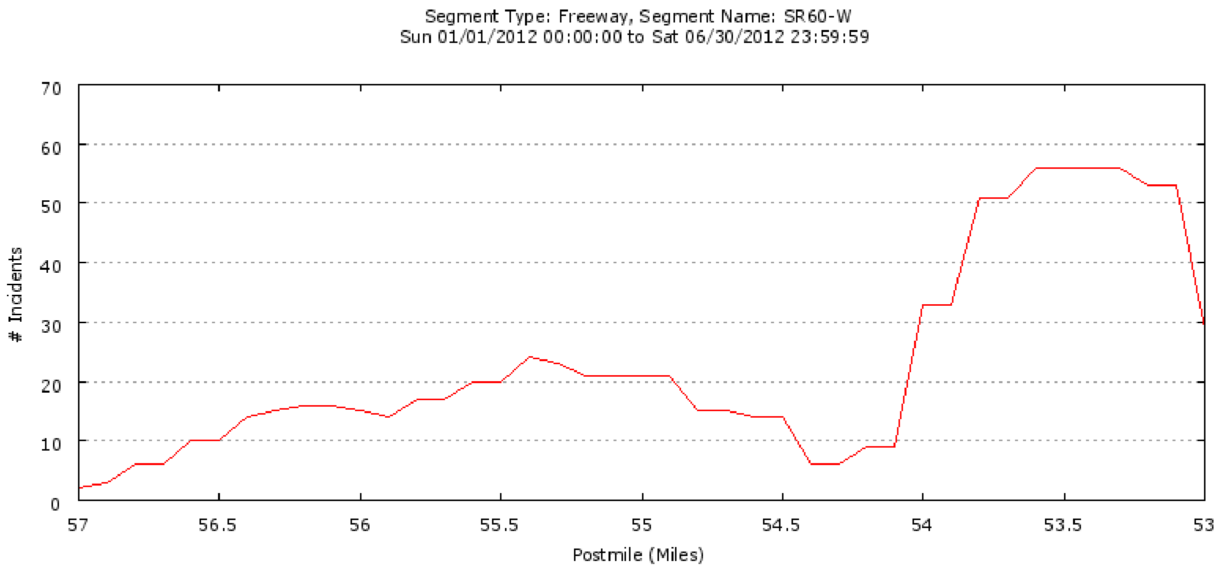


Figure 6-22. Number of accidents by postmile on westbound after the HOV conversion

6.3.6. Number of Complaints, Public Concerns, or Customer Satisfaction

There is no documented information available from Caltrans on number of complaints, public concerns, or customer satisfaction regarding the HOV conversion on SR-60. However, the local paper, The Press Enterprise, has published two articles about the conversion:

1. Car-pool lanes in Moreno Valley opening to lone drivers – sometimes (published February 16, 2011)[1]

2. MORENO VALLEY: Opening of car pool lanes pleases area drivers (published February 9, 2012)[2]

Both articles were focused more on the aspect of converting from full-time operation to part-time operation than on the aspect of converting from limited access to continuous access. The second article was published after the conversion was completed and offered reactions of the general public to the part-time operation of the lane. Some [excerpts] and "quotes" from this article were provided below. The full transcript of both articles is provided in Appendix H.

- […drivers are applauding a decision to open the car pool lanes along Highway 60 in Moreno Valley to solo drivers during non-peak hours.]

[1] http://www.pe.com/local-news/riverside-county/moreno-valley/moreno-valley-headlines-index/20110216-car-pool-lanes-in-moreno-valley-opening-to-lone-drivers----sometimes.ece
[2] http://www.pe.com/local-news/transportation-headlines/20120209-moreno-valley-opening-of-car-pool-lanes-pleases-area-drivers.ece

- [Drivers say traffic flow has greatly improved. Giving motorists a third lane helps them pass trucks and slower-moving traffic entering and exiting the freeway.]

- “It makes sense. If you have another lane, you can have more cars.” Jorge O. Ramos, 37

- “I use it every day and it makes a difference.” Krystal Waddell, 23

- “People have called and said, ‘We love it.’” Shelli Lombardo, Caltrans District 8 spokeswoman

Based on these limited evidences, it appears that the general public has had positive reactions to the HOV conversion, especially the conversion from full-time operation to part-time.

7. Conclusions and Recommendations

7.1. Summary of Findings

This research was aimed at addressing the question "which of the two HOV access types (limited access versus continuous access) is operationally better for the overall performance of the freeway." It has been successfully carried out using four different but complementary analysis approaches. The pros and cons of each analysis approach are summarized in Table 7-1.

Table 7-1. Summary of pros and cons of analysis approaches used in this study

Approaches	Pros	Cons
Corridor-Level Analysis	• Account for impacts of traffic demands and bottlenecks • Easy to comprehend by engineers/planners and the general public	• Findings are corridor-specific • Difficult to separate the effect of HOV lane configuration from other influencing factors
Statistical Modeling	• Based on large amount of real-world data • Able to quantify the effect of HOV lane configuration while controlling for other influencing factors	• Data processing is time consuming • Currently applicable to performance measured at VDS locations
Video Data Analysis	• Provide high-resolution traffic data in time and space, allowing weaving behavior to be captured and analyzed • Good supplement to PeMS	• Difficult and costly to collect and process data • Limited locations and surveillance periods
Traffic Simulation	• Full control of all geometric and traffic parameters • Can simulate multiple what-if scenarios	• Results dependent on model calibration and validation • May not capture extreme driving behaviors

Below is a summary of key findings based on the results from each analysis approach.

7.1.1. Corridor-Level Analysis

- Based on the 2008 District 8 HOV Monitoring Report statistics, it was found that:
  - The proportion of carpool vehicles in the District 8 corridors ranged from 10% to 20%. The share of carpool vehicles in HOV lane from the total carpool vehicles across all lanes was highest on I-215 S.
  - The AVO in MF lanes was slightly over 1.0 for all the corridors. The AVO in HOV lane was about 2.0 for most of the corridors. The HOV lane on I-210 W had the lowest AVO as it also had the highest HOV lane violation rate of 5%.
  - Passenger carried ratio of HOV lane to average MF lane was greater than 1 for most corridors.
- Based on the analysis of PeMS data for the entire year of 2009, it was found that:

- SR-91 was the most congested freeway in the district during peak hour. The average travel speeds (or corridor efficiencies) in both HOV and MF lanes of both SR-91 E and SR-91 W were among the lowest in the district.

- For I-215 N, the average travel speed was low in the MF lanes but high in the HOV lane. The approximately 15 mph higher average travel speed in the HOV lane would provide a significant amount of travel time savings to HOV lane-eligible vehicles.

- Recurrent bottlenecks often occurred at the locations where there is a significant amount of traffic weaving. For corridors with limited access HOV lane such as SR-91 E, the recurrent bottlenecks occurred around some ingress/egress areas, resulting in shockwaves that propagate upstream. For corridors with continuous access HOV lane such as I-215 N, the recurrent bottlenecks occurred around the interchange between I-215 and SR-60.

- Lastly, the travel time data collected by probe vehicle runs show that the travel time savings for HOV lanes varied significantly by corridor and time of day.

7.1.2. Statistical Modeling

- The results from all the developed regression models using the statewide HOV database consistently show that HOV lane access type has a statistically significant effect on freeway throughput. They also consistently suggest that a freeway with limited access HOV lane would have higher maximum throughput than a freeway with continuous access HOV lane, given that everything else being equal.

- In addition to HOV lane access type, other statistically significant variables in the MLR models for overall freeway throughput are number of lanes, inner shoulder width, district, and lane occupancy at capacity.

- Whether the freeway maximum throughput is determined by the PeMS or the Max-flow methods, the effects of the statistically significant variables are qualitatively the same but quantitatively different.

7.1.3. Video Data Analysis

- At the ingress/egress sections of the limited access HOV lanes on I-10 E and SR-91 W, most of the lane changes occurred early on within the first half of the sections. This lane-changing spatial intensity was more spread out for the continuous access HOV lane on I-215 S.

- Gaps and clearances of the vehicles changing lane from the HOV lane to the adjacent MF lane were smaller for the ingress/egress sections of the limited access HOV lanes on I-10 E and SR-91 W than for the continuous access HOV lane on I-215 S.

7.1.4. Traffic Simulation

- For SR-91 E, the Q values of the network with continuous access HOV lane are much higher than those of the network with limited access HOV lane. This is true for both HOV and MF lanes and for all the scenarios. The differences in the Q values for HOV lane between the two networks range from 17% to 29% in different scenarios, which is quite significant. For MF lanes, the Q values of continuous access HOV facilities are on average 6% higher than limited access ones in all scenarios.

- For SR-91 W, the Q values of both MF lanes and HOV lane do not have obvious change (within 3%) under two types of networks, because the traffic condition (especially on HOV lanes) is not getting worse in all these scenarios.

- For I-15 N and I-15 S, the Q values for both networks are also similar, with the differences mostly negligible. This is expected as there is no HOV lane, and thus no geometric differences between the two networks, on these two routes. The variations may result from the changes in traffic condition along SR-91 (i.e. traffic volumes from/to SR-91).

- Overall, it is found that when there is no congestion ($Q > 50$ mph), both networks with limited access and continuous access HOV lane tend to have similar average travel speeds (mostly less than 2 mph difference). However, as the networks get moderately congested ($35 \text{ mph} < Q \leq 50$ mph), the network with continuous access HOV lane has higher average travel speeds. These findings are consistent with those in the previous study [Boriboonsomsin and Barth, 2006].

7.1.5. Before-and-After Study of SR-60 HOV Conversion

- The eastbound direction was relatively more congested during the before analysis period, especially from 3 p.m. to 7 p.m. The westbound direction carried more traffic volumes during the after analysis period across all hours of day, which resulted in having slightly lower travel speeds.

- The HOV violation rates after the conversion were higher. During the AM period, the HOV violation rate after the HOV conversion increased from 16.6% to 24.9%. During the PM period, the HOV violation rate after the HOV conversion more than doubled from 12.0% to 25.6%.

- After the conversion to continuous access, the number of lane changes per mile traveled into and out of the HOV lane increased. However, these lane changes generally occurred at a larger clearance.

- After the conversion to continuous access, the number of collisions decreased, especially at the ingress/egress section at the Heacock St interchange in eastbound direction.

7.2. Conclusions

This research was aimed at addressing the question "which of the two HOV access types (limited access versus continuous access) is operationally better for the overall performance of the freeway." It has been successfully carried out using four different but complementary analysis approaches. Based on the research results and findings, the following conclusions are made:

- The operational performance of the HOV facilities in District 8 was varied by corridor due to several factors. But in general, all of them maintained average travel speeds greater than 45 mph even during their peak hours, except for the ones on SR-91. The HOV lanes on SR-91 experienced significant delays in the westbound during the morning peak and in the eastbound during the afternoon peak. Part of these delays was due to recurrent bottlenecks around the ingress/egress areas along the corridors.

- Based on statistical analyses of the statewide HOV database consisting of freeways with HOV facilities in Districts 4, 7, 8, and 12, it was found that a freeway with limited access HOV lane would have higher maximum throughput than a freeway with continuous access HOV lane (by 90 vehicles/hour/lane for the PeMS method and 180 vehicles/hour/lane for the Max method), given that everything else such as other geometric characteristics, traffic demand, truck proportion, etc. being equal.

- Collecting and analyzing videos of traffic was demonstrated to be a useful approach for examining vehicle weaving behavior along HOV lanes. The limited amount of lane changing data collected in this research suggested that lane changing between HOV lane and the adjacent MF lane was smoother for continuous access HOV lane. Vehicles changing lane from the HOV lane to the adjacent MF lane in the ingress/egress areas of limited access HOV lane had smaller gaps and clearances than in the case of continuous access HOV lane.

- Based on traffic simulation, it was found that when there is no congestion, freeways with limited access and continuous access HOV lane tend to have similar average travel speeds (mostly less than 2 mph difference). As traffic gets moderately congested, the freeway with continuous access HOV lane has higher average travel speeds.

- After converting the HOV lane on a segment of SR-60 from full-time limited access operation to part-time continuous access, the HOV violation rate increased but the number of collision decreased, especially at one location on the eastbound where it was an ingress/egress section.

It is interesting to find that limited access HOV lanes would result in the freeways having higher maximum throughput while continuous access HOV lanes would provide higher average travel speed along the corridors under moderate congestion. These findings seem to be contradictory, but may be explained as follows.

In this research, the freeway throughput is determined at the locations of PeMS' VDS. For freeways with limited access HOV lanes, the majority of the VDS are located on the buffered sections where lane changing is not allowed. Therefore, the freeway throughput measured at these locations would not be impacted by traffic perturbations caused by the lane changing between the HOV lane and the adjacent MF lane. On the other hand, the VDS on freeways with continuous access HOV lanes would be more likely to experience such traffic perturbations as lane changing is allowed anywhere along the lanes. In addition, it is hypothesized that drivers on freeways with continuous access HOV lanes could be more cautious and leave a slightly larger gap from the vehicle in front in preparation of a possible merging vehicle, which could also result in a lower freeway throughput.

When freeways are approaching its maximum throughput, the traffic is moderately congested. Under such condition, vehicles traveling on a freeway with limited access HOV lane are more likely to experience delays at the ingress/egress areas along the corridors, which are caused by the weaving activities in these areas. Some vehicles may even have to slow down significantly to wait for acceptable gaps to perform lane changes. These delays result in a lower average travel speed. On the other hand, weaving activities between the HOV and adjacent MF lanes are more spread out in the case of freeways with continuous access HOV lanes. This makes it less likely for the vehicles on these freeways to experience the similar heavy weaving-induced delays. Although these vehicles may still experience some traffic perturbation from lane changing maneuvers in to and out of the HOV lane, the resulting delays are not as much as those caused by such heavy weaving-induced delays as in the case of freeways with limited access HOV lanes.

Thus, there is a tradeoff between maximum throughput and average travel speed when comparing the operational performance of the two HOV access types. One of the Caltrans' Strategic Goals is "Mobility", which aims to "maximize transportation system performance and accessibility". In this context, a higher freeway throughput means more accessibility to travelers (i.e., allowing more travelers to access activities in the same amount of time) while a higher average travel speed means better system performance in terms of productivity (i.e., providing travelers more miles in the same amount of time).

7.3. Recommendations

Based on the synthesis of the results and findings from this research, the following recommendations are made for consideration:

- It is desirable to continue to monitor the performance of HOV facilities in District 8 on a periodic basis. Particular attention should be paid to the HOV lanes on SR-91 in both directions as they experience significant delays during peak hours. Increasing the HOV eligibility requirement during the peak periods may help alleviate congestion in the SR-91 HOV lanes.

- Both limited access and continuous access HOV lanes have their own unique advantages. The buffered sections of limited access HOV lanes are found to be good at separating traffic flows between HOV and MF lanes, thus resulting in higher freeway throughput. The continuous access HOV lanes are found to be good at spreading out lane changing activities, thus reducing major traffic perturbations that can cause significant delays. It is possible to design new types of HOV access that incorporate these advantages together. Specifically, an HOV lane can be designed to be continuous access for most of the corridor to achieve relatively higher average travel speed along the corridor, but have buffers strategically applied to critical freeway segments (e.g., around non-HOV-related bottlenecks and ramp merges) to facilitate relatively higher throughput on those segments.

- In exploring the alternative designs of HOV access, additional research should be undertaken to collect new data and develop new tools/methods that can help determine the locations of buffer placement.

8. References

Boriboonsomsin, K. and Barth, M. (2006). Modeling the effectiveness of HOV lanes at improving air quality. Contract No. RTA 65A0196, Final report to the California Department of Transportation, December, 122 pp.

Boriboonsomsin, K. and Barth, M. (2007). “Evaluating air quality benefits of freeway high occupancy vehicle lanes in Southern California.” *Transportation Research Record*, 2011, 137-147.

Boriboonsomsin, K. and Barth, M. (2008). Impacts of freeway high-occupancy vehicle lane configuration on vehicle emissions. *Transportation Research Part D*, 13(2), 112-125.

Boriboonsomsin, K., Barth, M., and Xu, H. (2009a). “Improvements to on-road mobile emissions modeling of freeways with high-occupancy vehicle facilities.” *Transportation Research Record*, 2123, 109-118.

Boriboonsomsin, K., Zhu, W., Scora, G., and Barth, M. (2009b). “Improving greenhouse gas emissions inventory estimation of heavy-duty trucks.” Final report to the Federal Highway Administration, November, 70 pp.

Breiman, L., Friedman, J. H., Olshen, R. A., Stone, C. J. (1884) *Classification and regression trees*. Chapman & Hall, USA

Brilon, W., Geistefeldt, J., Regler, M. (2005) Reliability of freeway traffic flow: a stochastic concept of capacity. Proceedings of the 16th International Symposium of Transportation and Traffic Theory, College Park, MD, July, pp. 125 – 144

Brownstone, D., et al. (2008) Evaluation of Incorporating Hybrid Vehicle Use of HOV Lanes. California PATH Research Report. UCB-ITS-PRR-2008-26

Caltrans (2003a). High-occupancy vehicle guidelines for planning, design, and operations. Division of Traffic Operations, California Department of Transportation, August.

Caltrans (2003b) Information memorandum: Year 2002 area freeway congestion data. District 4 Office of Highway Operations, California Department of Transportation, Oakland

Chung, K., Chan, C.-Y., Jang, K., Ragland, D., and Kim, Y.-H. (2007). HOV lane configurations and collision distribution on freeway lanes: investigation of historical collision data in California. Proceedings of the 86th Annual Meeting of the Transportation Research Board (CD-ROM), Washington, D.C., January.

Cook, R. D. (1977) Detection of Influential Observations in Linear Regression. *Technometrics*, American Statistical Association, 19 (1), pp. 15–18

Dervisoglu, G, Gomes, G., Kwon J., Horowitz, R., Varaiya, P. (2009) Automatic calibration of the fundamental diagram and empirical observations on capacity. In Proceedings of 88th Annual Meeting Transportation Research Board, Washington D. C., January

Evans, J. L., Elefteriadou, L., Gautam, N. (2001) Probability of breakdown at freeway merges using Markov chains. *Transportation Research Part B*, Vol. 35, pp. 237 – 254

Friedman, J. H. (1991) Multivariate adaptive regression splines. *The Annals of Statistics*, Vol. 19, No. 1, pp. 1 - 141

Gardes, Y., Kim, A., and May, A. D. (2003). Bay Area Simulation and Ramp Metering Study – Year 2 Report. California PATH Research Report UCB-ITS-PRR-2003-9, March.

Highway Safety Information System (2011). http://www.hsisinfo.org/, accessed November, 2011>

Jia, Z. Chen, C., Coifman, B., Varaiya, P. (2001) The PeMS algorithms for accurate, real-time estimates of g-factors and speeds from single-loop detectors. Proceedings of IEEE Intelligent Transportation Systems Conference, Oakland, CA, August, pp. 536 – 541

Kreft, I. and Deleeuw, J. (1998) *Introducing multilevel modeling*. London: Sage Publications Ltd.

Kwon, J., McCullough, B., Petty, K., Varaiya, P. (2007) Evaluation of PeMS to Improve the Congestion Monitoring Program. California PATH Research Report, UCB-ITS-PRR-2007-6

Kwon, J. and P. Varaiya. (2008) Effectiveness of California's High Occupancy Vehicle (HOV) System. *Transportation Research Part C*, No. 16, pp. 98-115

Lorenz, M. R., Elefteriadou, L. (2001) Defining freeway capacity as function of breakdown probability. *Transportation Research Record*, No. 1776, pp. 43 – 51

Orange County Transportation Authority (2002). Orange county high occupancy vehicle (HOV) operations policy study. Prepared by Parsons Brinckerhoff Quade and Douglas, Inc., August 1.

PeMS (2011). http://pems.dot.ca.gov/. Accessed November 8, 2011.

R Development Core Team (2011) R: a language and environment for statistical computing. Available from: <http://www.R-project.org accessed January, 2011>

Sullivan, E. (1998). Evaluating the impacts of the SR 91 variable-toll express lane facility. Final report to the California Department of Transportation, May, 132 pp.

Sullivan, E. (2000). Continuation study to evaluate the impacts of the SR 91 value-priced express lanes. Final report to the California Department of Transportation, December, 225 pp.

Transportation Research Board (1998) HOV systems manual. NCHRP Report 414, Transportation Research Board, prepared by Texas Transportation Institute

Transportation Research Board (2000). *Highway Capacity Manual 2000*.

Zhang, Y. (2005) Capacity modeling of freeway weaving sections. Ph. D. Thesis, Virginia Polytechnic Institute and State University, May

Appendix A:

Recurrent Bottlenecks of D8 HOV Facilities

Continuous-access

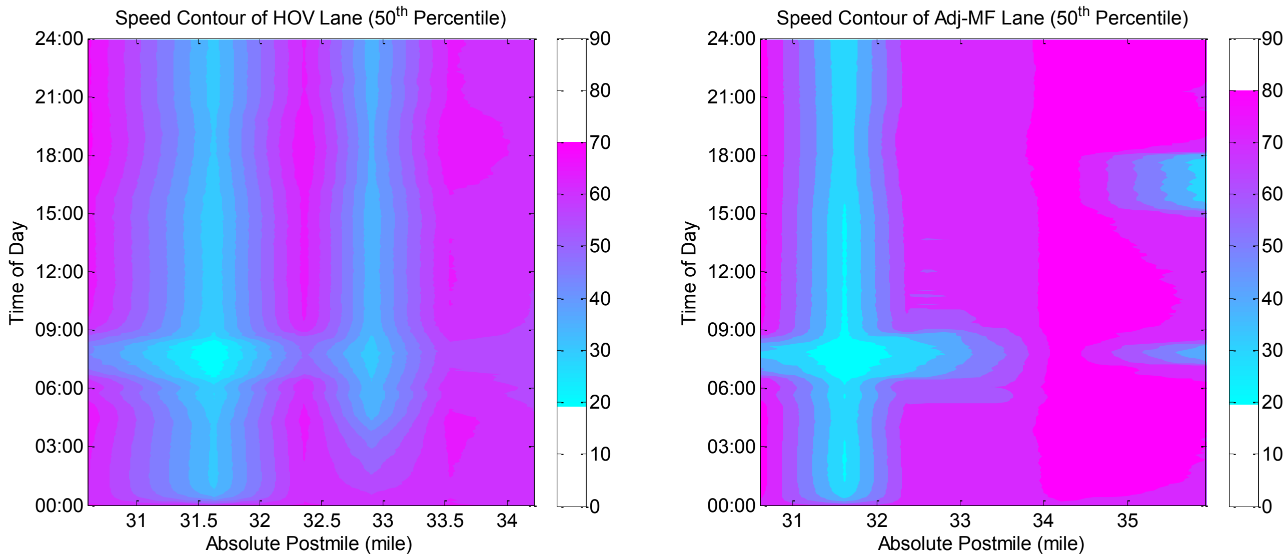


Figure A-1. 50th Percentile Speed Contours for I-215 N

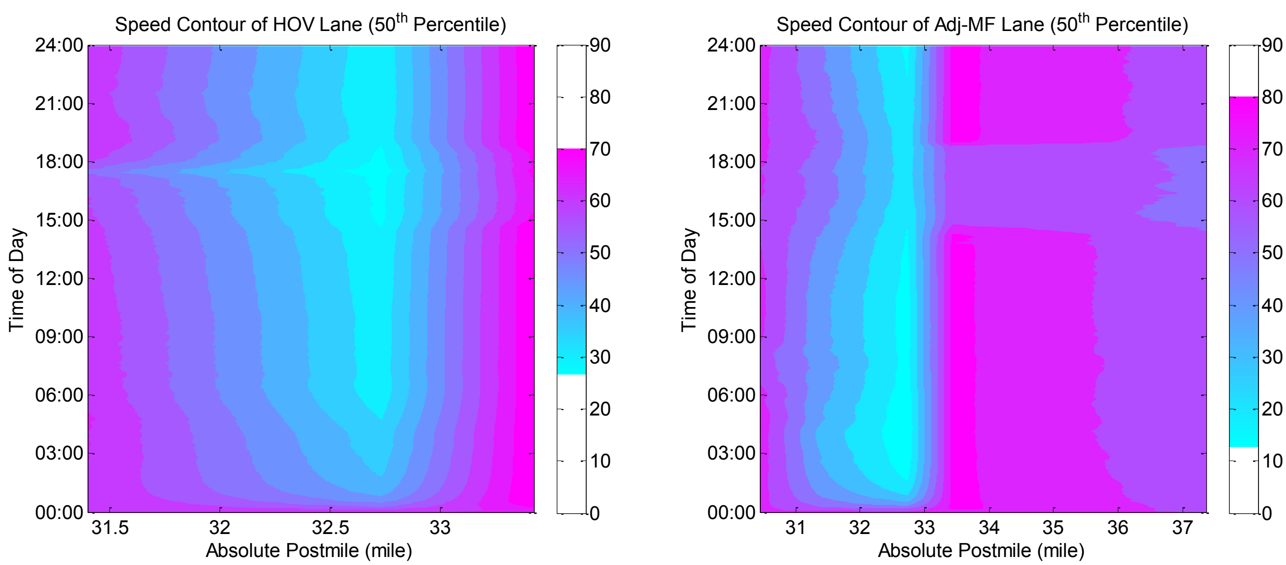


Figure A-2. 50th Percentile Speed Contours for I-215 S

Limited-access

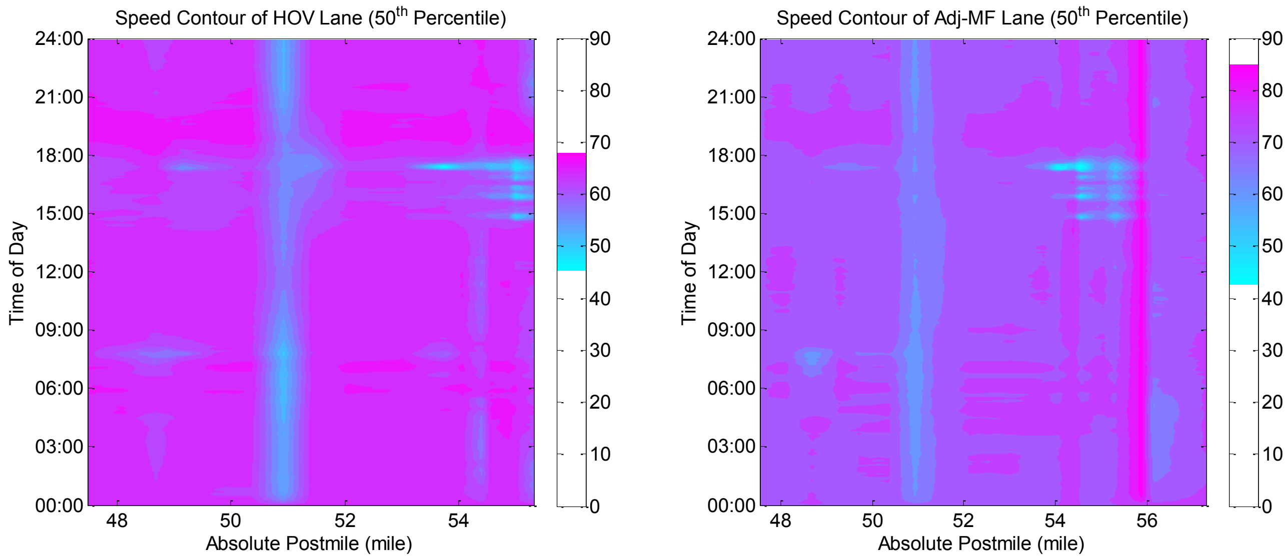


Figure A-1. 50th Percentile Speed Contours for I-10 E

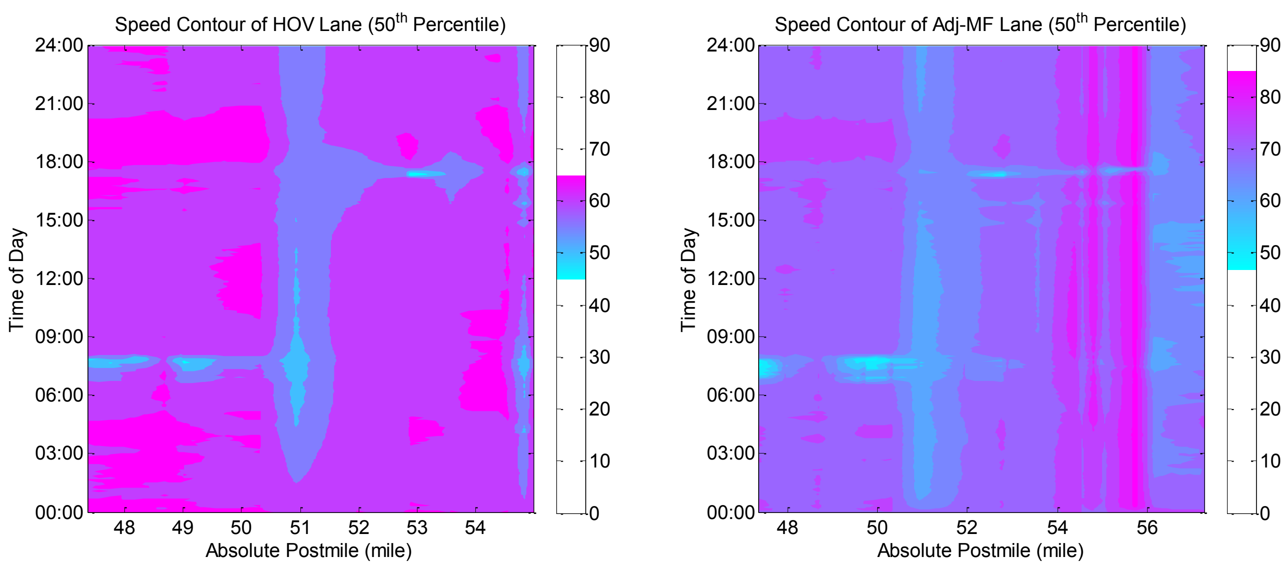


Figure A-2. 50th Percentile Speed Contours for I-10 W

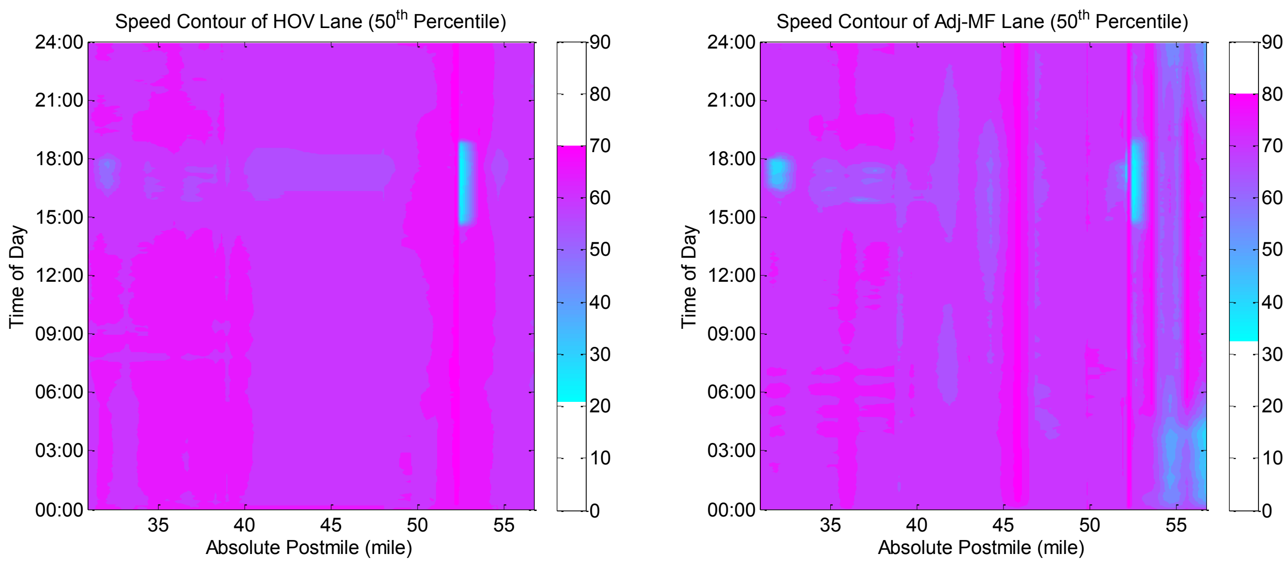


Figure A-3. 50th Percentile Speed Contours for SR-60 E

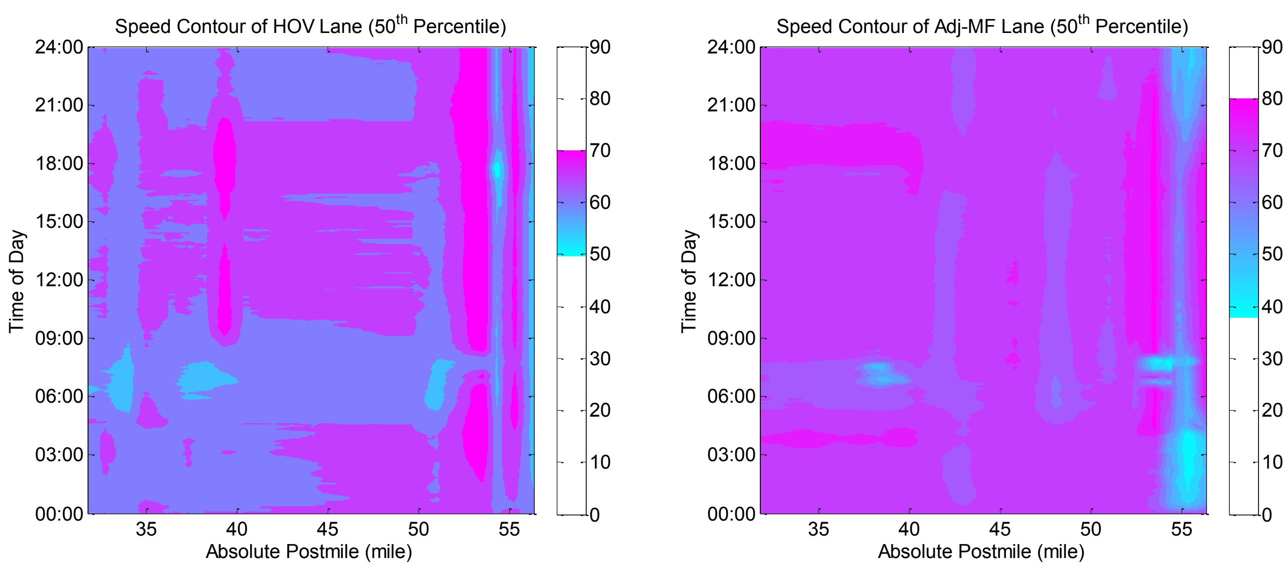


Figure A-4. 50th Percentile Speed Contours for SR-60 W

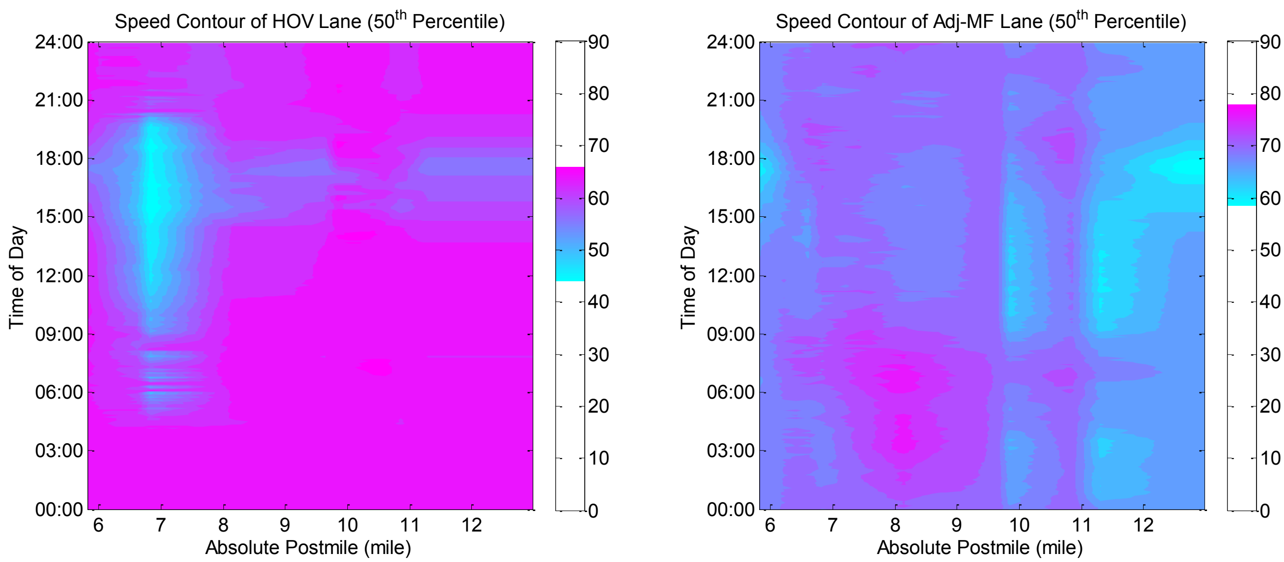


Figure A-5. 50th Percentile Speed Contours for SR-71 N

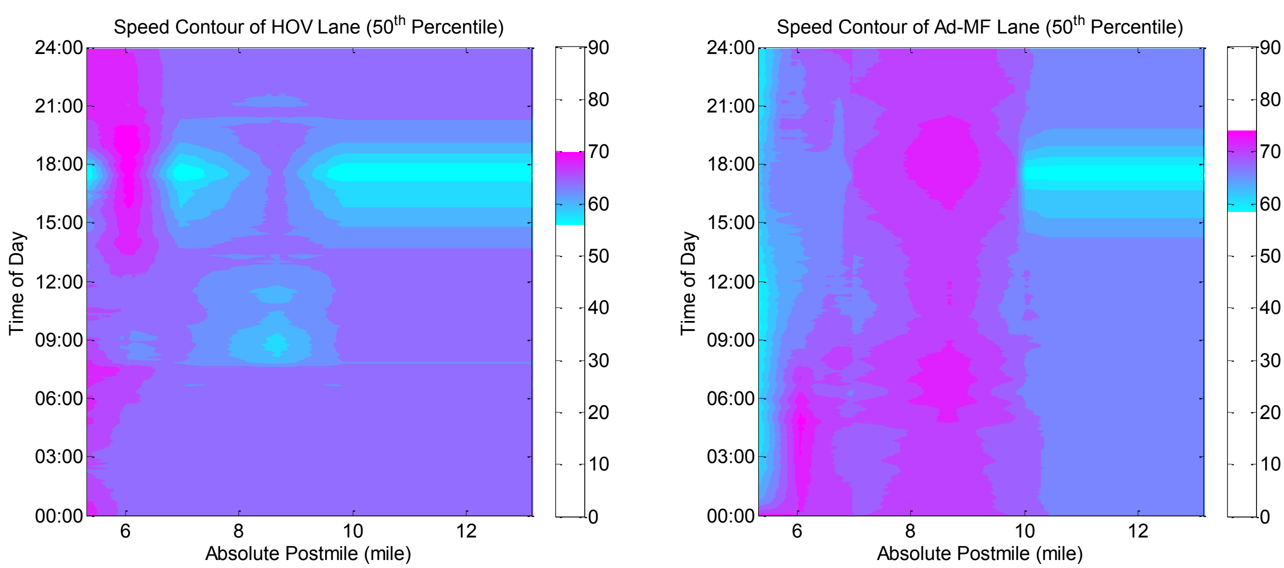


Figure A-6. 50th Percentile Speed Contours for SR-71 S

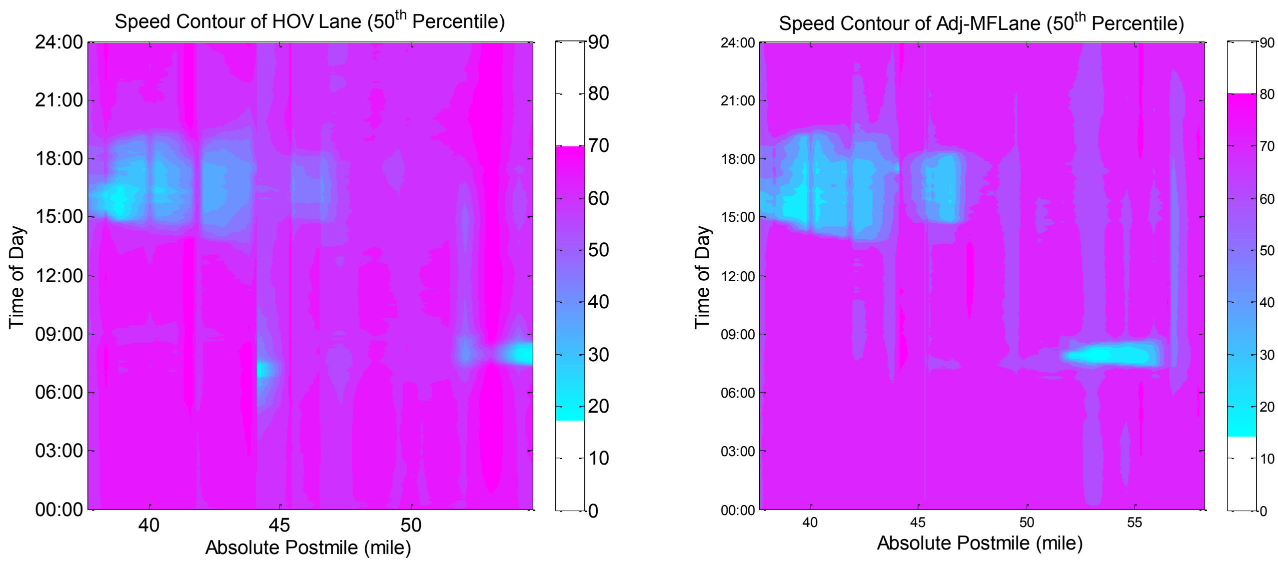


Figure A-7. 50th Percentile Speed Contours for SR-91 E

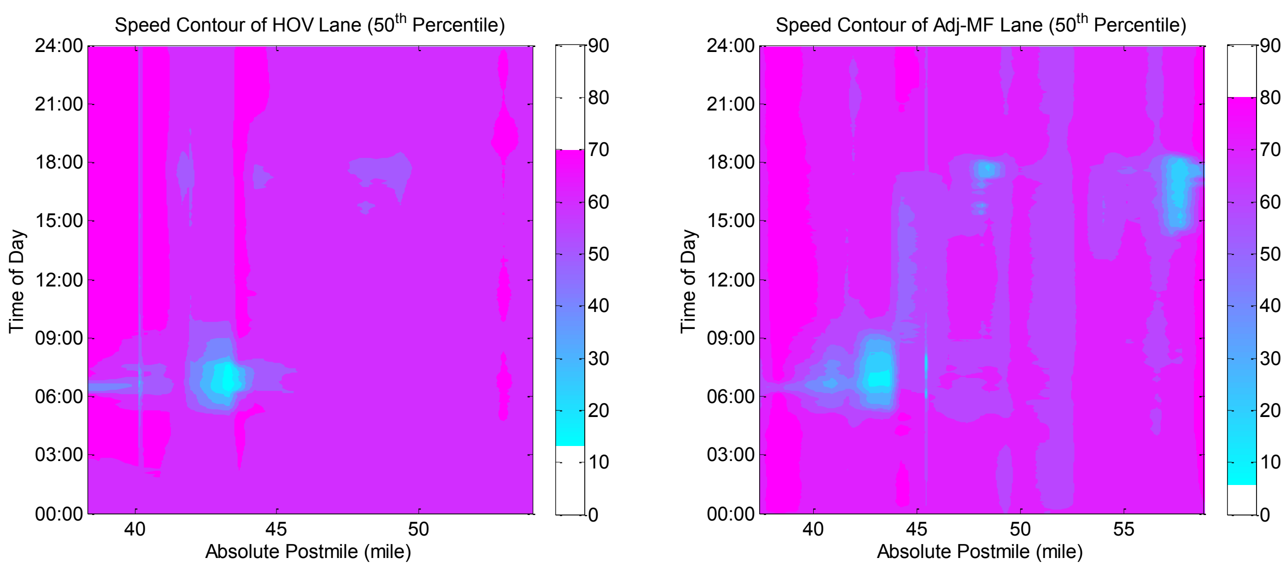


Figure A-8. 50th Percentile Speed Contours for SR-91 W

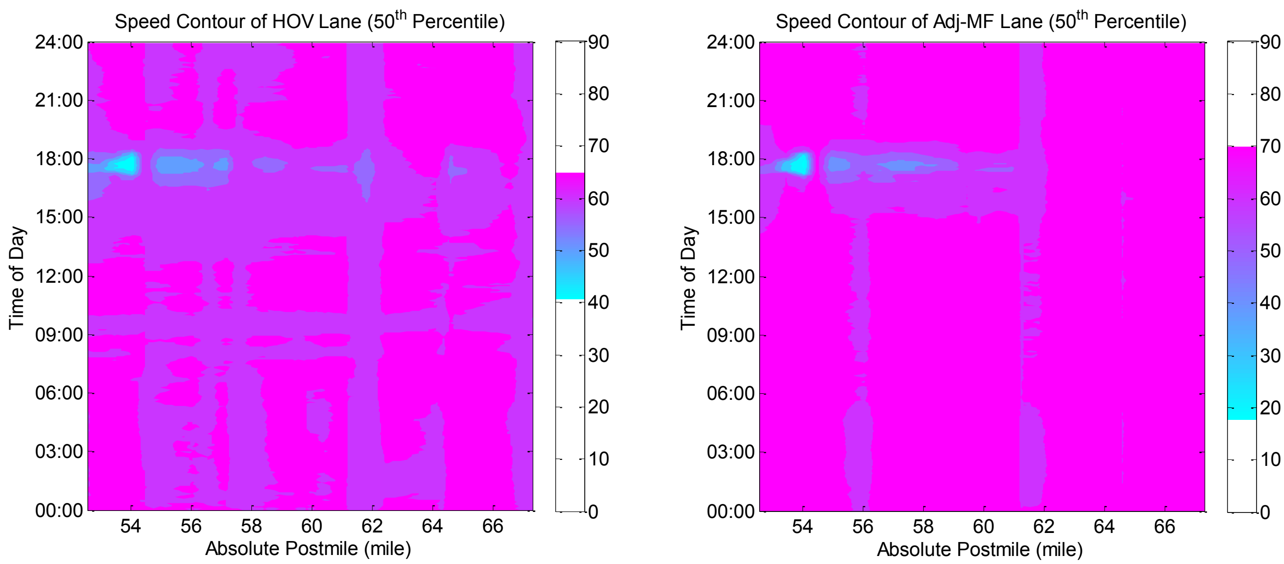


Figure A-9. 50th Percentile Speed Contours for I-210 E

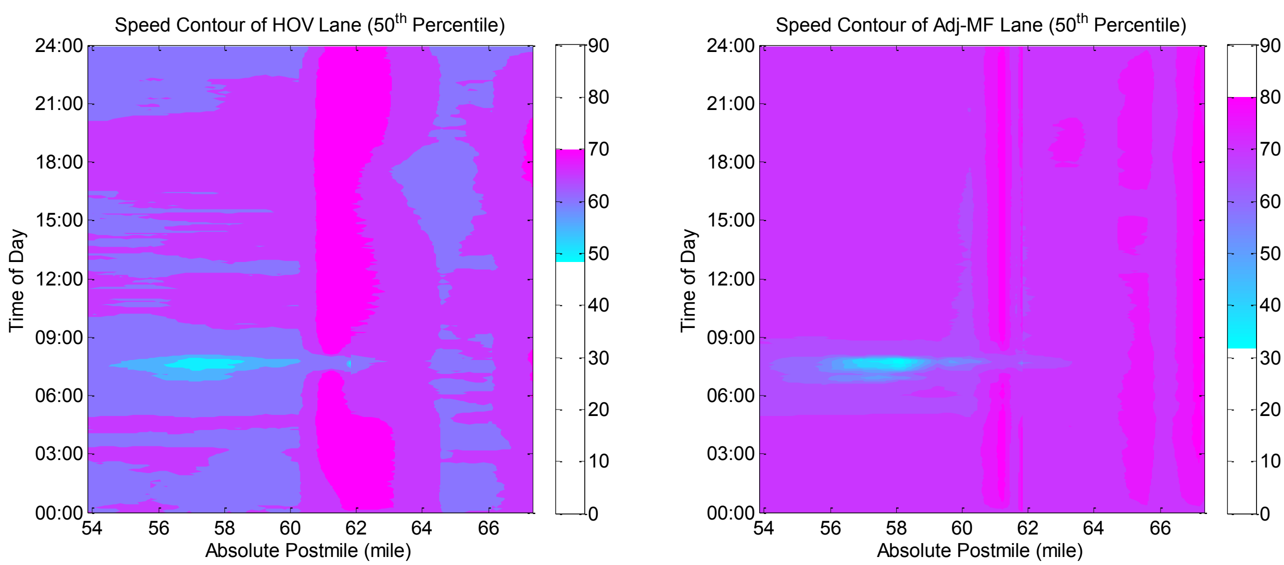


Figure A-10. 50th Percentile Speed Contours for I-210 W

Appendix B:

HOVL-MFL Joint LOS Matrix during Peak Hour

Continuous-access

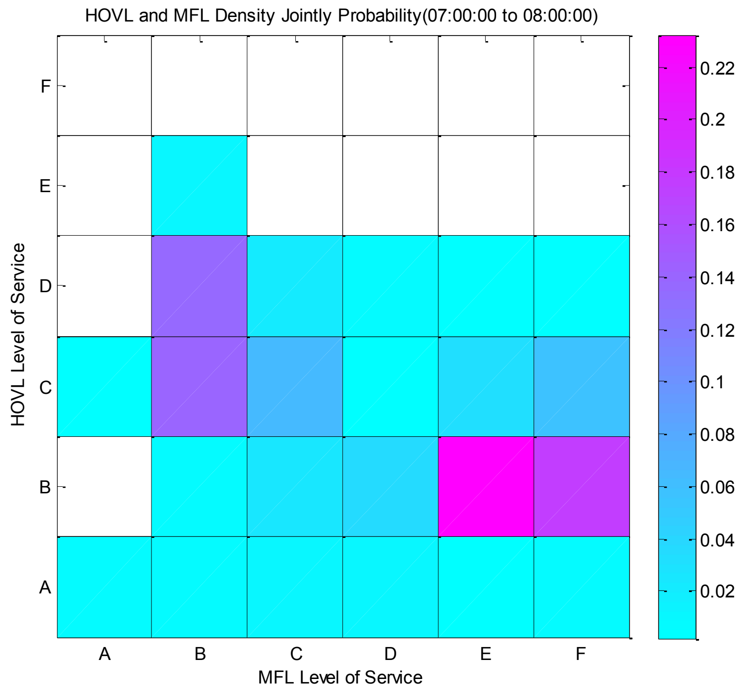


Figure B-1. HOVL-MFL Joint LOS Matrix during Peak Hour for I-215 N

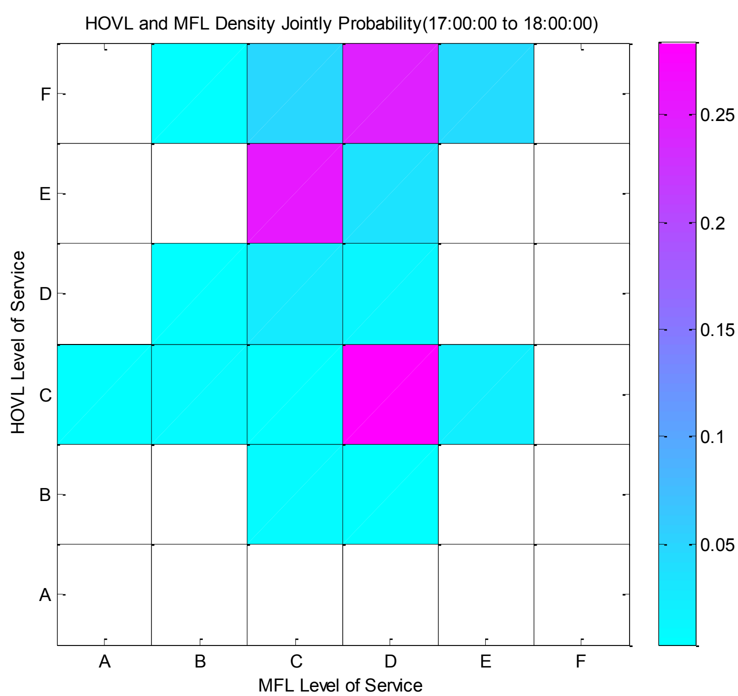


Figure B-2. HOVL-MFL Joint LOS Matrix during Peak Hour for I-215 S

Limited-access

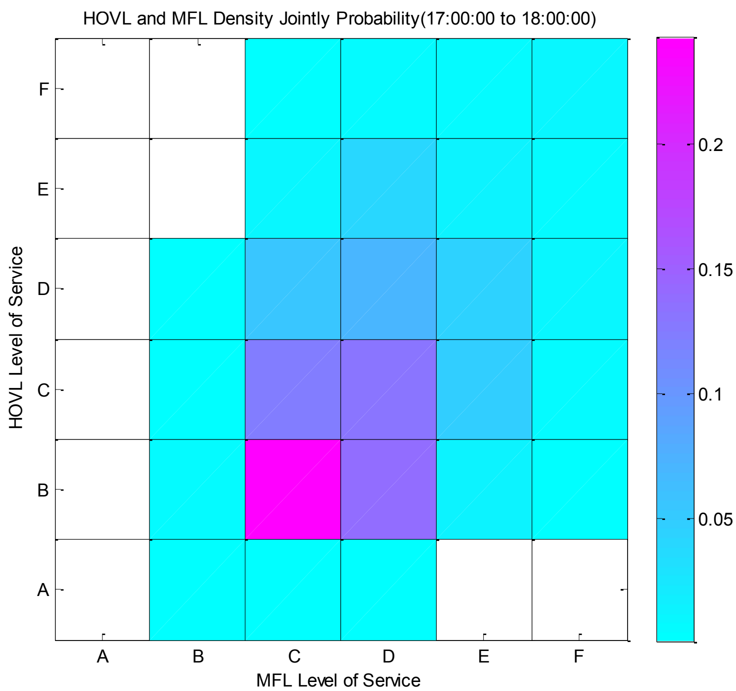


Figure B-3. HOVL-MFL Joint LOS Matrix during Peak Hour for I-10 E

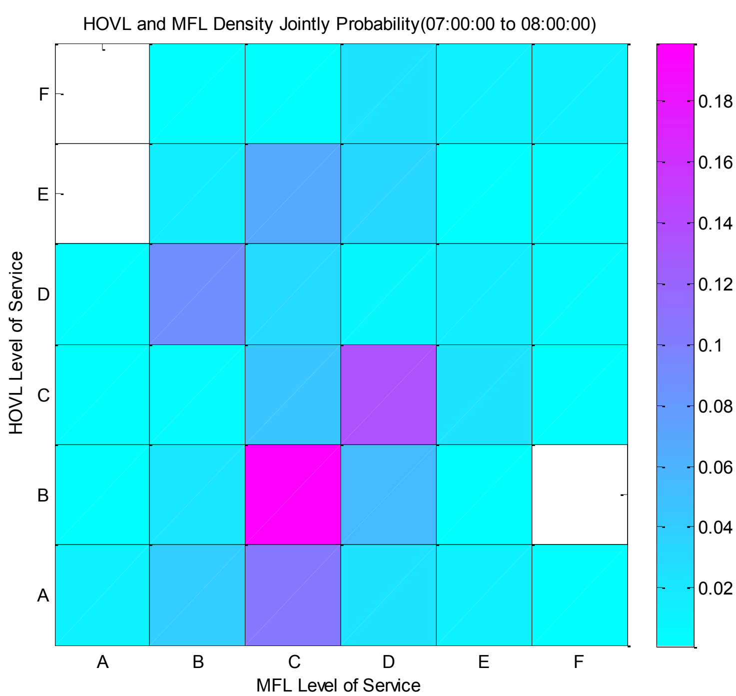


Figure B-4. HOVL-MFL Joint LOS Matrix during Peak Hour for I-10 W

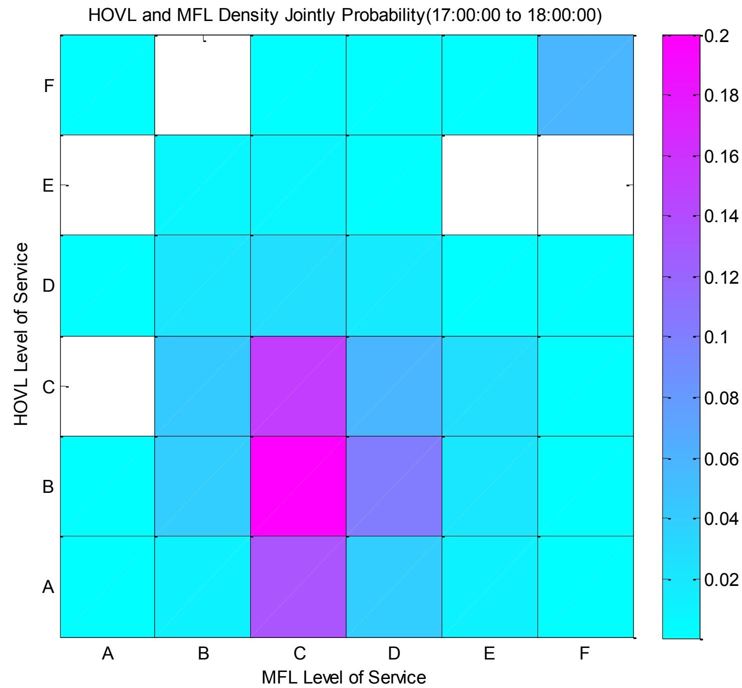


Figure B-5. HOVL-MFL Joint LOS Matrix during Peak Hour for SR-60 E

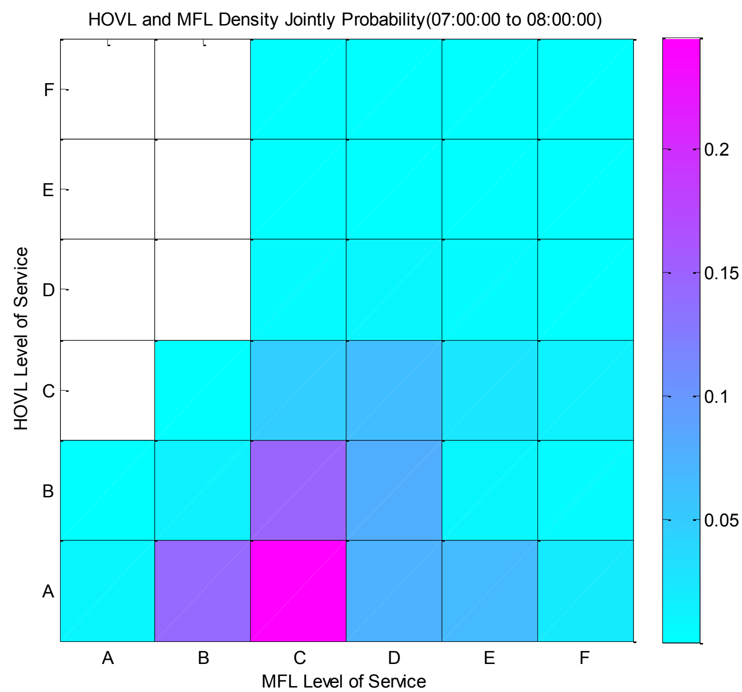


Figure B-6. HOVL-MFL Joint LOS Matrix during Peak Hour for SR-60 W

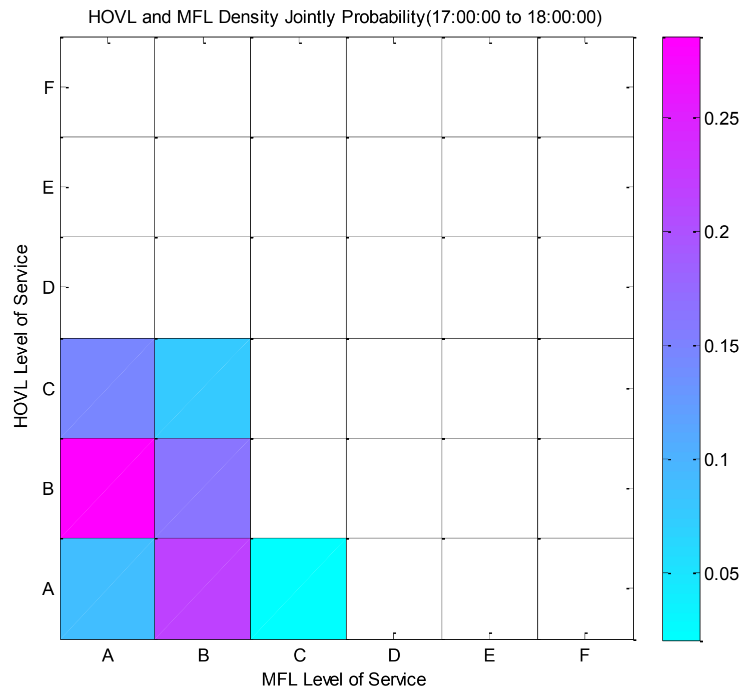


Figure B-7. HOVL-MFL Joint LOS Matrix during Peak Hour for SR-71 N

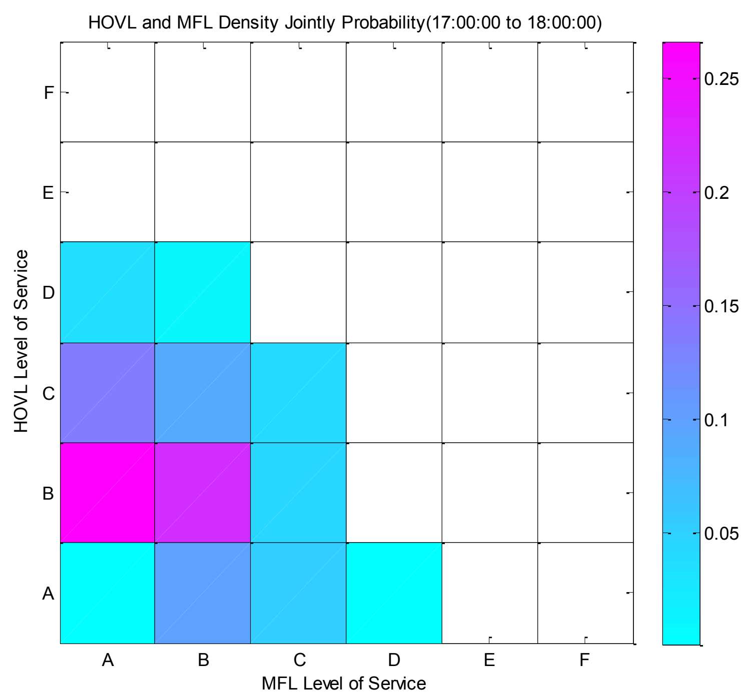


Figure B-8. HOVL-MFL Joint LOS Matrix during Peak Hour for SR-71 S

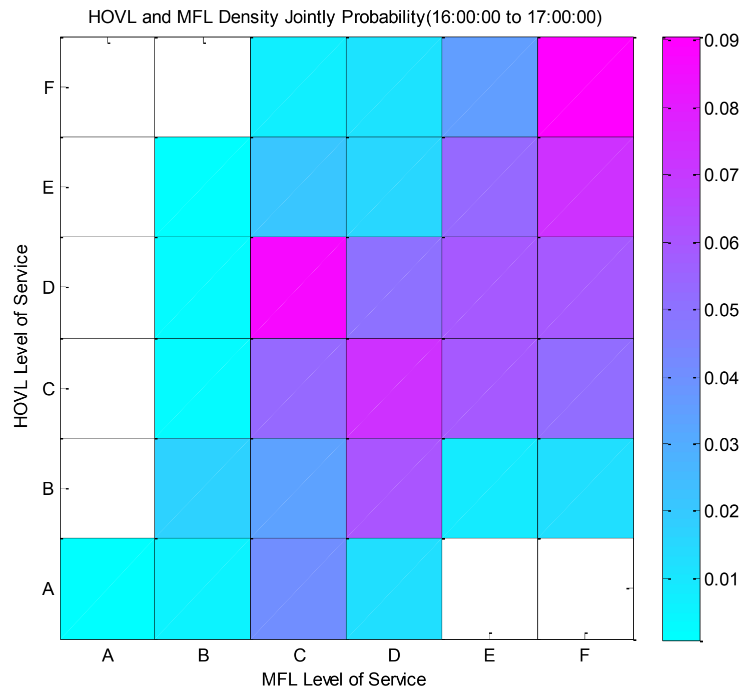


Figure B-9. HOVL-MFL Joint LOS Matrix during Peak Hour for SR-91 E

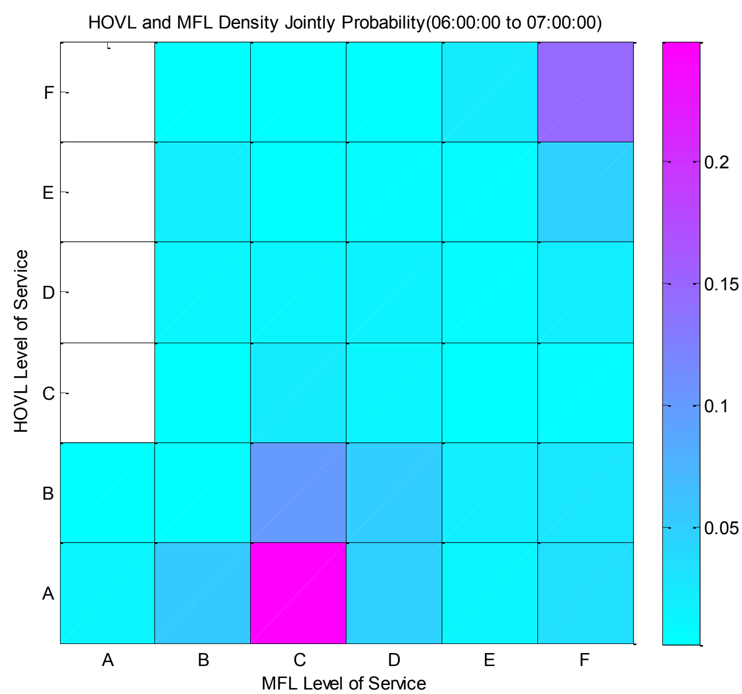


Figure B-10. HOVL-MFL Joint LOS Matrix during Peak Hour for SR-91 W

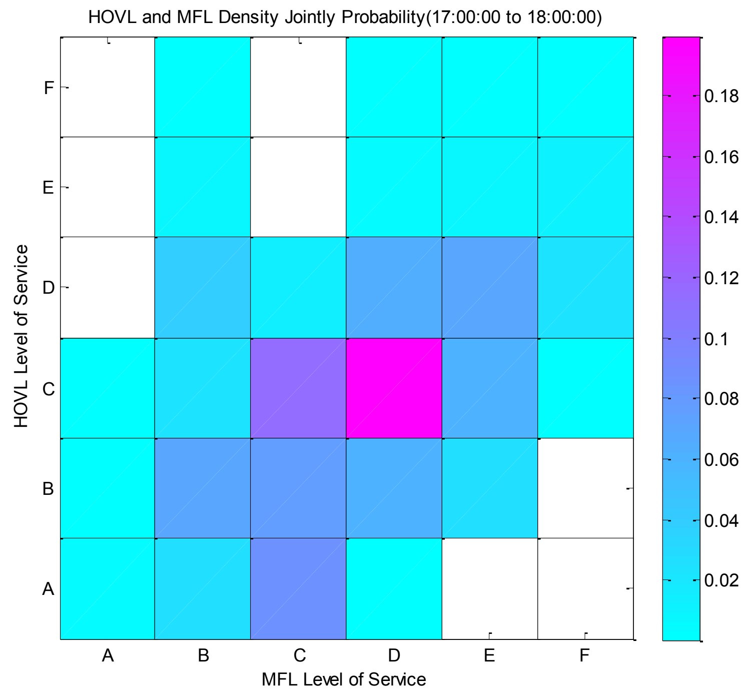


Figure B-11. HOVL-MFL Joint LOS Matrix during Peak Hour for I-210 E

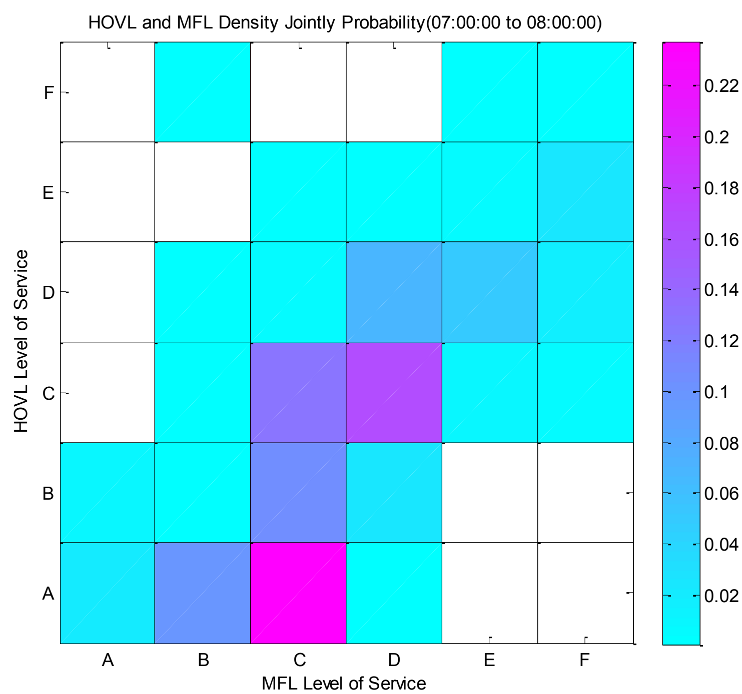


Figure B-12. HOVL-MFL Joint LOS Matrix during Peak Hour for I-210 W

Appendix C:

50th Percentile Speed Difference vs. Density

Continuous-access

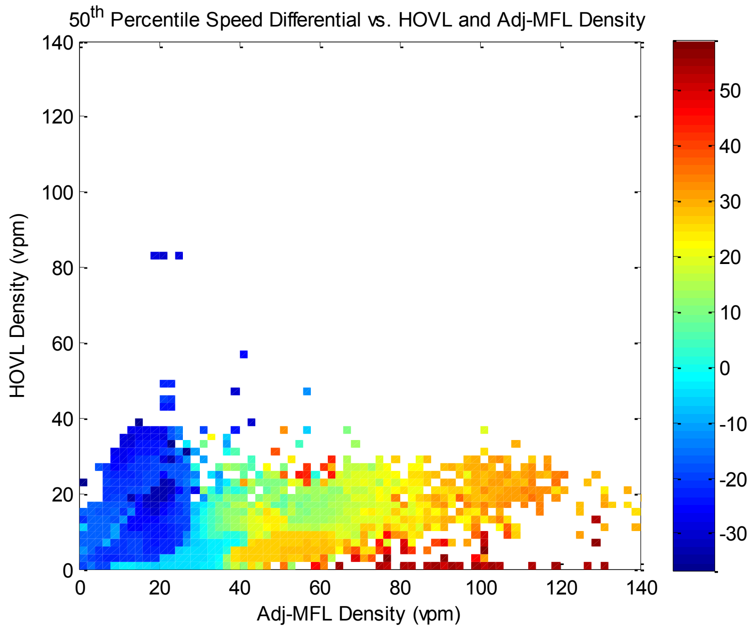


Figure C-1. 50th Percentile Speed Difference vs. Density of HOVL and Adj-MFL for I-215 N

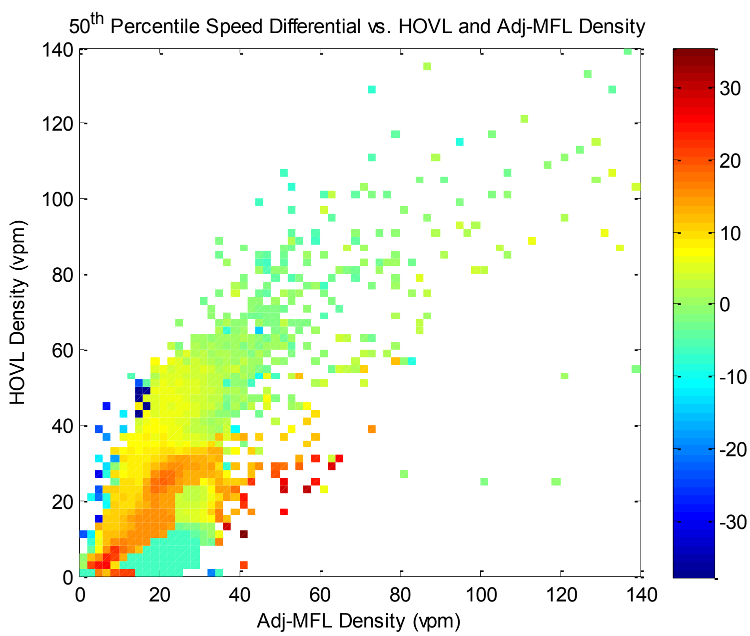


Figure C-2. 50th Percentile Speed Difference vs. Density of HOVL and Adj-MFL for I-215 S

Limited-access

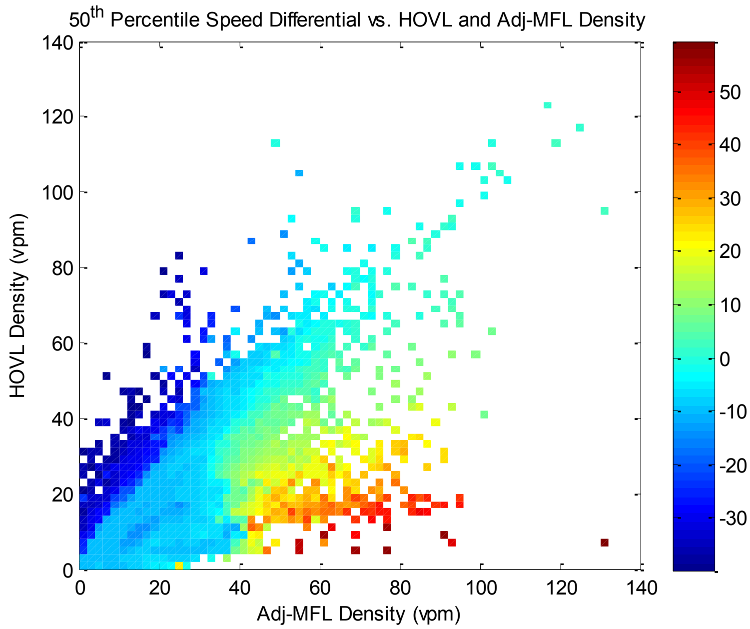


Figure C-3. 50th Percentile Speed Difference vs. Density of HOVL and Adj-MFL for I-10 E

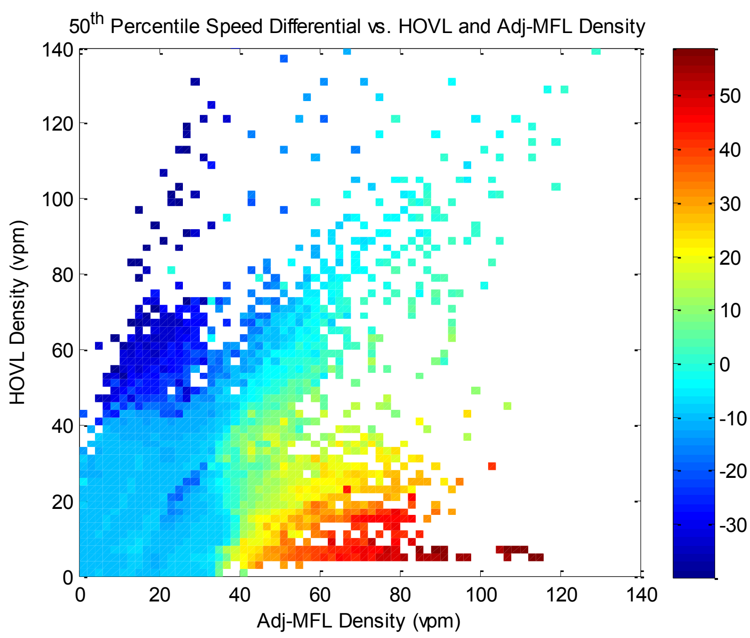


Figure C-4. 50th Percentile Speed Difference vs. Density of HOVL and Adj-MFL for I-10 W

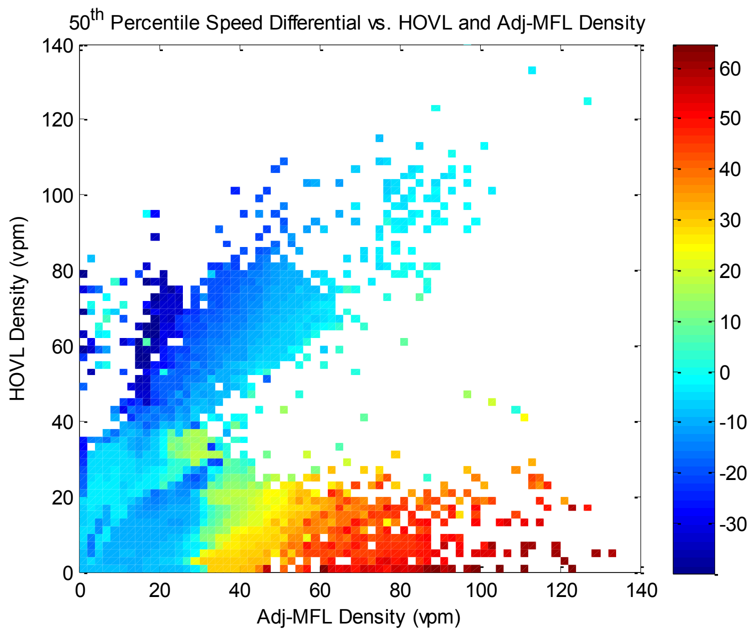


Figure C-5. 50th Percentile Speed Difference vs. Density of HOVL and Adj-MFL for SR-60 E

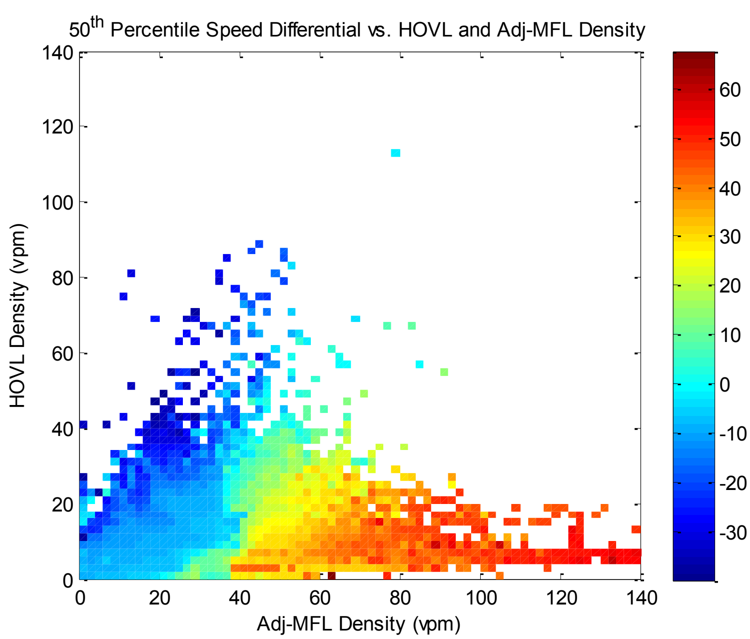


Figure C-6. 50th Percentile Speed Difference vs. Density of HOVL and Adj-MFL for SR-60 W

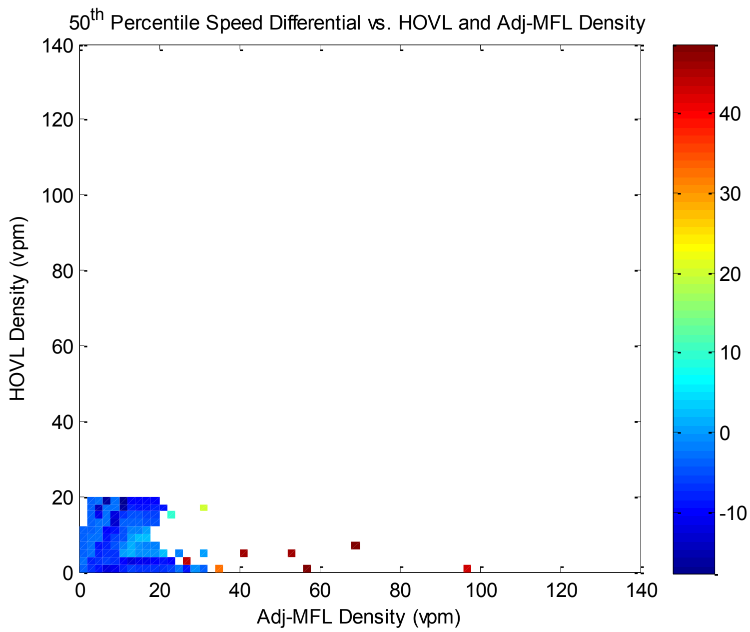


Figure C-7. 50th Percentile Speed Difference vs. Density of HOVL and Adj-MFL for SR-71 N

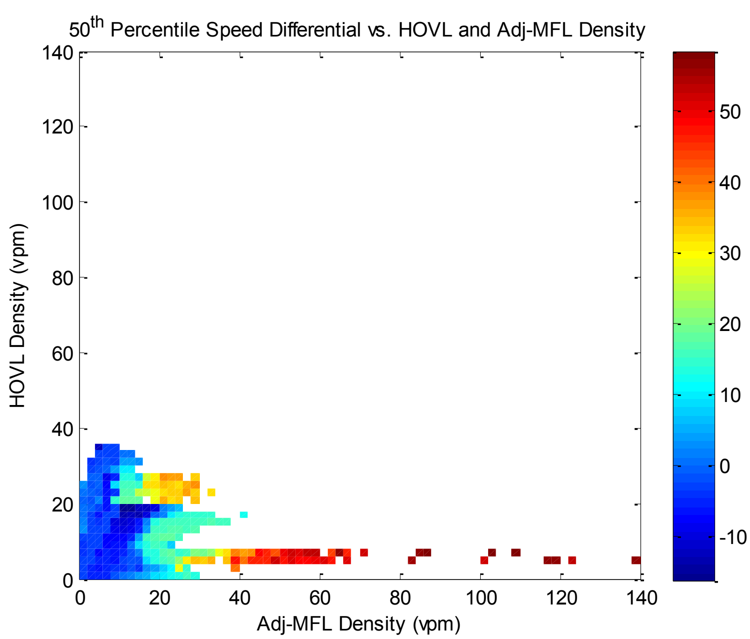


Figure C-8. 50th Percentile Speed Difference vs. Density of HOVL and Adj-MFL for SR-71 S

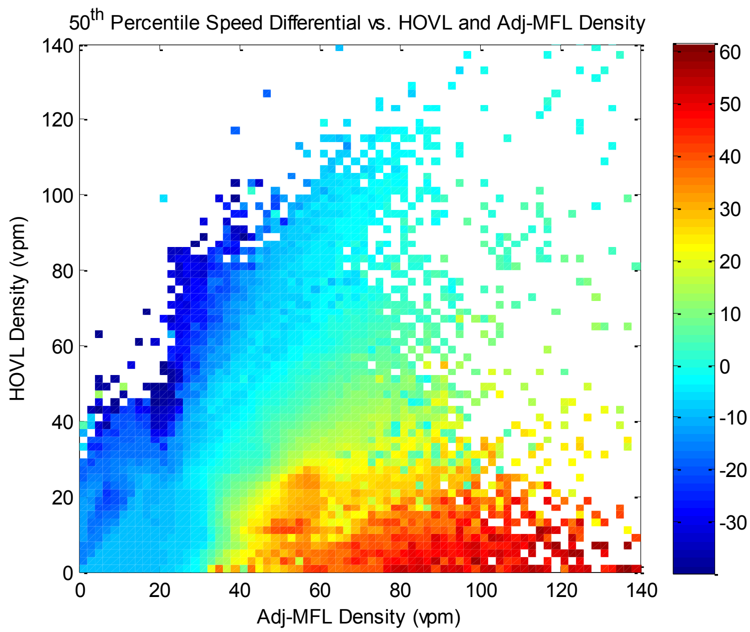


Figure C-9. 50th Percentile Speed Difference vs. Density of HOVL and Adj-MFL for SR-91 E

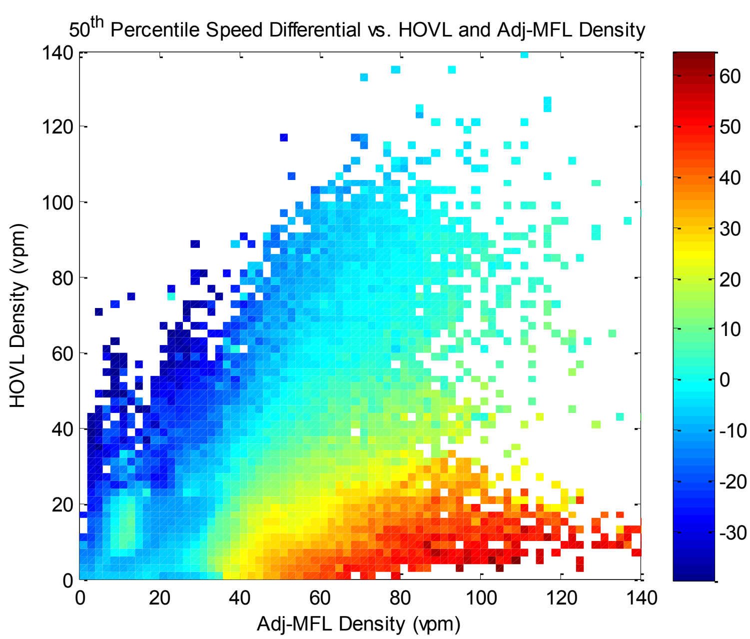


Figure C-10. 50th Percentile Speed Difference vs. Density of HOVL and Adj-MFL for SR-91 W

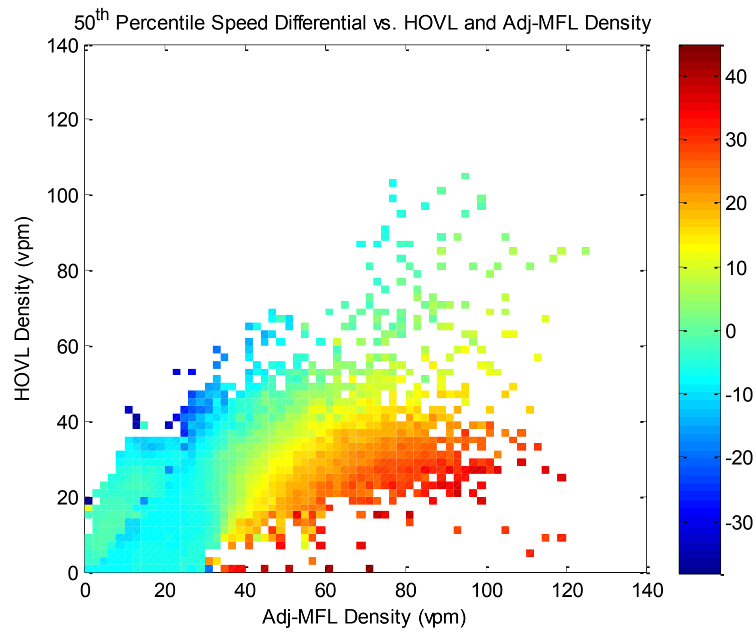


Figure C-11. 50th Percentile Speed Difference vs. Density of HOVL and Adj-MFL for I-210 E

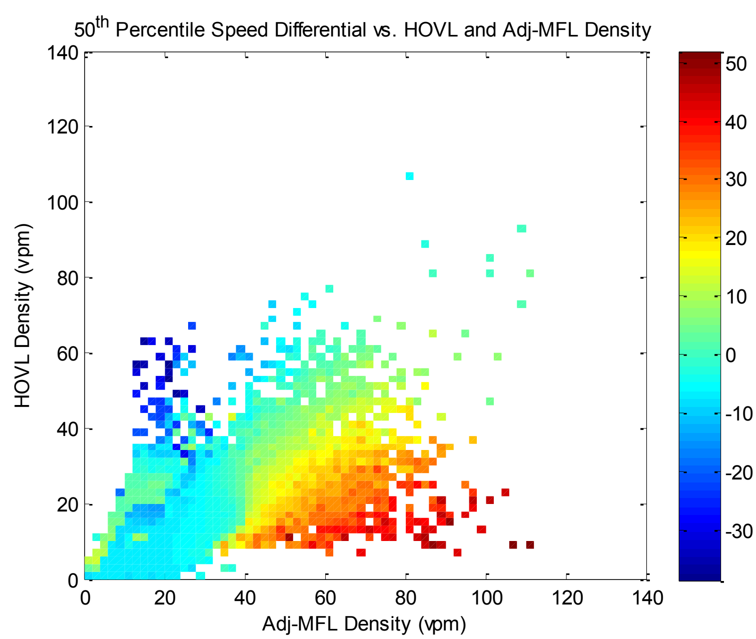


Figure C-12. 50th Percentile Speed Difference vs. Density of HOVL and Adj-MFL for I-210 W

Appendix D:

Speed-Flow Joint Probability Distribution

Continuous-access

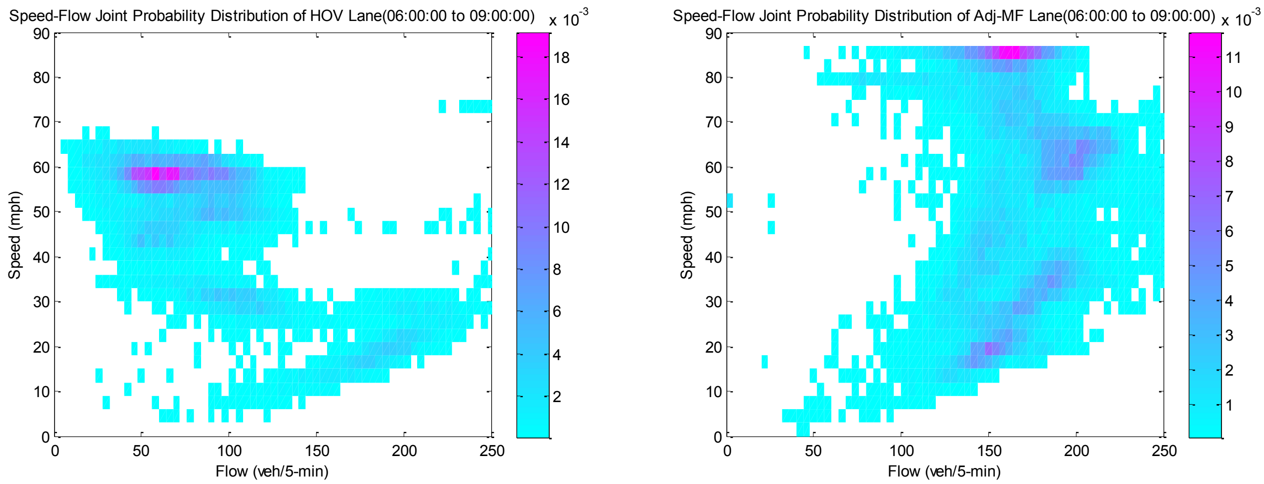


Figure D-1. Speed-Flow Joint Probability Distributions for I-215 N (a.m.)

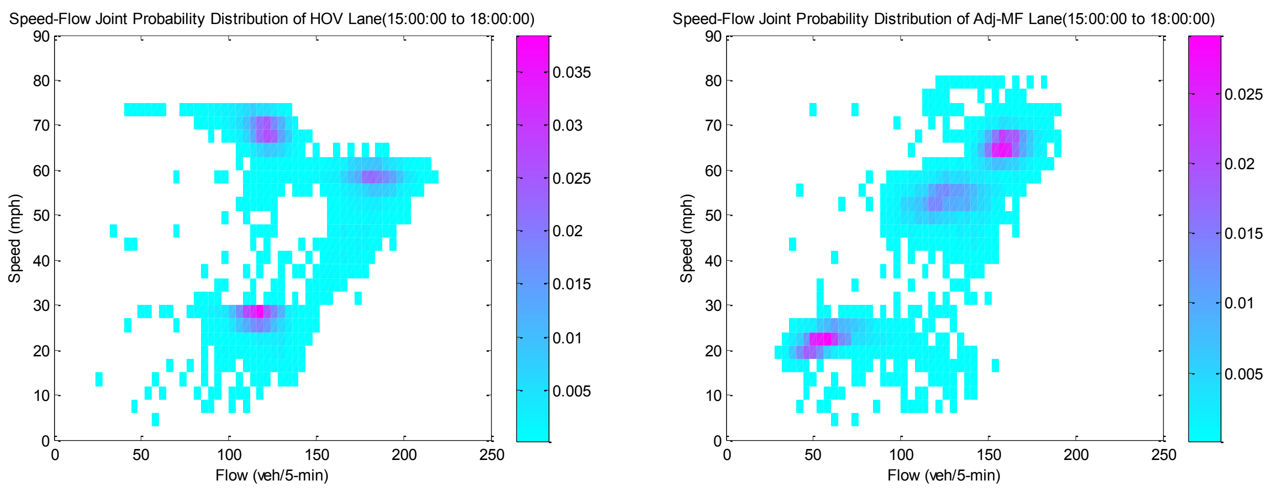


Figure D-2. Speed-Flow Joint Probability Distributions for I-215 S (p.m.)

Limited-access

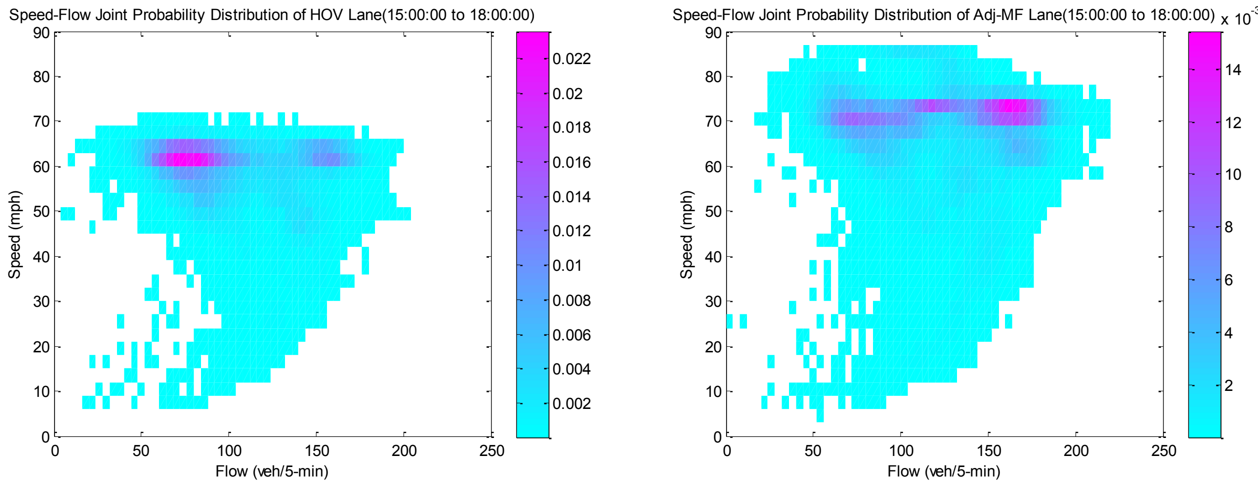


Figure D-3. Speed-Flow Joint Probability Distributions for I-10 E (p.m.)

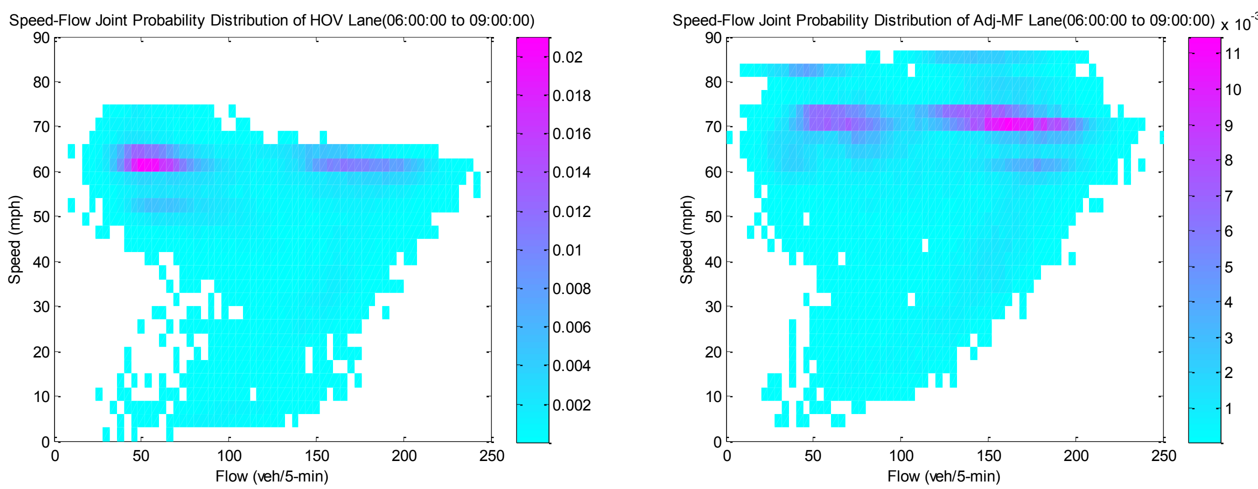


Figure D-4. Speed-Flow Joint Probability Distributions for I-10 W (a.m.)

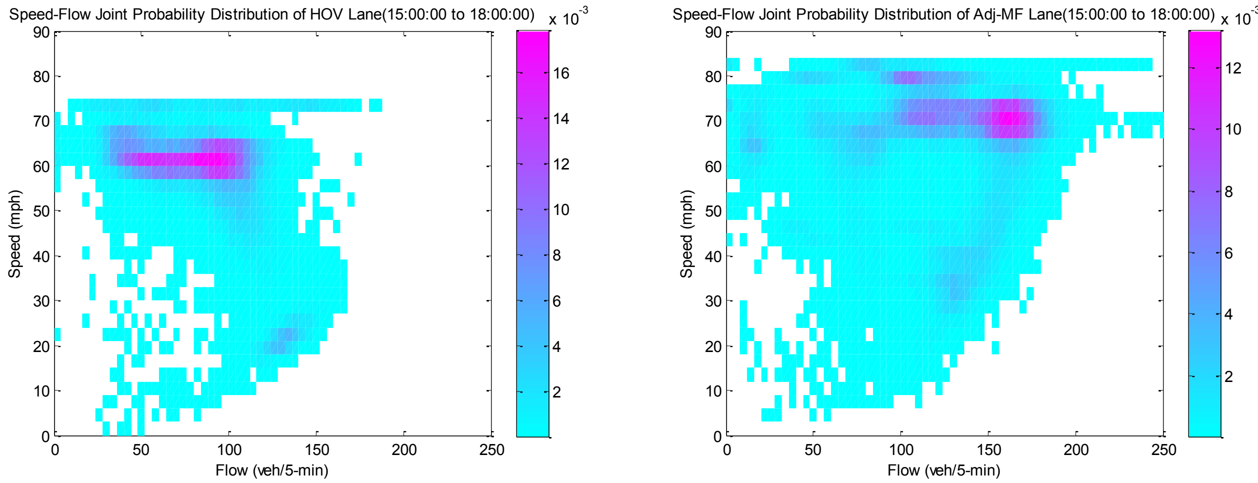


Figure D-5. Speed-Flow Joint Probability Distributions for SR-60 E (p.m.)

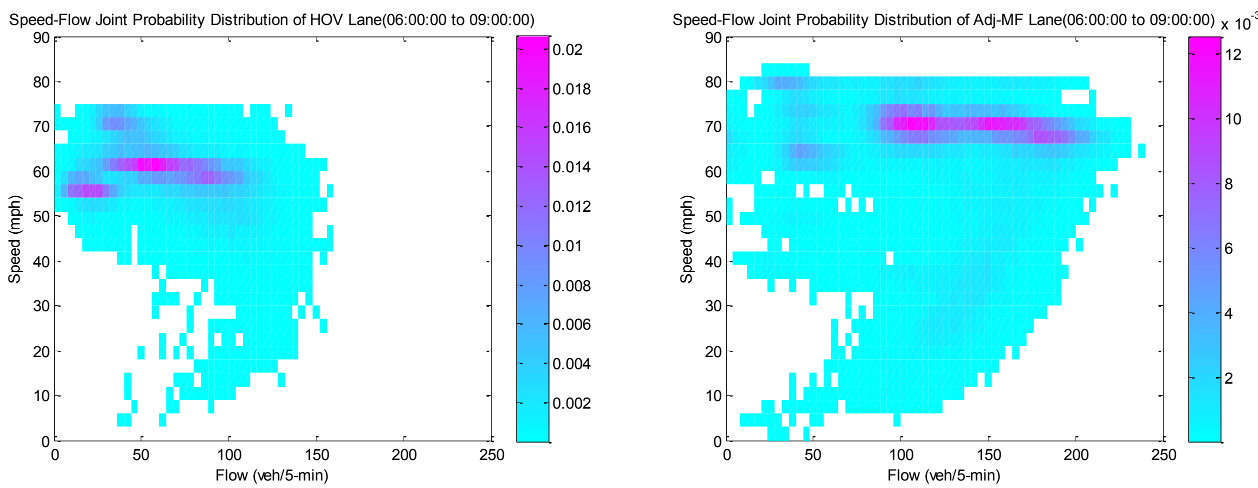


Figure D-6. Speed-Flow Joint Probability Distributions for SR-60 W (a.m.)

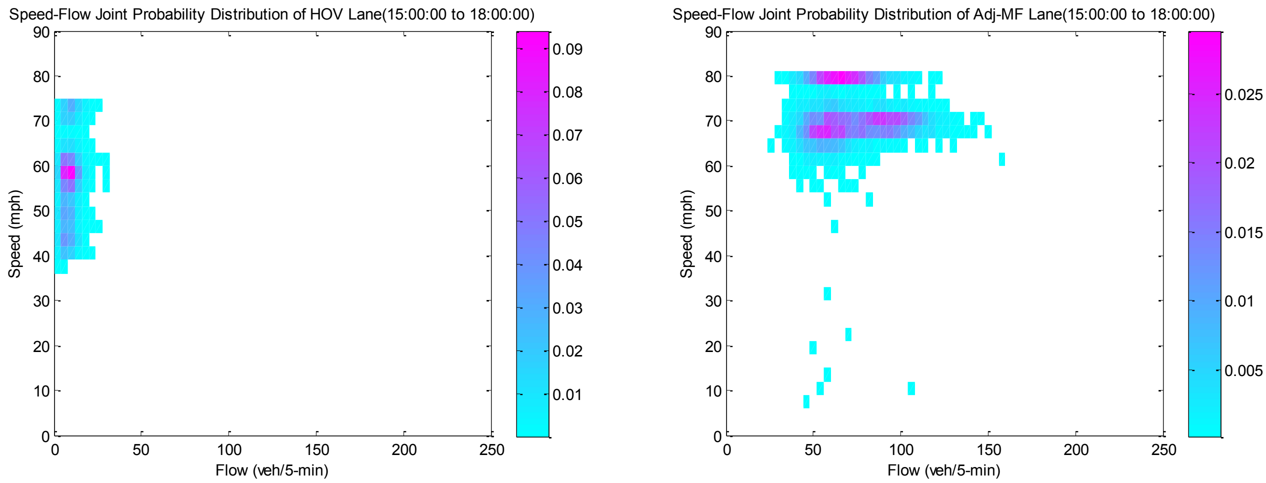


Figure D-7. Speed-Flow Joint Probability Distributions for SR-71 N (p.m.)

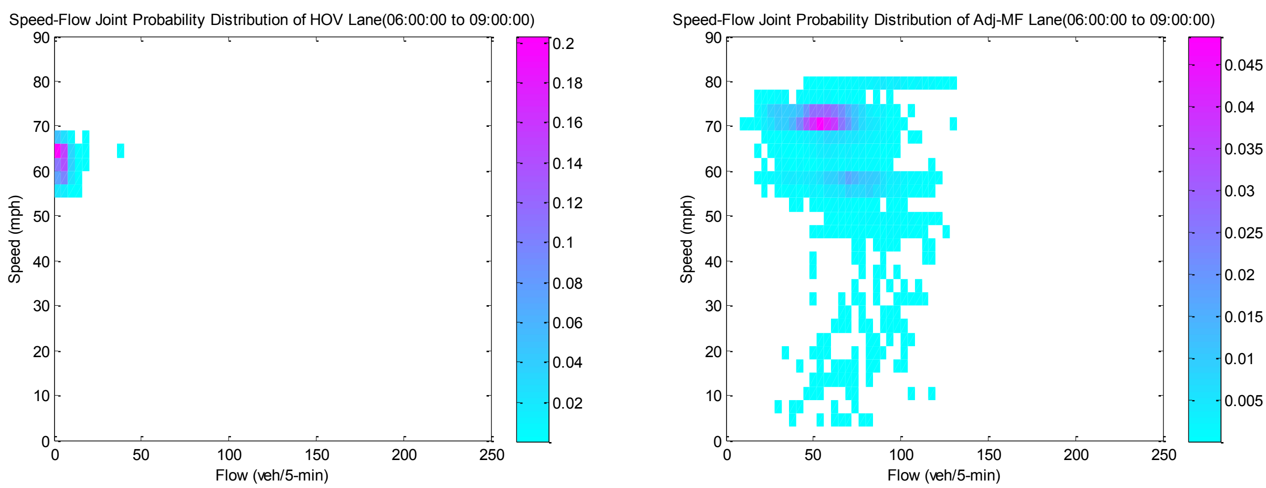


Figure D-8. Speed-Flow Joint Probability Distributions for SR-71 S (a.m.)

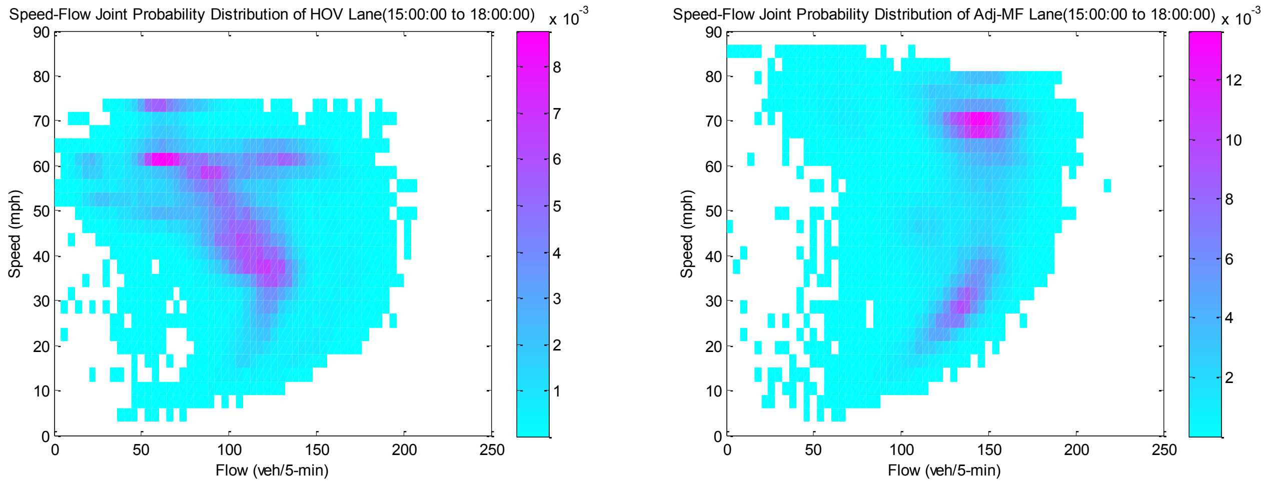


Figure D-9. Speed-Flow Joint Probability Distributions for SR-91 E (p.m.)

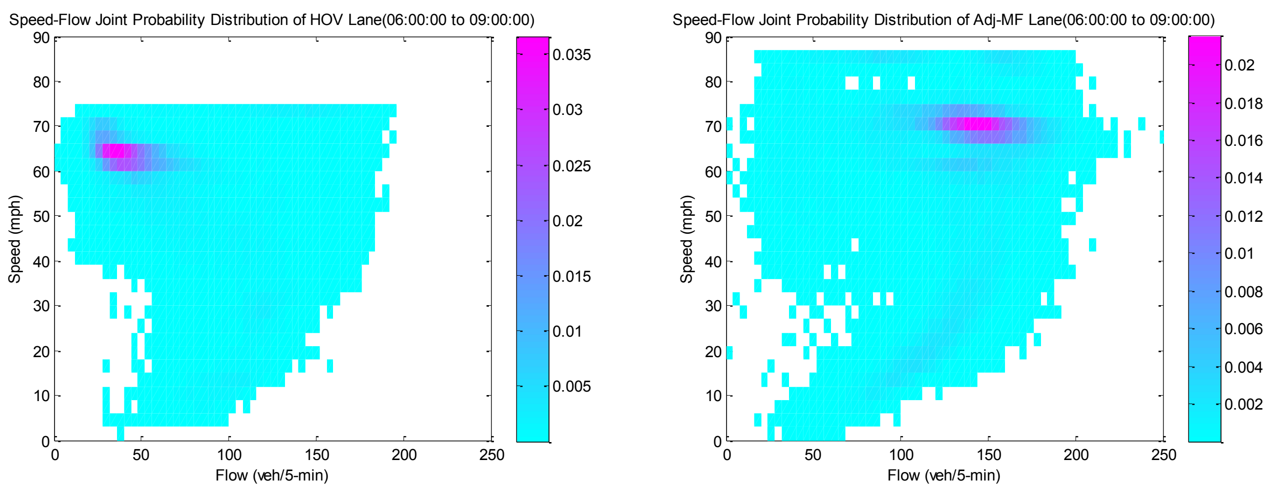


Figure D-10. Speed-Flow Joint Probability Distributions for SR-91 W (a.m.)

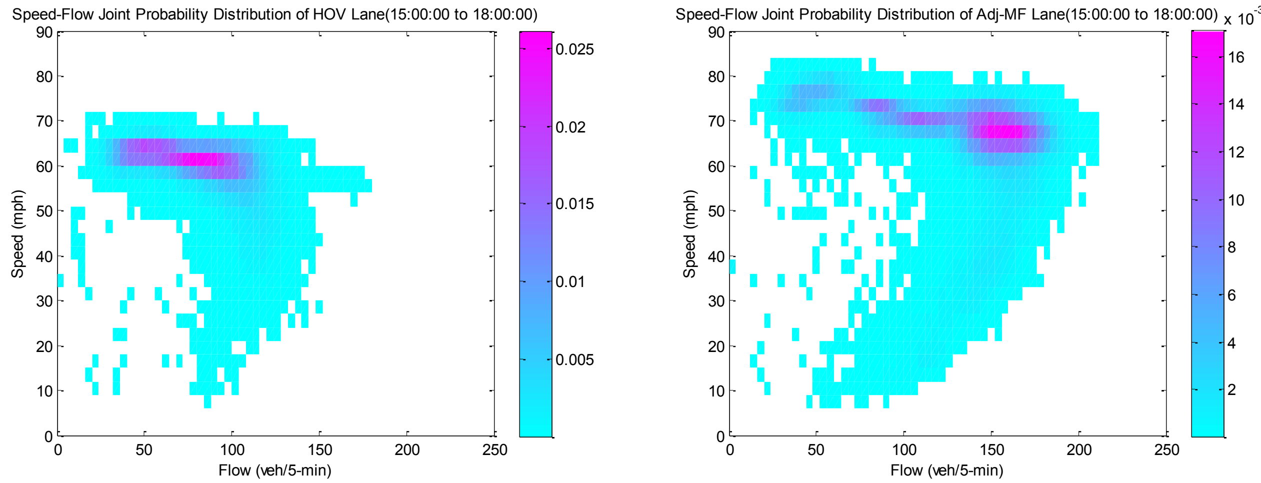


Figure D-11. Speed-Flow Joint Probability Distributions for I-210 E (p.m.)

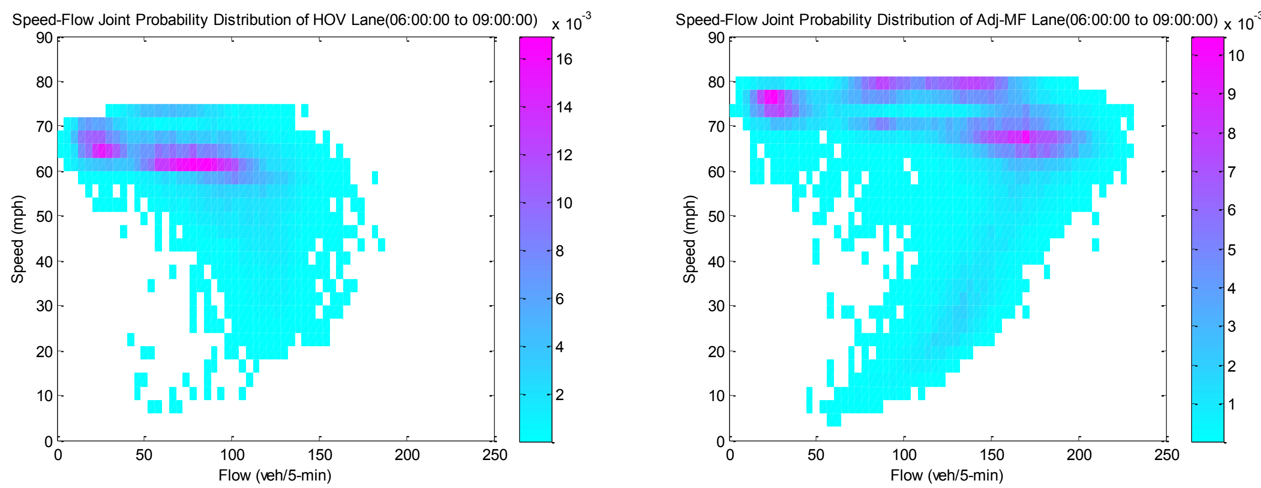


Figure D-12. Speed-Flow Joint Probability Distributions for I-210 W (a.m.)

Appendix E:

Distributions of Observed Maximum Throughput

Distributions by HOV Access Type

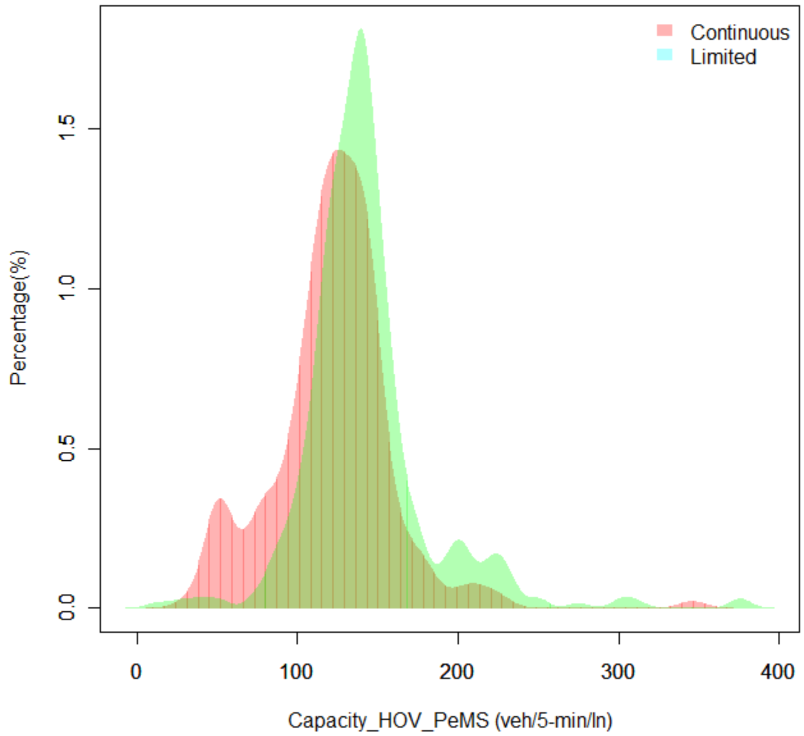


Figure E-1. HOVL Capacity Distributions by Access Type using PeMS Method

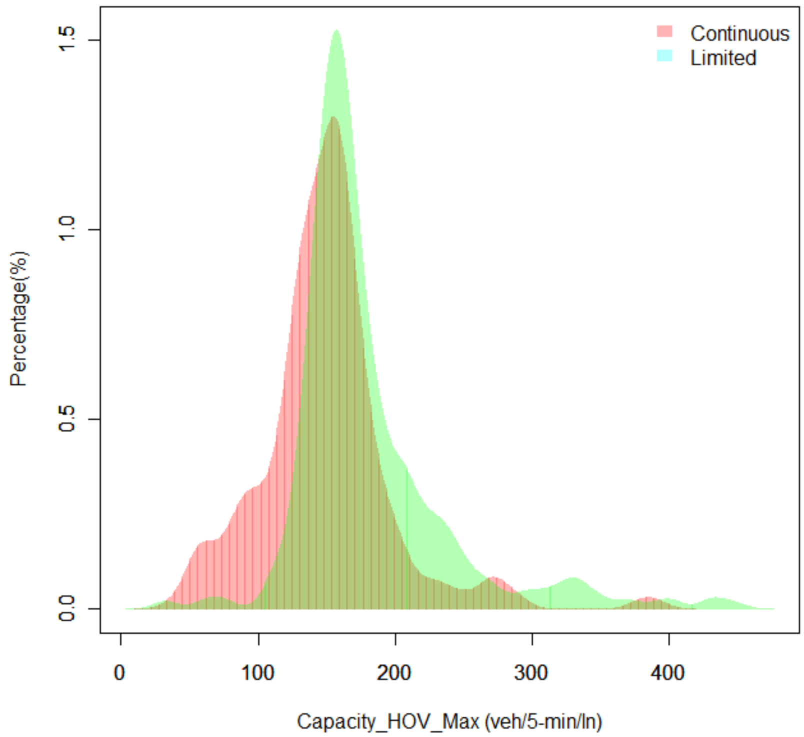


Figure E-2. HOVL Capacity Distributions by Access Type using Max-flow Method

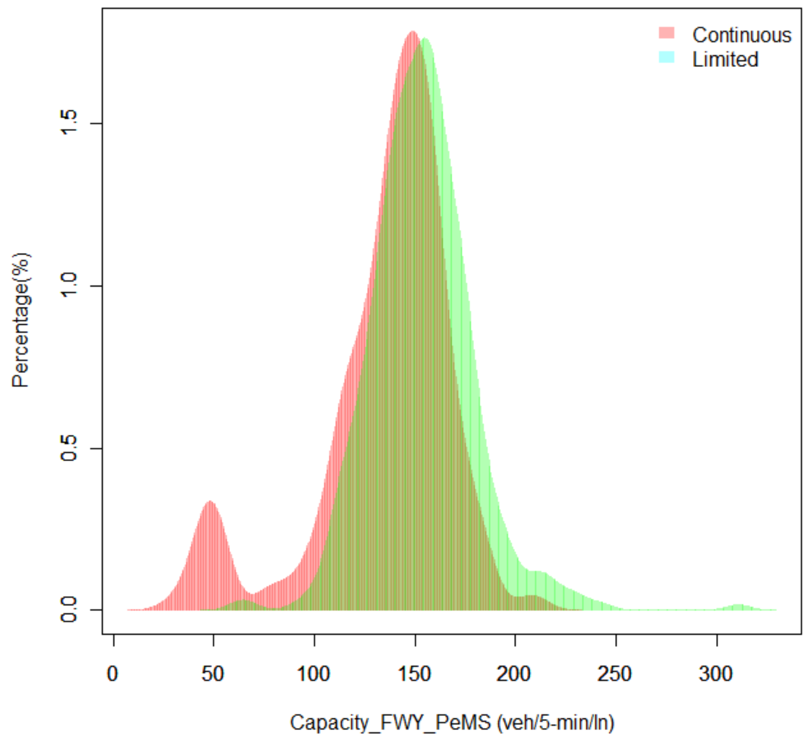


Figure E-3. FWYL Capacity Distributions by Access Type using PeMS Method

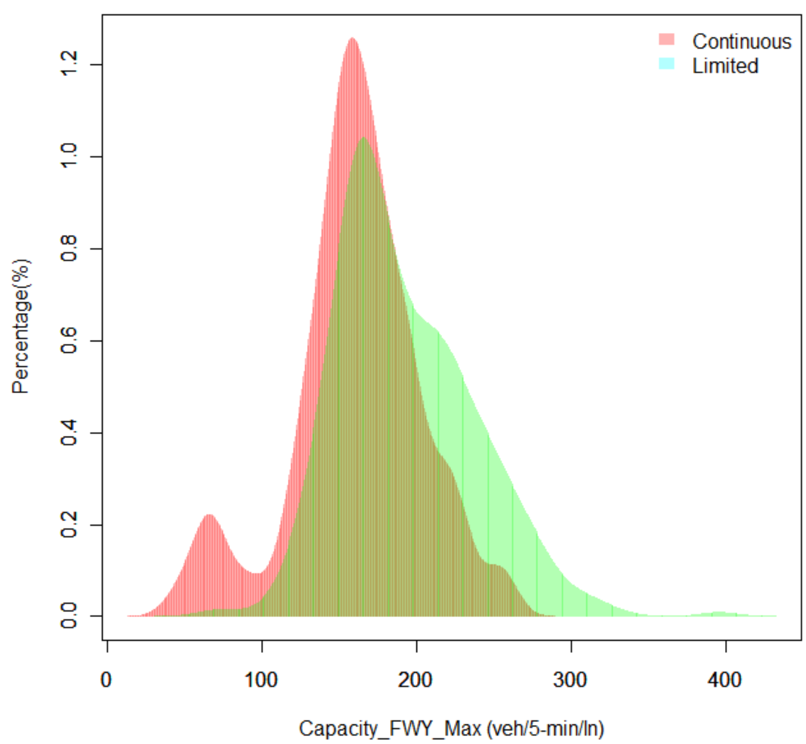


Figure E-4. FWYL Capacity Distributions by Access Type using Max-flow Method

Distributions by District

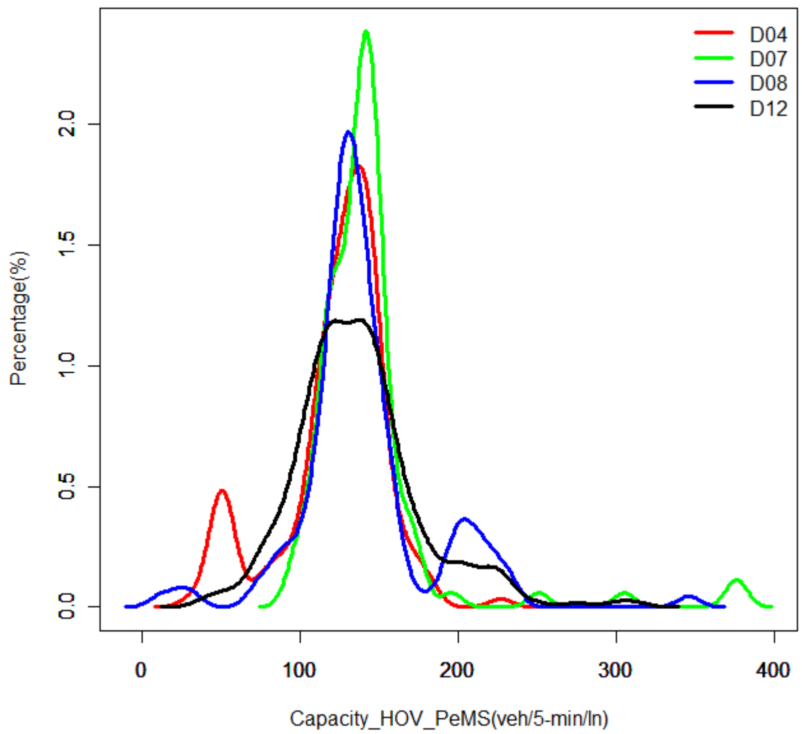


Figure E-5. HOVL Capacity Distributions by District using PeMS Method

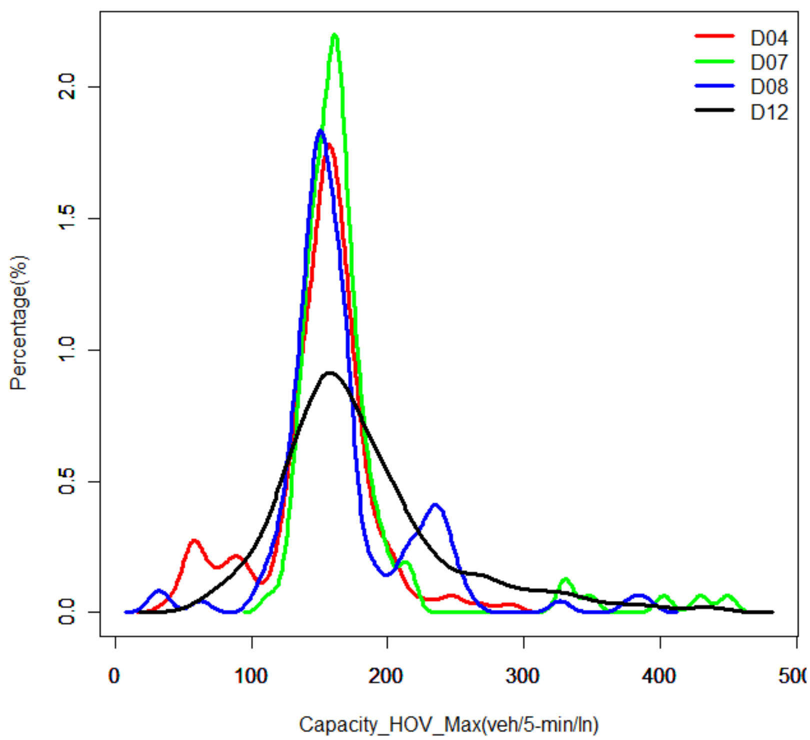


Figure E-6. HOVL Capacity Distributions by District using Max-flow Method

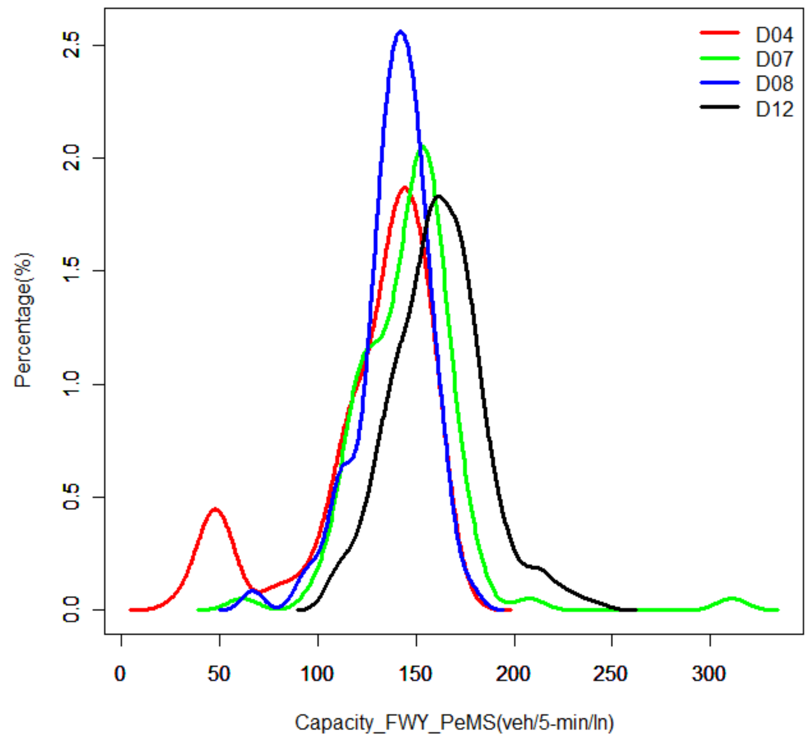


Figure E-7. FWYL Capacity Distributions by District using PeMS Method

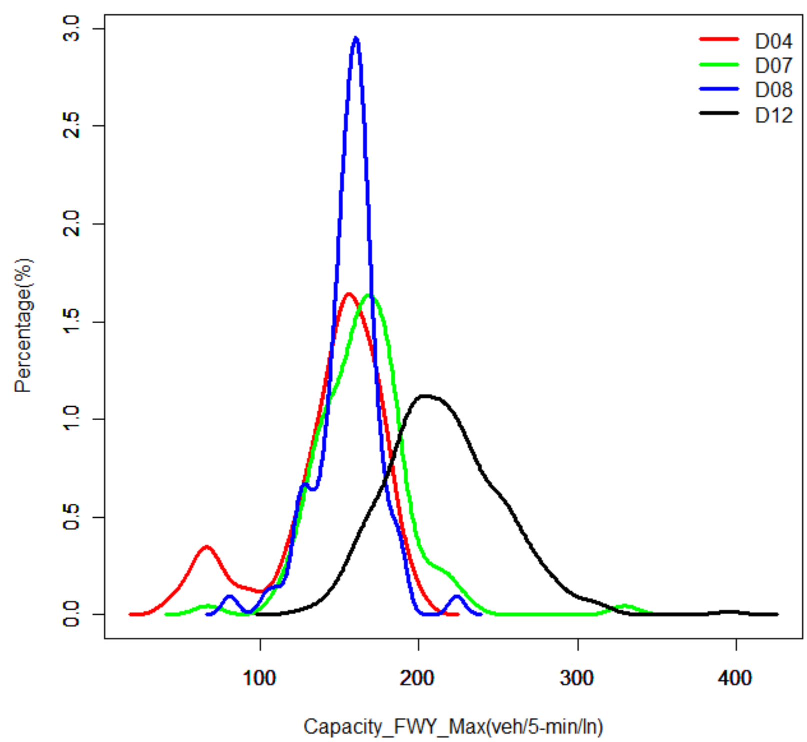


Figure E-8. FWYL Capacity Distributions by District using Max-flow Method

Distributions by Routes

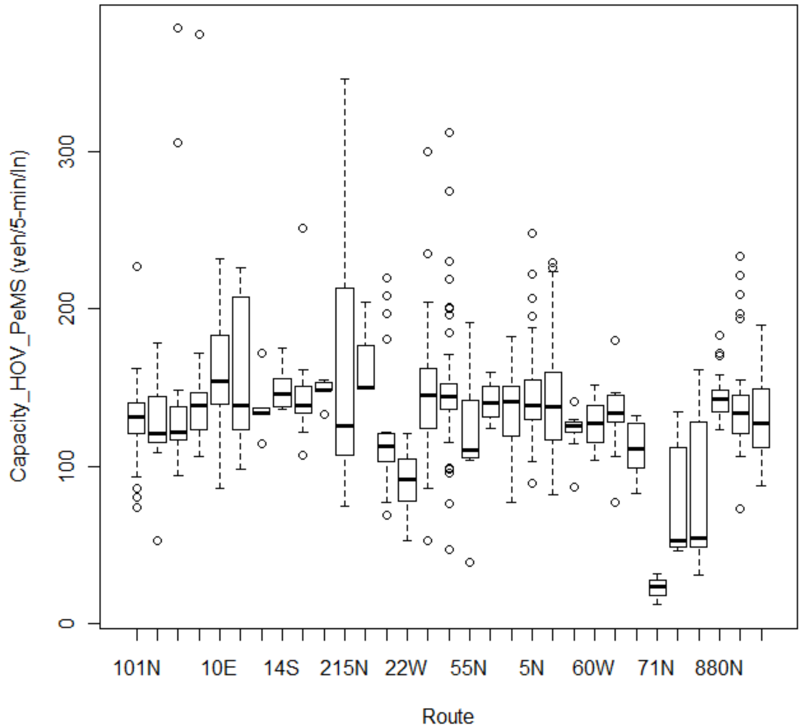


Figure E-9. HOVL Capacity Box-plots by Route using PeMS Method

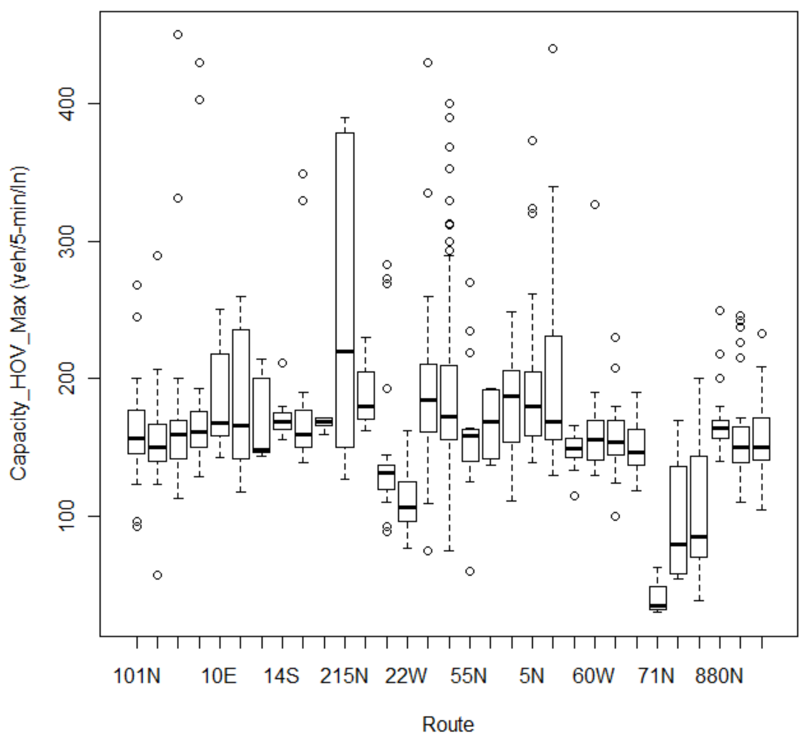


Figure E-10. HOVL Capacity Box-plots by Route using Max-flow Method

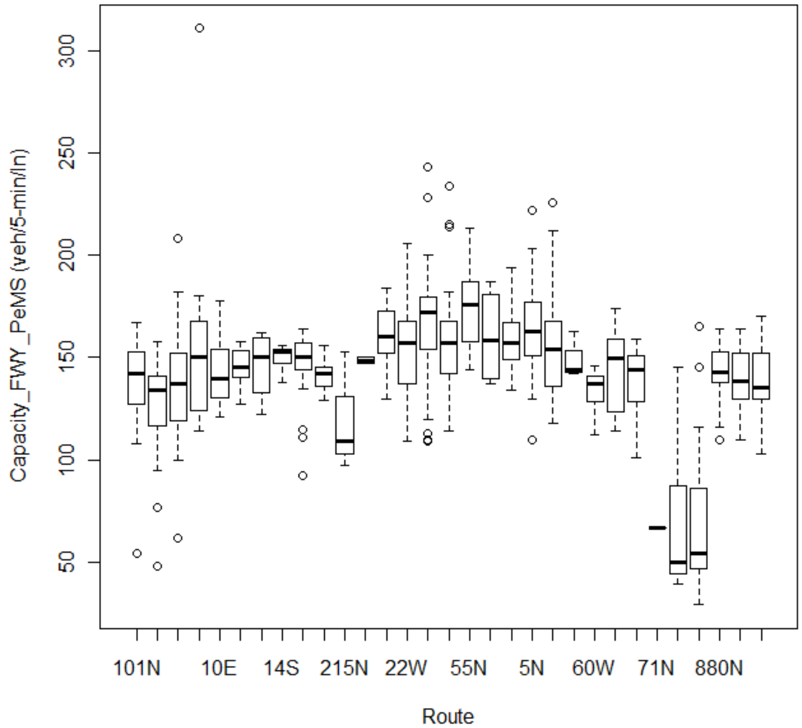


Figure E-11. FWYL Capacity Box-plots by Route using PeMS Method

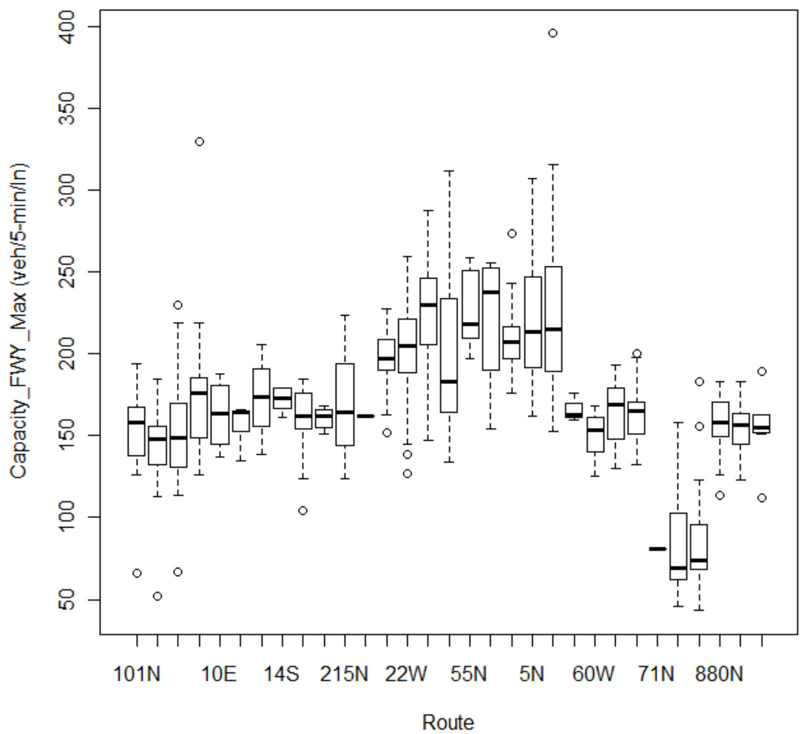


Figure E-12. FWYL Capacity Box-plots by Route using Max-flow Method

Appendix F:

Advanced Regression Analyses on Statewide HOV Dataset

Diagnostics of Multiple Linear Regression Models

Comparing between Table 3-7 and Table 3-8, it is obvious that the determinations of coefficient for FWYL models are higher than the HOVL ones. In particular, much more response variation can be “explained" by the proposed regressors in the models for overall freeway lane. Therefore, more efforts in the following regression analyses are focused on the overall FWYL models.

The regression diagnostic of the overall freeway lane models using the PeMS method reveal that, the model underestimates responses from some observations (e.g. #187 and #525) but overestimates other observations, such as #35 in Figure F-1(a) and Figure F-1(b). The residual r_i is defined as the difference between the observed and fitted values, and the standardized residual s_i is

$$s_i = r_i / \left[\hat{\sigma} \cdot \sqrt{1 - h_{ii}}\right] \tag{F-1}$$

where $\hat{\sigma}$ is the estimate of the standard deviation based on the residual sum of squares; h_{ii} is the i-th diagonal element of the *Hat matrix*, $\boldsymbol{H} = \boldsymbol{X}(\boldsymbol{X^T}\boldsymbol{X})^{-1}\boldsymbol{X^T}$; $\boldsymbol{X}$ and $\boldsymbol{X^T}$ are the design matrix and its transpose.

The Q-Q plot (see Figure F-1(c)) comes close to a straight line except for the lower and upper tails, where the residuals somewhat deviate from the expected. Figure F-1(d) shows the *Residual-Leverage* plot with the cut-off Cook's distance calculated by

$$d_c = 4/(n - k - 1) = 4/(530 - 16 - 1) = 0.0078 \tag{F-2}$$

where n is the number of observations and k is the number of explanatory variables. It is noted that a couple of data points are out of the envelope of cut-off Cook's distance, which means that coefficient estimates may change considerably if one or more of these data points are omitted.

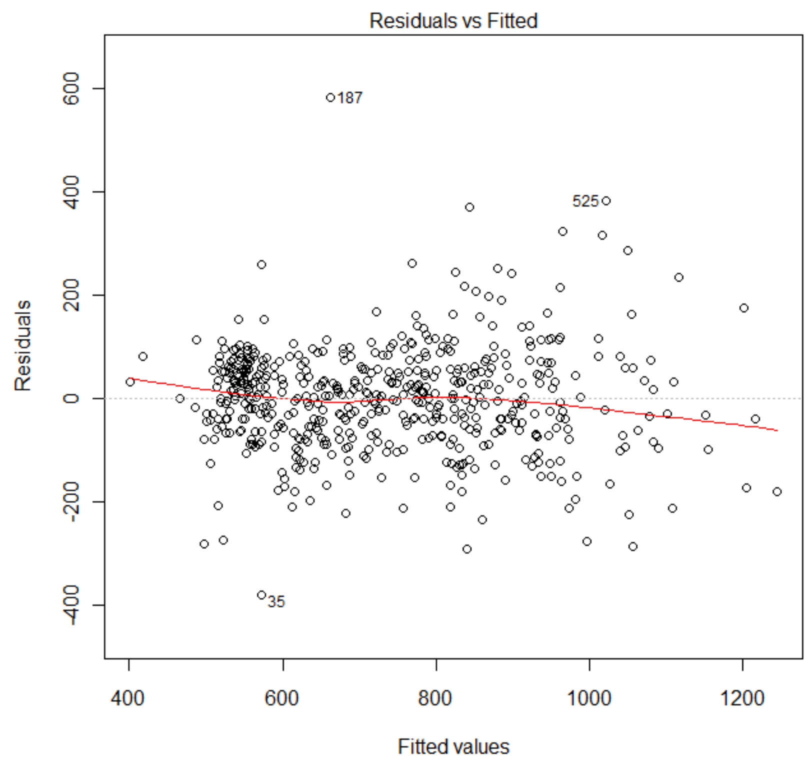
Robust Multiple Linear Regression (R-MLR) Model

The data points identified in Figure F-1 to deviate from the average are potentially outliers, which may result in violation of assumptions for linear regression, such as distributional normality. To circumvent the subjectivity of outlier removal and improve the model performance, the robust version of regression method have been employed using the Huber estimator, whose objective function is

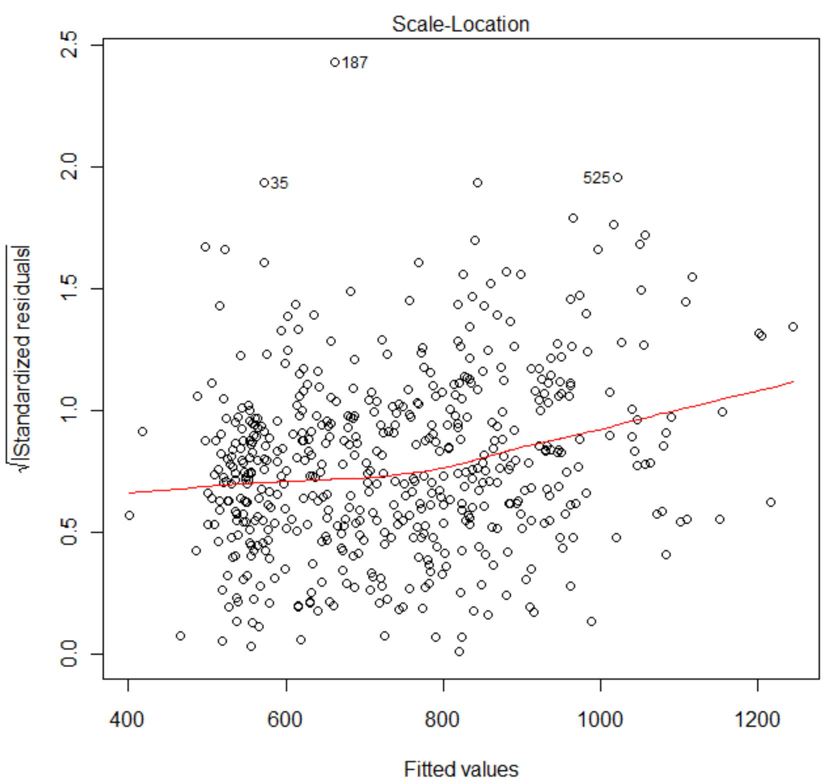
$$f_H(e) = \begin{cases} e^2/2, & |e| \le k \\ k|e| - k^2/2, & |e| > k \end{cases} \tag{F-3}$$

and the weighting function is

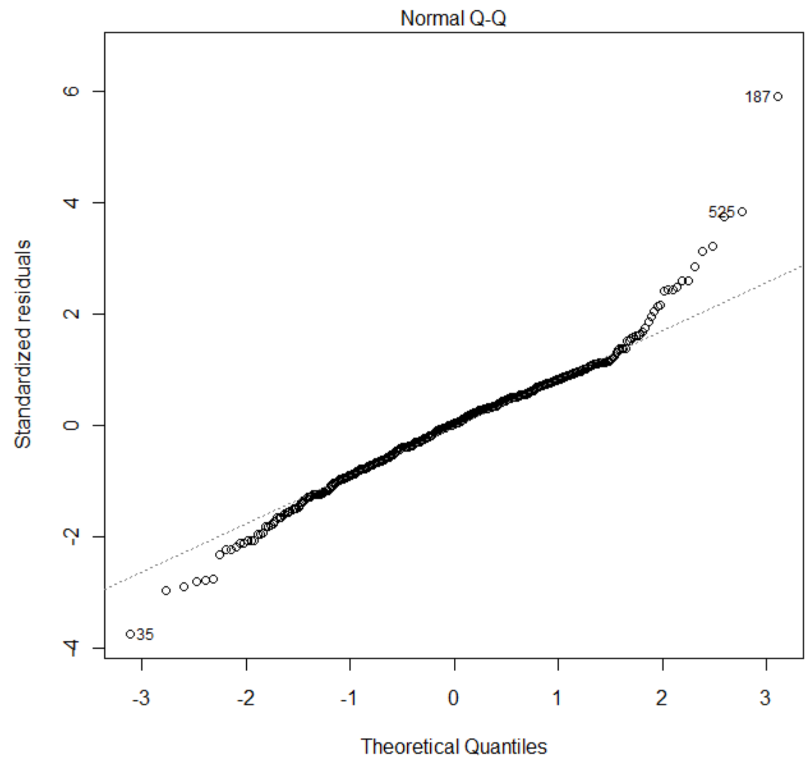
$$\omega_H(e) = \begin{cases} 1, & |e| \le k \\ k/|e|, & |e| > k \end{cases} \tag{F-4}$$



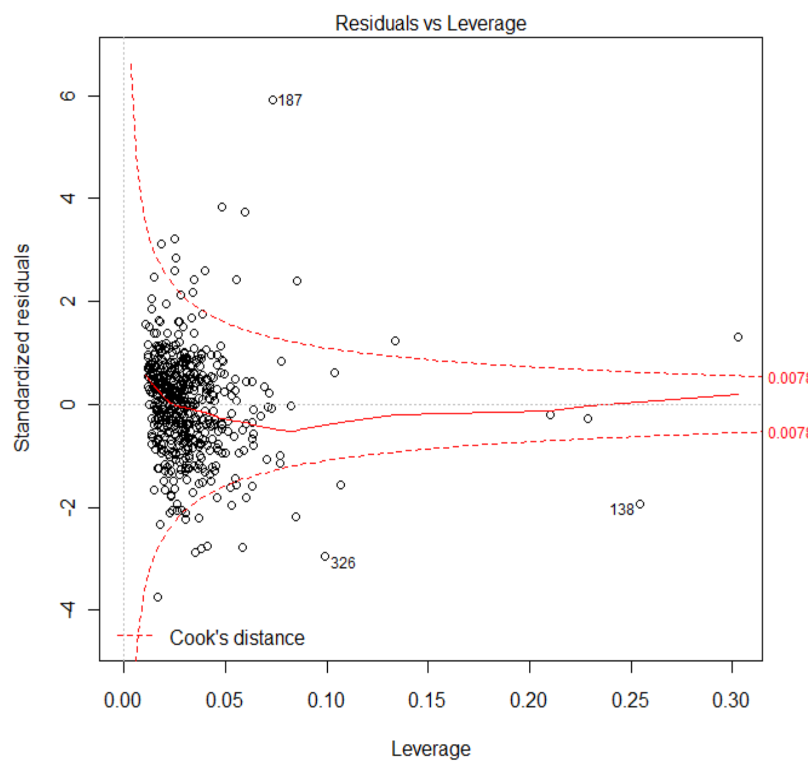
(a) Residuals vs. fitted plot



(b) Scale-location plot



(c) Q-Q plot



(d) Residuals vs. leverage plot

Figure F-1. Diagnostics plots of MLR model for FWYL (PeMS Method)

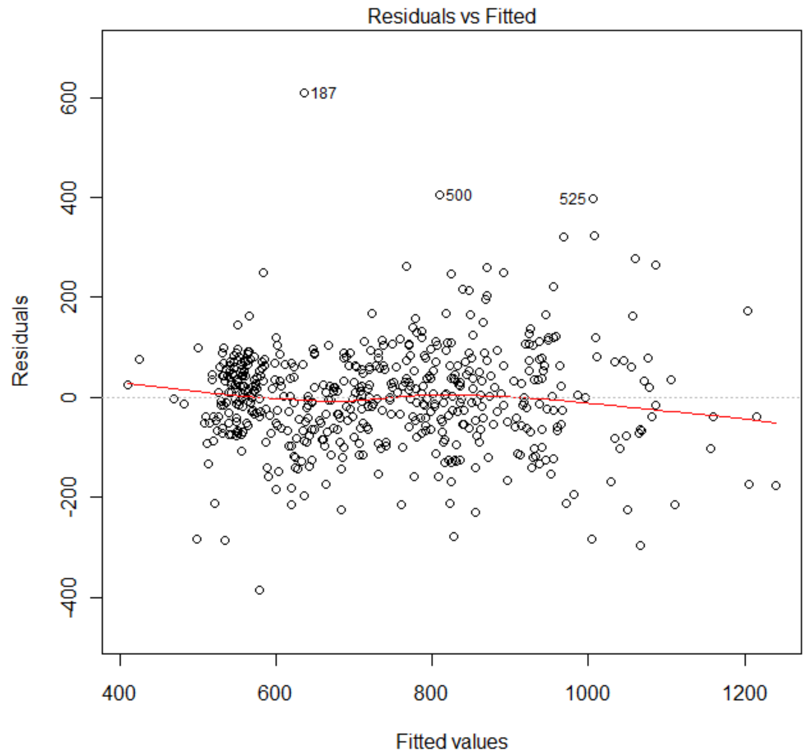
where e represents the residual and $k = 1.345$ for the Huber estimator. In essence, data samples with high residuals (outliers) may be down-weighted using such robust regression technique. The optimization problem can be solved in general by the method of iterative re-weighted least squares (IRLS), and estimated coefficients in the robust models for average and overall freeway lane are presented in Table F-1.

Table F-1. List of regression coefficients of R-MLR models for FWYL

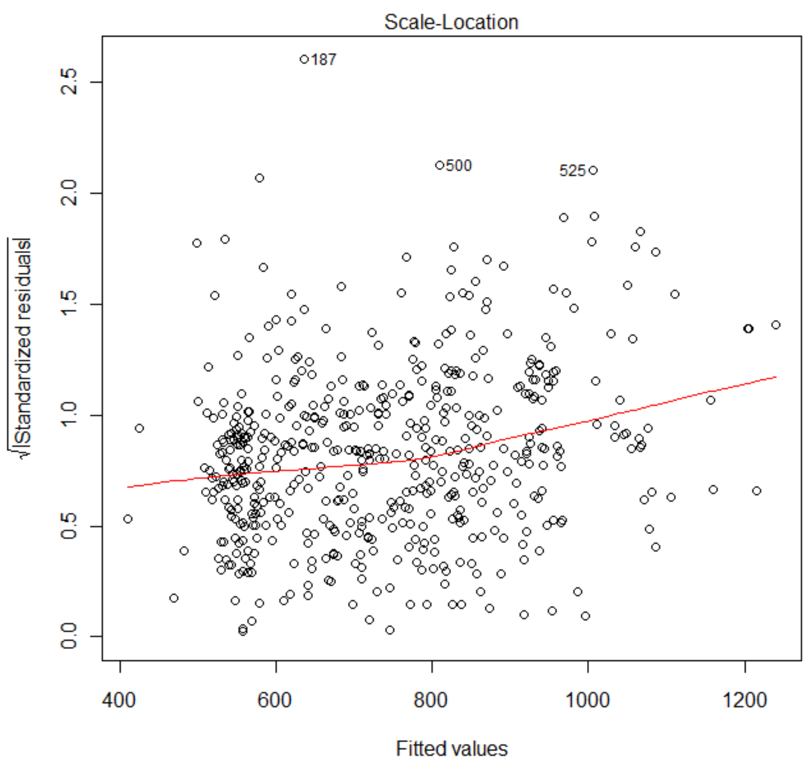
i	**Average FWYL, β_i**		**Overall FWYL, β_i**	
	PeMS Method	**Max-flow Method**	**PeMS Method**	**Max-flow Method**
0	**140.24**	**129.63**	-41.00	**-238.88**
1	**7.50**	**13.81**	**48.45**	**88.04**
2	-0.59	0.48	-1.75	5.80
3	-0.21	1.99	-1.30	12.51
4	**-4.94**	**-5.34**	**123.17**	**153.53**
5	0.56	**2.55**	2.81	13.08
6	0.33	-0.11	2.40	0.21
7	**-0.59**	**-0.87**	**-3.16**	**-4.37**
8	-0.51	1.81	-2.72	7.89
9	-0.50	-0.68	-2.68	-3.80
10	-3.10	-1.76	-15.48	-7.99
11	0.79	1.11	3.98	4.86
12	-2.16	**-15.58**	-27.29	**-115.60**
13	-6.07	**-14.86**	**-45.12**	**-106.87**
14	**23.47**	**61.03**	**106.16**	**282.04**
15	-12.26	-40.36	-68.14	-207.62
16	**141.06**	**259.96**	**686.87**	**1226.85**
Degree of Freedom	513	513	513	513
Residual SE**	16.89	19.81	90.40	102.4

Variables in bold-face are statistically significant at 5% α-level

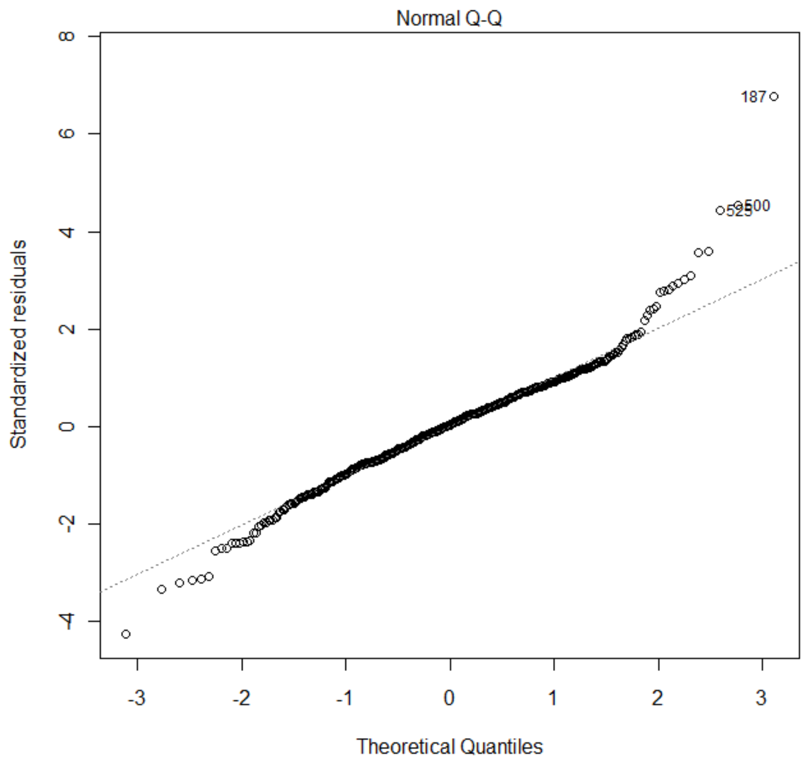
Compared with results from the traditional MLR model, it can be seen that results from the robust models are somewhat different in quantity. In particular, the relative differences of some variables for the Max-flow model may be as high as 15%, which is more significant than the counterpart for the PeMS one. In addition, the residual standard errors have been greatly reduced (up to 30%). But the interpretation of coefficients and associated statistical significance of regressors mean exactly the same as in the conventional regression. Similar to Figure F-1, Figure F-2 presents the diagnostic plots for the robust multiple linear regression (R-MLR) model for overall freeway lane results using PeMS method.



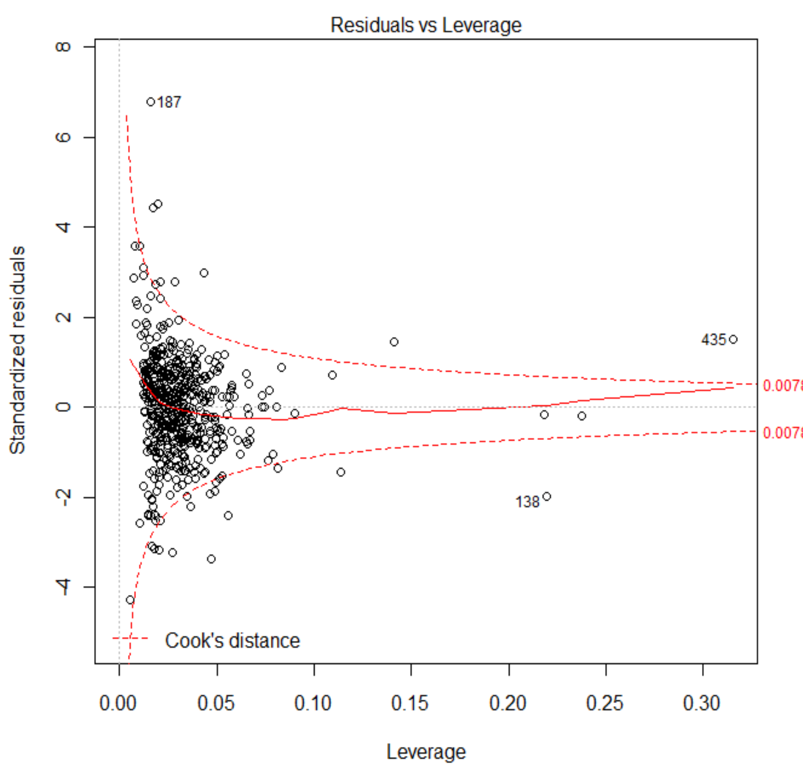
(a) Residuals vs. fitted plot



(b) Scale-location plot



(c) Q-Q plot



(d) Residuals vs. leverage plot

Figure F-2. Diagnostics plots of R-MLR model for FWYL (PeMS Method)

Linear Mixed Effect Model (LMEM)

As can be seen from the figures in Appendix E, the response distributions may vary with District. This may imply that the data samples should be in a structure nested within District. In other word, there would be a hierarchical design structure with a random effect for HOV facilities nested within Districts. The nested data structure assumes a relationship among groups such that members of a group are thought to be similar to others in the same group in such a way as to distinguish them from members of other groups.

Such case can be handled using the mixed effect (both fixed and random effects) modeling technique. In particular, linear mixed effect model simply model the fixed and random effects as having a linear form, where response is contributed to by additive fixed and random effects (as well as an error term). The linear mixed effect model can be written as

$$y(i,j) = \sum_k \beta_k \cdot x_k(i,j) + \sum_k b_k(i) \cdot z_k(i,j) + \varepsilon(i,j) \qquad \text{(F-5)}$$

where $y(i,j)$ is the value of the outcome variable for a particular (i,j) case; β_k is the fixed effect coefficient (like conventional regression coefficient) for the k-th explanatory variable; $x_k(i,j)$ is the fixed effect variable (predictor) for observation j in group i (usually the first is reserved for the intercept, i.e. $x_1(i,j) = 1$); $b_k(i)$ is the random effect coefficient with respect to the i-th group which is assumed to be multivariate normally distributed; $z_k(i,j)$ is the random effect variable (predictor) for observation j in group i; and $\varepsilon(i,j)$ is the error for case j in group i where each group's error is assumed to be multivariate normally distributed.

In the following, analysis on the observed overall freeway lane capacity using PeMS method has been elaborated as an example. The standard Analysis of Variance (ANOVA) shows that the variance between groups (District) is statistically significant in the study dataset (see Table F-2). The results from Intra-Class Correlation (ICC), which represents a measure of reliability or dependence among individuals [Kreft and DeLeeuw, 1998] and can be used to assess whether or not the random effect is present in the data, have revealed that 50.2% of the variance in the observed Capacity of overall freeway lane (using PeMS method) can be "explained" by the District group. The reliability index value of 0.993 indicates that District groups can be very reliably differentiated in terms of the observed Capacity.

Table F-2. ANOVA results of the District effect for Overall FWYL using PeMS method

	DF	Sum Sq.	Mean Sq.	F-Statistics	Pr(>F)
District	3	8475393	2825131	134.59	< 2.2E-16
Residuals	526	11041043	20991		

By assuming that the District indicator is random effect variables while others listed in Table 3-6 are fixed effect variables, a linear mixed effect model is fitted using the REstricted Maximum Likelihood (REML) criterion for optimization of parameter estimates. After multiple iterations, the estimates of both fixed effect coefficients and random effect ones can be obtained and be listed in Table F-3.

Table F-3. Coefficients for the linear mixed effect model (FWYL, PeMS)

i	x_i	D4	D7	D8	D12
0	Intercept	-52.92	-80.65	-99.97	56.31
1	HOV access type	**47.97**	**47.97**	**47.97**	**47.97**
2	Distance to Point A	1.29	1.29	1.29	1.29
3	Distance to Point B	6.81	6.81	6.81	6.81
4	Number of Lanes	**122.00**	**122.00**	**122.00**	**122.00**
5	Outer shoulder width	3.17	3.17	3.17	3.17
6	Average width per lane	3.04	3.04	3.04	3.04
7	Inner shoulder width	**-3.67**	**-3.67**	**-3.67**	**-3.67**
8	Type of upstream ramp with respect to. VDS	-1.00	-1.00	-1.00	-1.00
9	Distance to upstream ramp	0.95	0.95	0.95	0.95
10	Type of downstream ramp with respect to. VDS	-15.73	-15.73	-15.73	-15.73
11	Distance to downstream ramp	3.41	3.41	3.41	3.41
12	Truck proportion at capacity	-94.60	-94.60	-94.60	-94.60
13	VDS occupancy at capacity	**702.81**	**702.81**	**702.81**	**702.81**

Variables in bold-face are statistically significant at 5% α-level

It should be noted that the distinction between fixed and random effects is a murky one. Other hierarchical models with more level can be explored by assuming more variables to account for random effects, which can be one of research topics for future study.

Multivariate Adaptive Regression Splines (MARS)

Besides the parametric regression models, non-parametric ones have also been investigated in the analysis. Generally speaking, non-parametric regression models such as classification and regression tree [Breiman et al., 1984] and multivariate adaptive regression splines [Friedman, 1991], require less assumptions and pre-processing efforts for the data set and provide better fit than parametric models. However, the statistical properties of resulting estimators are more difficult to determine than those parametric modeling techniques. In this study, the mulitivariate adaptive regression splines (MARS) model has been explored in detail.

MARS is a non-parametric regression technique and can be seen as an extension of linear models that automatically models non-linearities and interactions using the following form

$$\hat{f}(x) = \sum_i c_i \cdot B_i(x) \qquad \text{(F-6)}$$

where $\hat{f}(x)$ is the estimated model output, $B_i(x)$ is the i-th basis function which can be (1) a constant 1; (2) a hinge function; and (3) a product of two or more hinge functions. The hinge function can take the form

$$max(0, x - c)$$

or,

$$max(0, c - x)$$

where c is a constant.

As is mentioned above, building a MARS model often requires little or no data preparation. The hinge functions automatically partition the input data, so the effect of outliers is contained. MARS model can handle both numeric and categorical data and outperforms the recursive partitioning (RP) for numerical data because hinge functions are more appropriate than the piece-wise constant segmentation. Moreover, a MARS model tends to have a good bias-variance tradeoff due to its enough flexibility but constrained form of basis functions to model non-linearity with fairly low bias and fairly low variance. However, as with any non-parametric regression models, parameter confidence intervals and other checks on MARS models cannot be obtained directly (unlike linear regression models), and cross-validation may be used for validating if necessary.

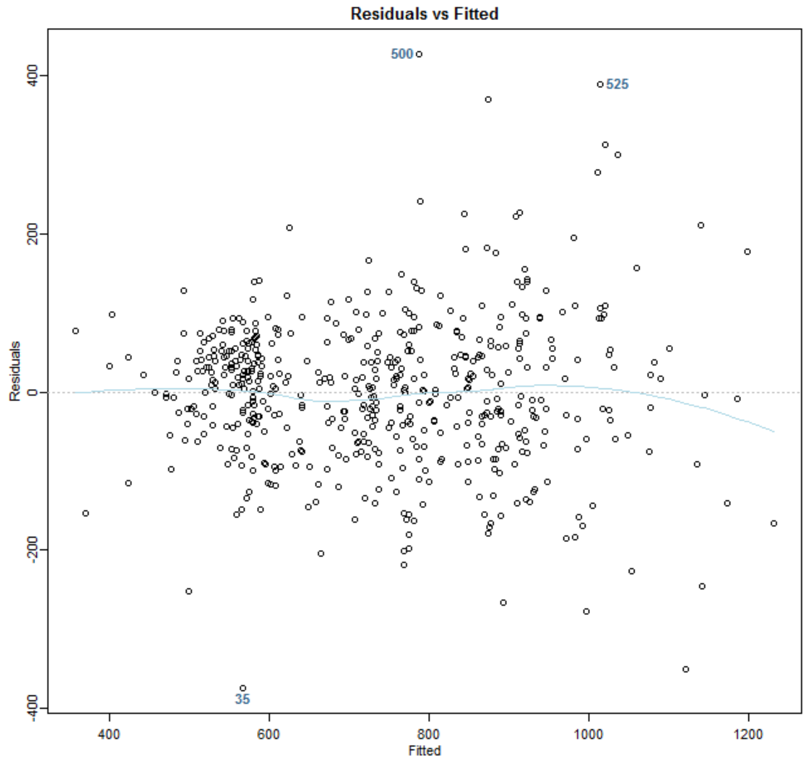
For the observed overall freeway lane capacity using the PeMS method, the MARS model can be written as

$$Y = 755.5 + 38.5 \cdot x_1 - 34.8 \cdot max(0, x_3 - 0.69) + 270.9 \cdot max(0, x_3 - 2.21) + 111.1 \cdot max(0, x_4 - 5) - 146.3 \cdot max(0, 5 - x_4) - 8.5 \cdot max(0, x_7 - 10) - 42.3 \cdot x_{13} + 146.7 \cdot x_{14} - 354.8 \cdot max(0, x_{16} - 0.08) - 2416.6 \cdot max(0, 0.13 - x_{16}) \quad \text{(F-7)}$$

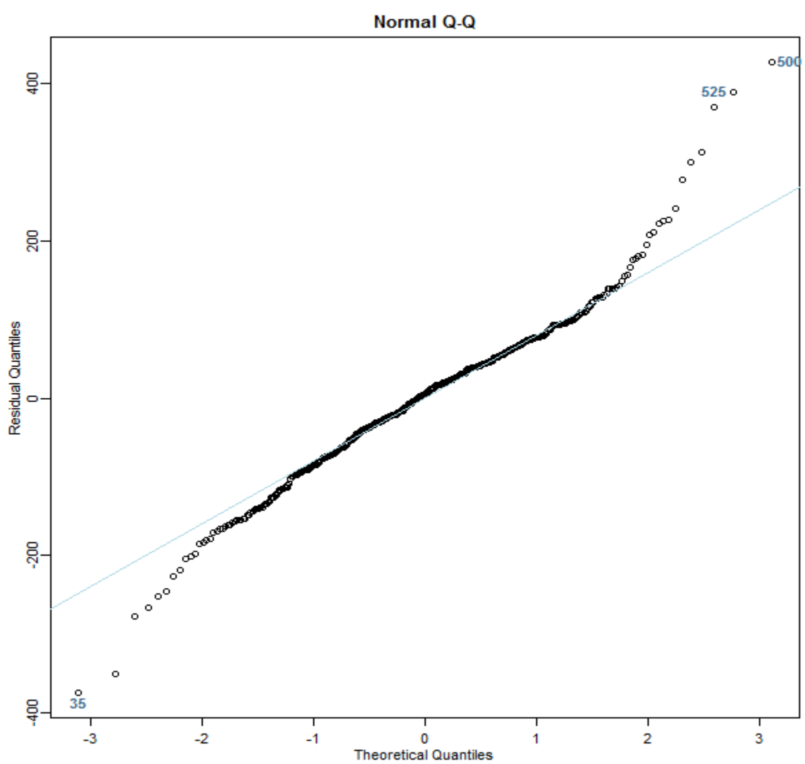
where Y represents the predicted overall freeway lane capacity (using the PeMS method), and x_i's are explanatory variables as listed in Table 3-6.

Therefore, the important variables determined by the MARS model include HOV access type, No. of lanes, inner shoulder width, indicator of District 8 and 12, and occupancy at capacity. This result, actually, coincides with those from the (robust) multiple linear regression model and linear mixed effect one. Specifically, as to the HOV access type, the predicted observed capacity for overall freeway lane segment with limited access is around 39 more vehicle/5-minute than that with continuous-access. In addition, some values (knots) are critical to the range partitioning for a certain set of numerical explanatory variables. For example, 0.08 and 0.13 are two critical partitioning point for occupancy at capacity and 5 for No. of lanes in the proposed model.

The result also reveals that the model may perform different depending on whether the inner shoulder width is greater than 10 feet or not. The R^2 is 0.760 which is better than the counterpart of MLR model (multiple R^2 is 0.725 and adjusted R^2 is 0.717). The measured residuals of MARS model are much better than those of MLR one in terms of sum of squares. However, since these residuals are measured on the training data (that were used to obtain parameters of the model) rather than on a new data set, the results give an optimistic view of the model,s predictive ability. The residuals vs. fitted values and Q-Q plot have been shown in Figure F-3 for reference.



(a) Residuals vs. fitted plot



(b) Q-Q plot

Figure F-3. Diagnostics Plots of MARS Model for FWYL (PeMS Method)

Appendix G:

Observed and Modeled Speed Contours

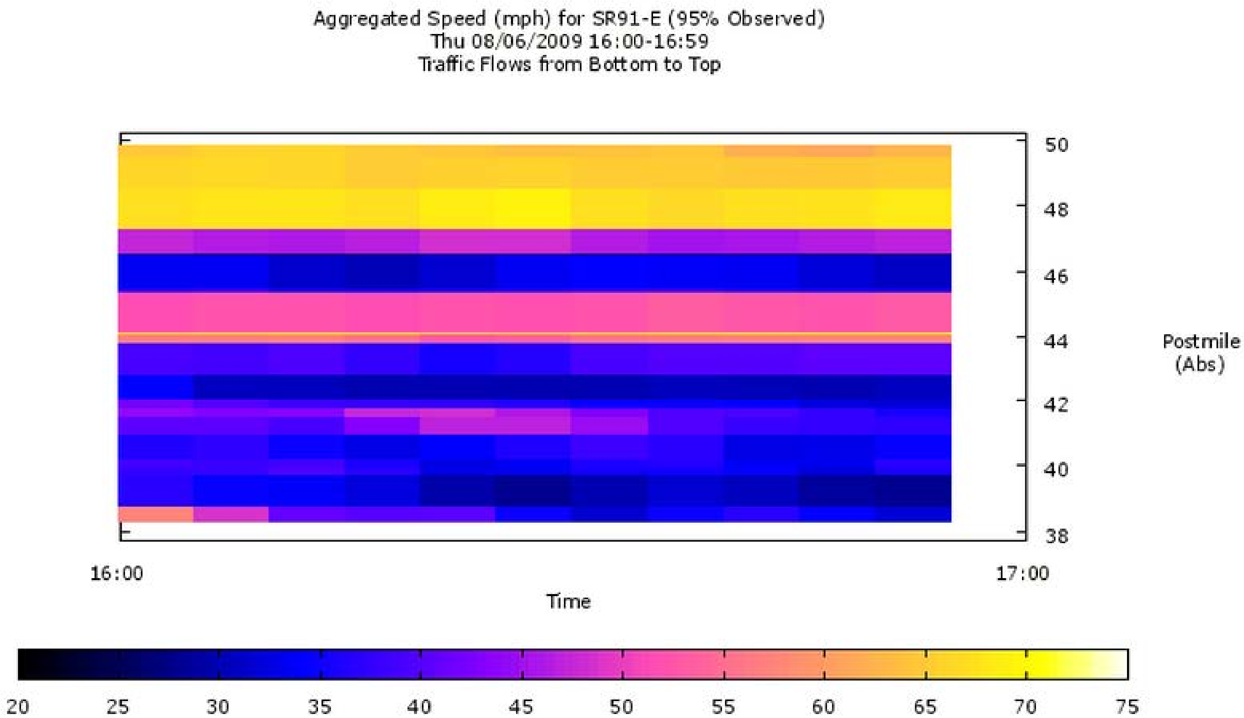


Figure G-1. Observed MFL speed contour for SR-91 E

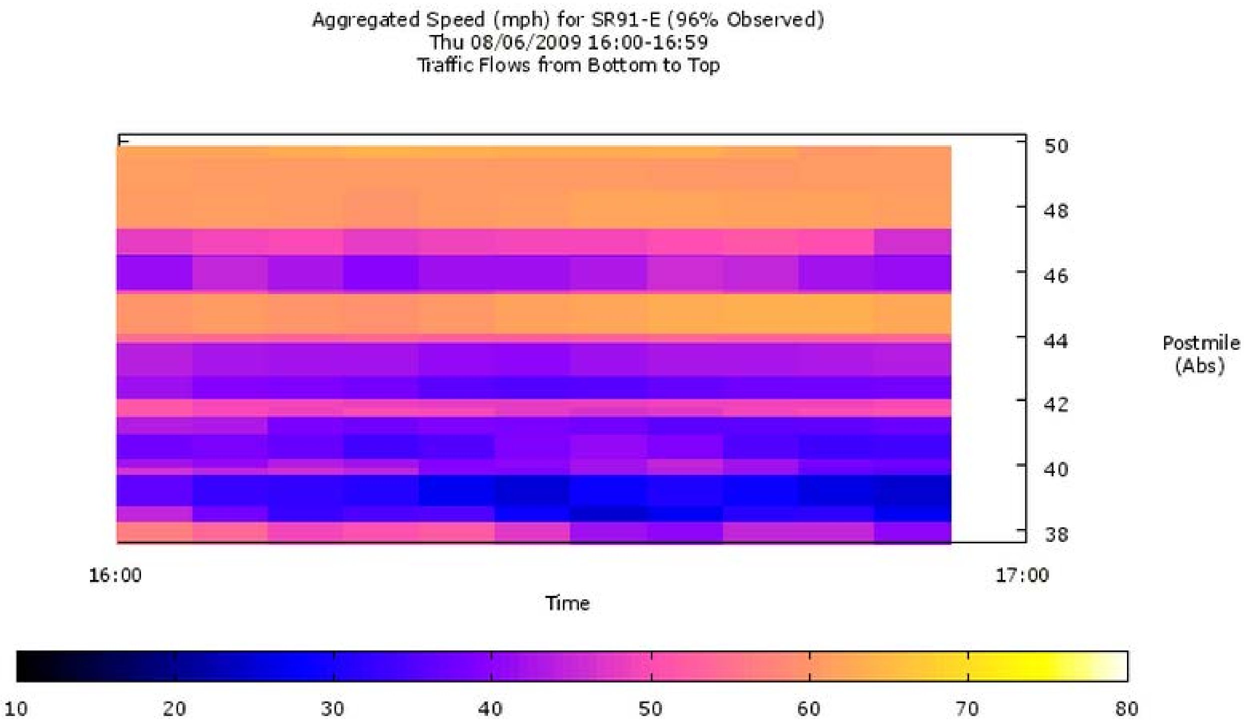


Figure G-2. Observed HOVL speed contour for SR-91 E

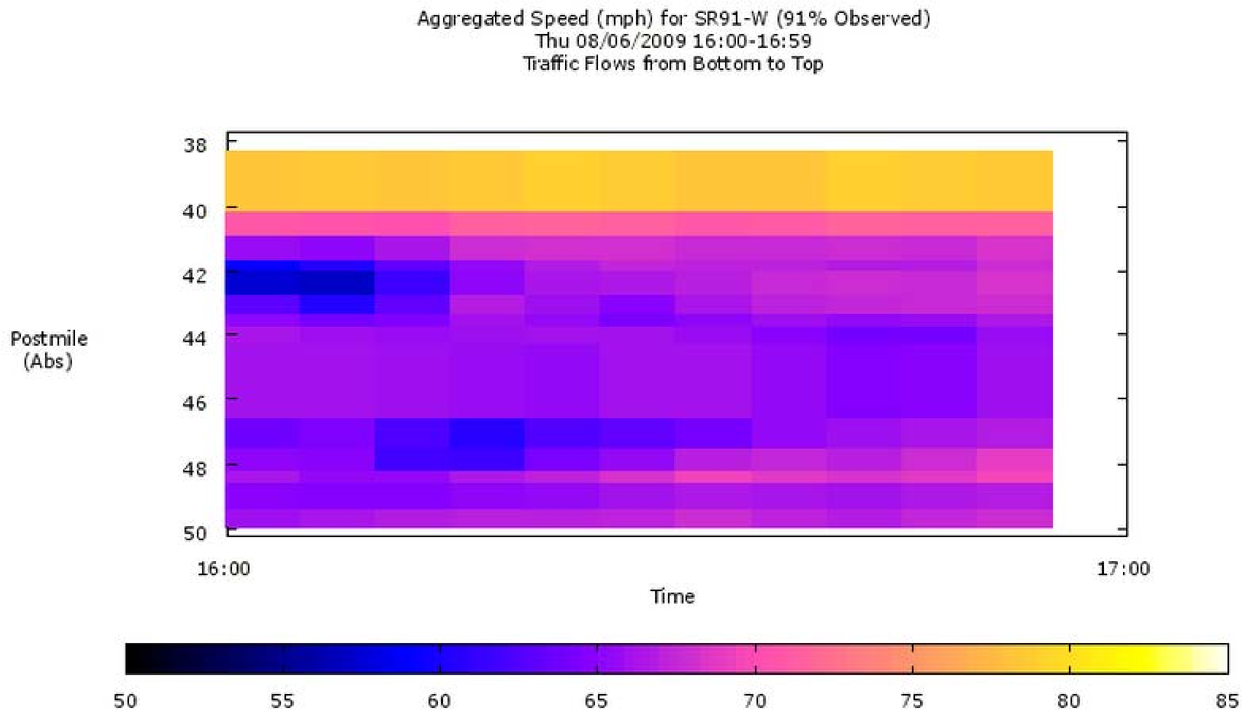


Figure G-3. Observed MFL speed contour for SR-91 W

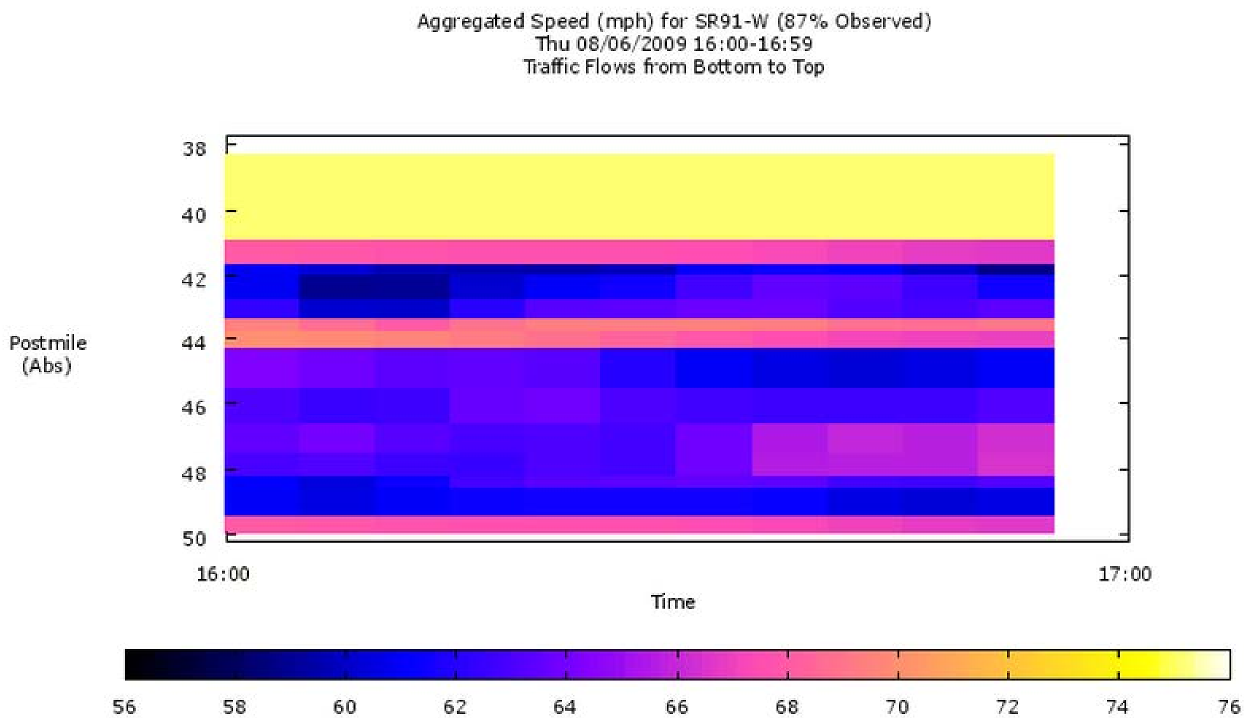


Figure G-4. Observed HOVL speed contour for SR-91 W

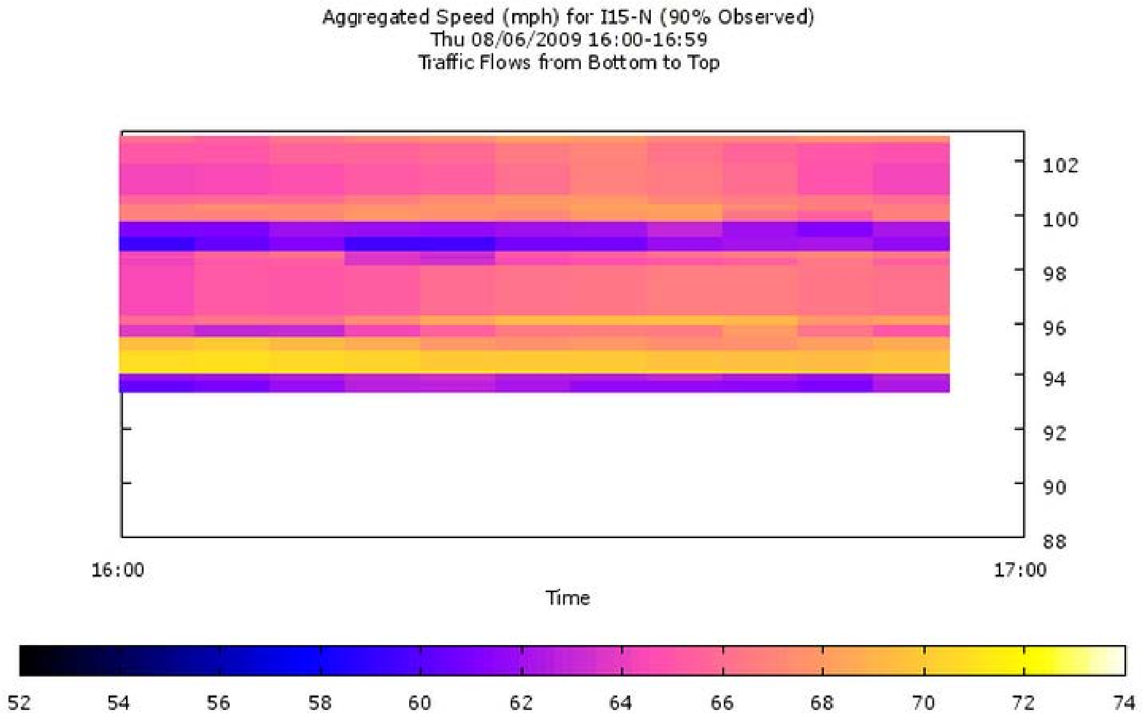


Figure G-5. Observed MFL speed contour for I-15 N

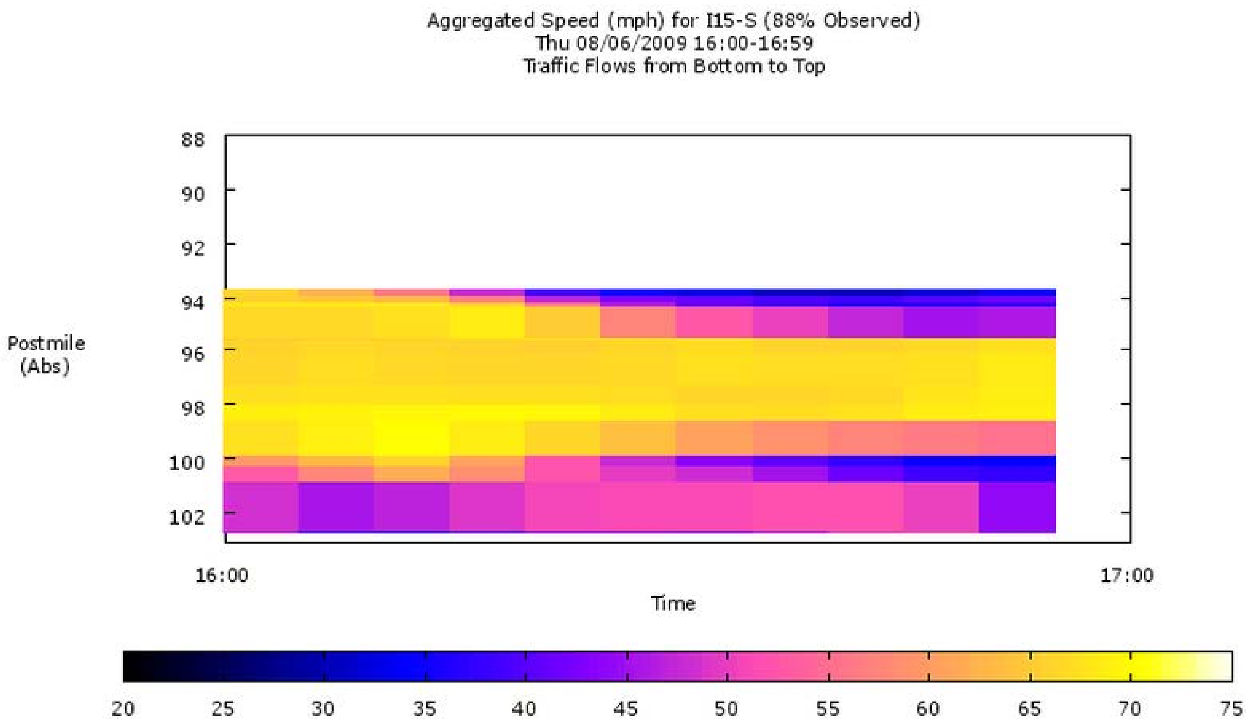


Figure G-6. Observed MFL speed contour for I-15 S

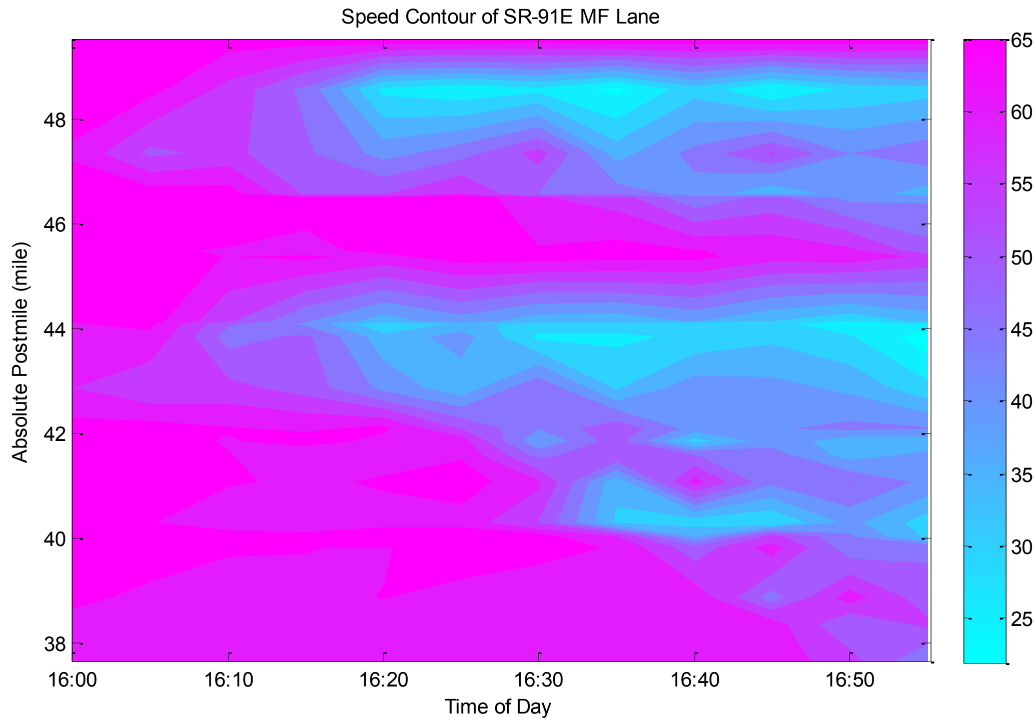


Figure G-7. Simulated MFL speed contour for SR-91 E

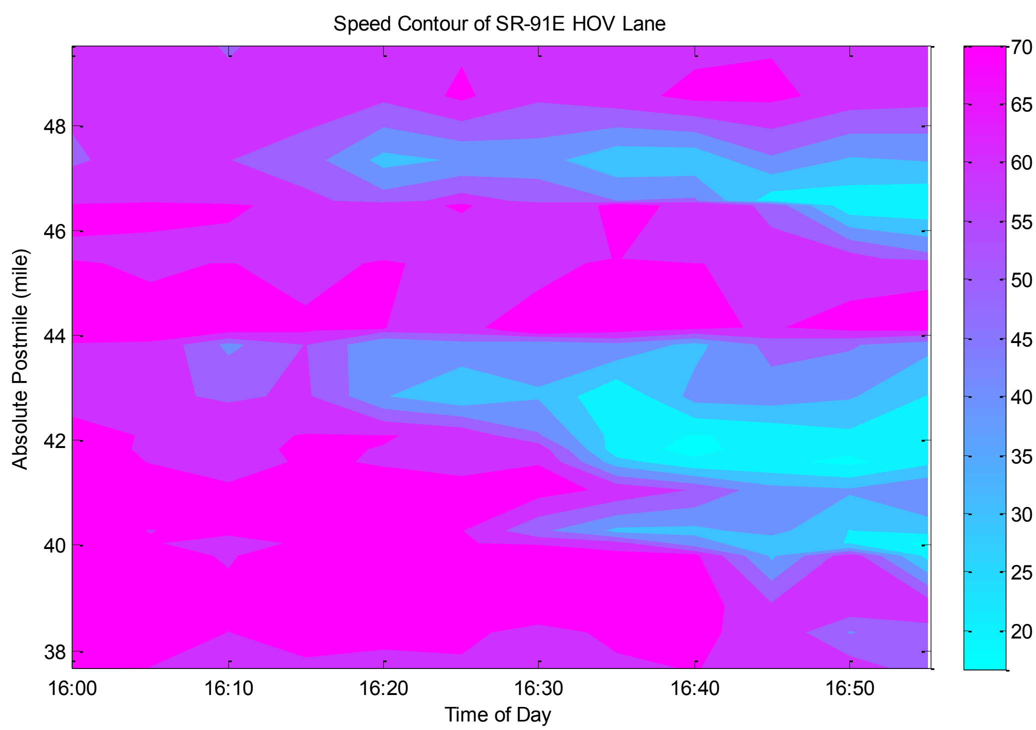


Figure G-8. Simulated HOVL speed contour for SR-91 E

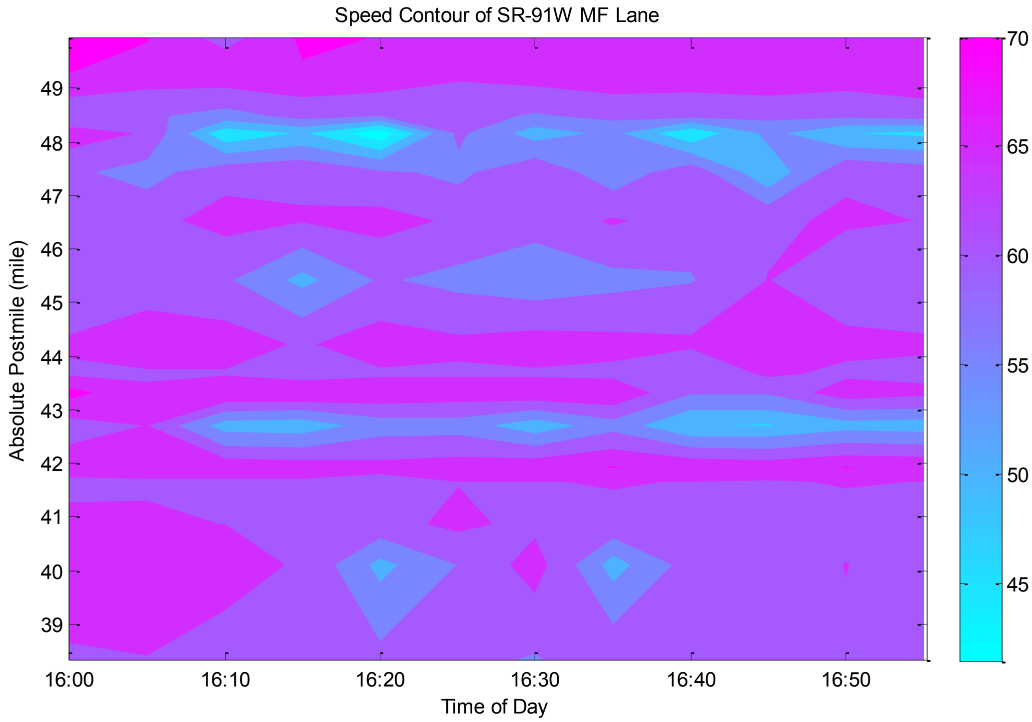


Figure G-9. Simulated MFL speed contour for SR-91 W

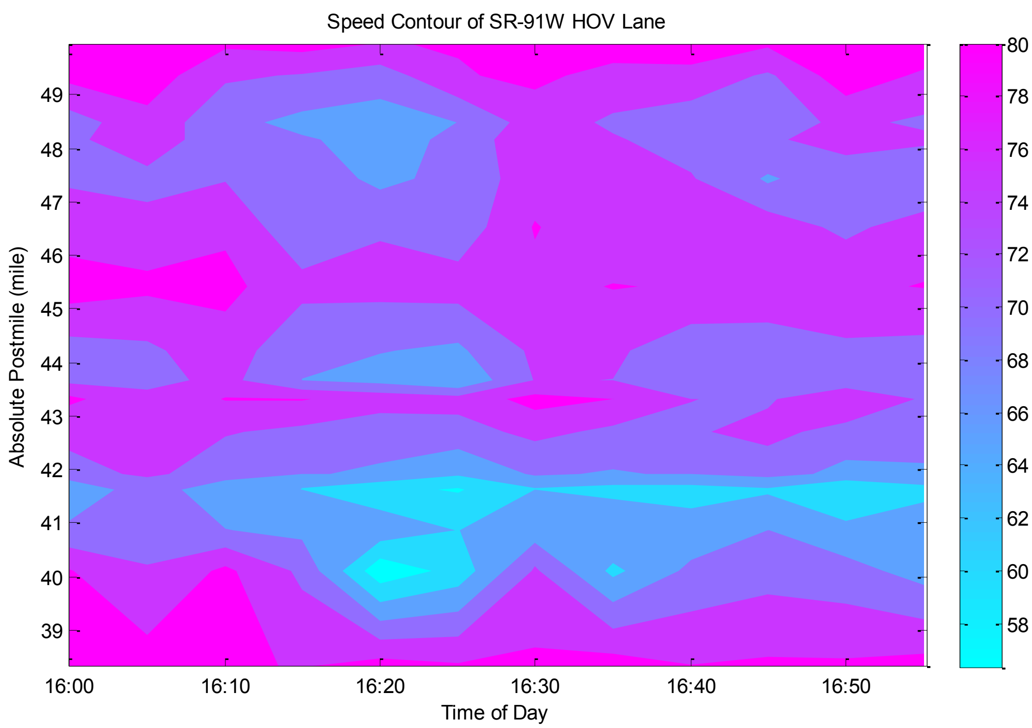


Figure G-10. Simulated HOVL speed contour for SR-91 W

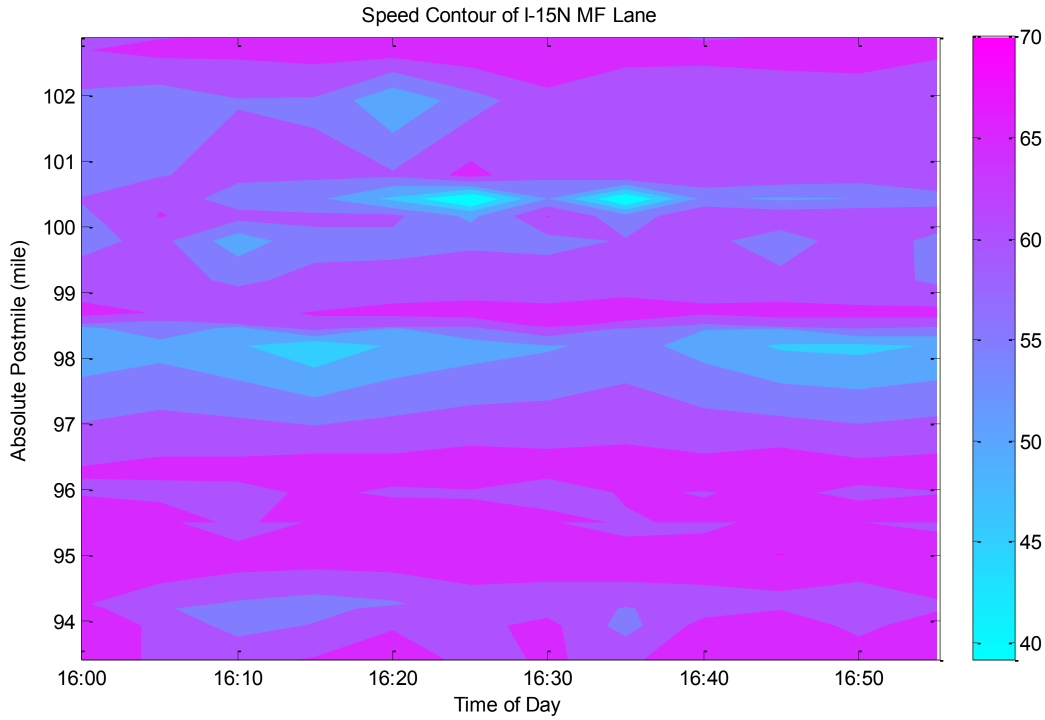


Figure G-11. Simulated MFL speed contour for I-15 N

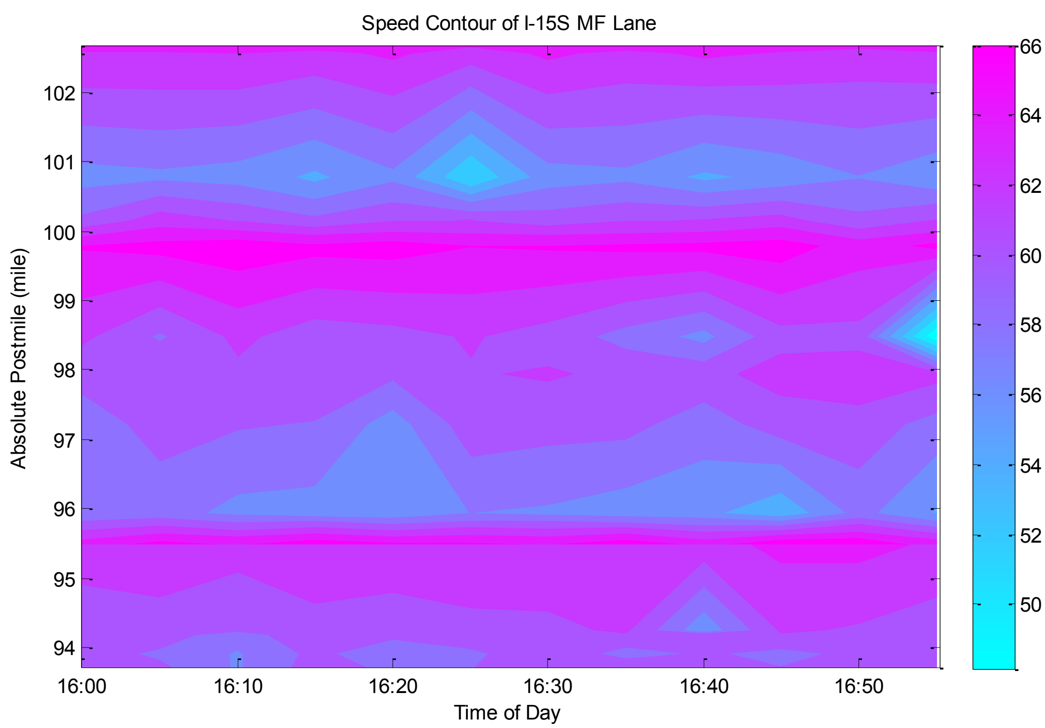


Figure G-12. Simulated MFL speed contour for I-15 S

Appendix H:

News Articles about SR-60 HOV Conversion

Car-pool lanes in Moreno Valley opening to lone drivers -- sometimes

By DUG BEGLEY | The Press-Enterprise

Published: 16 February 2011 09:03 AM

Solo drivers, welcome to the fast lane in Moreno Valley.

Federal officials have given the go-ahead to a Caltrans plan to allow anyone to use car-pool lanes along Highway 60 during non-rush-hour periods, in an effort to help traffic flow faster. It's not a done deal yet, with one more federal clearance to come, said Caltrans spokeswoman Barbara Miller.

But once Caltrans can re-stripe and hang signs outlining the rules, the Inland area's first peak-period-only car-pool lanes will be open to everyone.

"It has got to make a difference," said Anne Mayer, executive director of the Riverside County Transportation Commission.

Work to convert the lane to a part-time car-pool lane could begin later this year, Miller said. Drivers without a passenger likely will have the chance to use the lane by the end of the year, she said.

When the lanes open to solo drivers, they will be the first part-time car-pool lanes in the Inland area.

But don't expect drivers to get the OK to hop in car-pool lanes in other spots, officials said.

Despite many drivers relaying frustrating stories about clogged general-use lanes and empty car-pool lanes, traffic counts suggest handing the car-pool lane over to others won't do much good, and actually hurt car-pool users.

Though officials don't know exactly how many trips will be shortened in Moreno Valley, Mayer said "intuitively" officials know that weekend and nighttime drives likely will be easier.

"You're basically adding a lane," she said. "That will do something."

Traffic through the city is expected to increase, especially as development continues in eastern Moreno Valley. But officials do not plan to widen the freeway anytime soon. So sometimes opening the car-pool lane is a transitional step.

Another lane will help Maggie Goins, 39, of Moreno Valley, when she often gets stuck on the freeway running errands, or on her way to Palm Desert to see her parents on the weekend.

"Day Street backs up at the strangest times," Goins said. "I say let people use the lanes that are there."

Opening the lane to solo drivers also helps in case of a traffic wreck, Miller said.

In the event of an incident or closure, this would leave only one general-use lane for the majority of motorist to use," she said in an e-mail. "This could cause severe congestion which could be relieved by making the (car-pool) lane available part time for motorist to use during off-peak hours."

Approval for the change required agreement from the Federal Highway Administration because the car-pool lanes in Moreno Valley from Redlands Boulevard east to Day Street were built with federal air quality money.

Use of the lane by solo drivers will not be allowed during the morning and evening commutes, from 5 a.m. to 9 a.m. and 3 p.m. to 7 p.m.

One and done

Highway 60 is probably the only place where the lanes will open to solo drivers, Mayer said.

"When we started this, we looked at everything," Mayer said. "And I can understand people would say 'let people use the car-pool lane.' But when you look, you'll see for the most part, our lanes have cars in them all the time."

Cruising west on Highway 91 on most weekends, car-pool lane use is significant enough to leave the lane for ride-sharing drivers. During the work day, it is even more crowded, sometimes.

"By the time the morning commute is ending, the evening commute is starting," Mayer said.

Other freeways also have more general use lanes than the 60 in Moreno Valley, where only two lanes run in each direction -- plus a single car-pool lane. In places where there are three or more lanes open to all drivers, handing over the car-pool lane during off-peak times won't do much good, officials said.

Though critics abound, most federally funded freeway expansions -- such as widening Interstate 215 through San Bernardino -- include adding car-pool lanes.

But a notable exception is the planned widening along I-215 from Murrieta to Perris. Officials in Riverside County argued a third general-use lane was more important than installing a car-pool lane.

"We said look at the 60, a car-pool lane won't do as much good," Mayer said. "Car-pool lanes work where there are three or more general use lanes."

CHANGES AND CLOGS

But changes to car-pool lanes have been ineffective in the past. Changes to the rules for car-pool lanes on Interstate 10 in Los Angeles County -- reducing the needed number of passengers in a car from three to two -- clogged the lanes and led to Caltrans changing them back for peak commuting periods.

Not everyone agrees with the push for car-pool lanes, whether for two or three passengers.

"It's stupid to me," said Mel Reiter, 66, of Riverside. "Tax money should pay for everybody, not just commuters, to get more freeways."

MORENO VALLEY: Opening of car pool lanes pleases area drivers

BY DUG BEGLEY

STAFF WRITER

dbegley@pe.com

Published: 09 February 2012 07:28 PM

Aside from grumbling about how they wished Caltrans would have done it sooner, drivers are applauding a decision to open the car pool lanes along Highway 60 in Moreno Valley to solo drivers during non-peak hours.

But officials are cautiously optimistic of the success thus far, saying the benefits are still being evaluated and that drivers should not expect all car pool lanes in Southern California to suddenly switch to part-time status.

In July, between Day Street and Redlands Boulevard, the lanes opened to one-occupant vehicles except for peak morning and evening weekday commute times. Drivers say traffic flow has greatly improved. Giving motorists a third lane helps them pass trucks and slower-moving traffic entering and exiting the freeway.

Jorge O. Ramos doesn't mind shopping on weekends in Moreno Valley anymore, he said. Ramos, 37, said the return trip to his Woodcrest home in Riverside used to include a crawl down the 60. Even with construction at the 60 merger with Interstate 215, he said travel times have improved.

"It makes sense," Ramos said. "If you have another lane, you can have more cars."

According to the Performance Management System database of traffic data maintained by Caltrans and UC Berkeley researchers, noontime delays along the 60 in Moreno Valley were about 20 percent greater one month before the lanes opened, compared to one month after.

The city does not track freeway flow, but city residents said they have no doubt their trips are taking less time. Trips along the 60 during the day are much faster, said Krystal Waddell, 23.

"I use it every day and it makes a difference," she said.

But officials aren't ready to say how much time drivers are saving. Caltrans monitors the speed and flow of the lanes, but spokeswoman Shelli Lombardo said the agency isn't making a judgment until a yearlong study by UC Riverside researchers gives them a more complete idea of what opening the car pool lane did for traffic flow.

“People have called and said, ‘We love it,” Lombardo said. “But we don’t know what the time saving is.”

The study is expected to end in November and results released by January, said Kanok Boriboonsomsin, the research engineer overseeing the study for UCR’s Center for Environmental Research and Technology.

The 60 through Moreno Valley is unusual because it is one of the few places in the Inland area where the freeway only has three lanes, one of which is a car pool lane, Boriboonsomsin said.

Officials are also studying the benefits of allowing drivers continuous access to the Moreno Valley car pool lanes, Boriboonsomsin said, to see the change would help traffic flow. Most car pool lanes in Northern California allow drivers to come and go as they please, but the majority of lanes in Southern California let motorists enter and exit only at specific locales. In Moreno Valley, the lanes are continuous access to around Moreno Beach Drive, then limited access from there eastward.

Previous UC Berkeley studies have found there is no difference in the safety of continuous access and limited access. Boriboonsomsin said researchers now are studying whether continuous access helps traffic move faster.

The continuous access in Moreno Valley has improved traffic because drivers can change lanes to pass much more efficiently — something they cannot do when the car pool lane is cut off with a double-yellow line, limiting the access, said Eric Lewis, the city’s transportation engineer.

“You’re basically trapped in there until you get a break,” he said.

The findings on traffic flow could lead to changes along other routes.

“It could be a starting point if it turns out to be a success,” Boriboonsomsin said.

But officials cautioned car pool lanes will likely stay off-limits to solo drivers in most cases. It might work on Highway 60, said Anne Mayer, executive director of the Riverside County Transportation Commission, but would not on routes with more commuters, more car pool lane users and longer commute periods, because solo drivers would just slow the car pool lanes.

“I doubt (Highway) 91 would ever meet the criteria, for example,” Mayer said in an email.