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7. AUTHOR(S): Kanok Boriboonsomsin, Shams Tanvir, Zhensong Wei, Peng Hao, Guoyuan Wu

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16. ABSTRACT

With the increase in travel demand and the introduction of more clean air vehicles, some High Occupancy Vehicle (HOV) facilities have become congested and fail to meet the Federal degradation requirement of maintaining the average operating speed above 45 miles per hour (mph). Therefore, there is a need to research and evaluate alternative operational strategies that can be used to mitigate both recurrent and non-recurrent congestion to ensure that they will provide satisfactory performance and will meet the Federal minimum average operating speed requirement. Several strategies will be researched, such as increasing the minimum occupancy requirement in HOV lanes (e.g., from HOV2+ to HOV3+), dual HOV lanes, conversion of HOV lanes to High Occupancy Toll (HOT) lanes, and reassessment of HOV lane usage by clean air vehicles.

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Alternative HOV Lane Operational Strategies for Congestion Mitigation in California

FINAL REPORT

Prepared for:

California Department of Transportation

By:

Kanok Boriboonsomsin, Ph.D., P.E.
Shams Tanvir, Ph.D.
Zhensong Wei
Peng Hao, Ph.D.
Guoyuan Wu, Ph.D.

College of Engineering - Center for Environmental Research and Technology
University of California at Riverside

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Disclaimer Statement

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List of Abbreviations

ASC	Alternative-specific constants
AT PZEV	Advanced technology partial zero emissions vehicle
BPR	Bureau of Public Roads
Caltrans	California Department of Transportation
CAV	Clean air vehicle
CHP	California Highway Patrol
CNG	Compressed natural gas
DA	Drive alone passenger cars and trucks
FC	Full contraflow (lane)
FHWA	Federal Highway Administration
GEH	Geoffrey E. Havers (statistic)
HCM	Highway Capacity Manual
HDT	Heavy-duty truck
HHDT	Heavy heavy-duty trucks
HOT	High-occupancy toll
HOV	High-occupancy vehicle
HOV2	High-occupancy vehicle with two occupants
HOV2+	High-occupancy vehicle with two or more occupants
HOV3	High-occupancy vehicle with three occupants
HOV3+	High-occupancy vehicle with three or more occupants
ILEV	Inherently low-emission vehicle
LHDT	Light heavy-duty trucks
LOS	Level of service
LPG	Liquefied petroleum gas
MF	Mixed flow (lane)
MHDT	Medium heavy-duty trucks
MWCOG	Metropolitan Washington Council of Governments
PC	Partial contraflow (lane)
PeMS	Performance Measurement System
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users
SCAG	Southern California Association of Government
SOV	Single-occupancy vehicle
SR2 HOV	Passenger cars with 2 occupants using HOV lanes
SR3+ HOV	Passenger cars with 3+ occupants using HOV lanes
SR2 NONHOV	Passenger cars with 2 occupants not using HOV lanes
SR3+ NONHOV	Passenger cars with 3+ occupants not using HOV lanes
SULEV	Super ultra-low emission vehicle
TDM	Travel demand management
TZEV	Transitional zero emission vehicle
ULEV	Ultra-low emission vehicle
U.S.C.	United States Code
VDOT	Virginia Department of Transportation

List of Abbreviations (continued)

VDS	Vehicle detector station
VHT	Vehicle hours traveled
VMT	Vehicle miles traveled
VOT	Value of travel time
WSDOT	Washington State Department of Transportation
ZEV	Zero emission vehicle

Executive Summary

In California, the majority of high-occupancy vehicle (HOV) facilities are operated with a single HOV lane and the minimum occupancy requirement of two. This operational strategy has historically provided satisfactory performance for the most part. However, with the increase in travel demand and the introduction of more clean air vehicles over the last decade, some HOV facilities have become congested and failed to meet the Federal requirement of maintaining the average operating speed above 45 mph. Therefore, alternative operational strategies for mitigating congestion in HOV facilities need to be considered and their effectiveness evaluated in order to understand their potential for addressing the HOV lane performance degradation issue in California.

In this research project, the research team first reviewed the method for analyzing HOV lane performance degradation, and examined how different variations in the analysis method would impact the resulting performance degradation determination. Also, an alternative approach for determining HOV lane performance degradation that is based on the speed differential between HOV and mixed flow (MF) lanes was explored. In addition, a performance evaluation of several alternative HOV operational strategies was conducted. Key findings from these research efforts and recommendations for future research or implementation are summarized in the following sections.

Impacts of Variations in Performance Degradation Analysis Method

The research team analyzed the performance degradation of HOV facilities on SR-91 in Caltrans District 8 with three variations in the analysis method:

1. *Changing peak hour analysis periods from one hour to three hours* – The results are mixed, but in general, widening the peak hour analysis window from one hour to three hours can help capture the true peak period. It is recommended that the analysis windows of three hours be used, especially for HOV facilities in urban areas where the peak traffic tends to sustain for longer than one hour.

2. *Re-segmentation of HOV facilities for analysis* – The results suggest that segmenting HOV facilities to have consistent geometric characteristics and traffic patterns within each segment can help avoid projecting the impacts of localized congestion over a disproportionate length of HOV facilities. It is recommended that HOV facilities be segmented in this manner for the degradation analysis.

3. *Exclusion of incident-affected speed data from the analysis* – The results show that exclusion of incident-affected data reduces the frequency of HOV lane performance degradation. It is recommended that the impacts of traffic incidents on HOV lane performance degradation be monitored over time to identify HOV facilities that are consistently affected by incidents for possible investment in traffic incident management program.

Alternative Approach for Determining HOV Lane Performance Degradation

The current approach for determining HOV lane performance degradation requires the HOV lane to maintain an average operating speed above 45 mph. If the HOV lane speed drops below 45 mph, the level of service (LOS) of the lane will be deemed to be compromised (see the left diagram in Figure 1). However, this approach does not take into account the overall traffic condition on the freeway, and thus, does not reflect the primary objective of HOV lanes in providing travel time savings over the MF lanes. In this research, an alternative approach for determining HOV lane performance degradation based on the speed differential between the HOV lane and the adjacent MF lane was proposed (see the right diagram in Figure 1). In this approach, even if the HOV lane speed drops below 45 mph, the HOV lane will not be considered to have a compromised LOS as long as its average operating speed is higher than that of the MF lane. Although the current approach for determining HOV lane performance degradation that is based on a fixed speed threshold is a legislatively approved procedure, it is recommended that the speed differential measure be calculated and used as a complementary indicator of HOV lane performance in California.

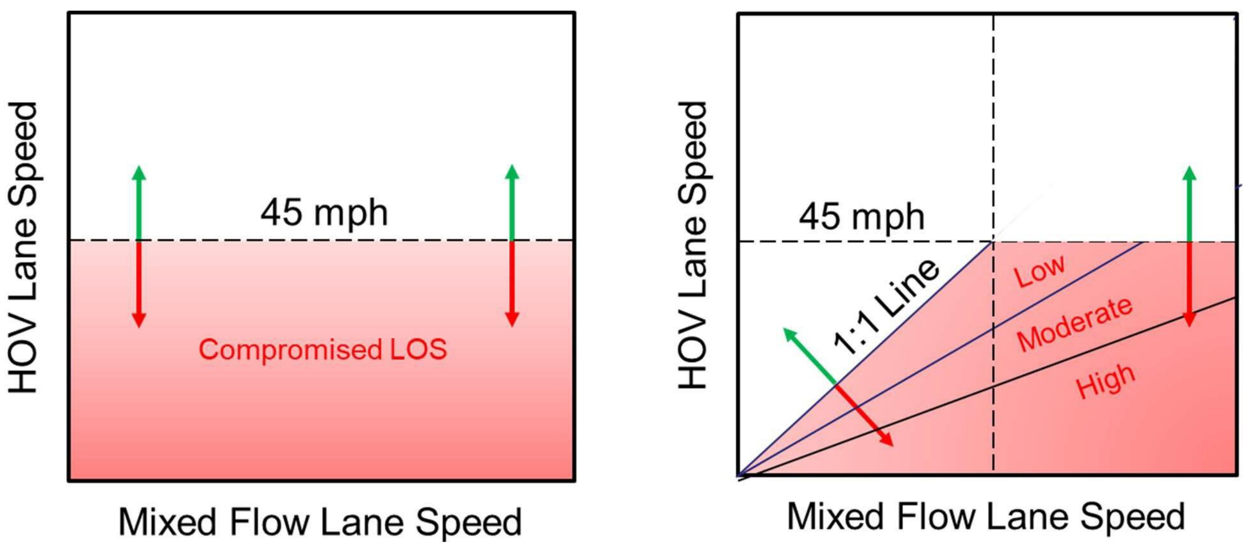

Figure 1. Conceptual diagrams of how a HOV facility is determined to have a compromised level of service (LOS); on the left is the current approach while on the right is the proposed approach

Assessment of Alternative HOV Lane Operational Strategies

The research team conducted a performance evaluation of several alternative HOV operational strategies using a combination of travel demand modeling, traffic simulation, and real-world observation. A summary of evaluation results is given below.

1. *Increasing the minimum occupancy requirement from HOV2+ to HOV3+* – A 16-mile section of SR-91 in Riverside county (District 8) was selected as a case study, which was focused on the afternoon peak period in the eastbound direction. The modeling results suggest that increasing the minimum occupancy requirement from HOV2+ to HOV3+ would result in an immediate congestion relief and travel speed

improvement in the HOV lane in the near term. However, the HOV lane speed could drop again once HOV3+ carpools are formed over time. For this specific case study, the increase in minimum occupancy requirement from HOV2+ to HOV3+ would not impact the speed in the MF lanes.

2. *Deploying dual HOV lanes* – This strategy is applicable where there is enough space to add a second HOV lane to the existing one. Based on this constraint, a 36-mile section of SR-14 in Los Angeles county (District 7) was selected as a case study. There is one existing HOV lane in each direction that operates with the HOV2+ minimum occupancy requirement. The modeling results show that the average HOV lane speed in both directions would improve significantly after adding a second HOV lane—from 49 mph to 65 mph for northbound and from 52 mph to 65 mph for southbound. In addition, the traffic flow improvements would also eliminate the bottlenecks in both directions as well.

3. *Reducing HOV lane usage by clean air vehicles* – To assess the impact of reducing HOV lane usage by CAVs on HOV lane performance, a modeling of roadways in Orange county (District 12) was conducted as a case study. The modeling results show that doubling the number of CAV decals from the baseline would decrease the average speed in the HOV lanes by 2.1% on average. On the other hand, halving the number of CAV decals from the baseline would increase the speed in the HOV lanes by 2.2% on average. Lastly, eliminating all the CAV decals would increase the speed in the HOV lanes by 5.7% on average.

4. *Converting HOV lanes to HOT lanes* – The HOT facilities in both directions of I-110 in Los Angeles county (District 7) were selected as a case study. Speed data from the Performance Measurement System (PeMS) were used to determine the degradation level of 12 segments before (2010) and after (2013) the lane conversion. The results show that the degradation level for a majority of these segments remained the same after the conversion to HOV lane. The degradation level for three segments actually increased during the morning peak period whereas the degradation level for one segment decreased during the afternoon peak period.

5. *Adding contraflow HOV lane* – Where there is not enough space to add a second HOV lane to the existing one in both directions, adding a new HOV lane that operates in a contraflow fashion could be a good compromise. A 5-mile section of I-215 in Riverside county (District 8) was selected as a case study for evaluating the effectiveness of this strategy in a traffic simulation tool. The simulation was conducted for the afternoon peak period, during which the peak direction is southbound. The results show that the addition of the contraflow HOV lane would increase the average speed in the southbound HOV facility from 38 mph to 55 mph, which is enough to lift this HOV facility out of the degradation status.

The results discussed above are for the specific case studies evaluated in this research. It is recommended that a similar modeling, simulation, or analysis be conducted when assessing the effectiveness of applying these strategies to other HOV facilities.

1. Introduction

1.1. Background

High-occupancy vehicle (HOV) lane has been used as a strategy to manage traffic congestion on California freeways for a long time, and most HOV lanes in the state have been effective at providing travel time savings for eligible vehicles. However, due to the growth in travel demand and the number of HOV lane-eligible vehicles, many HOV lanes in California have become congested with degraded performance. Performance of HOV facility is typically evaluated across factors such as level of service, throughput, transit service, safety, among others. Under 23 U.S.C. 166 (d) (2) (A) ‘minimum average operating speed’ is defined for HOV+ facilities (where HOV is combined with other single occupancy or low emissions vehicles). According to the code, the minimum average operating speed for facilities with a speed limit of 50 mph or greater is set to 45 mph and for the other facilities, the minimum average operating speed cannot be 10 mph below the speed limit.

The HOV facility operating agency has the freedom to choose the method to measure the speed; however, the monitoring should be conducted at least during the peak periods. Due to the lack of specificity in the measurement of facility-wide speed, confusion may arise in measuring speed where bottlenecks are present at parts of the facility. In those cases, agencies often measure the average speed for predominant usage patterns. If the predominant usage pattern consists of relatively short trips (5 or 10 miles) that pass through the bottleneck location, the average operating speed for these trips will be well under 45 mph and the trip would be considered as compromised level of service (LOS). An HOV facility is considered degraded if vehicles operating on it are experiencing compromised LOS 90% of the time over a consecutive 180-day period during morning and/or evening weekday peak hours.

According to the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU), “States are required to monitor, assess, and report on the operation of the facility to ensure that it does not become seriously degraded”. To meet the requirements, the California Department of Transportation (Caltrans) prepares an annual HOV lane performance degradation report for HOV facilities in California. In the report, Caltrans also includes an action plan that identified remediation strategies to bring degraded HOV facilities into compliance with the federal performance standard. Caltrans uses the performance criteria described above to determine whether a HOV facility has compromised LOS. However, Caltrans also further classifies all HOV facilities in five distinct levels as follows:

- *Level 0 - No Data:* Data collection infrastructure not available to track traffic speeds.

- *Level 1 - Not Degraded:* Degradation occurs less than 10 percent of the time, or two or less weekdays per month.

- *Level 2 - Slightly Degraded:* Degradation occurs from 10 to 49 percent of the time, or three to nine weekdays per month.

- *Level 3 - Very Degraded:* Degradation occurs from 50 to 74 percent of the time, or ten to 15 weekdays per month.

- *Level 4 - Extremely Degraded:* Degradation occurs 75 percent or more of the time, or 16 or more weekdays per month.

In California, the majority of HOV facilities are operated with a single HOV lane and the minimum occupancy requirement of two (i.e., HOV2+). This operational strategy has historically provided satisfactory performance for the most part. However, with the increase in travel demand and the introduction of more clean air vehicles over the last decade, some HOV facilities have become congested and failed to meet the Federal requirement of maintaining the average operating speed above 45 mph. In 2017, Caltrans monitored 1,322 lane-miles of HOV facilities out of a total of 1,778 lane-miles [Caltrans, 2018]. Out of the 1,322 lane miles, 951 lane-miles (72%) were degraded, as shown in Figure 2. Among the 951 degraded lane-miles, 332 lane-miles (35%) were slightly degraded, 220 lane-miles (23%) were very degraded, and 400 lane-miles (42%) were extremely degraded. Therefore, research is needed to assess alternative HOV operational strategies to understand their potential for addressing the HOV lane performance degradation issue in California.

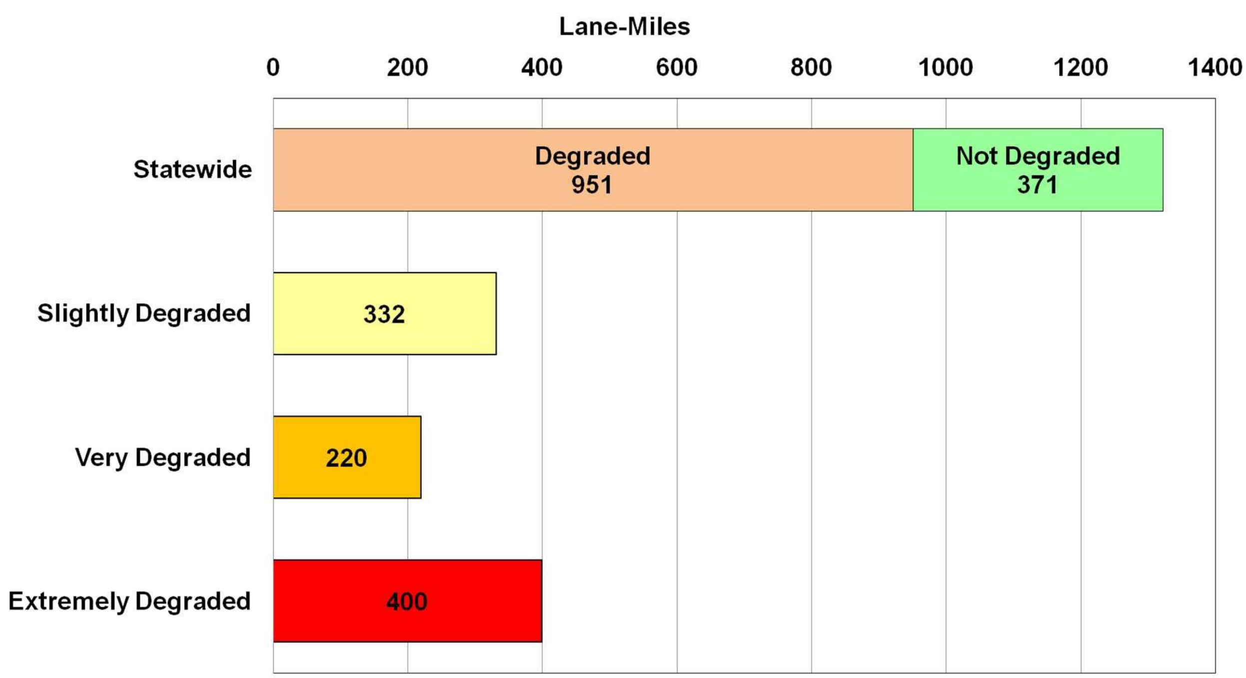

Figure 2. Degradation level summary of HOV facilities in California in 2017 [Caltrans, 2018]

1.2. Objectives

The goal of this research is to examine alternative HOV lane operational strategies for mitigating the performance degradation of HOV lanes in California. The specific objectives of this research are to: 1) evaluate the impacts of increasing the minimum occupancy requirement in HOV lanes (e.g., from HOV2+ to HOV3+); 2) quantify the effectiveness of deploying dual HOV lanes on a corridor with degraded HOV lane performance; 3) estimate the impacts of the HOV lane usage by clean air vehicles under different number of permits scenarios; 4) assess lane performance after converting HOV lanes to HOT lanes; and 5) design innovative strategies for mitigating HOV lane degradation.

1.3. Report Organization

This report presents every aspect of the research activities that were conducted during the course of the project. It is organized as follows:

- Chapter 2 reviews literature related to HOV lane operational strategies and how changing the operational strategy could impact HOV lane performance.
- Chapter 3 presents the performance degradation analysis of selected HOV facilities in California, and examines how different variations in the analysis method would impact the resulting level of HOV lane performance degradation.
- Chapter 4 presents the use of a regional travel demand model to assess a variety of alternative HOV lane operational strategies.
- Chapter 5 describes innovative strategies for mitigating HOV lane performance degradation for a selected corridor, and the evaluation of these strategies in traffic microsimulation.
- Finally, Chapter 6 provides conclusions of this research and recommendations for future research.

2. Literature Review

High-occupancy vehicle (HOV) lanes are reserved for vehicles with a driver and one or more passengers. In addition to the occupancy requirement, i.e. minimum vehicle occupancy levels, some HOV lanes may permit other vehicles to use the facility such as exempt vehicles. Examples of exempt vehicles are low emissions vehicles, hybrid and alternative fuel vehicles, emergency vehicles, law enforcement vehicles, transit vehicles, and motorcycles. Sometimes, the occupancy requirement is relaxed in exchange of a toll; such facilities are called high-occupancy toll (HOT) facilities.

The I-395 HOV lanes between Washington, DC and Capital Beltway in Virginia is the first HOV facility in the US, which was opened in 1969. According to the 2008 nationwide HOV facilities inventory [Chang et al., 2008], there were 301 HOV facilities in operation. As of 2012, California has the highest number of lane miles of active HOV facilities in the country, totaling more than 1,300 miles [Caltrans, 2012].

The purpose of HOV lanes varies from region to region. A 2008 Federal Highway Administration (FHWA) report [Chang et al., 2008] summarizes six common objectives of HOV lanes:

1) Maximizing person throughput;
2) Managing congestion by improving system efficiency;
3) Providing options for travel time savings and trip reliability;
4) Encouraging carpooling in peak periods;
5) Improving air quality; and
6) Supporting transit service and transit reliability

Operational strategies to ensure the above-mentioned objectives require balancing on the part of the agencies managing the HOV facilities. Too restrictive strategies can cause underutilization of the facilities where the HOV lane has low utilization while the parallel mixed flow (MF) lanes experience high level of congestion. Underutilization, sometime referred to as “empty-lane syndrome”, is a major cause for pushback from the public to relax occupancy and time-period requirements of HOV lanes. There have been instances where agencies were forced to reconsider HOV lane operational strategies in areas where it was difficult to form carpools [Spielberg & Shapiro, 2000]. In contrast, too relaxed strategies can cause overcrowding of HOV facilities. Congestion in the HOV lanes may cause the HOV-eligible vehicles to move to MF lanes due to the lack of speed differential between HOV lanes and MF lanes. Congress has enacted performance requirements for HOV facilities in Section 166 of Title 23 of the United States Code (U.S.C.). The code requires the agency operating HOV facility to prepare a report on the level of performance degradation for the facility allowing HOT or low emission vehicles. The agency needs to ensure that the facility is not degraded or if degraded, remedial actions are being taken.

In this report, we identify operational strategies available to HOV facility managers to attain balance in lane utilization. Then, we briefly examine the national trend of HOV facility operational strategies in light of the performance monitoring requirements. Next, we review the literature to identify studies conducted to inform policy decisions in the selection of operational strategies. We place particularly emphasis on demand level sensitivities under different operational strategies and available tools to estimate the sensitivities. Finally, we review the level of degradation of existing HOV facilities in California, and identify potential facilities for being case studies in this research.

2.1. HOV Facility Operational Strategies

There are two major schools of thought in managing HOV facilities: 1) managing the performance of the HOV facilities only, and 2) managing the corridor containing HOV facilities as a whole, including both the HOV lanes and the MF lanes. To attain maximum throughput per lane without losing much of the speed, the facility should be operating at level of service C to D. According to [Wang et al., 2012], the capacity of a single HOV lane with 65 mph free-flow speed is 1,600-1,700 passenger cars per hour per lane (pcphpl). To attain this level of utilization, there should be enough HOV-eligible vehicles and enough speed differential between the HOV and MF lanes for the HOV-eligible vehicles to choose the HOV lane. In most cases, maintaining a stable flow near capacity is not possible. Therefore, the desirable service flow rate in an HOV lane is generally between 1,200-1,600 pcphpl.

Operational strategies to ensure maximized throughput necessitates balancing in both the demand and supply domains. The demand to supply ratio dictates the level of service on the facility. Very low demand to supply ratio will cause underutilization and very high demand to supply ratio will cause congestion. The main operational variables for an HOV facility include:

1. *Occupancy requirement*: Minimum number of occupants for an HOV-eligible vehicle is a major determinant of demand. Vehicles with at least two occupants are termed as HOV2+ whereas vehicles with at least three occupants are termed as HOV3+. Thus, HOV2+ vehicles include all HOV3+ vehicles by definition. Depending on the route and traveler characteristics, the amount of HOV2+ and HOV3+ vehicles at a given time will vary.

2. *Exempt vehicles*: As mentioned earlier, exempt vehicles are allowed to use the HOV facility even if the occupancy requirement is not met. In California, clean air vehicles (i.e., very low emissions, hybrid, and electric vehicles) are allowed to access most of the HOV facilities as exempt vehicles. Emergency and law enforcement vehicles are allowed in most facilities nationwide. Similar exemptions are given to motorcycles and transits.

3. *Time-of-day operations:* The overall travel demand for a corridor follows a diurnal pattern in most urban areas where HOV facilities are deployed. In many cases, there are two peak periods—morning and afternoon peaks where the travel demand exceeds the capacity causing congestion. Therefore, some HOV

facilities only enact the occupancy requirement during the peak periods, and operates like MF lanes for the rest of the day. In cases where there is no discernable peak period or the congested condition continues throughout the day, the occupancy requirement is in effect all the time.

4. *Pricing*: Allowing vehicles not meeting the occupancy requirement to pay toll in exchange for access to the better level of service in HOV lanes is a measure often used to tackle underutilization of HOV facilities. To use HOT lanes, single-occupancy vehicles (SOVs) pay while HOVs can access for free or at a discounted rate. Socio-demographic conditions play a vital role in determining the willingness-to-pay for a tolled facility. Travel demand modelers often use value of travel time (VOT) as a variable to determine sensitivity to select a tolled facility.

Maintaining a desirable level of travel demand in HOV facilities requires an understanding of the overall demand pattern. Major traveler groups pertaining to the use of HOV lanes can be classified as follows:

1) Travelers in single occupancy vehicles with low VOT
2) Travelers in single occupancy vehicles with high VOT
3) Travelers in two-occupant vehicles with low VOT
4) Travelers in two-occupant vehicles with high VOT
5) Travelers in at least three-occupant vehicles with low VOT
6) Travelers in at least three-occupant vehicles with high VOT
7) Travelers using the exempt modes such as low emissions vehicles and transit

In a hypothetical scenario of travel demand shown in Table 1, we assume only two levels of VOT to illustrate the sensitivity of travel demand for a managed lane with respect to tolls when the parallel MF lanes become congested. We assume that travelers eligible to use the lane for free will do so irrespective of their VOT. And if the lane is tolled, high VOT travelers will pay toll to use the lane while low VOT travelers will stick to the MF lanes. For the purpose of this discussion, we consider the vehicles paying toll to use HOT or toll lanes to be "eligible" vehicles.

Table 1. Assumed fraction of total travel demand for different traveler groups

Group	Description	Fraction of Total Demand
1	SOV, low VOT	45
2	SOV, high VOT	15
3	HOV2, low VOT	13
4	HOV2, high VOT	9
5	HOV3+, low VOT	8
6	HOV3+, high VOT	5
7	Exempt vehicles	5
	Total	*100*

For example, under the HOT2+ policy, which provides free access to HOV2+ and allow SOV to pay toll to use the lane, all the HOV2+ vehicles (Groups 3-6) will use the lane. Also, SOV with high VOT (Group 2) will pay the toll to use the lane. Thus, the number of eligible vehicles will be 50% of the total number of vehicles. As another example, under the HOT3+ allowing exempt vehicles policy, all the HOV3+ vehicles (Groups 5 and 6) as well as the exempt vehicles (Group 7) will use the lane. In addition, SOV with high VOT (Group 2) and HOV2 with high VOT (Group 4) will pay the toll to use the lane. Therefore, the number of eligible vehicles will be 42% of the total number of vehicles.

Figure 3 illustrates how the level of travel demand for the managed lane would change due to the implementation of different operational policies. For instance, most of the HOV facilities in California operate under the HOV2+ allowing exempt vehicles policy. For this hypothetical scenario, the number of eligible vehicles under that policy is 40%. Disallowing the exempt vehicles will slightly reduce the number of eligible vehicles to 35%. Increasing the occupancy requirement to HOV3+ while still allowing exempt vehicles will substantially reduce the number of eligible vehicles to 13%. Converting the lane to HOT3+ while still allowing exempt vehicles will actually increase the number of eligible vehicles to 42%. Since the capacity of the lane remains the same, the changes in the number of eligible vehicles will be the primary factor affecting the operational performance of the lane.

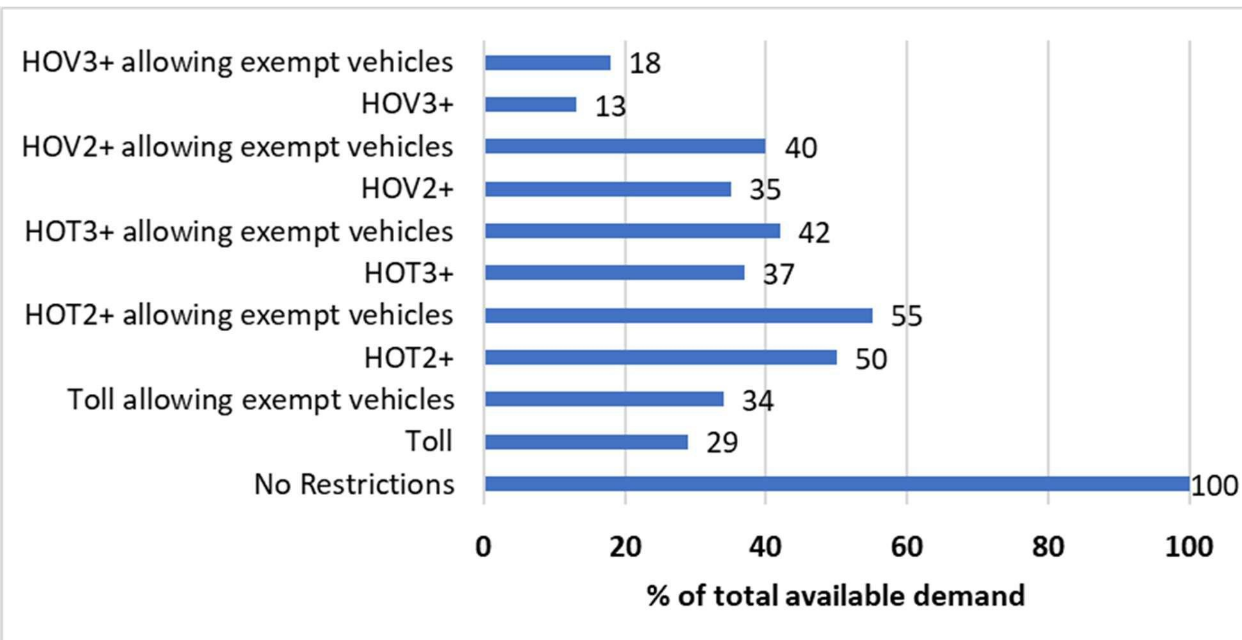

Figure 3. Eligible vehicles as percent of total number of vehicles under different operational policies

It should be noted that the number of eligible vehicles after a change in the operational policy of a managed lane could also be impacted by route choice, where vehicles that are no longer eligible may change to take a different route which is discussed in more detail in Chapter 3 of this report.

2.2. Performance Measures for HOV Facilities

The performance of HOV facilities is often evaluated in the same way as regular highway facilities where it is evaluated across factors such as level of service, throughput, safety, among others. Under 23 U.S.C. 166 (d) (2) (A), ‘minimum average operating speed’ is defined for HOV facilities that allow HOT or low emissions vehicles. According to the code, the minimum average operating speed for facilities with a speed limit of 50 mph or greater is 45 mph. For facilities with a lower speed limit than 50 mph, the minimum average operating speed cannot be 10 mph below the speed limit. The agency operating HOV facility has the freedom to choose the method for measuring the operating speed; however, the monitoring should be conducted during the peak periods. Due to the lack of specifics on the measurement of facility-wide speed, agencies often measure the operating speed for predominant usage pattern. If the predominant usage pattern consists of relatively short trips (5 or 10 miles) that pass through bottlenecks at parts of the facility, the average operating speed for these trips would likely be well under 45 mph and the facility would be considered degraded. An HOV facility is considered degraded if vehicles operating on it are failing to maintain a minimum average operating speed 90% of the time over a consecutive 180-day period during morning and/or evening weekday peak hours.

According to the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU), “States are required to establish occupancy requirements for HOV lanes, with mandatory exemption for motorcycles and bicycles unless it creates a safety hazard, and optional exemptions for public transportation vehicles, low-emission and energy-efficient vehicles, and HOT vehicles (otherwise-ineligible vehicles willing to pay a toll to use the facility). States are required to monitor, assess, and report on the operation of the facility to ensure that it does not become seriously degraded”. States are given the freedom to choose even more restrictive requirements other than the minimum speed requirement. Other performance measures typically used for HOV facilities are:

1. *Lane utilization*: Most HOV facilities do not have a reliable way to collect lane utilization related performance measures. Also, automated vehicle occupancy determination need much improvement. If properly measured and reported, total person throughput will be a useful performance measure.

2. *Violation rate*: Violation of HOV requirement deteriorates operating conditions in the HOV lane. Some agencies conduct regular surveys and enforcements to determine HOV violation rates, especially during peak periods.

3. *Travel time savings*: The estimation of travel time savings requires measurements in both HOV and MF lanes. A high level of travel time savings in well utilized HOV lanes is an indicator of the HOV lane operation as intended.

The Washington State Department of Transportation (WSDOT)'s guidance on HOV systems policy mentions the following metrics to measure corridor-wide system performance of HOV facilities.

"

1. *Speed*: Because the state policy standard for HOV lane performance requires an average speed of 45 mph or better, 90 percent of the time during the peak hour, the 90th percentile weekday HOV lane speeds are estimated for a range of trip start times throughout an average 24-hour weekday. This measurement indicates that nine times out of ten, a vehicle will travel at a particular speed or faster.

2. *Speed reliability*: In contrast to the 90th percentile average travel speed, this measurement indicates the percentage of weekdays that the average trip speed will be below 45 mph for a given trip start time. This measure indicates how frequently an HOV lane fails the 45 mph standard adopted for Puget Sound freeways.

3. *Level of traffic congestion*: To better understand how traffic conditions change as vehicles travel from one location to another on the HOV system, the researchers measure HOV lane congestion patterns at different mileposts along the corridor. The data presented are the average of conditions— specifically the average annual weekday lane occupancy data from WSDOT's loop detectors—measured for all weekdays during the year. The result is an image of the "routine" conditions in each HOV lane corridor for all 24 hours of the average weekday.

4. *Travel time savings*: Travel times are another measure of corridor-wide freeway performance. This measure is particularly useful for conveying corridor congestion because it is in a form that is readily understood by the public. It allows individual travelers to compare their own experiences against the reported statistics. It is also useful for tracking changes in facility performance over time, and for comparing MF and HOV lane performance. For this report, travel times are estimated for a range of start times for trips that traverse the length of particular MF and HOV lanes in the analysis. For a range of start times for each trip, the project estimated the average of MF and HOV lane travel times measured for the weekdays during the year.

"

2.3. Impacts of Changing HOV Operational Strategies

[Swisher et al., 2002] stressed the need to reevaluate operational strategies of HOV facilities from time-to-time across their life cycle due to the inherent difficulty with managing the performance of the facilities as demand increases. Most HOV facilities in the US started with HOV2+ designation. However, over time some facilities experienced performance degradation due to the increased number of HOV2+ eligible vehicles. Figure 4 illustrates how projected traffic volume would increase over time for different user groups (e.g., HOV2, HOV3+, bus/transit) [Swisher et al., 2002]. At a point in time, the traffic volume would reach a critical operating threshold, or the effective capacity of the managed lane. The operator would have a choice to either accept degraded conditions or restrict the access for some of the user groups. In the latter case (e.g., HOV2 no longer permitted to use the lane for free), a drop in traffic volume from those user groups is expected.

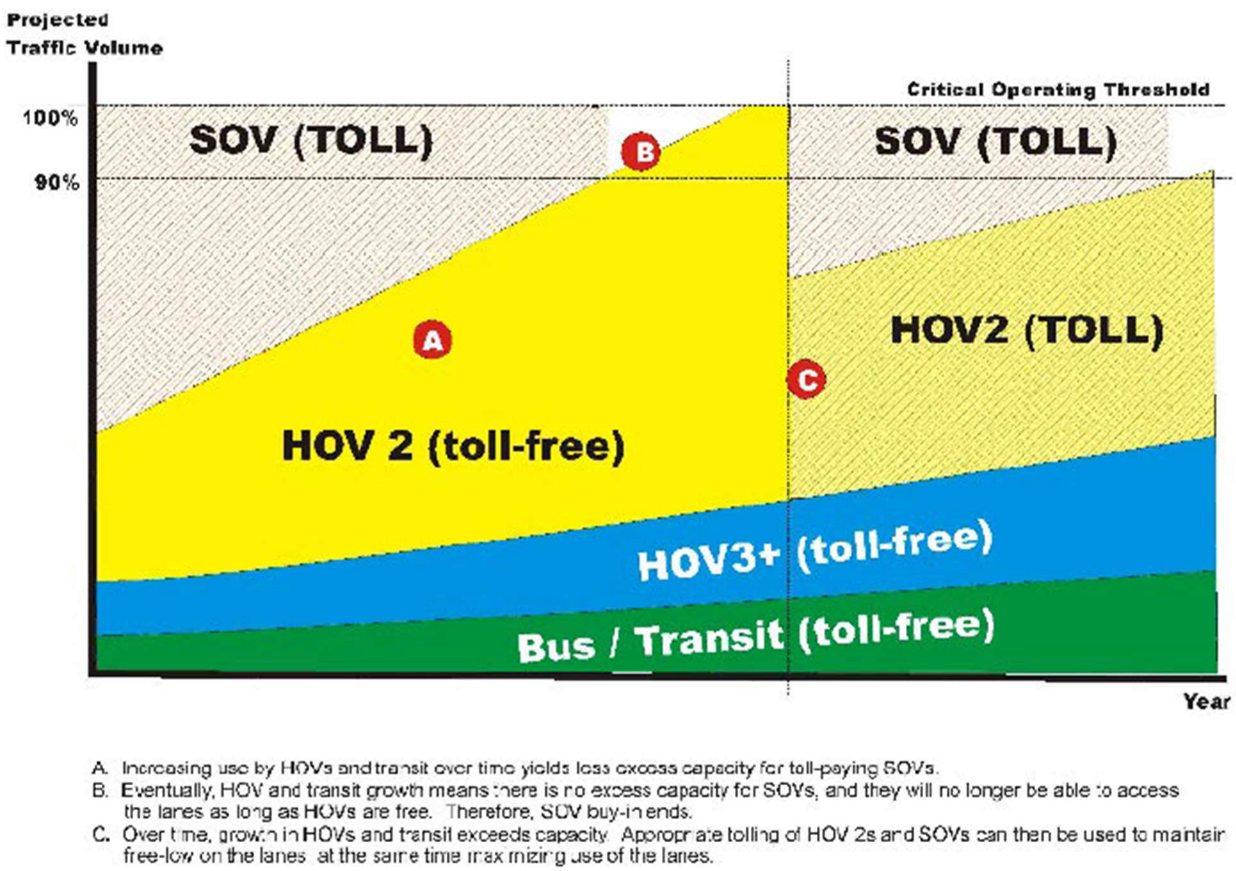

Figure 4. Different phases of HOV facility operation across the life-cycle [Swisher et al.,2009]

To answer 'what-if' questions related to an implementation of different HOV operational strategies, the analyst needs to determine traffic demand at different occupancy levels (e.g., HOV2, HOV3+). The NCHRP report 414 [Turnbull & Capelle, 1998] summarizes the techniques for demand estimation into the following categories:

1. *Sketch planning*: These techniques use pre-determined thresholds to calculate demand splits due to an implementation of different HOV policies. Examples include FHWA- Charles River model and FHWA – POET-ML model.

2. *Regionwide logit modeling:* Regional models are often trip-based travel demand models. Trip characteristics and traveler socio-demographic characteristics are used to determine travelers' preferred mode of travel. The mode choice models are calibrated using either stated preference or revealed preference surveys.

3. *Corridor demand modeling*: These models are simplified demand models compared to regional demand models. Examples include UTPS model and TTI model.

4. *Travel time savings estimation*: Travel times savings estimates are derived from volume to capacity ratio. The delay differential across multiple facilities helps in the estimation of modal splits. Examples include the Bureau of Public Roads (BPR) method and the Highway Capacity Manual (HCM) method.

5. *Freeway simulation*: Traffic simulation models can provide more accurate estimates of queueing and bottleneck impacts than trip-based travel demand models. Simulation model such as CORSIM and FREQ have been used to estimate demand split across HOV and MF lanes.

6. *Hybrid model*: Combinations of the above-mentioned models are often used to improve accuracy of demand estimation. Examples include using simulation model to update mode choice estimates in a regional travel demand model.

[Dahlgren, 2002] analytically studied the effects of adding an HOV, HOT, or MF lane to an existing freeway. She found that adding an HOV lane is the most effective in reducing the system delay if both the initial delay and the initial proportion of HOVs are high. However, she argued that if the initial proportion of HOVs is not high, then adding an HOT lane will be the most effective option.

[Pressaro and Buddenbrock, 2015] studied a hypothetical scenario for I-95 express lanes in Florida where all Travel Demand Management (TDM) strategies and toll exemptions were eliminated. They found that a large number of previously exempt low emissions vehicles would opt out of using the express lanes; however, the drop in express lane demand would be offset by HOV riders reverting to SOV drivers. Consequently, there would be a slight degradation in the level of service of the express lanes. In addition, the MF lanes would experience a severe level of congestion as a result of breakdown in carpooling habits. The traffic densities in the MF lanes would increase by 94% to 100% in the MF lanes.

The 2008 HOV pooled fund study [Chang et al., 2008] surveyed 73 HOV facility managers across the country to understand which operational policy changes had been implemented or were under consideration. Figure 5 summarizes the result from the survey. According to the survey, changing vehicle eligibility, access points, and hours of operation had been implemented the most. And pricing was the most popular policy change under consideration at the time.

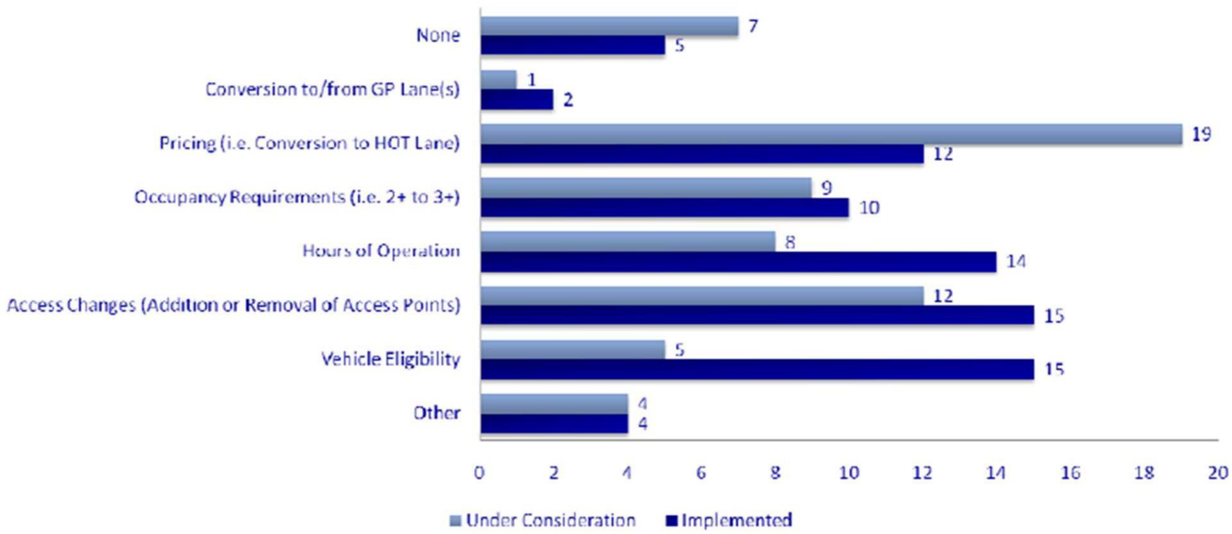

Figure 5. HOV facility managers' survey on policy considerations to change HOV operations [Chang et al., 2008]

[Wood et al., 2016] summarized the problem of balancing HOV and MF lane performance, and developed a sketch-planning tool to roughly estimate the impacts of various operational changes. The tool, called Thermostat, suggests optimal operational changes based on selected operational goals and desired measures of performance. The goals and measures of performances considered in the Thermostat tool are summarized in Table 2.

Table 2. Goals and measures of performance for operation of managed lanes [Wood et al., 2016]

Goals	Measures of Performance
Safe Travel	Number of Crashes
	Incident Clearance Times
High-Speed Travel	Average Speed
	Travel Time
Reliable Travel	Buffer Index
	Days Per Month below Threshold
Provide Choice	Public Perception of Users Choice
	Number of Unique Users
Maximize Throughput	Person Throughput
	Person Throughput in HOVs

[Goodin et al., 2009] summarized the effects of different policy scenarios on HOV lane performance objectives. They considered a total of 24 scenarios with four toll levels and six pricing policies, as shown in Figure 6. The pricing policies considered are as follows:

1. *All Vehicles Pay*: In this policy, the SOV, HOV2, and HOV3+ all pay the same toll amount to use the managed lane. In essence, this is similar to regular toll lanes.

2. *HOV3+ 50% HOV2 Pay*: HOV2 pay the same amount of toll as SOV. However, HOV3+ pay 50% of the SOV toll.

3. *All HOV 50% Toll*: SOV pay the full toll. HOV2 and HOV3+ pay 50% of SOV toll.

4. *HOV3+ Free HOV2 Pay*: SOV and HOV2 pay the full toll. HOV3+ use the facility for free.

5. *HOV3+ Free HOV2 50%*: SOV pay the full toll. HOV2 pay 50%. HOV3+ do not pay anything.

6. *All Carpoolers Free*: Only SOV pay the full toll. HOV2 and HOV3+ do not pay anything.

Carpool Policy Scenarios						
Managed Lanes Performance Objectives	**All Vehicles Pay**	**HOV3+ 50% HOV2 Pay**	**All HOV 50% Toll**	**HOV3+ Free HOV2 Pay**	**HOV3+ Free HOV2 50%**	**All Carpools Free**
Person throughput	○	◒	◒	●	●	●
Revenue generation	●	●	●	◒	◒	○
Emissions reduction	◒	◒	◒	◒	◒	◒
Operational performance	◒	◒	◒	◒	◒	◒
Enforcement and operational simplicity	●	◒	◒	◒	○	◒
Public perception and support	○	◒	◒	◒	◒	◒

Relative success in achieving performance objective: High ● Medium/Neutral ◒ Low ○

Figure 6. Relative comparison of HOV policy options for various performance objectives [Goodin et al., 2009]

2.3.1. Case Study 1: HOV2+ to HOV3+, Virginia I-66, 2020

Under the Financially Constrained Long-Range Transportation Plan, the Virginia Department of Transportation (VDOT) is considering to convert Interstate 66 HOV facility from HOV2+ to HOV3+ by 2020. In addition, [Ashe, 2015] reported that VDOT was planning to cancel the exemption status for clean air vehicles (CAVs). The decision to move towards a more demand restricted policy came from degraded operational condition of the existing facility. The Metropolitan Washington Council of Governments (MWCOG) conducted a study [MWCOG, 2015] to monitor HOV facilities in the metropolitan Washington region. MWCOG found that the HOV lane travel time on a 20-mile segment (I-66 Eastbound outside the Beltway during the AM peak period: 5:00 AM – 10:00 AM) increased from 22 minutes (equivalent to 55 mph) in 1996 to 63 minutes in 2014 (equivalent to 19 mph). According to the report, Fairfax County Supervisor Pat Herrity stated: “With HOV2 and the hybrids — our HOV is just not working. We need to get that fixed. We’re going to need to go to HOV3 in that corridor. It’s very unpopular, but if we want to move people through carpooling, then we need to go to HOV3.” However, Stewart Schwartz, Executive Director of the Coalition for Smarter Growth emphasized the need for market studies to measure a viability of the stricter HOV lane eligibility requirement. Schwartz noted: “We’ve recommended that VDOT do some market studies to make sure that HOV3 is going to be effective and there will be demand for it.”

Suzanne Shaw, the Megaprojects Director of VDOT, presented a study that estimated the impact of different HOV operational policies on the existing segment of I-66 between VA Route 234 and I-495 [Shaw, 2016]. The impact on travel speed is shown in Figure 7.

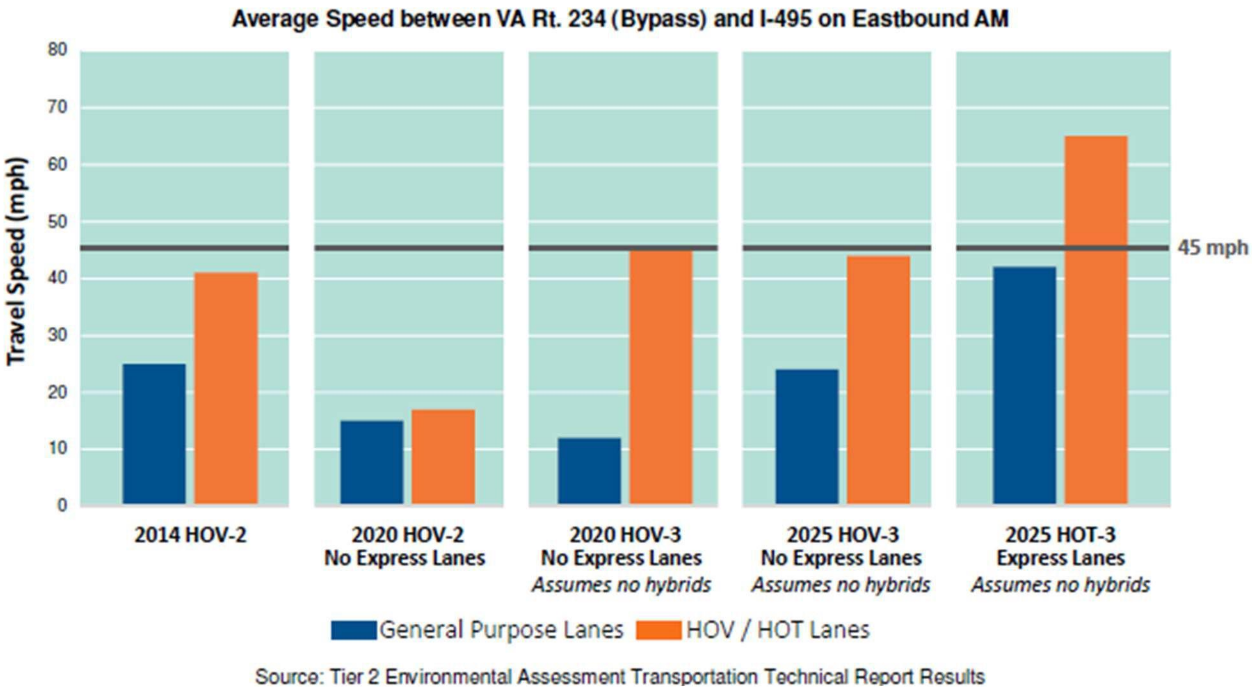

Figure 7. Predicted travel speeds on I-66 due to different HOV operational policy changes [Shaw, 2016]

As shown in Figure 7, the predicted travel speeds in both HOV and MF lanes would decrease significantly between 2014 and 2020 for the HOV2 scenario. When comparing the predicted travel speeds associated with the 2020 HOV2 and 2020 HOV3 scenarios, a marginal decrease was expected in the MF lanes as a result of the change in the occupancy requirement. This decrease can be attributed to an increase in HOV2 in the MF lanes as these vehicles are no longer eligible to use the HOV lane. On the other hand, the drop in traffic volume in the HOV lane due to the HOV3 requirement would result in an increase in travel speed in the HOV lane.

When comparing travel speeds between 2020 and 2025 for the HOV3 scenario, it was expected that there would be a gradual change in carpooling habits over time, as travelers begin to seek the benefits of traveling in the HOV lane in a three-person carpool. The ramp-up time for the formation of these carpools, in order to gain access into the HOV lane, was estimated to be approximately five years. This would correspond with the time it would take for additional car-pooling incentives to be developed under the corridor's Transportation Management Plan, or for other TDM strategies to be implemented for the corridor. These strategies could include specialized programs to incentivize ride sharing, van-pooling, transit service improvements (e.g., increased bus frequency), and "hotspot" transportation network improvements, regardless of whether the I-66 outside the Beltway Express Lanes project was built. In addition, planned roadway capacity improvements identified in the Financially Constrained Long-Range Transportation Plan on parallel facilities (such as US-29, US-50) and on the Fairfax County Parkway and VA Route 28 would aid in removing some trips from the I-66 MF lanes. By reducing traffic volume in the MF lanes, travel speeds would improve. As shown in Figure 7, the speeds in both directions on the Express Lanes in the HOT3 alternative would meet the Federal requirements of 45 mph.

The Code of Virginia 33.1-46.2 identifies several conditions, ranging from political processes and public involvement requirements to traffic operational conditions, that must be met in order for the HOV designation on I-66 to be changed from HOV2 to HOV3. These include the following:

1) Is changing the HOV2 designation to HOV3 in the public interest?
2) Is there quantitative and qualitative evidence that supports the argument that HOV3 will facilitate the flow of traffic on I-66?
3) Is changing the HOV2 designation beneficial to comply with the federal Clean Air Act Amendments of 1990?

The 'Transform 66 outside the Beltway- I-66 Corridor Improvements Project' report argued that the I-66 HOV2 to HOV3 conversion project complies with the Virginia code because of the following:

1) VDOT has issued Notice of Intent to Change Existing Designation, and conducted public hearings.
2) As shown in an analysis similar to Figure 7, by changing the HOV eligibility on I-66 outside the Beltway from HOV2 to HOV3, the average travel times would be reduced and the average travel speeds would increase on both the HOV and MF lanes.
3) The implementation of HOV3 would reduce the number of vehicle miles traveled in the I-66 outside the Beltway study corridor by 3% per day. A reduction in vehicles miles traveled on the corridor could result in lower vehicular emissions and air quality impacts. These benefits would be in the public interest and comply with the Federal Clean Air Act Amendments.

Other operational strategies considered as part of improving operations of HOV facilities include:

1) Increase enforcement to reduce the number of SOVs using the HOV lane.
2) Increase capacity on the HOV facility and use of tolling strategies.

Enforcement of occupancy is a difficult problem. [Ungemah et al., 2008] described an automated approach for checking occupancy requirement; however, it is difficult to implement such a technology. According to the 'Transform 66 outside the Beltway- I-66 Corridor Improvements Project' report, "The effectiveness of the increased enforcement strategy is limited. An example of the effects of enforcement can be obtained from previous efforts conducted on both the inside and outside the Beltway HOV lanes. As discussed in excerpts of Virginia's first quarterly update of the HOV Hybrid Vehicle Exemption Certification provided to FHWA by VDOT on August 17, 2015, enhanced law enforcement efforts were implemented on I-66 HOV facilities in June 2013 and June 2014. On June 19, 2014, 385 offenses were recorded, of which 377 were first time offenses, 7 were second time offenders, and 1 third time offender. An analysis of before and after data for the 2014 effort revealed that there were some short-term improvements in reducing degradation. On I-66 WB, the degradation rate decreased from 35% to 21% of the time upon concluding the effort. While an improvement was noted, the amount of continued HOV facilities degradation still exceeds the criteria of a maximum rate of 10% of the time. Based on both previous experiences, enhanced enforcement can be seen as a moderately effective measure; however, it cannot be used as the only measure for mitigation. Moreover, due to the additional expense of increased patrols on I-66, as well as the unintended residual congestion resulting from vehicles slowing because the presence of police vehicles, additional full-time enforcement may not be feasible."

2.3.2. Case Study 2: HOV3+ to HOV2+, El-Monte Busway I-10, 2000

Opening in 1973, the El Monte busway on the San Bernardino (I-10) freeway is the oldest HOV facility in the Los Angeles area. In 1999, the California Legislature approved Senate Bill 63, lowering the vehicle-occupancy requirement on the El Monte Busway from HOV3+ to HOV2+ full time. The legislation directed the California Department of Transportation (Caltrans) to make this change on January 1, 2000 as part of a temporary demonstration project, which was to extend until June 30, 2001. The legislation also required Caltrans to monitor and analyze the effect of this change on the operation of the freeway and the busway. Based on the operational effects of the change, as documented in the Caltrans operational study, new legislation was passed increasing the vehicle occupancy requirement back to HOV3+ during the morning and afternoon peak periods and maintaining the HOV2+ requirement at all other times, effective July 24, 2000.

[Turnbull, 2002] studied the effect of lowering the vehicle occupancy requirement from HOV3+ to HOV2+. The busway was significantly deteriorated and the MF lanes also suffered slight degradation. Morning peak period travel speeds in the busway were reduced from 65 mph to 20 mph in the morning eastbound direction, while travel speeds in the MF lanes decreased from 25 mph to 23 mph. Hourly busway vehicle volumes during the morning peak period increased from1,100 to 1,600 with the HOV2+ designation, but the number of persons carried declined from 5,900 to 5,200. The freeway lane vehicle volumes and passengers per lane per hour remained relatively similar. Although the El Monte busway demonstrated worsening congestion level from the implementation of a less restrictive HOV policy, inferences may be drawn about the implementation of opposite HOV policies such as moving from HOV2+ to HOV3+.

It should be noted that the research team could not find information about an HOV3+ facility that was converted from HOV2+. A 2013 study commissioned by Caltrans [CTC

& Associates LLC, 2013] also made a similar conclusion: “We did not find any cases of conversions of HOV2+ to HOV3+ facilities in the absence of the implementation of high occupancy tolling. There are a number of non-tolling HOV3+ facilities in the United States, but we found no information related to facilities increasing their occupancy requirements and no available related research concerning operational effects for cases in which there was a conversion from an HOV2+ facility to an HOV3+ facility without the implementation of tolling.”

2.4. Managed Lanes Inventory

2.4.1. National Inventory

According to the last nationwide HOV facility inventory [Chang et al., 2008], California had the most number of HOV facilities in the country followed by Minnesota, Washington, Texas, and Virginia. Figure 8 and Figure 9 show the national inventory of HOV facilities according to vehicle occupancy requirements and time of day operations level, respectively.

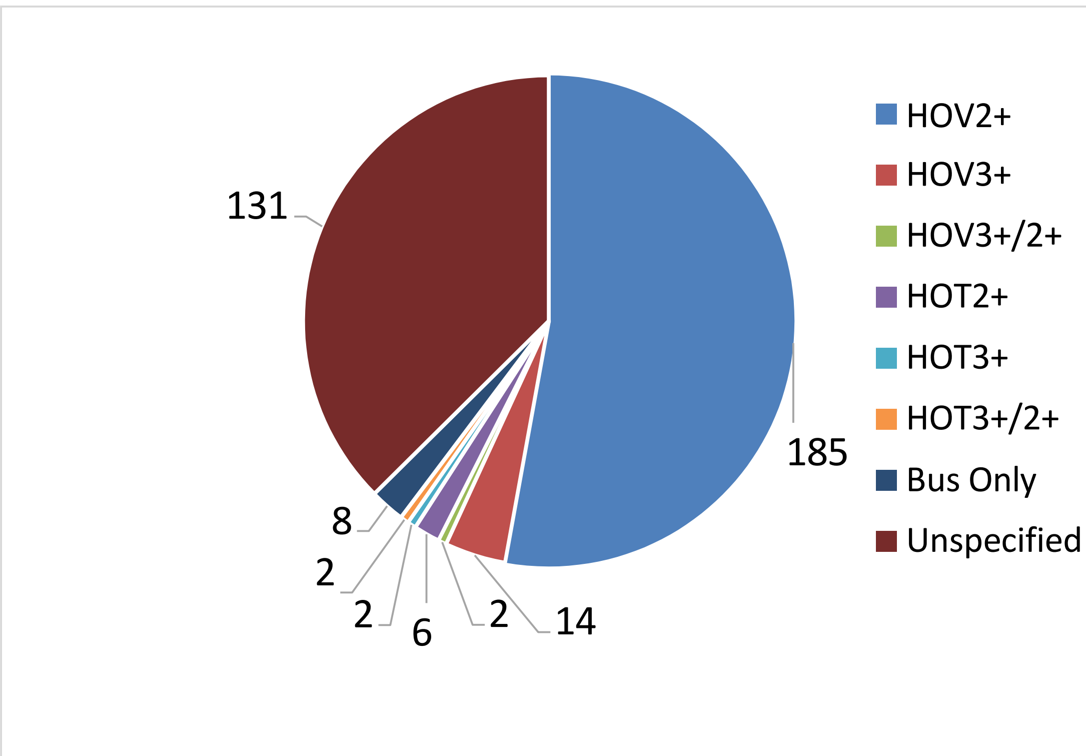

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Figure 8. National HOV facility inventory according to vehicle occupancy requirements [Chang et al., 2008]

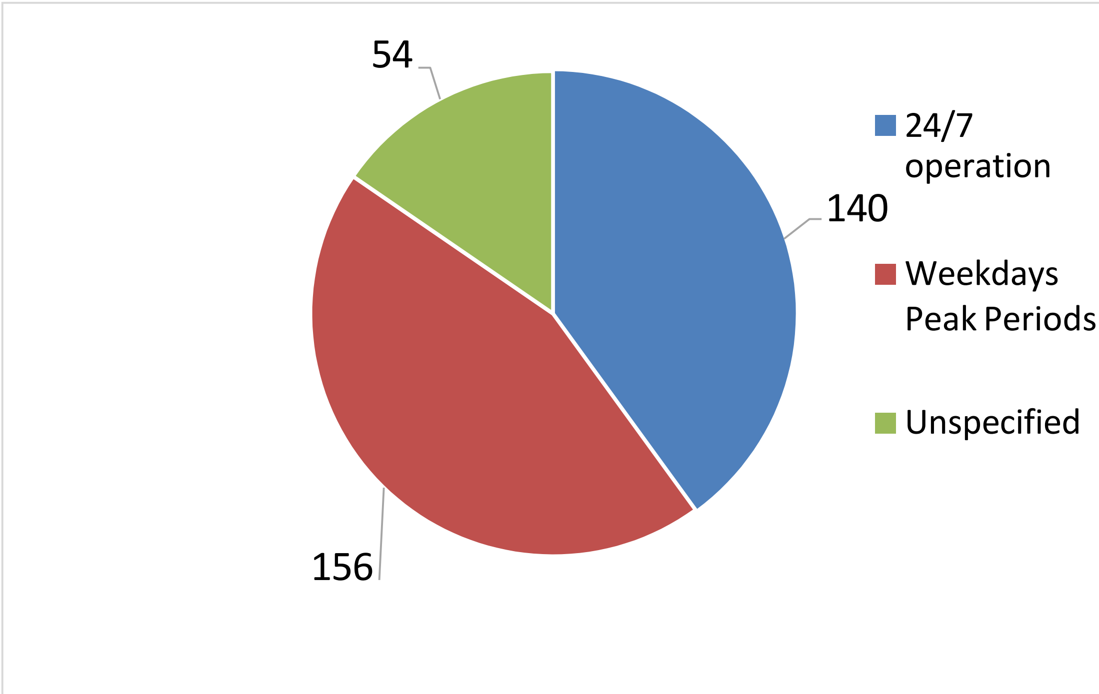


Figure 9. National HOV facility inventory according to time of day operation levels [Chang et al., 2008]

There is an ongoing effort to revise the nationwide HOV facility inventory; however, the current numbers are not yet available. The research team communicated with the FHWA Freeway Facility Program in April 2019. According to the FHWA, notable HOV3+ facilities across the country are:

- California I-10, I-80
- Washington I-405
- Texas US 290
- Colorado I-25, US 36
- Georgia I-85
- Florida I-95
- Virginia I-66, I-495

The states having dynamic priced-, access (time of day), or occupancy-managed lanes are: AZ, CO, CA, FL, GA, LA, PA, MA, HI, MD, NY, NJ, NV, NC, TN, UT, VA, TX, MN, OR, WA, CT, and Puerto Rico.

2.4.2. Inventory of California HOV Facilities

As of 2012, California has 1,371 lane miles of HOV facilities with 181 miles under construction and 567 miles are proposed or in the program. Table 3 summarizes the length of HOV facilities across different districts managed by Caltrans. Occupancy requirements for the existing HOV facilities are summarized in Table 4.

Table 3. HOV facilities in different Caltrans districts [Caltrans, 2012]

District	Region	Length (lane-miles)		
		Existing	Under Construction	Programmed or Proposed
3	Sacramento	93.5	24.1	113.8
4	San Francisco Bay Area	432.3	23.8	59.6
7	Los Angeles	438.5	65.4	80.5
8	San Bernardino	177.5	18.2	240.8
10	Stockton	0.0	13.9	0.0
11	San Diego	13.7	25.3	44.3
12	Orange County	215.7	10.9	27.98
Total		*1371.1*	*181.6*	*567.0*

Table 4. Occupancy requirements of existing HOV facilities in California (Caltrans, 2012)

Occupancy	Total Lane-Miles
2+	1325.13
3+	0.11
3+, 2-seat vehicles with 2 persons permitted	43.9
Buses	0.49
Buses, 3+, 2-seat vehicles with 2 persons permitted	1.5
Total	*1371.13*

Starting on January 1, 2019, vehicles with white or green CAV decals are no longer eligible to use HOV facilities as exempt vehicles. Instead, eligible CAV decals are red (to be expired on January 1, 2022) and purple (to be expired on January 1, 2023). The red and purple decals are issued to vehicles that meet California's super ultra-low emission vehicle (SULEV) standard for exhaust emissions and the federal inherently low-emission vehicle (ILEV) evaporative emission standard. As of December 31, 2017, the California DMV had issued 136,753 green decals and 166,873 white decals. There is no current information about the total number of red and purple decals issued; however, the number is likely to be lower than the previous decals.

2.4.3. Degraded HOV Facilities in California

As required by 23 U.S.C. Section 166, Caltrans prepared the ‘2017 California High-Occupancy Vehicle Facilities Degradation Report and Action Plan’ to report the performance of HOV facilities in California. Caltrans also prepared an action plan that identifies remediation strategies to bring degraded HOV facilities into compliance with the federal performance standard. The degradation report uses the methodology described in Section 1.1 of this report to determine whether an HOV facility is degraded, and if so, the severity of the degradation. In 2017, Caltrans monitored 1,322 lane-miles out of 1,778 lane-miles of HOV facilities statewide. Table 5 summarizes the levels of degradation of these HOV facilities. Caltrans also listed HOV operational improvement strategies for the degraded facilities in four categories, as summarized in Table 6.

Table 5. Degradation status of different California HOV facilities

Status	Lane-Miles	Percentage
Not Degraded	371	28%
Slightly Degraded	332	25%
Very Degraded	220	17%
Extremely Degraded	400	30%
Total	*1,322*	*100%*

Note: 1,322 lane miles monitored total (numbers may not add up due to rounding)

Table 6. HOV operational improvement strategies [Caltrans, 2018]

Category	Strategy
Enforcement	E1 - Enhanced, dedicated, and targeted HOV enforcement including the establishment of enforcement zones.
	E2 - Increase public awareness. Update HOV violation fine amount on the existing signs to the current value. Stripe the number of minimum occupancy in the middle of the pavement HOV diamond symbol.
Operational Improvement	O1A - Addition of general-purpose auxiliary lanes.
	O1B - Addition of HOV auxiliary (weave) lanes.
	O2 - Implement corridor-wide adaptive ramp metering.
	O3 - Convert HOV lanes to HOT/express lanes with consideration to increase the minimum occupancy.
	O4 - Revise pricing strategy on HOT/express lanes to address degradation.
	O5 - Implement or expand commuter assistance programs such as vanpools and Park-and-Ride facilities.
	O6 - Toll exempted clean air vehicles. Tiered or reduced toll rates.
	O7 - Change hours-of-operation for part-time HOV lanes.
	O8 - Install flexible delineators or buffer separation for HOV lanes if space allows.
	O9 - Implementation of Integrated Corridor Management, or other traffic management techniques such as speed harmonization and lane control signals to optimize system performance
	O10 - Improvement in Traffic Incident Management including the deployment or expansion of Freeway Service Patrol.
	O11 - Close gaps in the HOV lane network.
	O12 - Meter HOV lanes on ramps.
	O13 - Study and analyze the appropriate access strategies, including increasing the length of access area or frequency of access, continuous access, or modification/elimination of bottlenecks such as ingress/egress locations.
	O14 - Standardize HOV signing and markings statewide. Addition or enhanced signing and markings at the beginning and along the HOV lanes.
Improved Degradation Monitoring	M1 - Expand the HOV degradation analysis and report to peak periods.
	M2 - Exclude peak periods with non-recurrent congestion from the HOV degradation report.
	M3 - Update or repair vehicle detector systems to improve coverage and monitoring.

Category	Strategy
Capacity Improvement	C1 - Addition of a second HOV lane.
	C2 - Interchange improvements including, but not limited to, construction of direct HOV connectors, ramp widenings, or truck climbing lanes.
	C3 - Reversible lanes; contra-flow.

Among the different operational strategies listed, the following strategies are aligned with the planned research in this project:

- O1A - Addition of general-purpose auxiliary lanes.
- O1B - Addition of HOV auxiliary (weave) lanes.
- O3 - Convert HOV lanes to HOT/express lanes with consideration to increase the minimum occupancy.
- O6 - Toll exempted clean air vehicles. Tiered or reduced toll rates.
- C1 - Addition of a second HOV lane.

In the 2017 HOV facility degradation report [Caltrans, 2018], Caltrans reported the level of degradation for each 5-mile segment of the HOV facilities for each of the past five years. If we treat the level of degradation as a score and sum the scores for each HOV segment over the 5-year reporting period, then we can use the sum score to compare the severity of HOV facility degradation across segments, routes, and districts over the 5-year period. Table 7 lists the top ten degraded HOV segments based on data in the 2017 HOV facility degradation report. There are six segments in District 7, two segments in District 12, and 2 segments in District 4. The eight HOV segments in District 7 and District 12 have been extremely degraded throughout the period from 2013 to 2017. Appendix A provides a full list of HOV segments in the 2017 HOV facility degradation report as sorted by their cumulative degradation score over the period from 2013 to 2017.

Table 7. Most degraded HOV segments from 2013 to 2017

Dis-trict	Route	Di-rec-tion	Begin Coun-ty	Begin Post Mile	End County	End Post Mile	Degradation Score					
							2013	2014	2015	2016	2017	Sum
7	91	EB	LA	R6.400	LA	R11.167	4	4	4	4	4	20
7	105	WB	LA	R10.145	LA	R6.172	4	4	4	4	4	20
7	210	EB	LA	L29.568	LA	R33.827	4	4	4	4	4	20
7	210	WB	LA	R38.395	LA	R33.827	4	4	4	4	4	20
7	405	NB	LA	19.546	LA	24.388	4	4	4	4	4	20
7	405	SB	LA	19.546	LA	14.703	4	4	4	4	4	20
12	5	NB	ORA	R25.097	ORA	29.703	4	4	4	4	4	20
12	55	EB	ORA	R6.000	ORA	R9.761	4	4	4	4	4	20
4	85	SB	SCL	R19.005	SCL	R14.210	4	3	4	4	4	19
4	101	SB	SM	6.6	SM	1.876	4	3	4	4	4	19

Note that it may be more challenging to bring the extremely degraded HOV segments into compliance with the federal performance standard than the slightly degraded segments. Also, consideration should be given to the performance of the parallel MF lanes when selecting an HOV operational improvement strategies. For example, if traffic in the MF lanes is already very congested, then converting the innermost MF lane into a second HOV lane would exacerbate the congestion in the remaining MF lanes. In another example, increasing the occupancy requirement from HOV2+ to HOV3+ could divert a large portion of HOV traffic into the MF lanes, worsening the performance of the MF lanes.

3. HOV Lane Performance Degradation Analysis

In this chapter, the research team analyzed the real-world performance data of HOV facilities and evaluated different methods and measures of performance analysis. The Caltrans' Performance Measurement System (PeMS) was used to obtain real-world traffic conditions (e.g., volume and speed). The research team also combined the data for multiple selected HOV facilities for multiple years into a single database. First, the research team selected the current FHWA approved HOV facility performance analysis approach for a selected HOV facility. Different variants of the FHWA analysis approaches such as changing peak hour period, re-segmenting the sections, removal of incident affected days were applied to the selected HOV facility. The research team then performed the FHWA approved HOV performance analysis for all the major HOV facilities in Caltrans districts 7, 8, and 12 for 2017, 2018, and 2019. Next, the team investigated the use of alternative metrics representing HOV performance degradation. One of the major metrics was the speed differential between the HOV lanes and the MF lanes. Finally, the research team analyzed the average delay induced by different types of incidents and developed statistical models to determine the impact of the incident on HOV lane performance.

3.1. Data

3.1.1. Data Collection

PeMS was the sole source of data for the analysis conducted in this task. PeMS collects, filters, processes, aggregates and examines traffic data. This includes continuous measurements recorded by detectors and tag readers. Traffic detectors originally transmit the data at 30-second resolution. Then, PeMS aggregates the data in a per lane basis at 5-minutes resolution. This is when PeMS reports that there is a hole in the data. A hole means that there was no data reported during that 5-minute interval. PeMS has an internal process of computing the missing data using a detector specific pre-computed g-factor. The 5-minute lane-by-lane data are aggregated across lanes to form an aggregate/ station value for a location. The method for traffic detector data reporting and aggregation is shown in Figure 10.

PeMS data were obtained for selected freeways for use as case studies. Since this research project is focused on congestion mitigation in HOV facilities, the research team was focused on HOV facilities which are degraded. In addition, the research team planned to use the Southern California Association of Government (SCAG)'s regional travel demand model for assessing several alternative HOV operational policies, the selected HOV facilities should be in the SCAG model boundary. Given these criteria and in consultation with the Caltrans project panel, the research team selected the following HOV facilities:

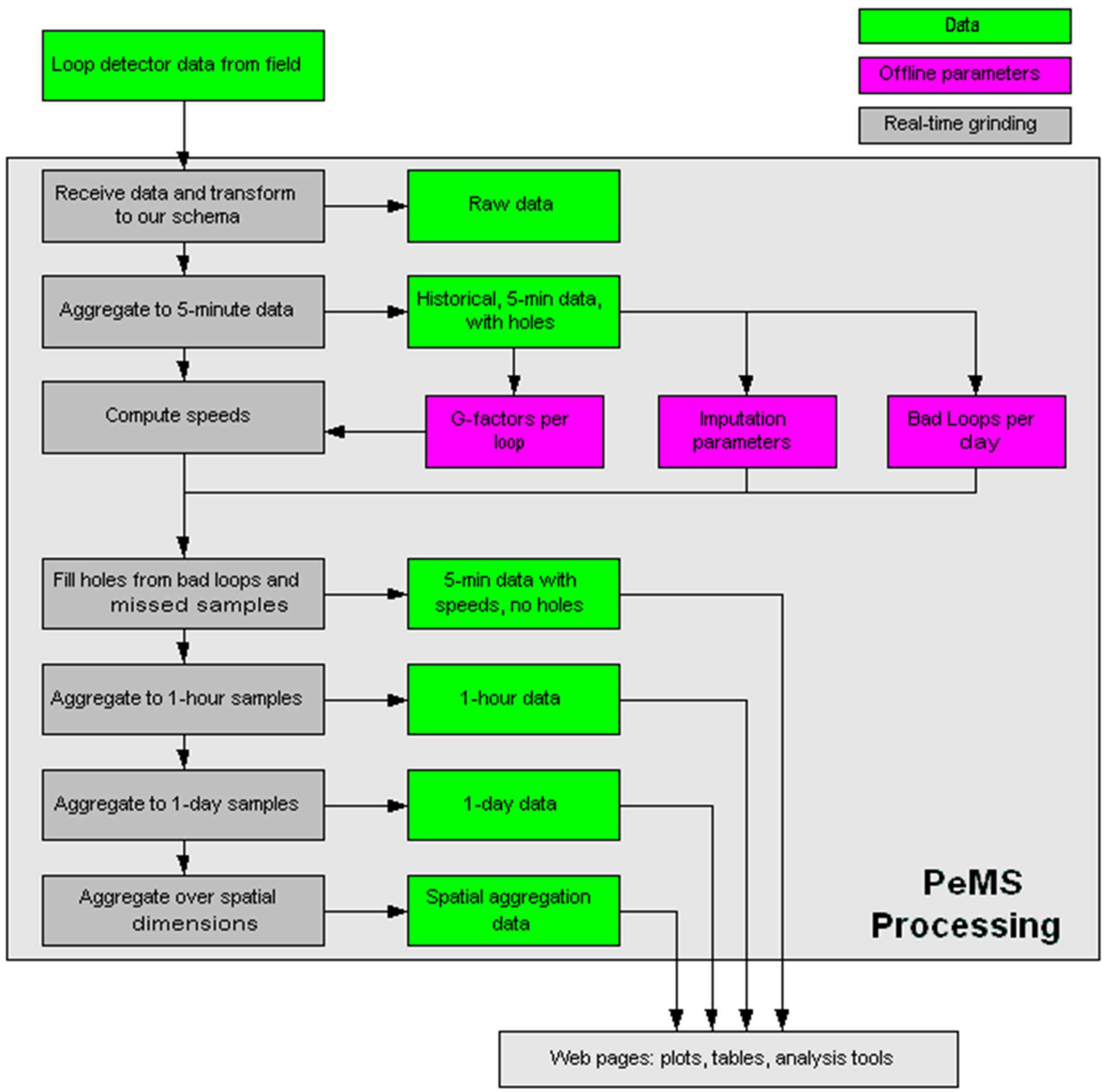


Figure 10. PeMS Data Aggregation and Reporting Process (source: www.pems.dot.ca.gov)

- District 7 – Los Angeles County
  - SR -91 E and SR- 91 W (between absolute post miles 0 and 15)
  - I-105 E and I-105 W (between absolute post miles 0 and 20)
  - I-405 N and I-405 S (between absolute post miles 20 and 75)
  - I-10 E and I-10 W (between absolute post miles 15 and 48)

- District 8 – San Bernardino and Riverside Counties
  - I-10 E and I-10 W (between absolute post miles 48 and 60)
  - SR-91 E and SR-91 W (between absolute post miles 38 and 60)

- District 12 – Orange County
    - I-5 N and I-5 S (between absolute post miles 75 and 120)
    - SR-91 E and SR-91 W (between absolute post miles 15 and 38)

The research team selected 5 miles as the spatial aggregation interval for the PeMS data. The data were downloaded in the hourly aggregation format. The fields in the hourly aggregated file are shown in Table 8. Each lane in the hourly station files had separate speed observations. The hourly average speeds for the HOV and MF lanes were recorded separately.

Table 8. Specification of Data Fields in the Hourly Station Data

Name	Comment	Units
Timestamp	The date and time of the beginning of the summary interval. For example, a time of 08:00:00 indicates that the aggregate(s) contain measurements collected between 08:00:00 and 08:59:59. Note that minute and second values are always 0 for hourly aggregations. The format is MM/DD/YYYY HH24:MI:SS.	
Station	Unique station identifier. Use this value to cross-reference with *Metadata* files.	
District	District #	
Route	Route #	
Direction of Travel	N | S | E | W	
Lane Type	A string indicating the type of lane. Possible values (and their meaning are: • CD (Coll/Dist) • CH (Conventional Highway) • FF (Fwy-Fwy connector) • FR (Off Ramp) • HV (HOV) • ML (Mainline) • OR (On Ramp)	
Station Length	Segment length covered by the station in miles/km.	
Samples	Total number of samples received for all lanes.	
% Observed	Percentage of 5-minute lane points that were observed (e.g. not imputed).	%
Total Flow	Sum of 5-minute flows over the hour. Note that the basic 5-minute rollup normalizes flow by the number of good samples received from the controller.	Veh/Hour
Avg Occupancy	Average of 5-minute station occupancies over the hour expressed as a decimal number between 0 and 1.	%
Avg Speed	Flow-weighted average of 5-minute station speeds. If flow is 0, mathematical average of 5-minute station speeds.	Mph
Delay (V_t=35)	The average delay over the station length, with respect to a threshold speed of 35 mph.	
Delay (V_t=40)	The average delay over the station length, with respect to a threshold speed of 40 mph.	

Name	Comment	Units
Delay (V_t=45)	The average delay over the station length, with respect to a threshold speed of 45 mph.	
Delay (V_t=50)	The average delay over the station length, with respect to a threshold speed of 50 mph.	
Delay (V_t=55)	The average delay over the station length, with respect to a threshold speed of 55 mph.	
Delay (V_t=60)	The average delay over the station length, with respect to a threshold speed of 60 mph.	
Lane N Flow	Sum of 5-minute flows for lane N over the hour. Note that the basic 5-minute rollup normalizes flow by the number of good samples received from the controller. N ranges from 1 to the number of lanes at the location.	Veh/Hour
Lane N Avg Occ	Average of 5-minute occupancies for lane N over the hour expressed as a decimal number between 0 and 1. N ranges from 1 to the number of lanes at the location.	%
Lane N Avg Speed	Flow-weighted average of 5-minute lane N speeds. If flow is 0, mathematical average of 5-minute lane speeds. N ranges from 1 to the number of lanes at the location.	Mph

The research team downloaded three years of data to analyze the HOV lane performance. Since the team had access to the 2017 HOV Lane Degradation Report from Caltrans at the beginning of this project, a decision was made to start the performance analysis from 2017. The research team collected the station data for the selected HOV facilities for all subsequent years after 2017. So far, three years of data were selected – 2017, 2018, and 2019.

3.1.2. Incident Statistics

The research team analyzed the incident data reported by the California Highway Patrol (CHP) and listed in PeMS as the CHP Incidents Month data. The dataset contains CHP Incidents from all Caltrans Districts where each downloadable file contains all incidents that occurred in one month. The explanation for different fields in the CHP incidents months file is given in Table 9. Each reported incident is given a unique incidentID in the system. CHP also determines an incident type from a fixed set of previously determined incident categories. It is to be noted that the incident data has spatial granularity in the longitudinal direction, but not laterally. That means CHP reports which mile-marker the reported incident had happened on a given freeway and freeway direction. However, CHP does not report the exact lane location where the incident had occurred.

Table 9. Field Specification for CHP Incidents Months Files

Field Name	Comment	Units
Incident ID	An integer value that uniquely identifies this incident within PeMS.	-
CC Code	CC Code	-
Incident Number	an integer incident number	-

Timestamp	Date and time of the incident with a format of MM/DD/YYYY HH24:MI:SS. For example 9/3/2013 13:58, indicating 9/3/2013 1:58 PM.	-
Description	A textual description of the incident.	-
Location	A textual description of the location.	-
Area	A textual description of the Area. For example, East Sac.	-
Zoom Map	Zoom Map	-
TB xy	Lat/lon in state plane. Available from 4/9/2009	-
Latitude	Latitude	-
Longitude	Longitude	-
District	the District number	-
County FIPS ID	The FIPS County identifier.	-
City FIPS ID	The FIPS City identifier.	-
Freeway Number	Freeway Number	-
Freeway Direction	A string indicating the freeway direction.	-
State Postmile	State Postmile	-
Absolute Postmile	Absolute Postmile	-
Severity	Severity	-
Duration>/td>	Duration	minutes

Table 10, Table 11, and Table 12 summarize the frequency of different incident types that happened in Districts 7, 8, and 12 during 2017 – 2019. Nearly half of the incidents were listed as '1125-Traffic Hazard'. Approximately 30% of the incidents were traffic collisions where no injuries or unknown injuries were reported. Nearly 5% of cases were hit and run conditions. About 15% of incidents required ambulance calls.

Table 10. Incident Frequency by Types of Incidents during 2017

Incident Type	District 7	District 8	District 12
1013-Road/Weather Conditions	16	17	4
1125-Traffic Hazard	81580	30303	23330
1125-Traffic Hazard (CHP)	1	0	0
1125A-Animal Hazard	1756	1118	202
1144-Fatality	8	6	4
1166-Defective Traffic Signals	248	168	67
1179-Trfc Collision-1141 Enrt	8121	4270	2002
1179-Trfc Collision-1141Enrt	2186	758	582
1180-Trfc Collision-Major Inj	6	3	2
1181-Trfc Collision-Minor Inj	45	29	11
1182-Trfc Collision-No Inj	29910	8245	6536
1183-Trfc Collision-Unkn Inj	21920	10263	5509
1184-Provide Traffic Control	39	38	14
1184-Req CHP Traffic Control	4	186	6

Incident Type	District 7	District 8	District 12
20001-Hit and Run w/Injuries	323	3193	84
20002-Hit and Run No Injuries	7325	332	1734
23114-Object Flying From Veh	373	5	175
AMBER Alert	14	250	7
ANIMAL-Live or Dead Animal	1016	416	97
BREAK-FSP Req Traffic Break	18	1077	0
BREAK-Traffic Break	1216	937	315
CFIRE-Car Fire	1727	2	375
CLOSURE of a Road	1213	309	260
CZP-Assist with Construction	305	1	127
DOT-Request CalTrans Notify	128	143	29
ESCORT for Road Conditions	3	12	0
FIRE-Report of Fire	2959	1123	214
FLOOD-Roadway Flooding	95	49	51
FOG-Foggy Conditions	1	1	0
HAZMAT-Hazardous Materials Inc	6	5	0
JUMPER	285	183	109
MAYDAY-Aircraft Emergency	2	133	1
MZP-Assist CT with Maintenance	532	1	58
SIG Alert	1306	438	347
SILVER Alert	2	1	0
SLIDE-Mud/Dirt/Rock	18	12	1
SPILL-Spilled Material Inc	22	20	7
TADV-Traffic Advisory	17	109	11
WIND Advisory	62	25	2
WW-Wrong Way Driver	664	394	207
YELLOW ALERT	1	0	0
CORD-County Roads	1	0	0
Total	**165,474**	**64,575**	**42,480**

Table 11. Incident Frequency by Types of Incidents during 2018

Incident Type	District 7	District 8	District 12
1013-Road/Weather Conditions	8	20	3
1125-Traffic Hazard	79657	32519	23684
1125A-Animal Hazard	1656	1159	222
1144-Fatality	6	7	5
1166-Defective Traffic Signals	247	138	41
1179-Trfc Collision-1141 Enrt	7713	4201	1837
1179-Trfc Collision-1141Enrt	2142	797	479
1180-Trfc Collision-Major Inj	6	3	1
1181-Trfc Collision-Minor Inj	44	19	14
1182-Trfc Collision-No Inj	29571	8494	5801
1183-Trfc Collision-Unkn Inj	21558	9637	5592
1184-Provide Traffic Control	53	41	24
1184-Req CHP Traffic Control	5	NA	17
20001-Hit and Run w/Injuries	313	143	87
20002-Hit and Run No Injuries	7322	3274	1719
23114-Object Flying From Veh	395	368	160
AMBER Alert	11	1	12
ANIMAL-Live or Dead Animal	952	259	111
BREAK-FSP Req Traffic Break	13	NA	273

Incident Type	District 7	District 8	District 12
BREAK-Traffic Break	1095	313	NA
CFIRE-Car Fire	1577	1132	338
CLOSURE of a Road	1008	835	273
CZP-Assist with Construction	428	275	165
DOT-Request CalTrans Notify	101	193	32
FIRE-Report of Fire	2796	963	187
FLOOD-Roadway Flooding	82	47	42
FOG-Foggy Conditions	2	2	NA
HAZMAT-Hazardous Materials Inc	2	2	1
JUMPER	359	248	94
MAYDAY-Aircraft Emergency	7	2	NA
MZP-Assist CT with Maintenance	651	156	108
RKRUN-Rock Run	1	NA	NA
SIG Alert	1625	429	281
SILVER Alert	2	NA	NA
SLIDE-Mud/Dirt/Rock	9	NA	NA
SNOFL-Joint Weather Ops	1	NA	NA
SNOW Information	1	2	NA
SPILL-Spilled Material Inc	10	17	8
SPINOUT	140	29	25
TADV-Traffic Advisory	11	140	11
WIND Advisory	49	18	NA
WW-Wrong Way Driver	642	355	186
ESCORT for Road Conditions	NA	9	NA
Total	**162,271**	**66,247**	**41,833**

Table 12. Incident Frequency by Types of Incidents during 2019

Incident Type	District 7	District 8	District 12
1013-Road/Weather Conditions	22	18	1
1125-Traffic Hazard	76753	32639	25068
1125-Traffic Hazard (CHP)	2	NA	NA
1125A-Animal Hazard	1733	1087	197
1144-Fatality	14	13	3
1166-Defective Traffic Signals	257	198	30
1179-Trfc Collision-1141 Enrt	7842	4183	1744
1179-Trfc Collision-1141Enrt	2209	883	619
1180-Trfc Collision-Major Inj	5	4	3
1181-Trfc Collision-Minor Inj	43	20	12
1182-Trfc Collision-No Inj	28361	9037	5375
1183-Trfc Collision-Unkn Inj	21509	9877	6251
1184-Provide Traffic Control	55	57	33
1184-Req CHP Traffic Control	6	2	1
20001-Hit and Run w/Injuries	319	171	75
20002-Hit and Run No Injuries	7213	3315	1657
23114-Object Flying from Veh	397	335	156
AMBER Alert	2	1	2
ANIMAL-Live or Dead Animal	990	255	127
BREAK-FSP Req Traffic Break	15	1	1
BREAK-Traffic Break	1342	397	307
CFIRE-Car Fire	1512	972	338
CLOSURE of a Road	747	888	97

Incident Type	District 7	District 8	District 12
CZP-Assist with Construction	807	407	150
DOT-Request CalTrans Notify	105	200	33
ESCORT for Road Conditions	2	9	NA
FIRE-Report of Fire	3297	923	151
FLOOD-Roadway Flooding	182	64	34
FOG-Foggy Conditions	8	1	NA
JUMPER	322	295	70
MAYDAY-Aircraft Emergency	1	4	NA
MZP-Assist CT with Maintenance	533	183	61
SIG Alert	1635	416	243
SILVER Alert	1	NA	NA
SLIDE-Mud/Dirt/Rock	19	9	NA
SNOFL-Joint Weather Ops	6	NA	NA
SNOW Information	2	2	NA
SPILL-Spilled Material Inc	22	14	4
SPINOUT	433	92	77
TADV-Traffic Advisory	10	100	8
WIND Advisory	48	30	
WW-Wrong Way Driver	638	430	197
YELLOW ALERT	1	NA	1
RKRUN-Rock Run	NA	2	NA
HAZMAT-Hazardous Materials Inc	NA	4	NA
Total	**159,420**	**67,538**	**43,126**

The distribution of incident durations for the selected districts in 2019 is shown in Figure 11. The bin width for the histogram is 5 minutes. Approximately 70% of the incidents had a duration of fewer than 25 minutes. More than 95% of the incidents had a duration of fewer than 100 minutes.

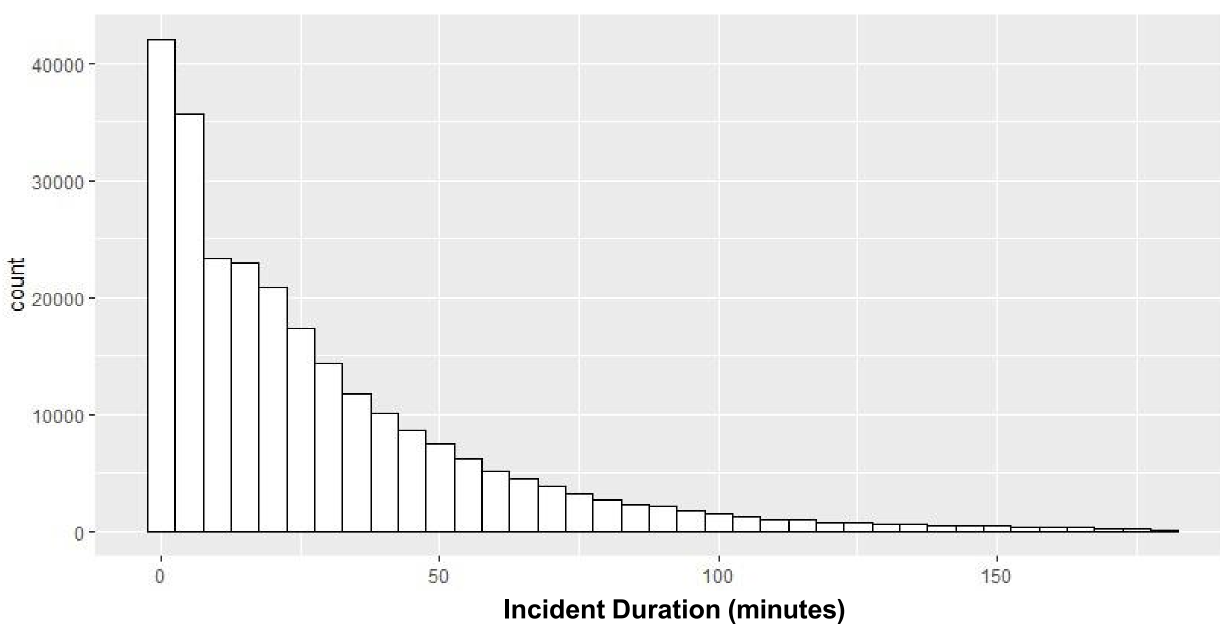


Figure 11. Distribution of Incident Durations for All the Incidents in Districts 7, 8, and 12 in the year 2019

3.2. HOV Lane Performance Degradation Sensitivity Analysis

HOV lane performance is currently evaluated using thresholds of average facility speed only. If the average speed is less than 45 miles per hour in a five-mile segment for the anyone of the chosen peak hour, the entire segment is considered to have a compromised LOS. This approach for a fixed speed threshold-based approach is shown in Figure 12.

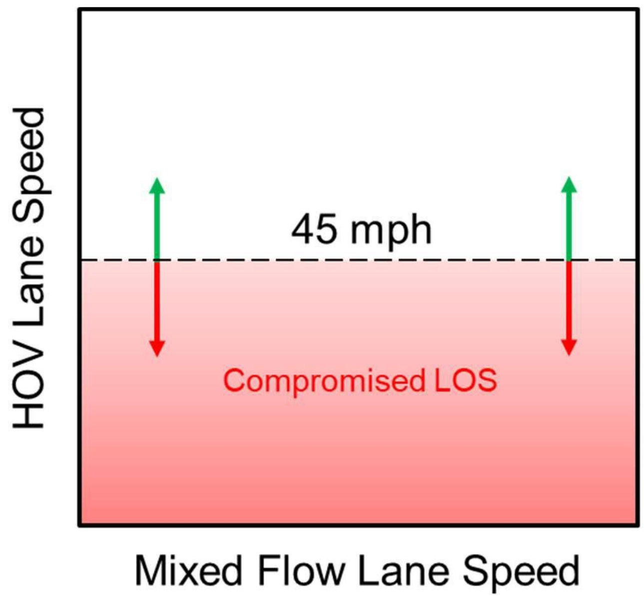


Figure 12. Existing Method for Determining a Fixed Speed Threshold to determine compromised LOS

This approach for the determination of compromised LOS depends highly on the process of spatial and temporal aggregation of the measure of performance under consideration. The methodology for the parameter sensitivity analysis of the HOV facilities using the PeMS station data is described in the following sections.

3.2.1. Methodology

The research team selected SR-91 in District 8 as the HOV facility to test parameter sensitivity. Figure 13 shows the degradation status of the facility in the 2017 degradation report. The segment had a few sections degraded according to the FHWA definition for degradation.

Route	Direction	Begin County	Begin Post Mile	End County	End Post Mile	Latest 5-Year Degradation Status[4]				
						2013	2014	2015	2016	2017
91	EB	RIV	R0.000	RIV	4.266	4	4	4	3	1
		RIV	4.266	RIV	8.644	3	4	1	1	2
		RIV	8.644	RIV	13.022	1	1	1	2	3
		RIV	13.022	RIV	17.400	1	2	4	2	4
91	WB	RIV	17.400	RIV	13.022	1	1	1	2	2
		RIV	13.022	RIV	8.644	1	1	2	2	2
		RIV	8.644	RIV	4.266	3	4	2	2	1
		RIV	4.266	RIV	R0.000	2	3	2	1	1

Figure 13. Degradation status for SR-91 in the 2017 degradation report

The research team has analyzed the HOV lane performance for SR-91 using changes in the following parameters:

- *Changing peak hours*: The approach adopted in the 2017 degradation report considers a fixed morning and afternoon peak hours for all the facilities across the state. The morning peak hour was selected between 8 am to 9 am. The afternoon peak hour was selected between 5 pm – 6 pm. In the modified analysis approach, the research team considered a 3-hour peak period. The modified morning peak hour was between 6 am to 9 am. Similarly, the modified afternoon peak hour was considered between 3 pm to 6 pm.

- *Re-segmentation of the facility*: In the 2017 degradation report, segments were selected according to approximate 5-mile segmentation. However, the automated analysis approach adopted in this task did not allow us to use arbitrary mile markers to segment the facility. Therefore, the research team ended up in segmenting the facility in equal 5-mile segments which corresponded similarly to the segmentation adopted in the 2017 report. In the re-segmented analysis, segmentation break-point was selected at major interchange locations. Figure 14 shows the segmentation for SR-91 WB according to the baseline assumption and with re-segmentation. Figure 15 shows the segmentation for SR-91 EB for similar segmentation assumptions.

- *Removal of incident affected days*: Incidents happening during the same time period of the HOV performance measurement could affect the determination of compromised LOS for the time period. Therefore, the research team filtered out all the station data when all three of the following conditions were satisfied
    - An incident with a duration of more than 5 minutes had happened
    - The incident happened within the same 5-mile segmentation

- The incident happened within the same peak time periods i.e. 8 am – 9 am and 5 pm – 6 pm.

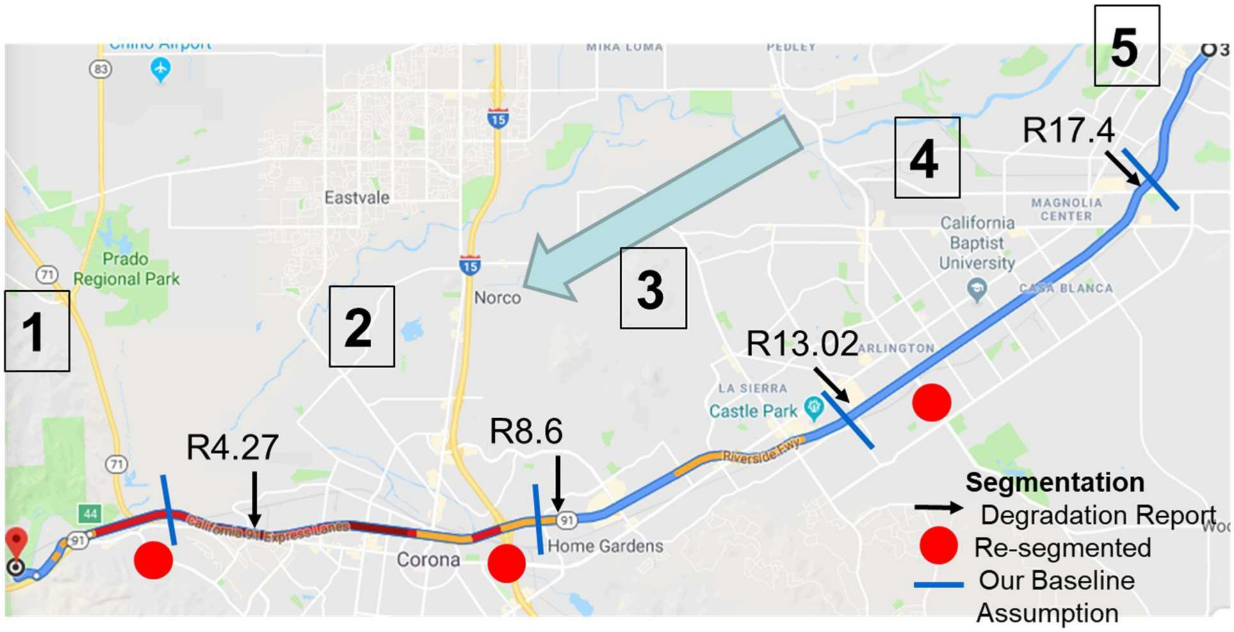


Figure 14. Different Segmentation Scenarios for SR-91 WB in District 8

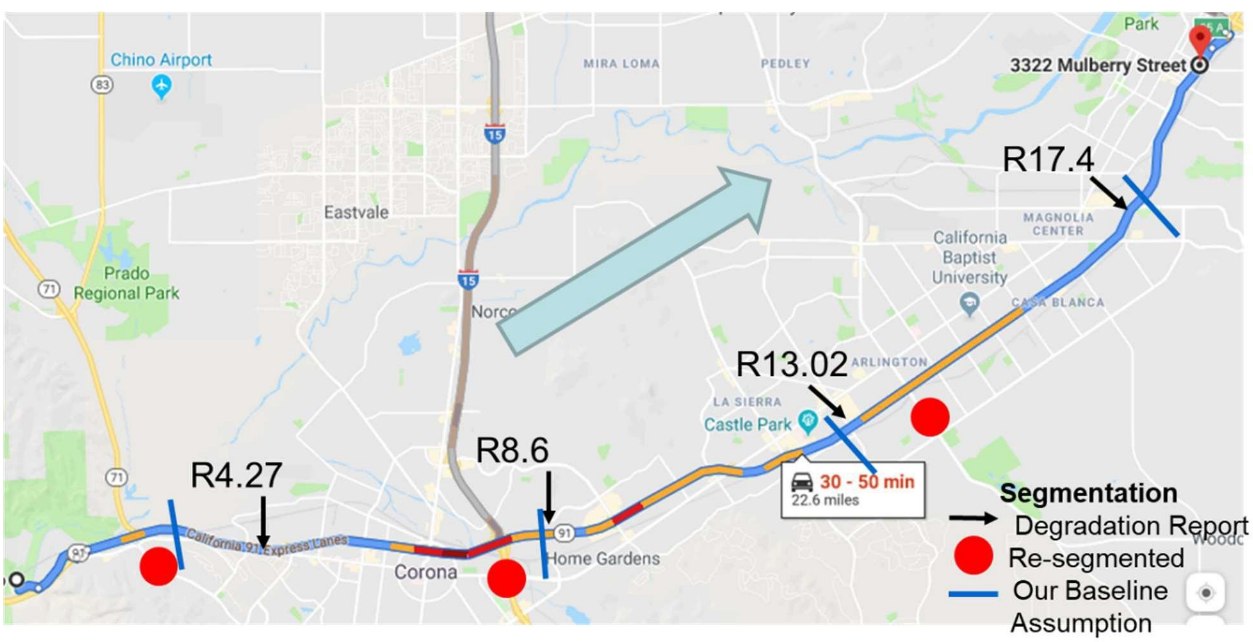


Figure 15. Different Segmentation Scenarios for SR-91 EB in District 8

3.2.2. Changing Peak Hours

The results for changing peak hour consideration are shown in Figure 16 and Figure 17. In the Westbound direction, most of the degradation determination was improved except for segment 4. In the Eastbound direction, the degradation determination worsened in almost all the segments. The reason for this change may be explained by the fact that a three-hour peak period has a high likelihood of capturing the real-peak hour for the facility. However, different facilities have different peaking patterns. Some facility travel times (or delay) will peak sharply at the peak hour or maybe during the peak 15 minutes. Some facility travel times may sustain during the entire 3-hour peak period. In cases where the real peak hour does not sustain for a longer period and the previously considered 1-hour window did not capture the true peak, the three-hour peak consideration worsened the degradation determination. Conversely, if the previous 1-hour window did capture the true peak, then the 3-hour degradation determination will be milder. In fact, the more peaked the worst conditions are, the milder will be the degradation determination for a 3-hour peak.

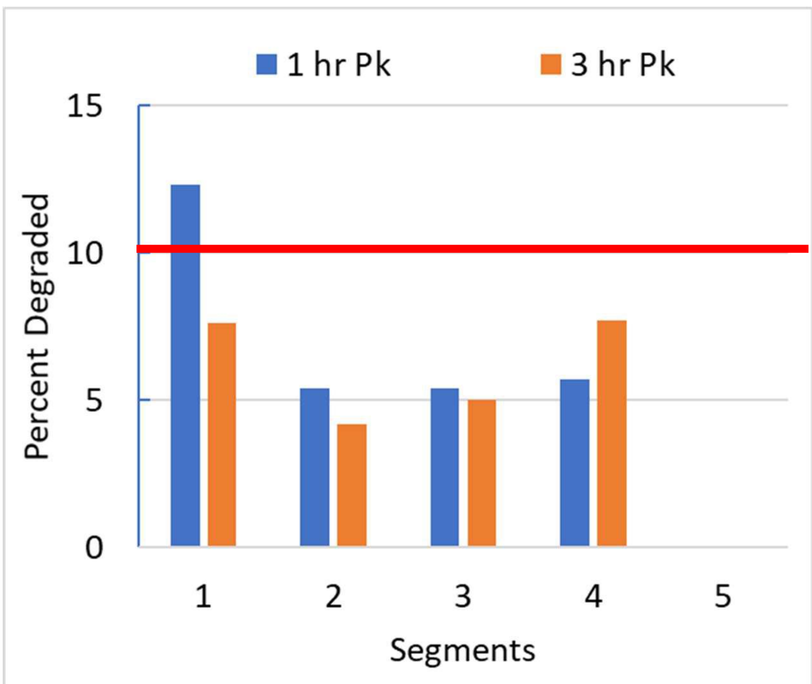


Figure 16. Degradation results for SR-91 WB for Changing Peak Hours

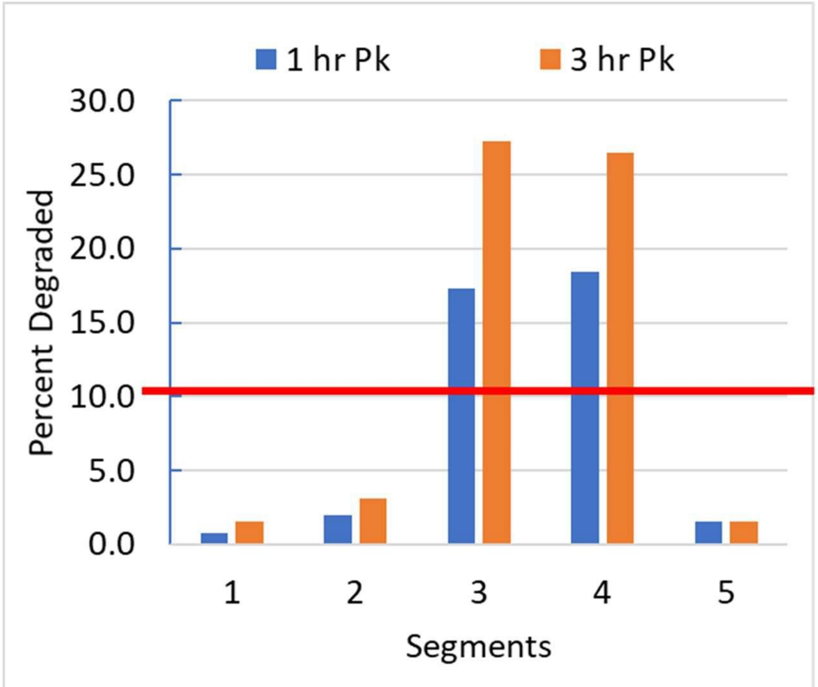


Figure 17. Degradation results for SR-91 EB for Changing Peak Hours

3.2.3. Re-segmentation

The results for re-segmentation is shown in Figure 18 and Figure 19.

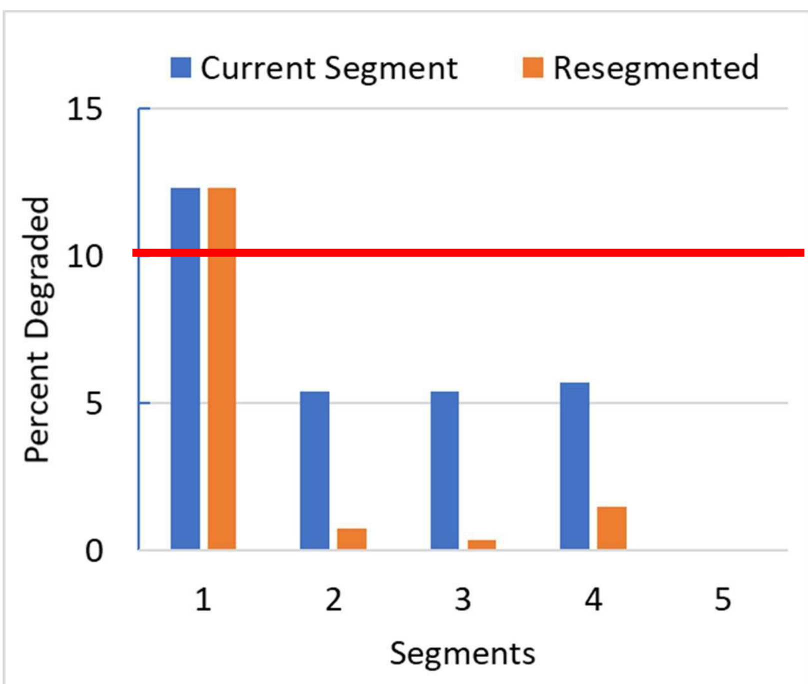


Figure 18. SR-91 WB Change in Degradation Performance Due to Re-segmentation

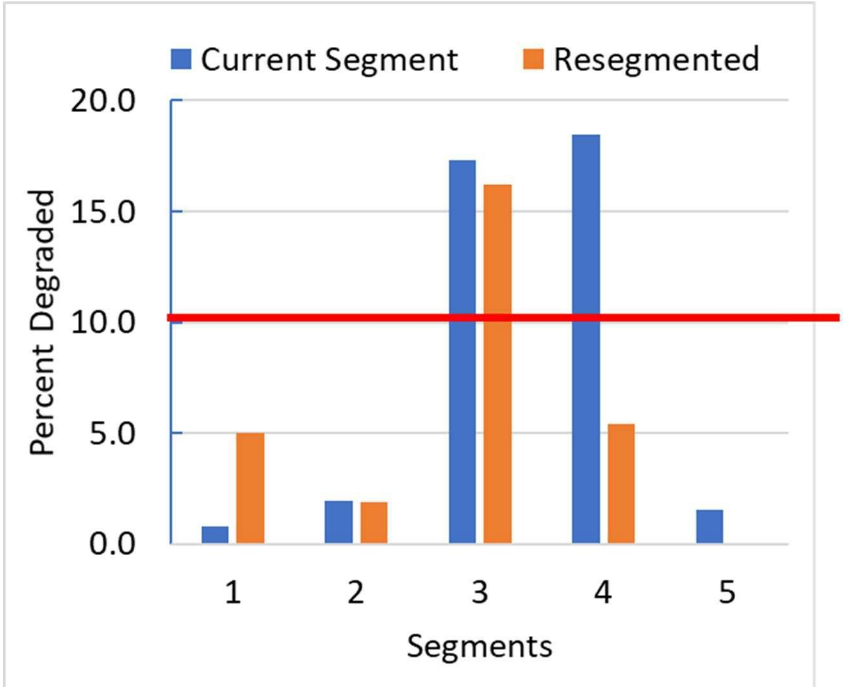


Figure 19. SR-91 EB Change in Degradation Performance Due to Re-segmentation

In most cases, re-segmentation of the facility according to the actual geometric and demand patterns of the facility concentrates vehicle detector stations with low speed in a single segment. Previously, some of these vehicle detector stations were split onto multiple analysis segments causing all these analysis segments to be determined as degraded.

The research team found that concentrating vehicle detector stations with low speed in a single analysis segment did not considerably increase the degradation determination for that segment. On the other hand, removing some of the vehicle detector stations with low speed from the re-segmented condition improves the performance of the degraded segment as determined with random segmentation.

3.2.4. Removal of Incident Affected Data

As expected, removing incident affected data for the selected facility (SR-91 in District 8) resulted in improved performance of the HOV facility in both directions. The results for this change are shown in Figure 20 and Figure 21. In both figures, the drops in percent time degraded varied by segment. The drops were generally more pronounced for the segments that were more congested. This is somewhat expected as incidents partly contributed to the congestion on these segments.

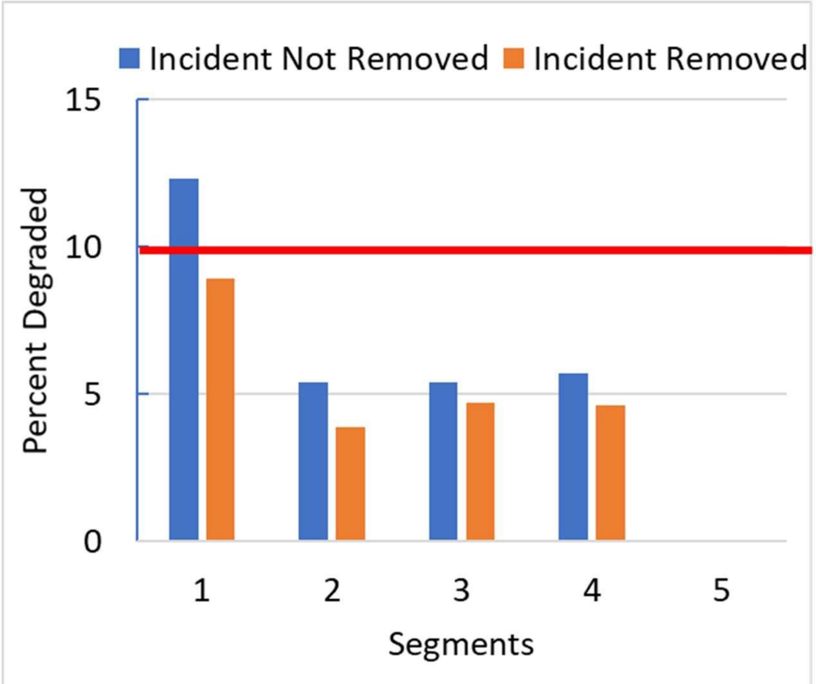


Figure 20. Change in Degradation Performance Due to Incident Affected Data Removal for SR-91 WB (District 8)

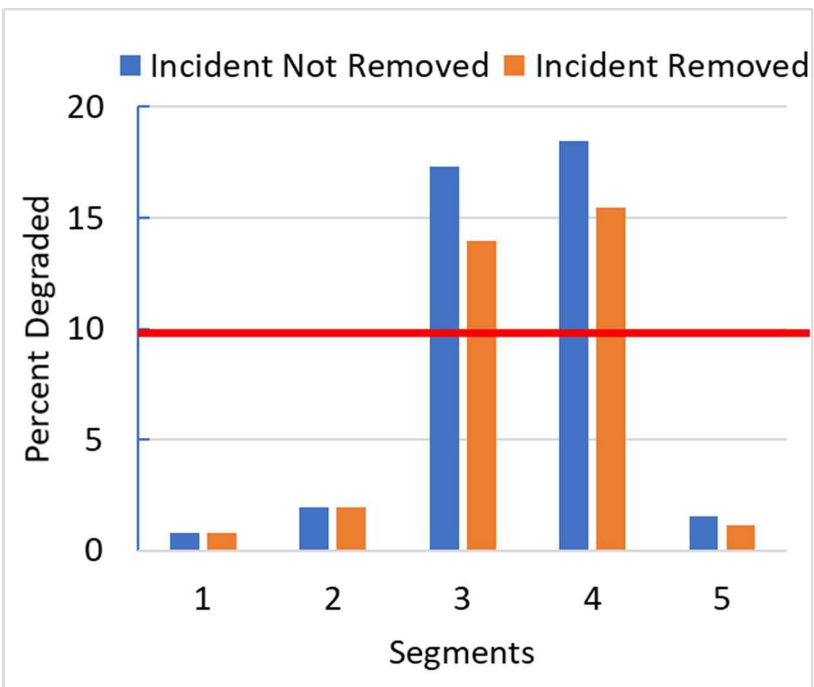


Figure 21. Change in Degradation Performance Due to Incident Affected Data Removal for SR-91 EB (District 8)

3.3. Performance Degradation for Selected HOV Facilities

In this section, the research team applied the HOV lane performance analysis for the selected facilities as mentioned in Section 3.1. The research team, in consultations with the Caltrans Project Panel, also decided to use the following parameters for degradation analysis:

1. *Peak Period*: Three-hour peaks were considered. The rationale for this selection was that in Southern California, a highly peaked travel time condition is unlikely. However, the temporal location of the peak varies with the geographical condition of the segment. In many cases, the morning peak happens early in the day, sometimes as early as 6 am in the morning. The selected peak period for this analysis was 6 am – 9 am for the morning peak period and 3 pm – 6 pm for the afternoon peak period.

2. *Segmentation*: The manual generation of segmentation is time-consuming and requires field level familiarity with the demands and operations of the facility. Therefore, the research team refrained from considering the re-segmentation of the facility. However, segmentation is an important consideration for degradation analysis and segments need to be picked carefully to not overestimate the impacts of some localized congestions over a disproportionate length of the facility.

3. *Incident Affected Data Removal*: The research team has concluded from the parameter sensitivity study that the removal of incident affected days improves the degradation performance of the facility. However, the team also understands that removing the data for an entire peak period because of a single incident happening at that space-time will cause underestimation of the degradation performance for that facility. Therefore, no incident removal was done while determining the HOV lane performance degradation.

3.3.1. Performance Degradation over Time

The level of degradation changes over the years for the selected facilities is shown in Figure 12 – Figure 17. In these figures, the x-axis shows different 5-mile segments. The adopted naming convention for the segments was according to the following:

1. *First part*: Numerical naming for the freeway. Example: 91 for SR-91, 10 for I-10.

2. *Second part*: Direction of the freeway. Example: “E” for Eastbound.

3. *Third part*: Absolute posted mileage for the segment. Example: (10, 15] means a segment that started at mile-marker 10 and ended just before mile-marker 15.

The two red lines in the figure represent the frequency thresholds for the determination of degradation. As per the FHWA definition, a segment degraded by more than 10 percent of the weekdays during a 180-day period is considered degraded. It is to be noted that in this analysis we have taken the entire 365- days of the year as the analysis period. Therefore, the degradation statistics reported in the subsequent figures will be milder compared to actual degradation statistics for a partial year. Since this analysis is not performed to make actual determination of degradation for reporting purposes, rather was performed to make multi-year comparisons, a full-year degradation determination will serve its purpose. The second horizontal red-line at 75 percent degradation level shows thresholds for extremely degraded segments as defined in the 2017 degradation report.

Figure 22, Figure 23, and Figure 24 show degradation performance over time for district 7 facilities.

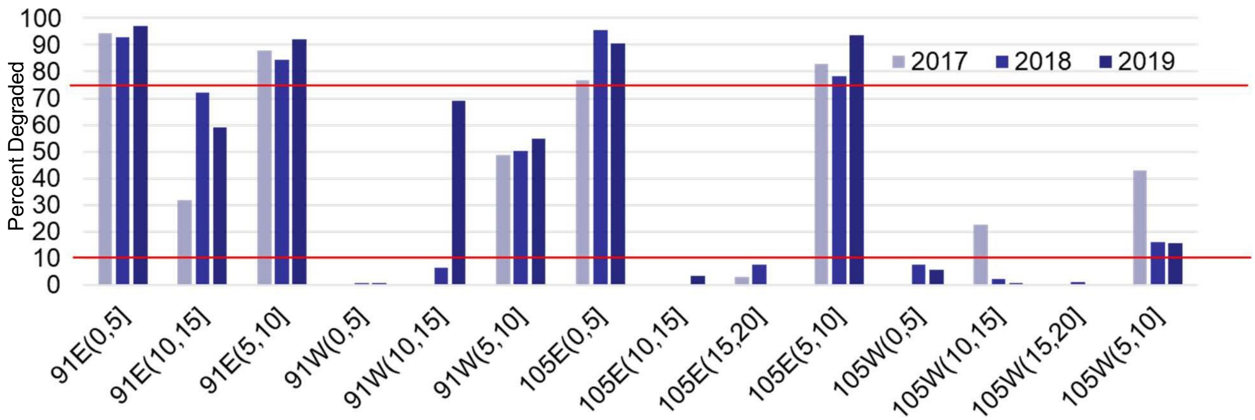


Figure 22. Degradation Trend for District 7 Selected Facilities (part -1)

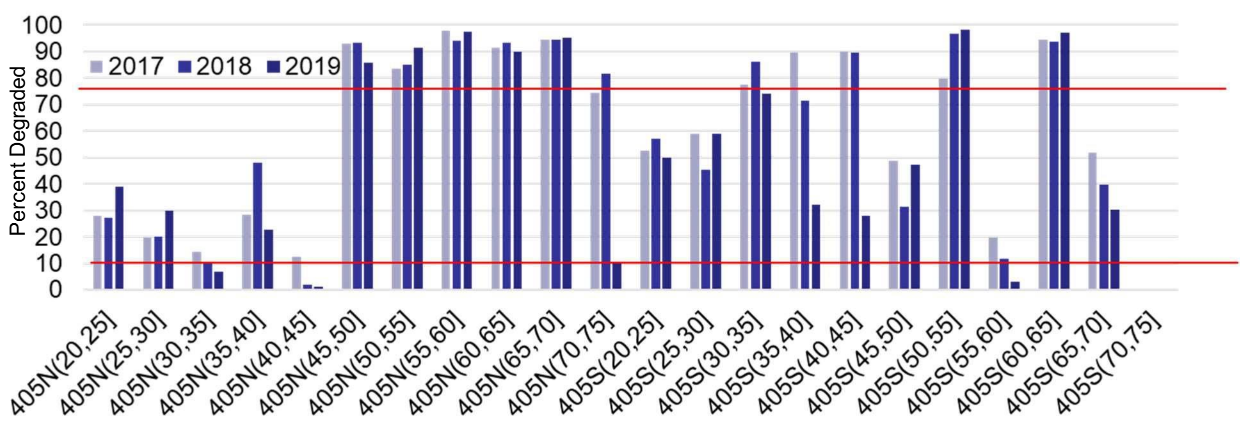


Figure 23. Degradation Trend for District 7 Selected Facilities (part -2)

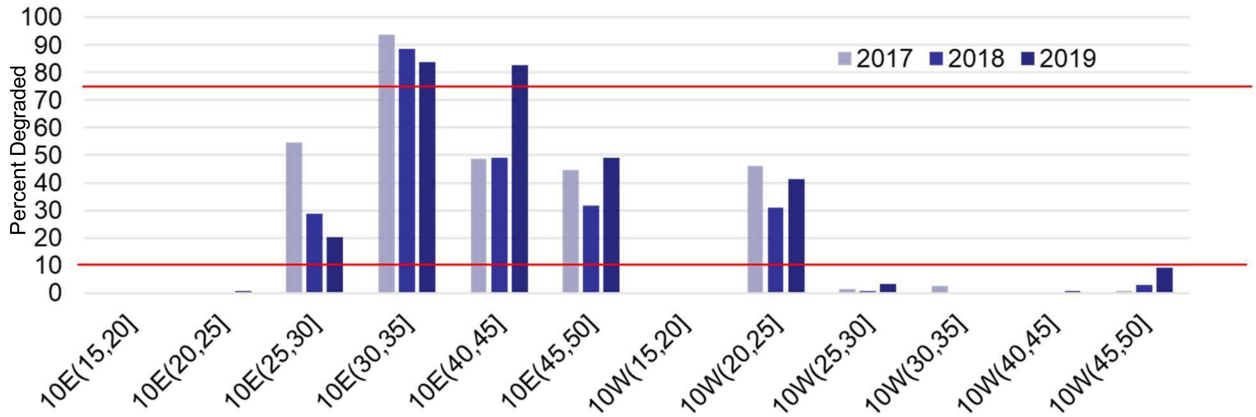


Figure 24. Degradation Trend for District 7 Selected Facilities (part -3)

Figure 25 shows degradation performance over time for district 8 selected facilities.

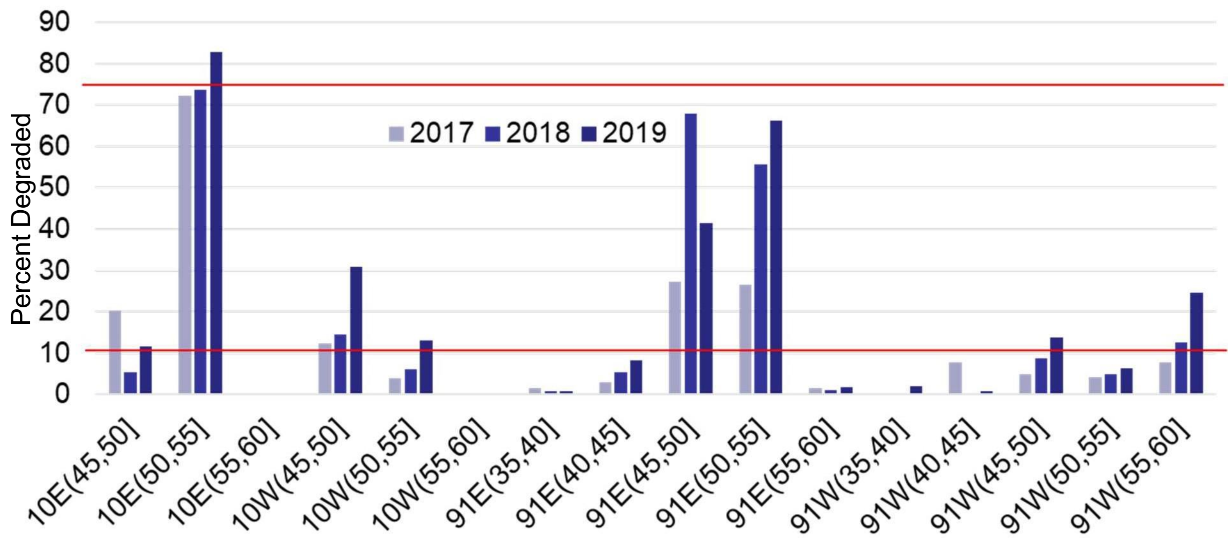


Figure 25. Degradation Trend for District 8 Selected Facilities

Figure 26 and Figure 27 shows degradation performance over time for district 12 selected facilities.

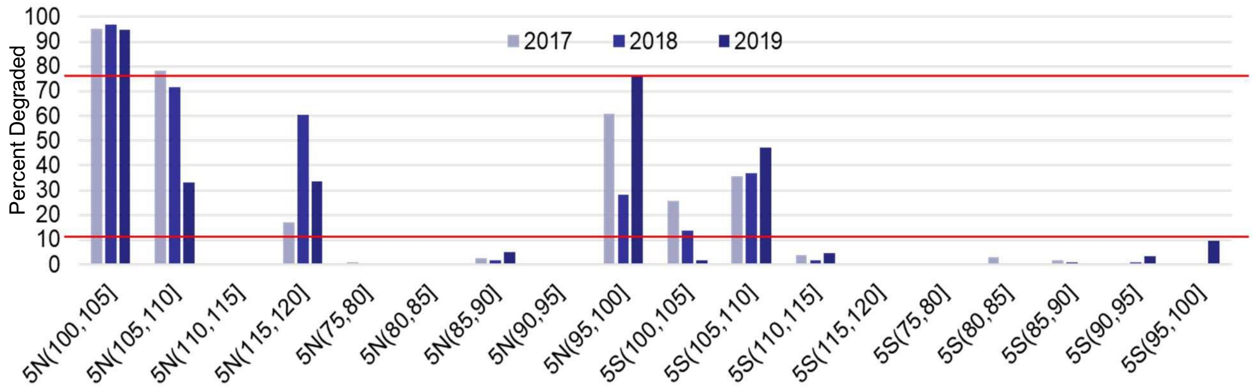


Figure 26. Degradation Trend for District 12 Selected Facilities (part-1)

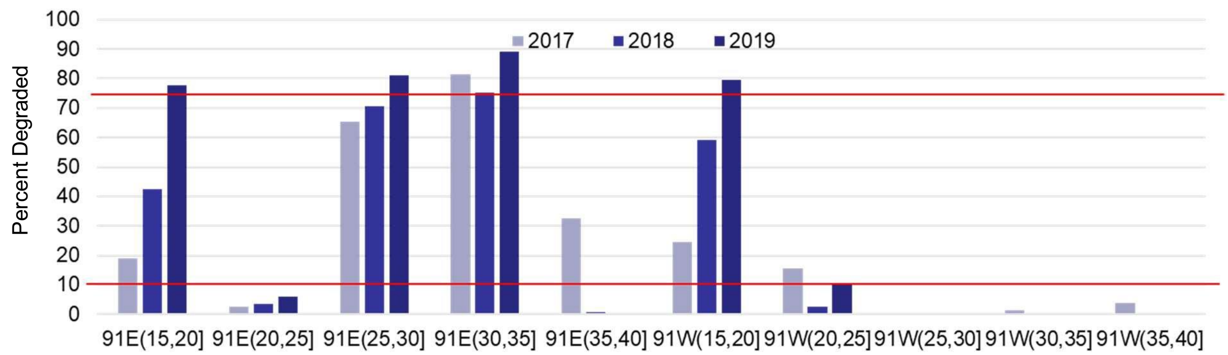


Figure 27. Degradation Trend for District 12 Selected Facilities (part-2)

3.3.2. Traffic Flow Mechanism for HOV Facilities

The traffic flow mechanism of the HOV facilities was also analyzed as part of this task. The research team analyzed speed-flow, speed-density, and flow-density relationships for all the selected HOV facilities across the years 2017, 2018, and 2019.

Figure 28 and Figure 29 shows, respectively, the speed-flow relationship for SR-91 EB and I-10 WB in District 8 during 2017. The SR-91 is a combination of express lanes and regular HOV lanes within District 8. In contrast, I-10 is an all-through single HOV lane facility.

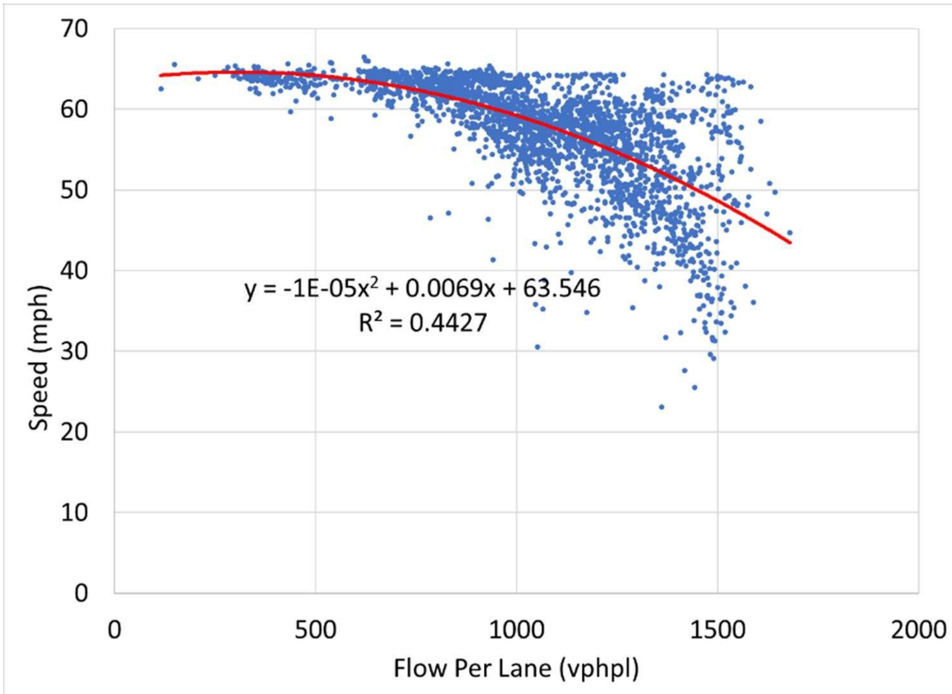


Figure 28. Speed-Flow Relationship for HOV Segments on SR-91 EB in 2017 (District-8)

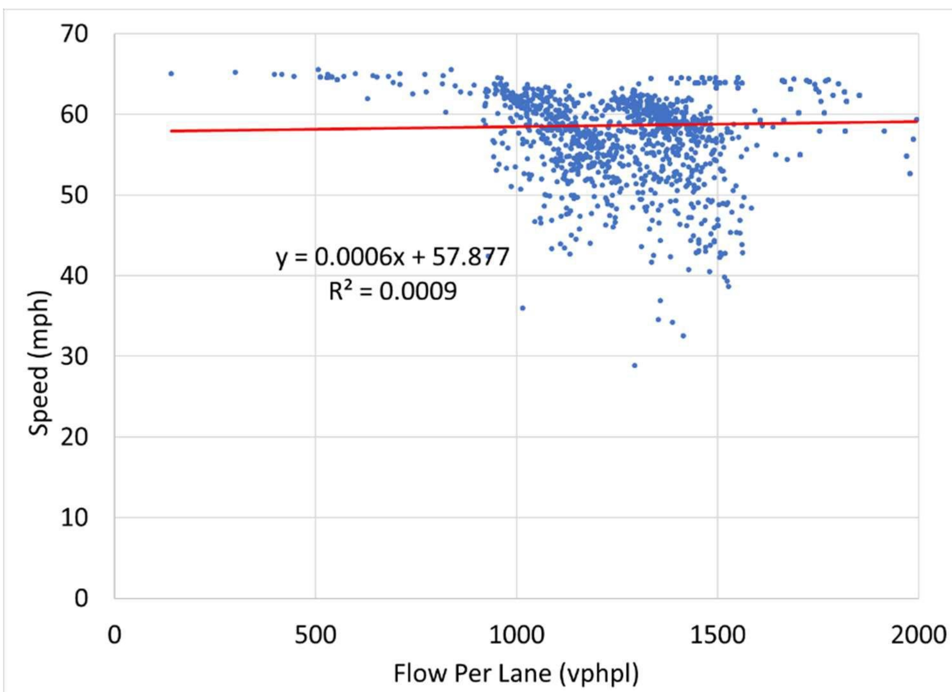


Figure 29. Speed-Flow Relationship for HOV Segments on I-10 WB in 2017 (District-8)

The speed-occupancy relationships of the same facilities are shown in Figure 30 and Figure 31.

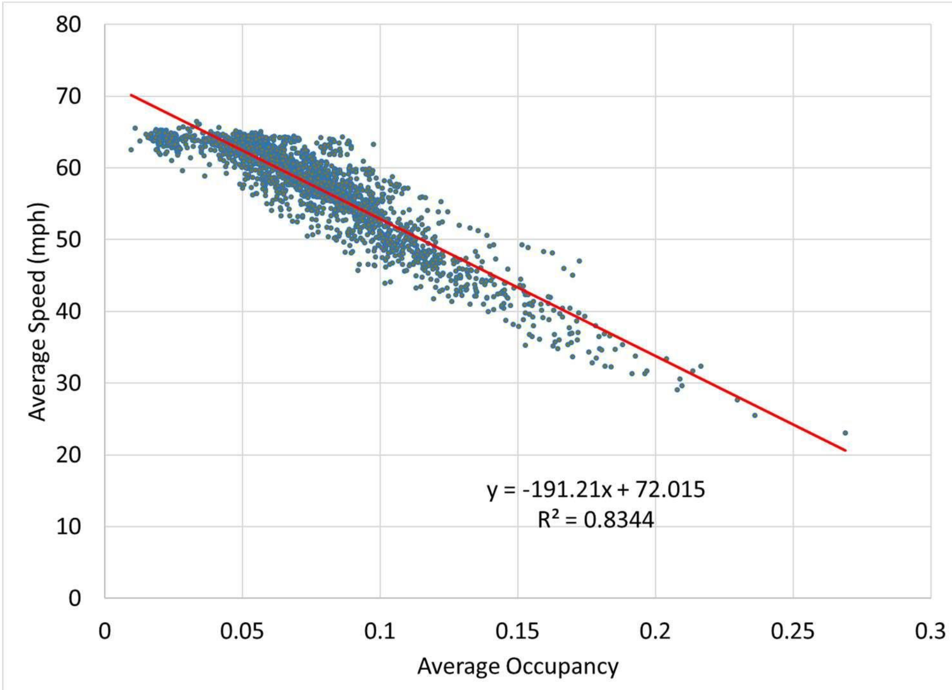


Figure 30. Speed-Occupancy Relationship for HOV Segments on SR-91 EB in 2017 (District-8)

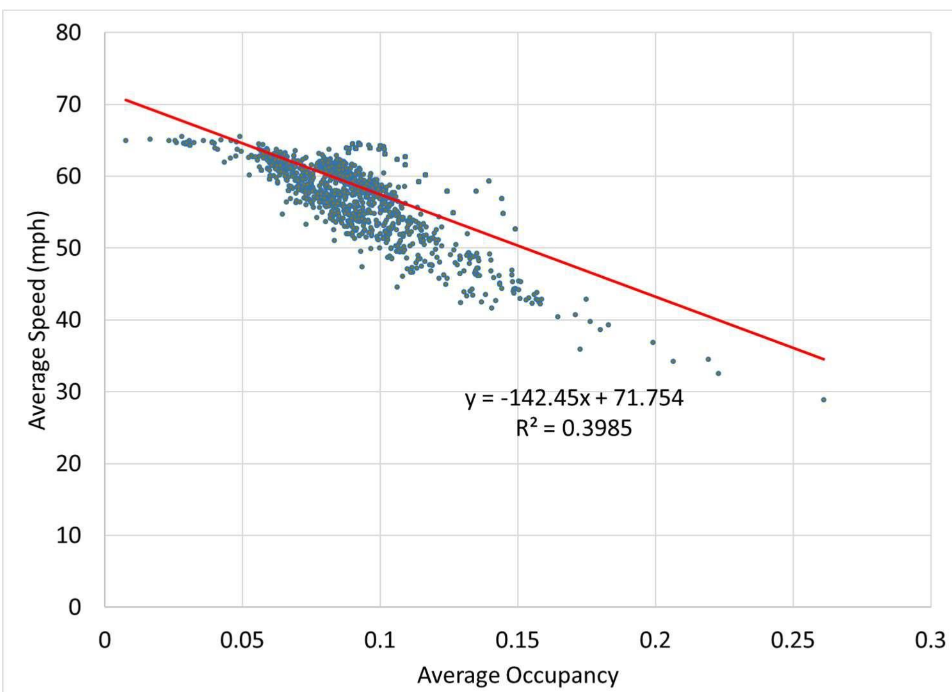


Figure 31. Speed-Occupancy Relationship for HOV Segments on I-10 WB in 2017 (District-8)

The flow-occupancy relationship for the same facilities are shown in Figure 32 and Figure 33.

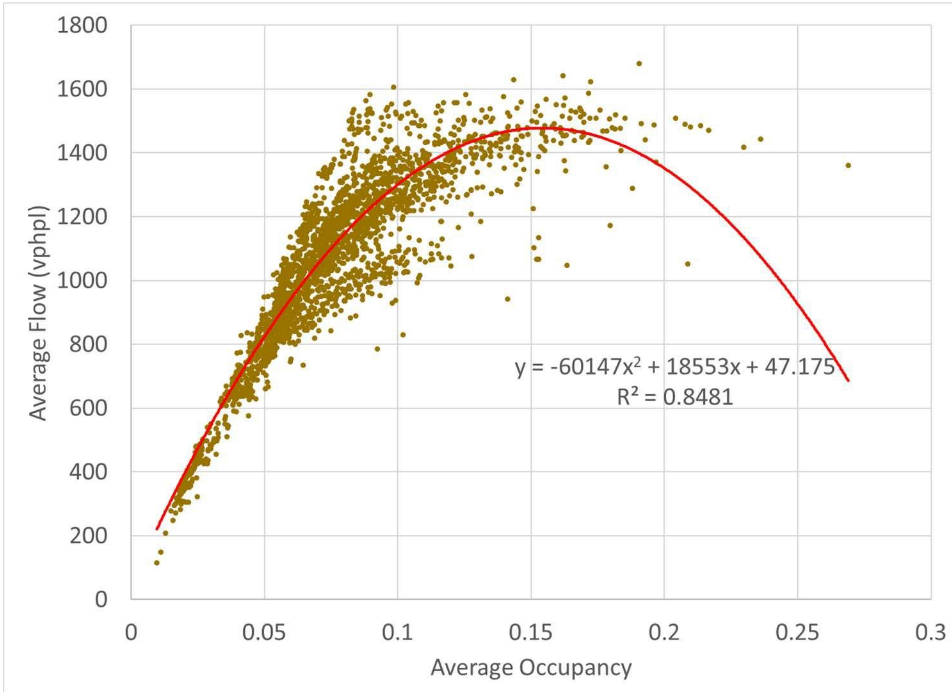


Figure 32. Flow-Occupancy Relationship for HOV Segments on SR-91 EB in 2017 (District-8)

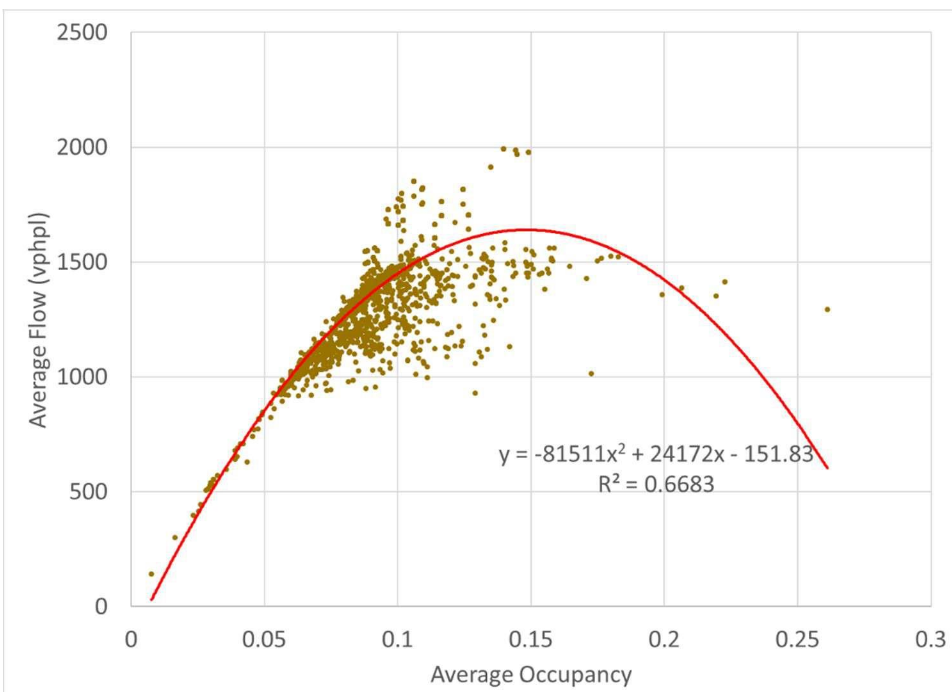


Figure 33. Flow-Occupancy Relationship for HOV Segments on I-10 WB in 2017 (District-8)

3.3.3. Impact of Missing Data

As described in Section 3.1, the PeMS system fills the void in station data by imputing values from historical average. In this task, the research team evaluated the effect of missing data on the estimated peak hour segment average.

Figure 34 shows the reported average speed at different confidence levels. A confidence of 100% means all the stations reported valid data during the aggregated time period. Similarly, a confidence of 0% means that all the reported data is estimated. It is noticeable from Figure 34 that the range of estimated average speed narrows as the confidence decreases. The narrowing mostly happens at the lower speed situations. Therefore, it is possible that over-reporting of speeds can happen when there is lot of missing observations.

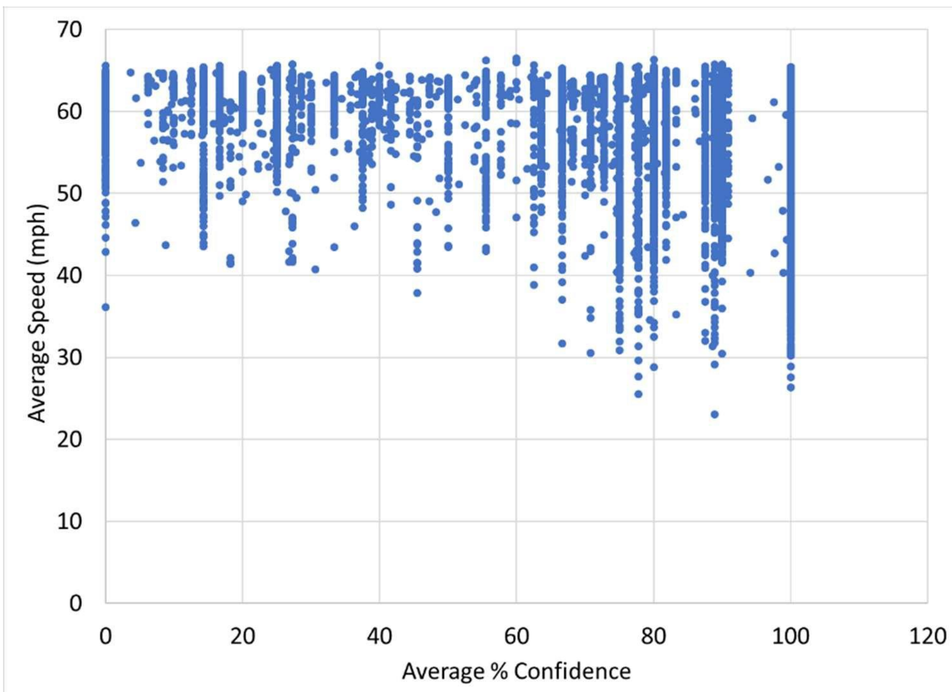


Figure 34. Segment Average Speed Variations by Average Confidence Percentage for District 8 Facilities During 2017

Similar relations are observed when the average occupancy and average flow distributions were drawn at different average percent confidence levels. Figure 35 and Figure 36 shows the corresponding variations of segment average flow and segment average occupancy respectively.

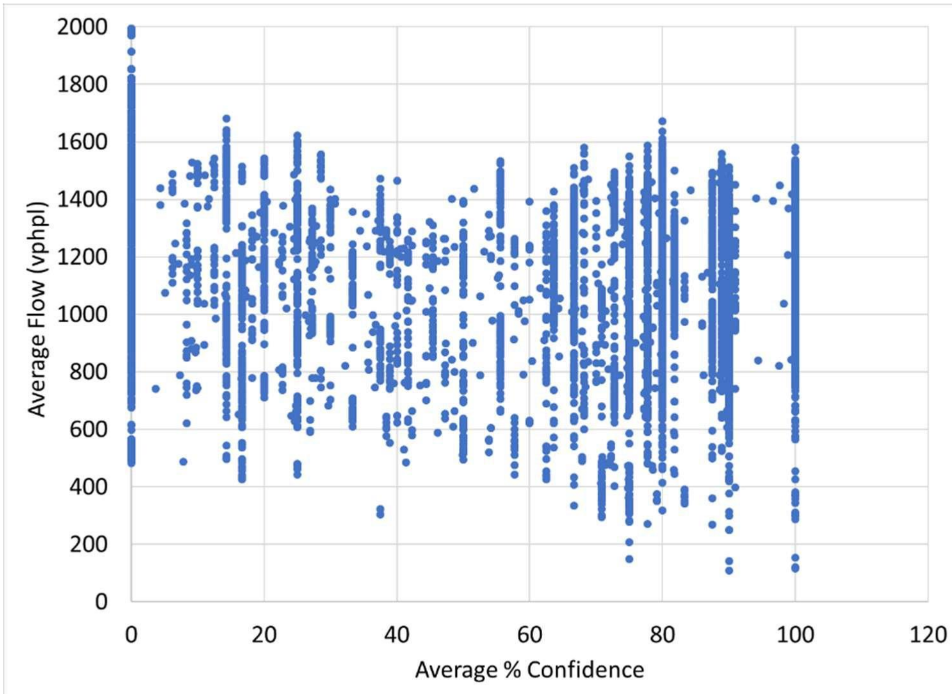


Figure 35. Segment Average Flow Variations by Average Confidence Percentage for District 8 Facilities During 2017

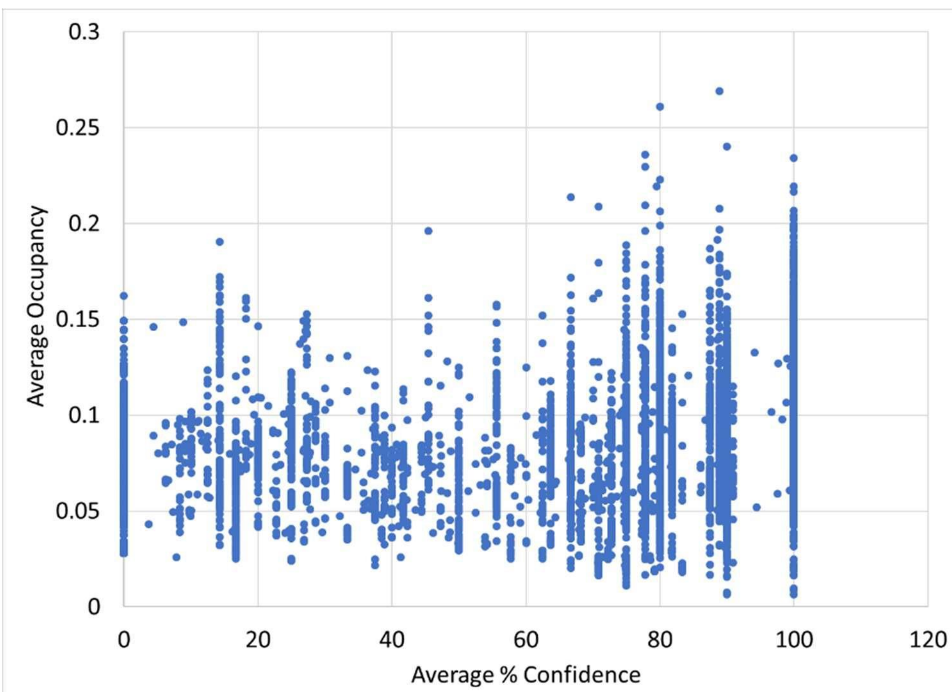


Figure 36. Segment Average Occupancy Variations by Average Confidence Percentage for District 8 Facilities During 2017

3.4. Alternative Approach for Determining HOV Lane Performance Degradation

The difference in average seed between the HOV lanes and the MF lanes is an indicator of how the HOV facility is operating compared to the level of the overall traffic. The MF lanes carry all of the non-HOV-eligible vehicles as well as some of the HOV-eligible vehicles that choose not to use the HOV lanes. Therefore, the average speed in the MF lanes is a good indicator of how much travel demand is there on the freeway facility.

The following four situations may happen at different levels of demand for the HOV and the MF lanes:

1. *Both HOV-eligible and non-HOV-eligible demands are low*: There will be less propensity for HOV-eligible vehicles to choose the HOV lanes as the marginal gain from using the HOV lanes will be low. However, the average MF lane speed will still be a good indicator of the total demand.

2. *HOV-eligible demand is low, but non-HOV-eligible demand is high*: The overall demand is high. The average MF lane speed will be low. Therefore, MF lane speed can serve as an indicator of the total facility demand.

3. *HOV-eligible demand is high, but non-HOV-eligible demand is low*: The marginal benefit of choosing the HOV lane would be negative. Therefore, most HOV-eligible demand will stick to using MF lanes, causing a drop in the MF lane speed. Therefore, MF lane speed will correspond to the total facility demand.

4. *Both HOV-eligible and non-HOV-eligible demands are high*: In this case, both the HOV and MF lanes will be congested. The speed drop in the MF lane will serve as an indicator of high demand in the facility.

Speed differential, therefore, is defined as the difference between the average speed of the HOV lanes and the representative MF lane speed. In this task, the research team has assumed that the representative MF lane speed as the speed of the left-most lane among the MF lanes. In addition, the particular detector measuring the MF lane speed should be neighboring the HOV lane detector. A positive speed differential means the average HOV lane speed is higher than the average MF lane speed. Conversely, a negative speed differential means that the average HOV lane speed is lower than the corresponding average MF lane speed.

Figure 37 summarizes different scenarios corresponding to the speed differential approach in contrast to the traditional speed threshold-based approach. In the traditional approach, any average speed below the 45-mph threshold was considered as compromised LOS. However, Figure 37 proposes that the average speeds in the positive speed differential ranges i.e. where the average HOV lane speed was higher than the average MF lane speed can be excluded from the so-called "compromised LOS" batch. The justifications behind this assumption are:

1) The region where HOV lane speed is higher than MF speed cannot be considered as compromised LOS since the HOV lane is providing value to the users in terms of travel time savings.

2) In case of improper management of HOV facilities such as improper geometric design, faulty entry/exit designs, untimely removal of incident debris, etc., the HOV lane speed might drop significantly compared to the MF lanes. The lack of proper operation should be included in the severity of compromised LOS conditions. Therefore, the negative speed differential region should be included in the compromised LOS.

In addition, Figure 37 shows three levels of severity for HOV speeds in the negative speed differential range. The three severity levels are defined as follows –

- LOW: $95\%\ v_{\mathrm{MF}} > v_{\mathrm{HOV}} > 85\%\ v_{\mathrm{MF}}$
- MODERATE: $85\%\ v_{\mathrm{MF}} > v_{\mathrm{HOV}} > 75\%\ v_{\mathrm{MF}}$
- HIGH: $75\%\ v_{\mathrm{MF}} > v_{\mathrm{HOV}}$

The low range was considered leaving a 5% buffer for misreading of speeds. The two other severity ranges were selected according to the joint HOV-MF speed distribution for the selected HOV facilities.

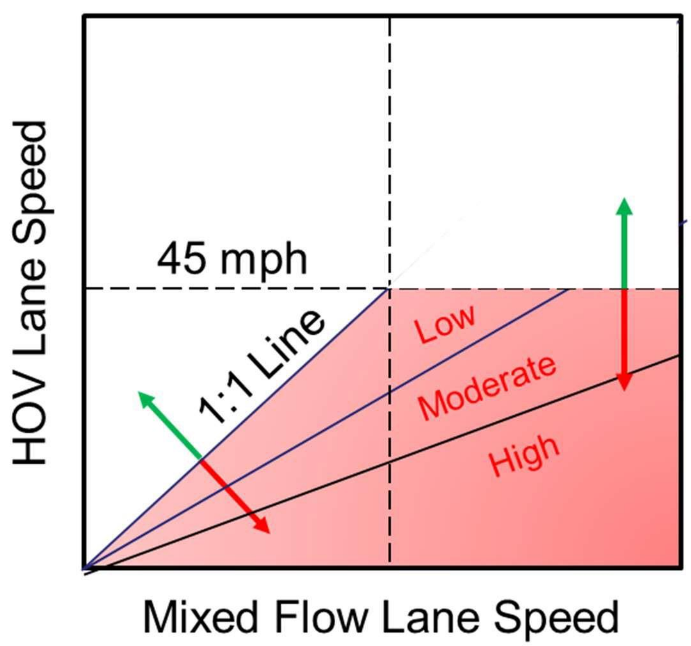


Figure 37. Contrast between the speed differential approach and the fixed speed threshold approach

The different severity levels can be selected to determine the level of compromised LOS conditions. For example:

- The data points in the moderate and high severity ranges can be combined to find the aggregated frequency of HOV operation that was at least moderately severe according to the speed differential thresholds.

- The data points in the high severity range will depict the frequency of events when the speed of the HOV lanes significantly deteriorated compared to the MF lanes.

3.4.1. Results of Speed Differential Analysis

Degradation determination depends on two major factors according to the FHWA approach for determination of degraded HOV facilities:

1. *Severity of degradation* – In the conventional approach there was only the 45-mph threshold determining compromised LOS. In the previous section, we have discussed three more severity levels considering the speed differential.

2. *Frequency of the severe events* – The conventional approach determines degradation if a compromised LOS condition had happened more than 10% of the time. However, the 2017 degradation report adds three more levels of frequency to classify the level of degradation. The levels are as follows:

    - Slightly Degraded - Degradation occurs from 10 to 49 percent of the time or three to nine weekdays per month.

    - Very Degraded - Degradation occurs from 50 to 74 percent of the time or ten to 15 weekdays per month.

    - Extremely Degraded - Degradation occurs 75 percent or more of the time, or 16 or more weekdays per month.

Figure 38 shows degradation determination for SR-91 and I-10 in District 8 for 2018 considering the low or worse speed differential (i.e., HOV facility is considered to be degraded if HOV speed is less than 95% of MF speed). The numbers alongside the bars represent the number of lane-miles in each of the categories. The speed differential-based approach results in a higher number of lane-miles being degraded than the fixed speed-based approach (55 lane-miles as compared to 45). It increases the number of slightly degrade and extremely degraded lane-miles by 10 each. On the other hand, it decreases the number of very degraded lane-miles by 10.

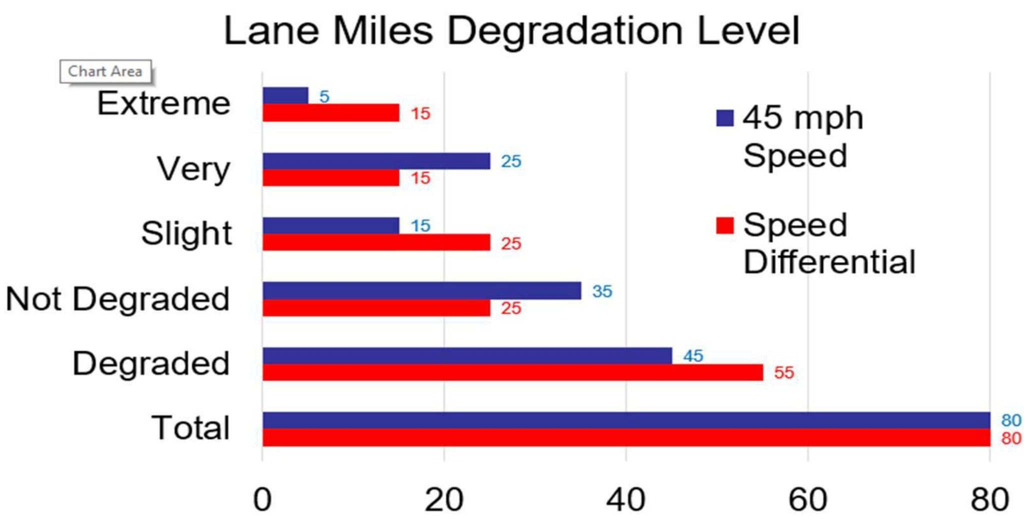


Figure 38. Degradation statistics of HOV facilities in District 8 (I-10 and SR-91) during 2018 considering low severity threshold

Figure 39 shows degradation determination for SR-91 and I-10 in District 8 for 2018 considering the moderate or worse speed differential (i.e., HOV facility is considered to be degraded if HOV speed is less than 85% of MF speed). In this case, only 15 lane-miles out of the total 80 lane-miles were considered degraded. Also, all of these 15 lane-miles were considered to be in the slightly degraded condition.

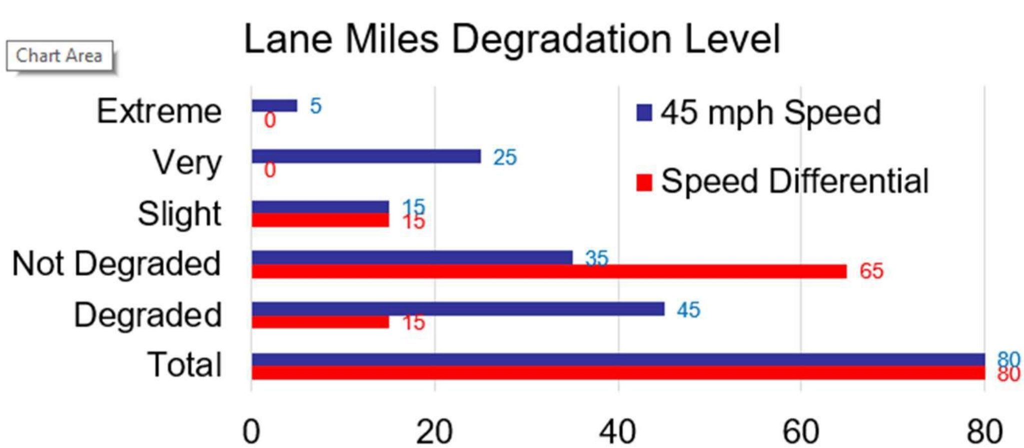


Figure 39. Degradation statistics of HOV facilities in District 8 (I-10 and SR-91) during 2018 considering moderate severity threshold

3.4.2. Impact of Missing Data on Speed Differential Statistics

The research team studied the impact of missing observation of the estimated speed differential. Figure 40 shows the variation of speed differential at different levels of missing data. In contrast to the observations made on the effects of missing data in the previous section, the range of estimated speed differential widened with the level of missing data.

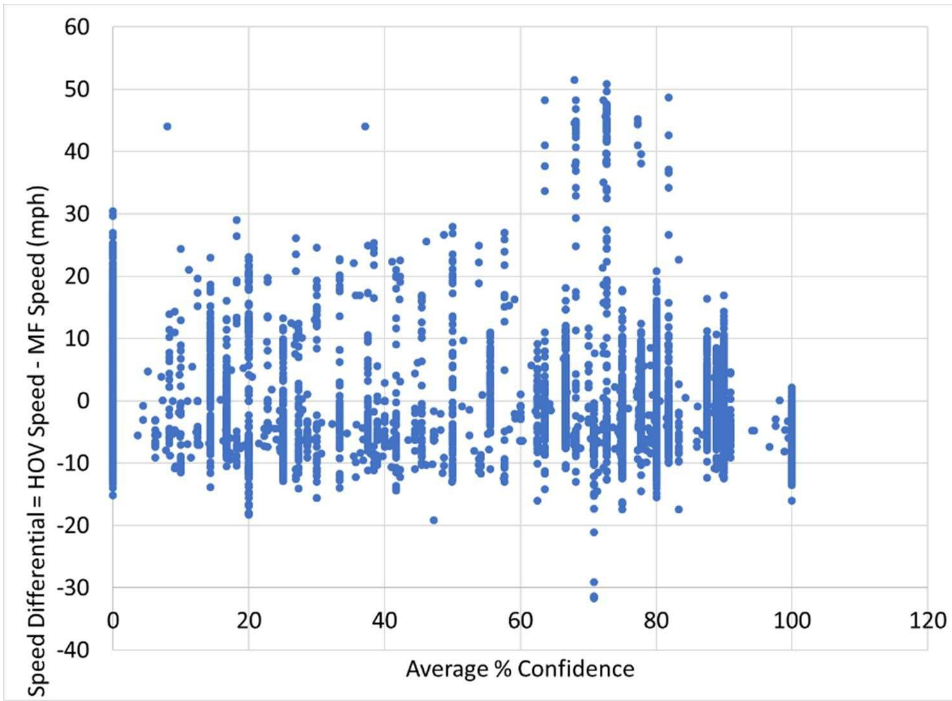


Figure 40. Speed differential variations for different levels of confidence for District 8 during 2017

4. Assessment of Alternative HOV Lane Operational Strategies with Travel Demand Modeling

In this chapter, the research team conducted an assessment of the effectiveness of alternative HOV lane operational strategies using travel demand model. Specifically, we employed the Southern California Association of Governments's regional travel demand model to assess the impact of the three alternative HOV lane operational strategies: 1) increasing the minimum occupancy requirement to HOV3+, 2) deploying dual HOV lanes, and 3) reducing or eliminating the HOV lane usage by clean air vehicles. The use of travel demand model allows for an assessment of how the implementation of the alternative HOV lane operational strategies would affect decisions of travelers in the region with respect to lane choice (e.g., whether to use an HOV lane if travel speed in the lane improves) as well as route choice (e.g., whether to take another route instead if no longer eligible to use an HOV lane), and how these decisions would impact the operational performance of the HOV lane.

In addition, we assessed the impact of a conversion of HOV lane to HOT lane using historical lane performance data from Caltrans' Performance Measurement System (PeMS). Unlike the other alternative HOV lane operational strategies, there has been HOV-to-HOT lane conversion at multiple HOV facilities in the state. These conversions offer opportunities to assess the impact of this alternative HOV lane operational strategy based on real-world lane performance data by comparing the lane performance before and after the conversion.

4.1. SCAG Regional Travel Demand Model

SCAG develops and maintains a regional travel demand model (generally referred to as "SCAG model" in this report) for transportation planning and regulatory purposes. The SCAG model is a trip-based, multi-modal travel demand model, which covers the area of six counties in the SCAG region, including Los Angeles, Orange, Riverside, San Bernardino, Ventura, and Imperial counties. The model is developed in TransCAD software platform. It uses an integrated highway and transit network created in a GIS environment. In general, the SCAG model follows the traditional four-step travel demand modeling approach, which includes trip generation, trip distribution, mode choice, and trip assignment steps. It also has several sub-models that prepare or refine input data for the core modeling steps. In addition, it includes specialized sub-models such as heavy-duty truck model and time-of-day choice model that interface with the core model. Figure 41shows the area coverage of the SCAG region and roadway network in the SCAG model.

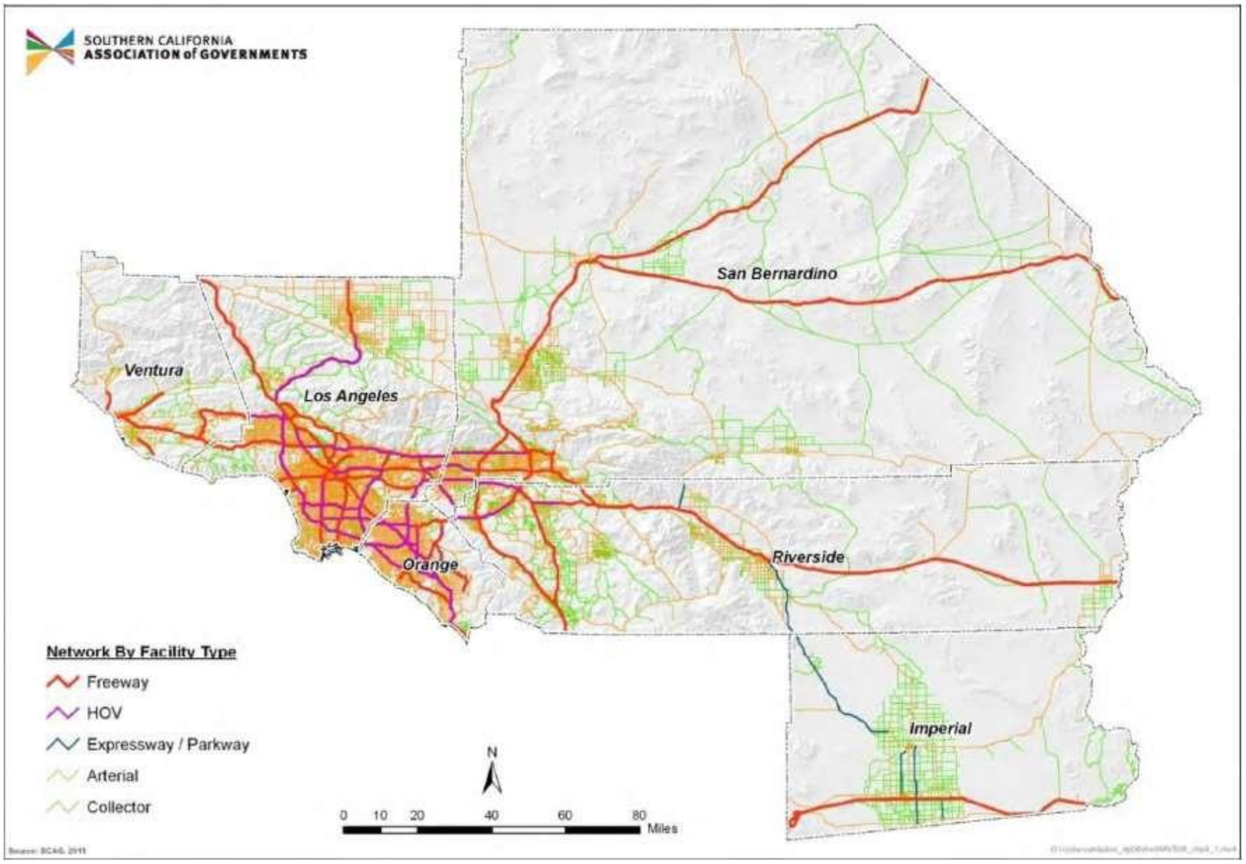


Figure 41. Area coverage of SCAG region and roadway network in SCAG model

Figure 42 shows managed lanes in the SCAG region. Currently, the region has over 400 centerline miles of HOV lanes restricted to 2+ person carpools, one 10-mile HOV facility restricted to 3+ person carpools, and several toll facilities including four HOT facilities. The HOV facilities in the SCAG region are operated and maintained by Caltrans Districts 7, 8, and 12, while the toll facilities are operated and maintained by other regional agencies.

In the SCAG model, the amount of travel demand utilizing HOV or HOT facilities is determined during the mode choice modeling step. The mode choice model is a nested logit model, structured as shown in Figure 43. Among the auto modes, the model distinguishes between four levels of vehicle occupancy (1, 2, 3 and 4 persons per vehicle), and includes a pre-route toll/no-toll binary choice. This differentiation is necessary for modeling the travel demands for managed lanes. Although not shown Figure 43, the mode choice model also includes an HOV/non-HOV path subnest for the shared-ride choices. This model and the toll choice model may be used in lieu of the assignment-based diversion models.

Figure 42. HOV facilities in SCAG region

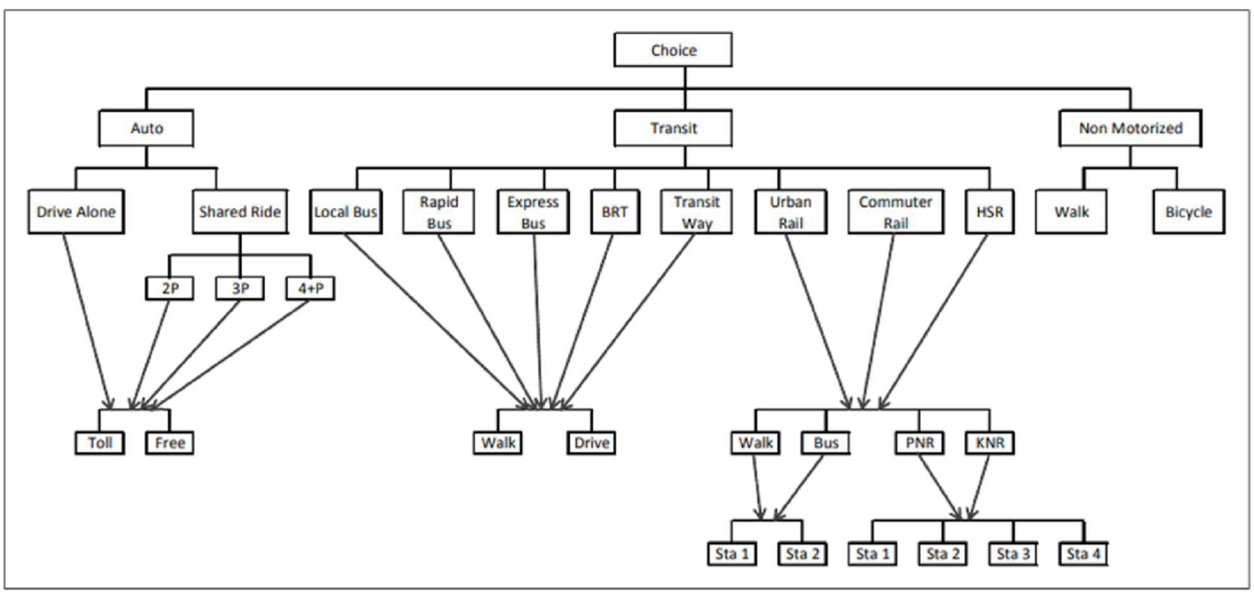


Figure 43. Nest structure in SCAG mode choice model

The SCAG's mode choice model is initially segmented by trip purpose, time period, and four household income levels. This is the minimum level of segmentation required to expose trips to the correct transportation level of service and ensure that the model coefficients capture differences in travel behavior due to the type of trip and household income, in particular the value of time. The final model is stratified by a combination of household income and vehicle sufficiency, in order to better reflect the effect of transit-dependent users on mode and destination choices. An important element of the market segmentation is the stratification of the alternative-specific constants (ASC). The specification of the ASCs responds to an understanding of the expected contribution of unincluded attributes to the utility of each choice. Unincluded attributes can be thought of as being a function of trip-maker characteristics, trip characteristics, or mode characteristics. The ASC can be considered to be composed of two parts, one part that varies across demographic characteristics (for example, across household income groups or car ownership groups), and a second part that varies across mode and/or trip characteristics.

The general form of utility function for the auto modes is shown in the equation below:

$$Utility_m^{mkt} = civt \times (in\ vehicle\ travel\ time) + covt \times (terminal\ time) + ccost^{mkt} \times \frac{(parking\ cost)}{2 \times occfac} ccost^{mkt} + \frac{(veh.operating\ cost \times distance)}{occfac} ccost^{mkt} + \frac{(toll\ cost)}{occfac} ccost^{mkt} + (HOT\ lane\ toll) \times \frac{distance}{occfac} + toll\ penalty_m + K_m$$

where *occfac* is the factor to discount travel costs among occupants of a carpool. Typically, this factor is smaller than the average vehicle occupancy. For the drive alone mode, *occfac* is 1.0.

After the mode choice modeling step, the travel demand in passenger cars with 4+ occupants is combined with the travel demand in passenger cars with 3 occupants to reduce the number of travel demand classes. Together with the three travel demand classes from the heavy-duty truck model, there is a total of eight travel demand classes for traffic assigment on the highway network as listed below.

- Drive alone passenger cars and trucks (DA)
- Passenger cars with 2 occupants using HOV lanes (SR2 HOV)
- Passenger cars with 3+ occupants using HOV lanes (SR3+ HOV)
- Passenger cars with 2 occupants not using HOV lanes (SR2 NONHOV)
- Passenger cars with 3+ occupants not using HOV lanes (SR3+ NONHOV)
- Light heavy-duty trucks (LHDT)
- Medium heavy-duty trucks (MHDT)
- Heavy heavy-duty trucks (HHDT)

During the traffic assigment step, the number of vehicles utilizing HOV lanes is also influenced by the HOV diversion model. It is a binomial model that is applied prior to traffic assignment to split carpool trips between HOV-eligible vehicles that use the HOV lanes and those that remain on the MF lanes. The probability of HOV-eligible vehicles choosing the HOV facility is given by the function below:

$$P(HOV) = \frac{b}{b + e^{at}}$$

where t represents the travel time savings from using the HOV facility; t = *HOV travel time – MF travel time + HOV access penalty*; a and b are calibrating factors. The HOV access penalty measures the inconvenience of entering and exiting the lanes, given that many of them are buffer or barrier-separated with limited opportunities for access and egress. The access penalty is assumed to be 5 minutes across all time periods. The calibrating factor a determines the steepness of the logistic curve, while the calibrating factor b determines the likelihood of using the HOV facility at zero travel time savings. To encourage carpool trips to stay on HOV lanes, a factor of 1.1 is used on the mainline travel times. All the parameters of the HOV diversion function can be specified by time period, however, currently the same parameters are used for all time periods.

Figure 44 depicts the probability of HOV-eligible vehicles choosing HOV lanes based on the parameters specified in the HOV diversion model. It can be seen that when there is no travel time savings from using HOV lanes, the probability of HOV-eligible vehicles choosing HOV lanes is 25%. This probability increases as the travel time savings increases, reaching 95% when the travel time savings is 10 minutes.

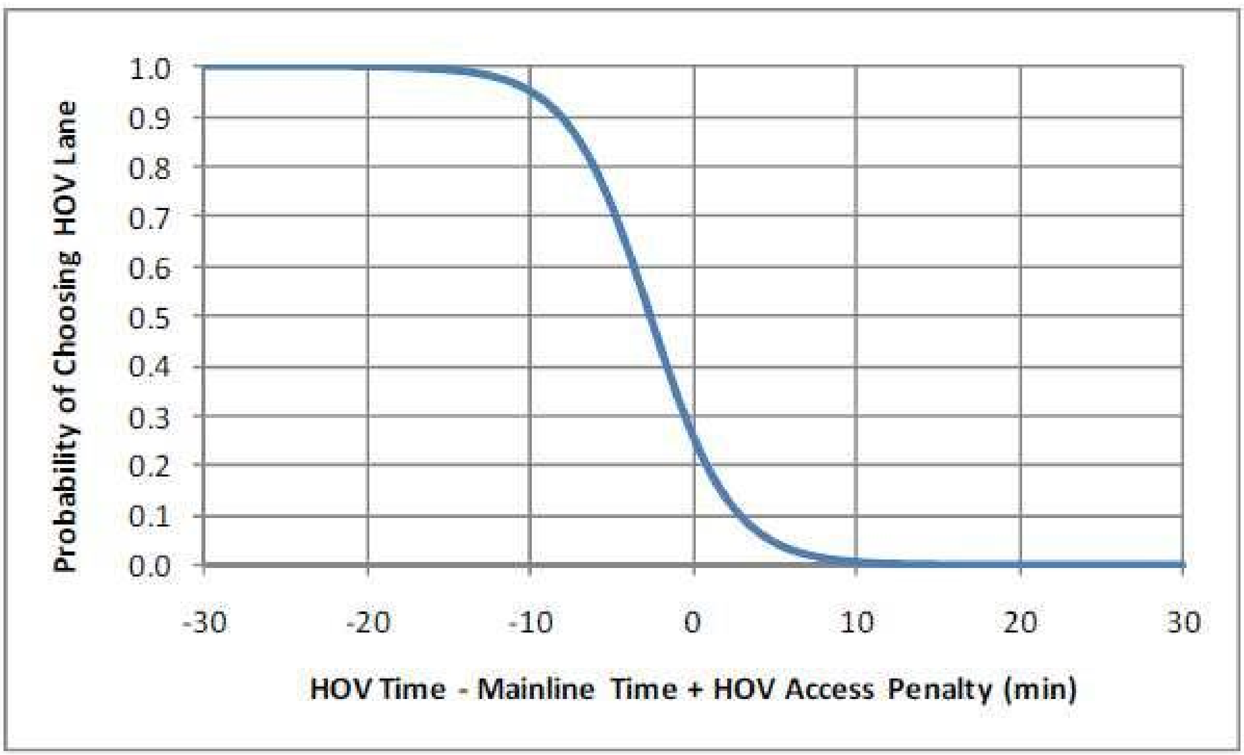


Figure 44. HOV diversion curve used in the SCAG model

4.2. Assessment of Alternative Operational Strategies

This section describes the application of the SCAG model to assess the impact of three alternative HOV lane operational strategies: 1) increasing the minimum occupancy requirement to HOV3+, 2) deploying dual HOV lanes, and 3) reducing or eliminating the HOV lane usage by clean air vehicles. For each operational strategy, the assessment was conducted for a case study of HOV facility that could benefit from such operational strategy. The assessment results are presented in the following subsections.

4.2.1. Increasing Minimum Occupancy Requirement to HOV3+

HOV facilities in California currently have the minimum occupancy requirement of 2 persons or more. They have been a major component of California's freeway systems over the last several decades, providing travel time savings for eligible vehicles traveling on the freeway systems. However, due to the growth in travel demand including the increase in the number of HOV2+ vehicles, several HOV lanes have been over-utilized. This has resulted in their performance being impacted, for many of them to the level that does not meet the federal requirements, as documented in Caltrans's HOV degradation reports.

One HOV lane operational strategy that could help address the over-utilization of these HOV lanes is to increase the minimum occupancy requirement from HOV2+ to HOV3+. Doing so will reduce the number of vehicles eligible to use HOV lane, but the extent of the reduction will vary by region and corridor, depending largely on the current fraction of HOV3+ vehicles out of all HOVs on the corridor. It is plausible that such increase in the minimum occupancy requirement could induce some HOV2+ vehicles on the corridor to find another person to form HOV3+ carpools. However, carpool formation is complex and takes time, and thus, the increase in HOV3+ vehicles would likely be small at least in the short-term.

To assess the impact of increasing the minimum occupancy requirement on the performance of HOV lane, a section of SR-91 in Riverside County was selected as a case study. It is a 16-mile segment between the county line with Orange County and Adams St in Riverside, as shown in Figure 45. This section of SR-91 had HOV lanes with HOV2+ requirement in 2016, which is the base year of the SCAG model used in this study. These HOV lanes connected to the 18-mile SR-91 Expressway in Orange County to the west. This means that HOV3+ vehicles that were traveling eastbound in the SR-91 Expressway could directly transition to the HOV lane (with 3+ occupancy requirement) once the Expressway ended. However, HOV2+ vehicles traveling eastbound in the SR-91 Expressway would no longer be eligible to use the HOV lane, and would have to move into the MF lanes once the Expressway ended.

Instead of modeling the entire SCAG region, which is very large (as shown in Figure 3), the modeling was conducted for the subarea shown in Figure 45 in order to keep the model run time manageable. The SCAG model has five time-of-day periods for traffic assignment on the roadway network: 1) morning peak, which is from 6:00 AM to 9:00 AM, 2) midday, which is from 9:00 AM to 3:00 PM, 3) afternoon peak, which is from 3:00

PM to 7:00 PM, 4) evening, which is from 7:00 PM to 9:00 PM, and 5) night, which is from 9:00 PM to 6:00 AM. The assessment of the increase the minimum occupancy requirement from HOV2+ to HOV3+ in this case study was focused on the afternoon peak period in the eastbound direction. For the baseline scenario where the minimum occupancy requirement is HOV2+, vehicle occupancy count data from Caltrans District 12 were used to calibrate the split between SR2 HOV vehicles and SR2 NONHOV vehicles, as well as the split between SR3+ HOV vehicles and SR3+ NONHOV vehicles.

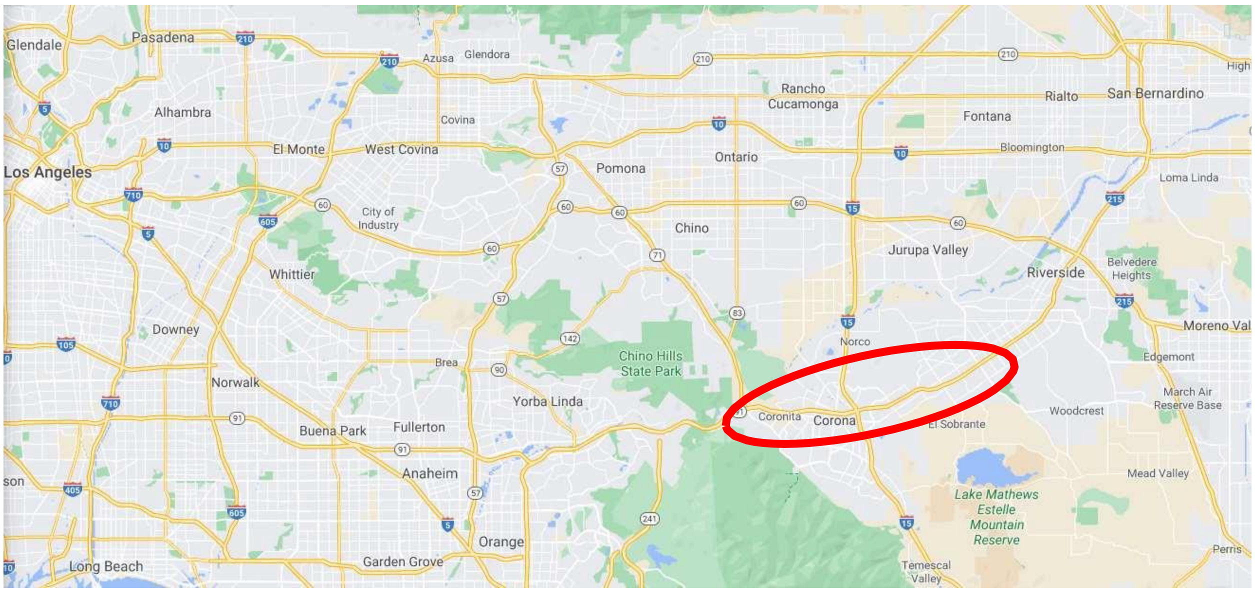


Figure 45. Case study section of HOV lane on SR-91 for increasing minimum occupancy requirement to HOV3+

In addition to the baseline scenario, the modeling was conducted for the four scenarios defined below. These scenarios represent the different levels of increase in SR3+ vehicles after increasing the minimum occupancy requirement for the section of HOV lane on SR-91 in this case study:

1. *Scenario 1 – No SR3+ vehicles increase*. This scenario assumes that there is no increase in SR3+ vehicles. It represents the possible situation immediately after the increase in minimum occupancy requirement where new SR3+ carpools have not had time to form.

2. *Scenario 2 – 50% SR3+ vehicles increase with proportionate decrease in SR2 and DA vehicles*. This scenario assumes that the number of SR3+ vehicles would increase by 50%. It also assumes that the increase in the number of SR3+ vehicles is a result of travel mode shift from SR2 and DA. Therefore, the number of SR2 vehicles and the number of DA vehicles in the model run were decreased accordingly.

3. *Scenario 3 – 300% SR3+ vehicles increase with proportionate decrease in SR2 and DA vehicles*. This scenario assumes that the number of SR3+ vehicles would increase by 300%. As in Scenario 2, it also assumes that the increase in the number of SR3+ vehicles is a result of travel mode shift from SR2 and DA, and thus, the number of SR2 vehicles and the number of DA vehicles in the model run were decreased proportionally.

4. *Scenario 4 – All SR2 vehicles change to SR3+ vehicles*. This scenario assumes that all the SR2 vehicles would be able to find additional passenger(s) and turn into SR3+ vehicles. Essentially, the number of vehicles eligible to use the HOV lane in this scenario is the same as that in the baseline scenario.

Figure 46 and Figure 47 present the modeling results of the different scenarios. Figure 46 shows the speed averaged across the case study section, while Figure 47 shows the minimum speed on the case study section where traffic is most congested. The results in each of these figures include separate speed values for the HOV and MF lanes. The MF lane speeds are for all MF lanes combined. In addition to the modeled speed results from the SCAG model runs, the observed speed values on the case study section obtained from PeMS are also provided.

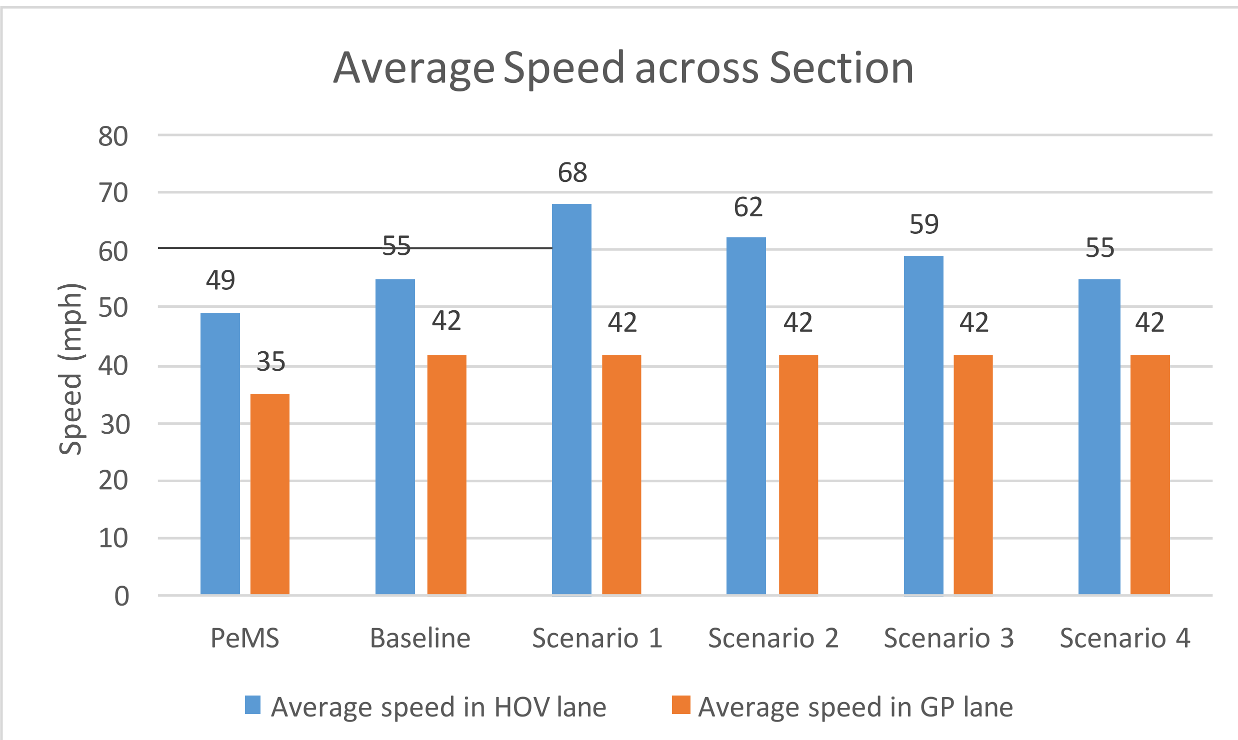


Figure 46. Average speed on the case study section on SR-91 in Riverside County

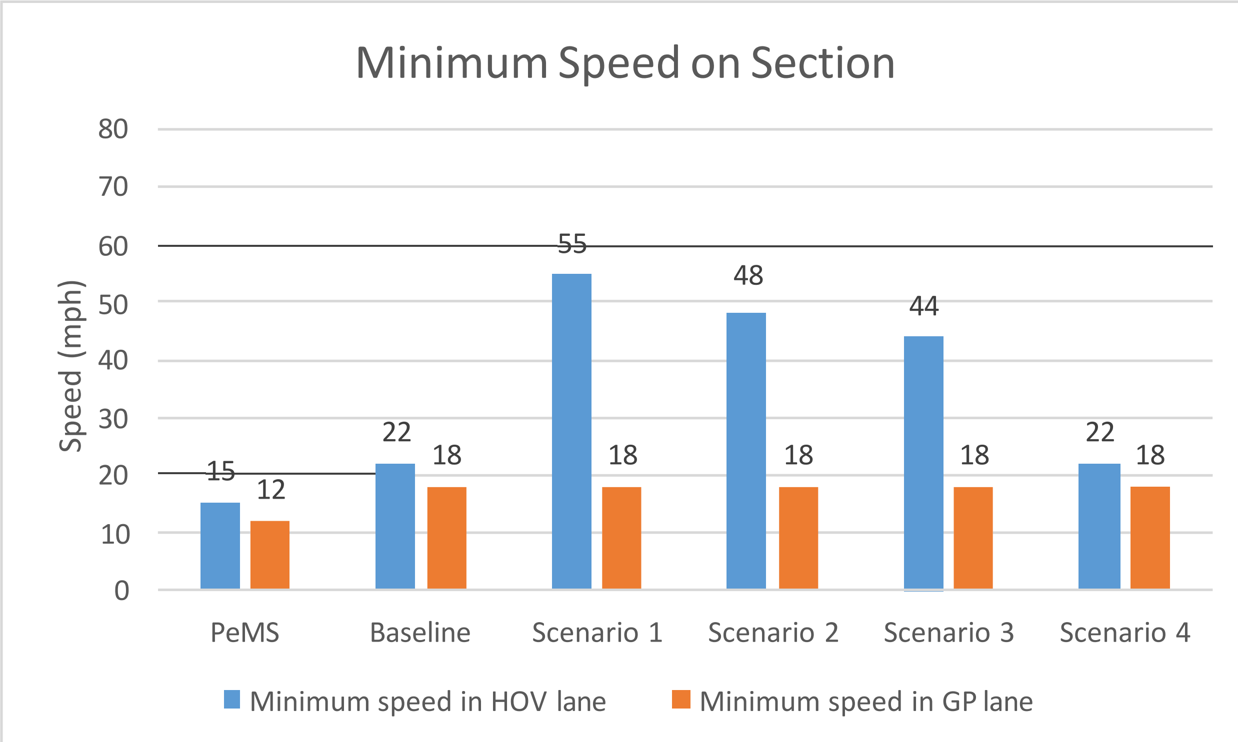


Figure 47. Minimum speed on the case study section on SR-91 in Riverside County

According to Figure 46 and Figure 47, the following observations can be made:

- The modeled speed values in the baseline scenario are 6-7 mph higher than the observed speed values in the real world. This level of discrepancies is reasonable. It also reflects the fact that the observed speed values include data where traffic speed on the case study section was impacted by incidents. On the other hand, traffic speed calculated by the SCAG model represents the speed in a typical weekday without incidents.

- In the baseline scenario, the average speed across the case study section in the HOV lane is 55 mph whereas the average speed in the MF lanes is 42 mph. Thus, the HOV lane provides a significant travel time savings over the MF lanes (about 5.4 minutes over the 16-mile section). On the other hand, at the location where traffic is most congested, the HOV lane speed is 22 mph, while the MF lane speed is 18 mph.

- In Scenario 1, it is assumed that there is no increase in SR3+ vehicles after increasing the minimum occupancy requirement to HOV3+. That means all SR2 vehicles that are no longer eligible to use the HOV lane will have to either use the MF lanes instead or change the travel route altogether. According to the modeling results, the average speed in the HOV lane increases from 55 mph before implementing the HOV3+ requirement to 68 mph after the implementation. On the other hand, the average speed in the MF lanes remains the same at 42 mph. These results suggest that the increase in the minimum occupancy requirement would improve the performance of the HOV lane, while not affecting the performance of the MF lanes. This is because some of the SR2 vehicles that are no longer eligible to use the HOV lane change their travel routes to the parallel corridors such as SR-60 and I-10. The remaining SR2 vehicles that still use SR-91 are spread across multiple MF lanes, which does not have a significant effect on the overall MF lane speed.

- Scenarios 2 and 3 are similar to Scenario 1, except that there is 50% and 300% increase in SR3+ vehicles, respectively, after increasing the minimum occupancy requirement to HOV3+. Because there are more vehicles eligible to use the HOV lane in these scenarios, the improvement in average HOV lane speed is not as much as in Scenario 1. The average HOV lane speed for Scenarios 2 and 3 is 62 and 59 mph, respectively. As in Scenario 1, the average MF lane speed remains the same at 42 mph in both scenarios.

- In Scenario 4, it is assumed that all the SR2 vehicles would turn into SR3+ vehicles, which essentially, keeps the number of vehicles eligible to use the HOV lane the same as that in the baseline scenario. Therefore, it is not surprising that the average speeds in both the HOV lane and the MF lanes are the same as in the baseline scenario, which are 55 and 42 mph, respectively.

- According to the minimum speed results in Figure 47, the increase in the minimum occupancy requirement to HOV3+ would improve the HOV lane speed at the bottleneck location significantly, from 22 mph to 55, 48, or 44 mph depending on the scenario.

4.2.2. Deploying Dual HOV Lanes

Almost all of the existing HOV lanes in California have one lane per direction. This has largely been sufficient to serve HOV travel demand in the state over the last several decades. However, due to the growth in travel demand and the permission of CAVs to use HOV lanes, traffic volumes in HOV lanes have generally increased over time. As indicated by Caltrans' HOV degradation reports in recent years, HOV traffic volumes have exceeded the capacity, and consequently degraded the performance, of many HOV lanes in the state.

One strategy to directly address the increase in HOV traffic volume is to deploy dual HOV lanes, which approximately doubles the capacity of the HOV facility. This strategy is applicable where there is enough space to add a second HOV lane to the existing one. An example is shown in Figure 48, which is a picture of SR-14 in Los Angeles County. Currently, there is a single HOV lane in each direction, but the shoulders of the freeway are possibly wide enough to add a second HOV lane to the existing one in each direction. Note that for many HOV facilities, especially in highly urbanized areas, this strategy may not be an option as there is no space left on the freeway for adding another lane to it.

Figure 48. SR-14 with single HOV lane in each direction

To assess the impact of deploying dual HOV lanes, the 36-mile section of SR-14 between the interchange with I-5 and Palmdale Blvd in Palmdale, as shown in Figure 49, was selected as a case study. There is one existing HOV lane in each direction that has HOV2+ minimum occupancy requirement. The HOV lanes are in operation part-time—during 5-9 a.m. for the southbound direction and during 3-7 p.m. for the northbound direction.

The modeling subarea is shown by the map in Figure 49. As can be seen from the map, the case study section on SR-14 is fairly isolated and there is no alternative or competing route for carrying traffic from north Los Angeles to Palmdale, and vice versa. Thus, the use of this modeling subarea should not have a significant impact from route diversion on the traffic volumes on that section of the freeway.

In the assessment of this HOV operational strategy, the baseline scenario is the scenario with one HOV lane in each direction, and the alternative scenario is one where a second HOV lane is added to the existing HOV lane in each direction. The modeling was conducted for the morning peak and afternoon peak periods in the SCAG model. To simulate the induced HOV travel demand due to the increase in HOV lane capacity, the number of SR2 HOV vehicles and the number of SR3+ HOV vehicles choosing to use the HOV lanes were increased by 5%. On the other hand, the numbers of DA, SR2 NONHOV, and SR3+ NONHOV vehicles in the MF lanes were assumed to remain the same.

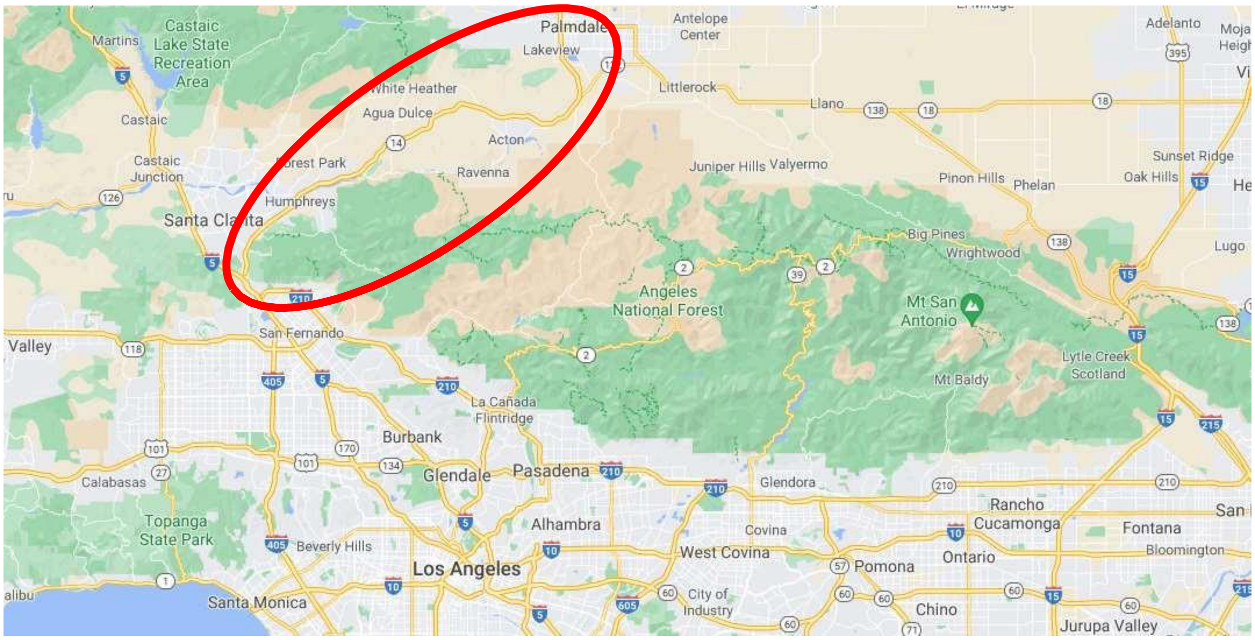


Figure 49. Case study section of HOV lane on SR-14 for deploying dual HOV lanes

Figure 50 presents the modeling results for the northbound direction during the afternoon peak period. Figure 51 then presents the modeling results for the southbound direction during the morning peak period. Both figure show the average speed across the case study section as well as the minimum speed on the case study section where traffic is most congested. The results in each of these figures include separate speed values for the HOV and MF lanes. For each direction of traffic, the HOV lane speeds in the case of duel HOV lanes are for the two HOV lanes combined. Likewise, the MF lane speeds are for all the MF lanes combined.

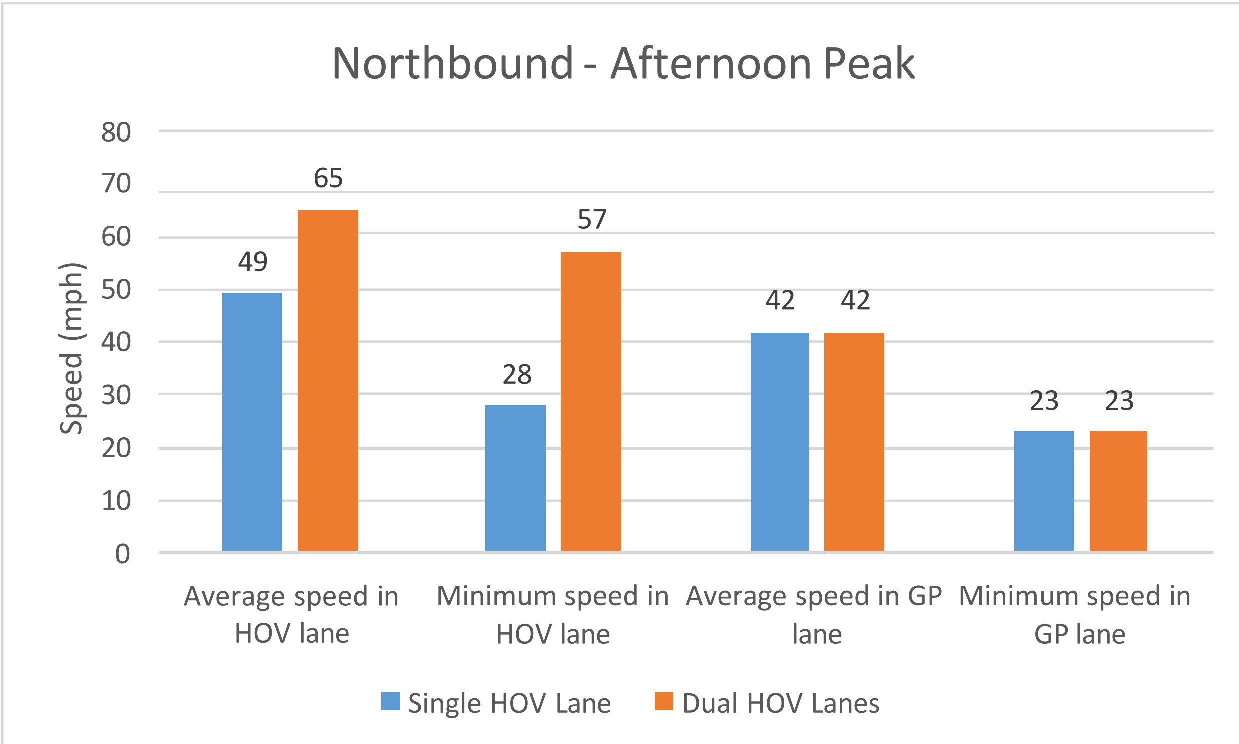


Figure 50. HOV and MF lane speed on SR-14 northbound during afternoon peak

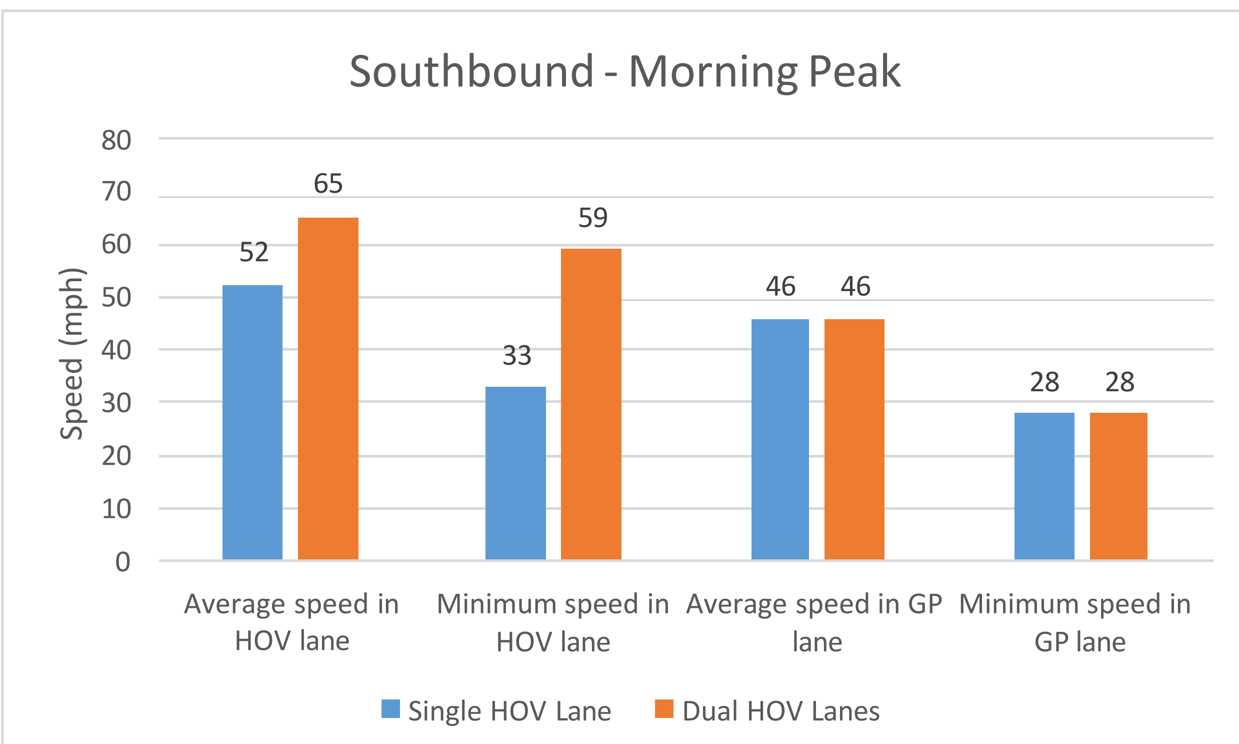


Figure 51. HOV and MF lane speed on SR-14 southbound during morning peak

According to Figure 50 and Figure 51, the following observations can be made:

- The average HOV lane speed in both directions would improve significantly after deploying dual HOV lanes. In the northbound direction, the average HOV lane speed would improve from 49 mph to a free-flow speed of 65 mph. In the southbound direction, it would improve from 52 mph to 65 mph. These results are expected as doubling the HOV lane capacity would allow HOV traffic in the lanes to flow better. Despite the slight increase in HOV traffic due to induced demand, the overall traffic condition in the dual HOV lanes would be free-flow.

- The traffic flow improvements as a result of deploying dual HOV lanes would also eliminate the bottlenecks on the case study section in both directions as well. In the northbound direction, the minimum HOV lane speed would improve from 28 mph to 57 mph. In the southbound direction, it would improve from 33 mph to 59 mph. Again, it is not surprising that doubling the HOV lane capacity would alleviate congestion in the HOV lanes considerably.

- The modeling results show that both the average MF lane speed and the minimum MF lane speed in both directions would not be impacted. This is because, in the modeling, the numbers of DA, SR2 NONHOV, and SR3+ NONHOV vehicles in the MF lanes were assumed to remain the same after deploying dual HOV lanes. This is a conservative assumption as some of the SR2 NONHOV and SR3+ NONHOV vehicles may actually choose to use the dual HOV lanes as these lanes would provide more travel time savings than in the case of single HOV lane.

4.2.3. Reducing or Eliminating HOV Lane Usage by Clean Air Vehicles

California has had the CAV decal program for many years. It allows a vehicle that meets specified emissions standards and properly displays CAV decals to use HOV lanes with only one occupant in the vehicle. The program is designed to provide an incentive for the purchase and use of CAVs in California. Since the program started in 2004, the CAV decals have evolved through different colors and eligibility criteria as summarized in Table 13. Currently, CAV decals are issued to vehicles that have never received a CAV decal and that meet California’s super ultra-low emission vehicle (SULEV), inherently low-emission vehicle (ILEV), and transitional zero emission vehicle (TZEV) evaporative emission standard for exhaust emissions. Compressed natural gas (CNG) and liquefied petroleum gas (LPG) fueled vehicles may also qualify. At the time of writing, the CAV decal program is set to end on September 30, 2025.

Table 13. Different types of CAV decals

Decal Type	Year First Issued	Decal Expires	Description
	2021	1/1/2025	These CAV decals are issued to vehicles that meet California's super ultra-low emission vehicle (SULEV), inherently low-emission vehicle (ILEV), and transitional zero emission vehicle (TZEV) evaporative emission standards for exhaust emissions. Compressed natural gas (CNG) and liquefied petroleum gas (LPG) fueled vehicles may also qualify for the CAV decal program.
	2020	1/1/2024	
	2019	1/1/2023	
	2018	1/1/2022	
	2012	1/1/2019	Green CAV decals were issued to vehicles that met California's TZEV standards for exhaust emissions, also known as enhanced advanced technology partial zero emissions vehicles (AT PZEV).
	2000	1/1/2019	White CAV Decals were issued to zero emission vehicles (ZEVs), ultra-low emission vehicles (ULEVs), CNG vehicles, and LPG vehicles meeting the federal inherently low emissions vehicle (ILEV) standard for fuel vapor emissions.
	2004	7/1/2011	These decals were issued to early models of qualifying hybrid vehicles.

It should be noted that the yellow decals were limited to 85,000 qualified vehicles, and the green decals were limited to 70,000 vehicles. However, the white decals were available to an unlimited number of qualifying vehicles. As the number of CAV decals issued increases, the number of single-occupant CAVs in HOV lanes will also increase. This in turn can impact the performance of the HOV lanes. The severity of the impact would vary, depending on the prevalence of HOV lane-eligible CAVs in the area or on the corridor.

One strategy to address the impact of an excessive number of CAVs on HOV lane performance is to limit the number of CAV decals at any given time. This strategy has recently been implemented by the California Department of Motor Vehicles where all the white and green decals were set to expire on January 1, 2019. Then, a new program was started where CAV decals are issued only to qualifying vehicles that have never received a CAV decal before. These new CAV decals will expire on January 1st of the fourth year after the year they are issued, providing HOV lane access for three full years plus the partial year from when the decal was issued. This approach essentially establishes a soft limit on the number of HOV lane-eligible CAVs in a given year on a rolling basis.

The impact of limiting CAV decals on HOV lane performance is difficult to measure in the real world with a before-and-after comparison as there are other factors that can also influence the performance of an HOV lane. These include, for example, the overall travel demand on the corridor, the number of SR2 and SR3+ vehicles, and the frequency and severity of traffic incidents on the corridor. An alternative way to quantify the impact of limiting CAV decals on HOV lane performance is through modeling. It can control for all the other influencing factors, and allows for the impact of limiting CAV decals on HOV lane performance to be estimated.

To assess the impact of reducing or eliminating HOV lane usage by CAVs on HOV lane performance, a modeling of roadways in Orange county (Caltrans District 12) was conducted. This was because any changes in HOV access eligibility for CAVs would be implemented statewide, and Orange county was selected as a case study for evaluating the impact of such implementation in this task. In the modeling, the drive alone passenger cars and trucks (DA) were first divided into those that are clean air vehicles (DA CAV) and those that are not (DA NONCAV), based on vehicle registration records. Then, the DA CAV were further divided into those using HOV lanes (DA CAV HOV) and those not using HOV lanes (DA CAV NONHOV). While there is data from Caltrans District 12 on the split between SR2 HOV and SR2 NONHOV vehicles, there is no data on the split between DA CAV HOV and DA CAV NONHOV vehicles. Therefore, an assumption was made that the DA CAV HOV vehicles to DA CAV NONHOV vehicles ratio is 50% higher than the SR2 HOV vehicles to SR2 NONHOV vehicles ratio. This means that during the mode choice modeling step, DA CAV vehicles are more likely than SR2 vehicles to choose to use HOV lanes.

Three scenarios were modeled—CAV Doubled, CAV Halved, and CAV Eliminated. Figure 52 and Figure 53 show the changes in average traffic volume and average traffic speed, respectively, on freeways in Orange county for each modeling scenario. As the impact of reducing or eliminating HOV lane usage by CAVs on HOV lane performance would vary by corridor depending on the prevalence of HOV lane-eligible CAVs on the corridor before the change, the average impact for the entire county is shown here.

The modeling results for each scenario are discussed below:

1. *CAV Doubled*. This scenario assumes that the number of CAV decals is doubled from the baseline. It represents a hypothetical scenario if CAV decals continue to be issued without a limit. Based on the modeling results, the average traffic volume in HOV lanes would increase by 2.6%, due largely to the increase in number of CAVs in the lanes. On the other hand, the average traffic volume in MF lanes would decrease by 0.5% as CAVs switch to use the HOV lanes. In terms of traffic speed, the increase in traffic volume in HOV lanes would cause the traffic speed in the lanes to drop by 2.1% on average. On the other hand, the decrease in traffic volume in MF lanes would cause the average traffic speed in the lanes to increase by 0.6%.

2. *CAV Halved*. This scenario assumes that the number of CAV decals is reduced by half from the baseline. It represents a scenario somewhat similar to the current situation where a couple hundred thousand of green and white decals have expired, but new red, purple, orange, and blue decals have been issued instead. According to the modeling results, the average traffic volume in HOV lanes would decrease by 1.4%, which can be attributable to the drop in number of CAVs in the lanes. On the other hand, the average traffic volume in MF lanes would increase slightly by 0.2% as CAVs that are no longer eligible to use HOV lane will have to use the MF lanes instead. In terms of traffic speed, the decrease in traffic volume in HOV lanes would help increase the traffic speed in the lanes by 2.2% on average. On the other hand, the increase in traffic volume in MF lanes would cause the average traffic speed in the lanes to drop by 0.3%.

3. *CAV Eliminated*. This scenario assumes that all the CAV decals are eliminated. It represents a scenario similar to when the CAV decal program ends. In such scenario, all DA CAV vehicles will not be able to use HOV lane and have to use MF lanes. According to the modeling results, the average traffic volume in HOV lanes would decrease by 2.9%, while the average traffic volume in MF lanes would increase by 0.5%. The decrease in traffic volume in HOV lanes would increase the traffic speed in the lanes by 5.7% on average. On the other hand, the increase in traffic volume in MF lanes would cause the average traffic speed in the lanes to drop by 0.8%.

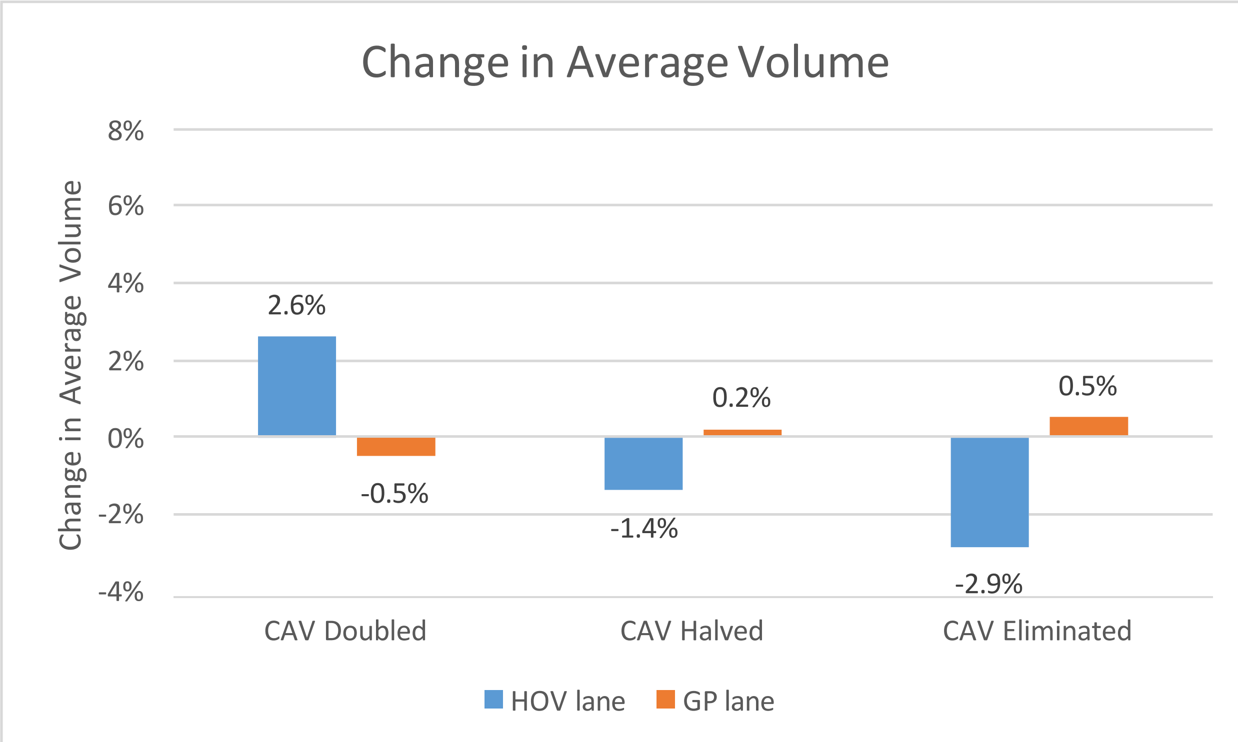


Figure 52. Change in average traffic volume on freeways in Orange county

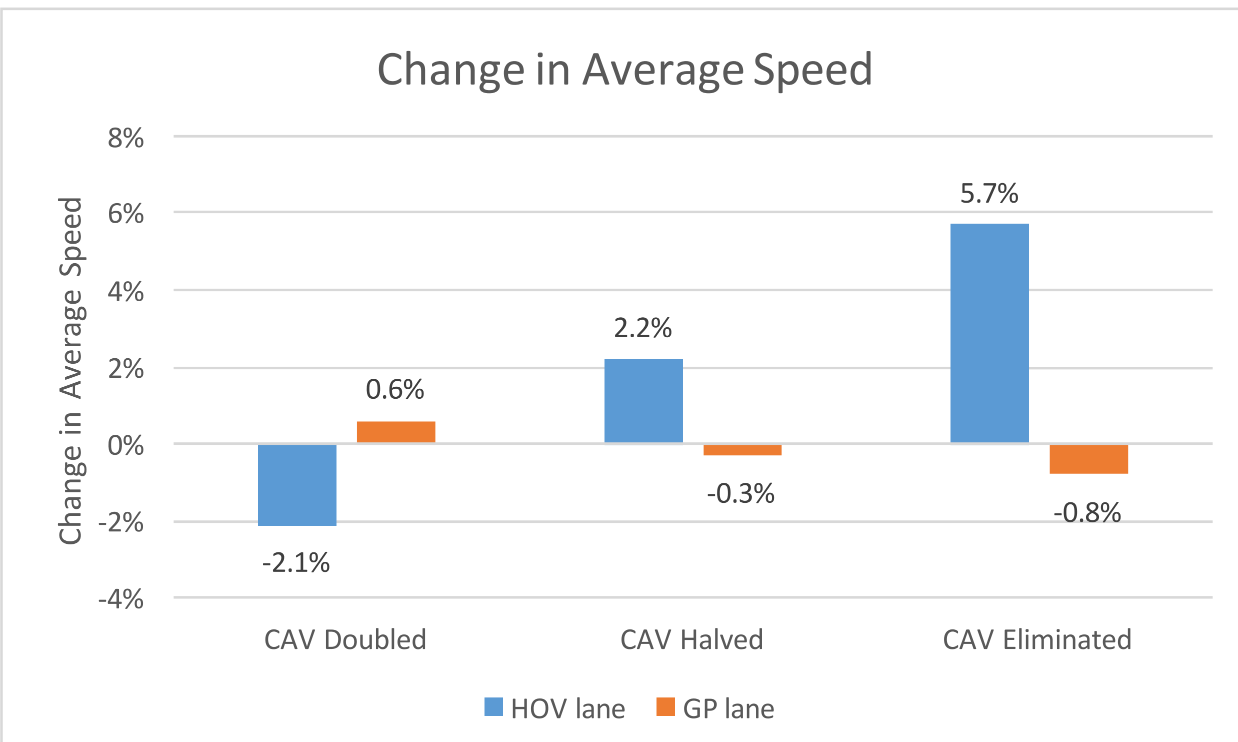


Figure 53. Change in average traffic speed on freeways in Orange county

4.2.4. Conversion of HOV Lane to HOT Lane

A conversion of HOV lane to HOT lane has been used as a congestion mitigation strategy for many HOV facilities across the U.S., including several in California. The evolution of HOV lane into HOT lane as traffic volume in the HOV lane grows over time as a result of the increasing number of HOV2+ vehicles is illustrated in Figure 54. At a point in time, the traffic volume would reach a critical operating threshold or the effective capacity of the HOV lane. To avoid degradation of the HOV lane performance, the operator may restrict HOV lane access for some of the user groups, for example, by converting the HOV lane to HOT lane and then requiring that single-occupant vehicles (SOV) and HOV2 vehicles pay toll in order to use the HOT lane. The access restriction would reduce the number of eligible vehicles and traffic volume in the lane, and thus, helping to alleviate congestion in the lane.

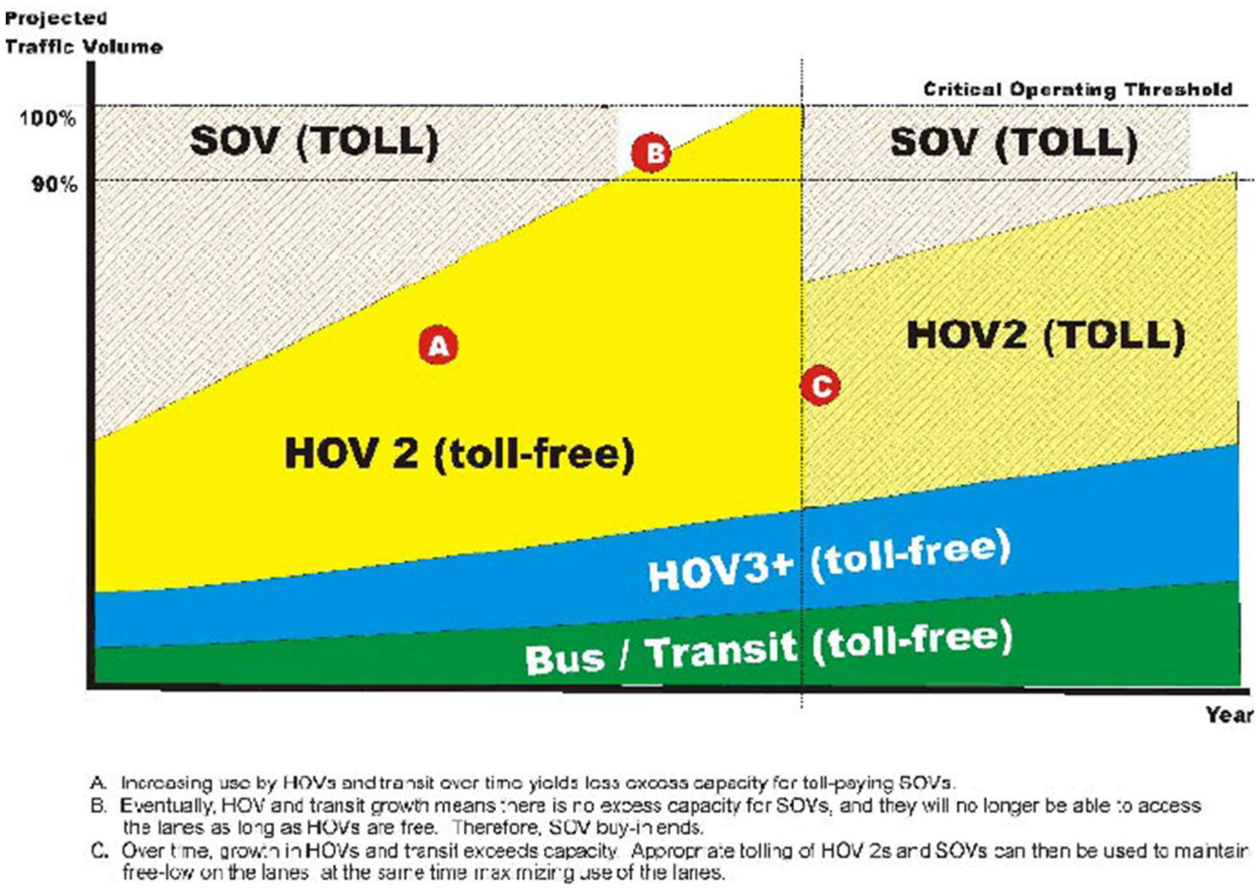


Figure 54. Different phases of HOV facility operation across the life-cycle [Swisher et al.,2009]

There are several HOT facilities in California, including the ones on I-580, I-680, I-880, and SR-237 in Northern California, as well as those on I-10, I-15, I-110, and SR-91 in Southern California. Some of these HOT facilities have been in operation for many years, which present an opportunity to assess the effectiveness of HOV-to-HOT lane conversion in addressing HOV lane performance degradation based on real-world data.

The assessment would compare the HOV lane performance before and after the conversion to HOT lane.

In this task, the HOT lanes in both directions of I-110 in Los Angeles county were selected as a case study. These HOT lanes use dynamic pricing; that is, the toll is based on real-time traffic conditions in the lanes and varies according to the level of congestion. HOV2+ vehicles can use the HOT lanes toll-free at all hours with a valid transponder. CAVs with a valid decal were originally exempt from tolls on these HOT lanes. However, since 2019 those CAVs have had to pay a discounted toll (15% off the posted toll rate) to use the lanes.

The construction of the lane conversion (from HOV lane to HOT lane) began in July 2011, and the HOT lanes were opened to the public in November 2012. Therefore, the analysis periods used for the lane performance comparison are given below. The use of the period from July 1 to December 31 in each year was intended to follow the practice for determining HOV lane degradation.

- “Before” analysis period was from July 1 to December 31, 2010.
- “After” analysis period was from July 1 to December 31, 2013.

The red rectangles in Figure 55 show the start and end points of the HOT lanes, which are about 11 miles apart. The blue circles represent the locations of vehicle detector stations (VDS) along the HOT lanes in each direction. These VDS, which are part of the PeMS, are the source of traffic volume and speed data used in the performance assessment.

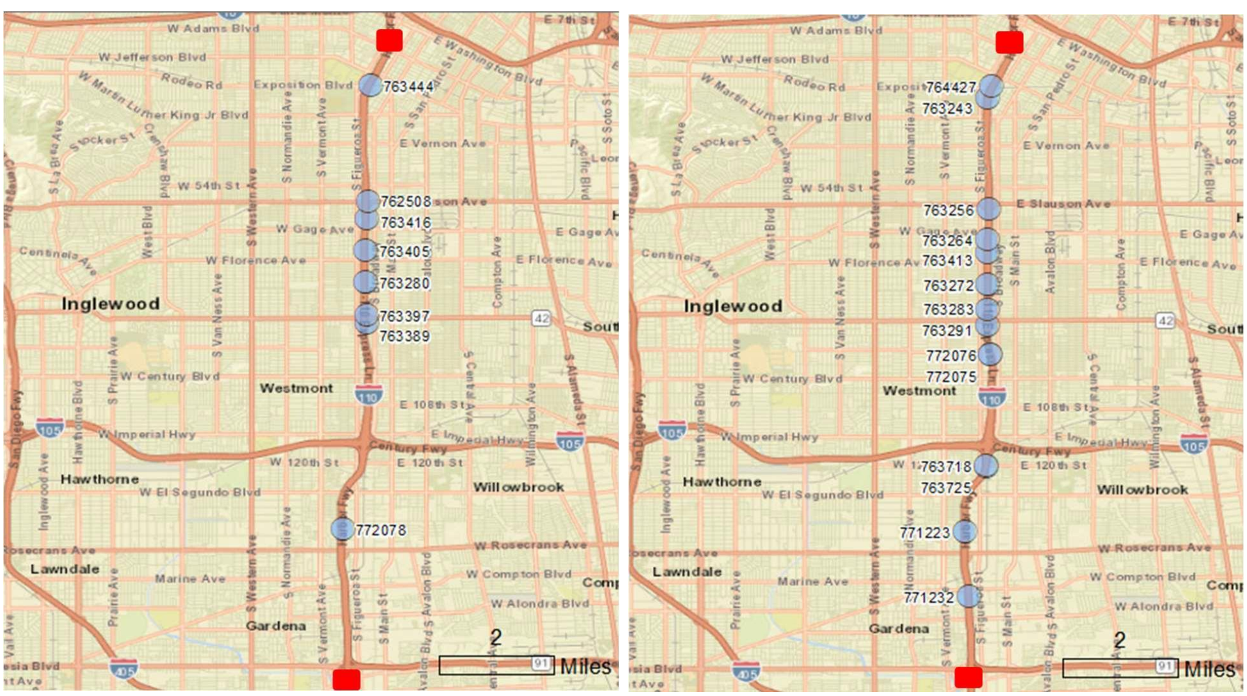


Figure 55. Vehicle detector stations in northbound (left) and southbound (right) directions of I-110

Traffic volume and speed data at the VDS shown in Figure 55 during the before and after analysis periods were downloaded from PeMS. The data were used to determine the level of performance degradation in the lanes following the data processing procedures described in the "2019 California High-Occupancy Vehicle Facilities Degradation Report and Action Plan" [Caltrans, 2020] as summarized briefly below:

- Using data from the second half of each calendar year, from July 1 to December 31
- Analysis data separately for the morning peak hour period (AM peak; from 6 a.m. to 9 a.m.) and the afternoon peak hour period (PM peak; from 3 p.m. to 6 p.m.)
- Excluding data that was imputed or estimated by PeMS

Table 14 through Table 17 shows the average traffic performance as measured by each VDS over the I-110 HOV/HOT lanes during both analysis periods. The VDS where there was no valid data during one or both analysis periods are grayed out as a before-and-after comparison of traffic performance in the lanes cannot be made at these VDS. The speed, flow, and percent observation data represent the average value over the 6-month analysis period. The lane performance degradation level was determined according to the definition in the "2019 California High-Occupancy Vehicle Facilities Degradation Report and Action Plan" [Caltrans, 2020].

Table 14. Average traffic performance in HOV/HOT lane on I-110 NB during AM peak

VDS	Length (mile)	Abs PM	2010				2013			
			Speed (mph)	Deg. Level	Flow (vph)	Obs. (%)	Speed (mph)	Deg. Level	Flow (vph)	Obs. (%)
772078	4.32	12.17	47.5	2	883	71.5	49.2	2	986	68.9
763389	1.89	15.81	50.2	2	2,142	82.8	44.4	2	2,402	99.7
763397	0.35	15.95	50.8	2	2,147	91.9	49.2	2	2,371	99.7
763280	0.56	16.51	52.3	1	1,399	83.6	56.5	1	1,560	43.9
763405	0.55	17.06	47.3	2	2,447	91.9	45.7	2	2,915	96.5
763416	0.42	17.61	46.0	2	3,446	91.9	40.2	3	2,746	86.4
762508	1.16	17.90	48.8	2	2,454	90.9	41.0	3	2,658	97.2
763444	3.52	19.93	NaN	-	NaN	0.0	NaN	-	NaN	0.0

Table 15. Average traffic performance in HOV/HOT lane on I-110 NB during PM peak

VDS	Length (mile)	Abs PM	2010				2013			
			Speed (mph)	Deg. Level	Flow (vph)	Obs. (%)	Speed (mph)	Deg. Level	Flow (vph)	Obs. (%)
772078	4.32	12.17	57.6	1	793	67.9	60.4	1	596	68.7
763389	1.89	15.81	58.0	1	1,899	80.6	61.4	1	1,396	99.7
763397	0.35	15.95	57.7	1	1,895	90.4	66.6	1	1,366	100.0
763280	0.56	16.51	58.4	1	2,098	79.8	63.7	1	1,771	35.1
763405	0.55	17.06	58.9	1	1,933	90.4	68.0	1	1,615	96.2
763416	0.42	17.61	51.2	1	3,012	90.4	59.0	1	1,525	86.6
762508	1.16	17.90	56.6	1	1,935	89.9	62.0	1	1,461	97.2
763444	3.52	19.93	NaN	-	NaN	0.0	NaN	-	NaN	0.0

Table 16. Average traffic performance in HOV/HOT lane on I-110 SB during AM peak

VDS	Length (mile)	Abs PM	2010				2013			
			Speed (mph)	Deg. Level	Flow (vph)	Obs. (%)	Speed (mph)	Deg. Level	Flow (vph)	Obs. (%)
771232	3.07	11.04	NaN	-	NaN	0.0	NaN	-	NaN	0.0
771223	1.17	12.17	55.6	1	510	71.5	54.3	2	408	68.9
763725	0.61	13.37	64.7	1	1,572	51.5	NaN	-	NaN	0.0
763718	0.96	13.38	64.4	1	1,089	80.8	NaN	-	NaN	0.0
772075	0.96	15.29	64.1	1	1,227	52.8	NaN	-	NaN	0.0
772076	0.26	15.29	NaN	-	NaN	0.0	NaN	-	NaN	0.0
763291	0.40	15.81	63.8	1	1,162	51.5	NaN	-	NaN	0.0
763283	0.35	16.09	63.5	1	1,202	77.5	62.4	1	1,161	83.1
763272	0.49	16.51	62.0	1	1,024	11.6	66.1	1	1,136	81.1
763413	0.39	17.06	63.9	1	1,042	91.9	63.6	1	1,108	96.5
763264	0.38	17.29	NaN	-	NaN	0.0	66.6	1	1,099	84.8
763256	1.22	17.81	63.9	1	1,025	89.4	64.1	1	1,106	86.9
763243	1.06	19.73	NaN	-	NaN	0.0	58.9	1	1,101	93.9
764427	2.60	19.93	NaN	-	NaN	0.0	NaN	-	NaN	0.0

Table 17. Average traffic performance in HOV/HOT lane on I-110 SB during PM peak

VDS	Length (mile)	Abs PM	2010				2013			
			Speed (mph)	Deg. Level	Flow (vph)	Obs. (%)	Speed (mph)	Deg. Level	Flow (vph)	Obs. (%)
771232	3.07	11.04	NaN	-	NaN	0.0	NaN	-	NaN	0.0
771223	1.17	12.17	35.7	4	875	67.9	49.5	2	1,019	68.7
763725	0.61	13.37	64.6	1	1,575	50.3	NaN	-	NaN	0.0
763718	0.96	13.38	64.0	1	1,637	79.8	NaN	-	NaN	0.0
772075	0.96	15.29	58.1	1	2,283	52.0	NaN	-	NaN	0.0
772076	0.26	15.29	NaN	-	NaN	0.0	NaN	-	NaN	0.0
763291	0.40	15.81	58.5	1	2,310	48.0	NaN	-	NaN	0.0
763283	0.35	16.09	57.3	1	2,365	75.0	58.5	1	2,323	82.8
763272	0.49	16.51	55.7	1	2,256	10.1	63.1	1	2,281	80.1
763413	0.39	17.06	56.7	1	2,457	90.4	59.6	1	2,438	96.2
763264	0.38	17.29	NaN	-	NaN	0.0	62.4	1	2,418	83.3
763256	1.22	17.81	56.2	1	2,472	86.9	58.5	1	2,452	87.1
763243	1.06	19.73	NaN	-	NaN	0.0	51.8	1	2,331	94.4
764427	2.60	19.93	NaN	-	NaN	0.0	NaN	-	NaN	0.0

For the VDS where there are valid data during both analysis period (7 VDS in the northbound direction and 5 VDS in the southbound direction), the comparison of the lane performance degradation level was plotted in Figure 56 through Figure 59. According to these figures, the performance degradation level remained the same after the conversion to HOV lanes at the majority of the VDS. The performance degradation of the lanes actually increased at three VDS. The degradation level increased from 2 to 3 at two VDS in the northbound direction during AM peak. And the degradation level increased from 1 to 2 at one VDS in the southbound direction during AM peak. On the other hand, the degradation level at one VDS in the southbound direction during PM peak decreased from 4 to 2.

Based on the comparison results, the conversion of the HOV lanes on I-110 to HOT lanes did not help alleviate the degraded performance of the lanes, except at one VDS location during the afternoon peak period. This could be because HOV2+ vehicles and CAVs were able to use the HOT lanes toll-free. That means the number of HOV lane-eligible vehicles were about the same before and after the conversion, and any changes in the lane performance would likely be attributable to other reasons (e.g., changes in the overall travel demand and its variation, changes in the fraction of HOV2+ vehicles). And since the performance of the HOV lanes was already degraded during the peak periods before the conversion, it is not surprising that their performance remained degraded after being converted to HOT lanes.

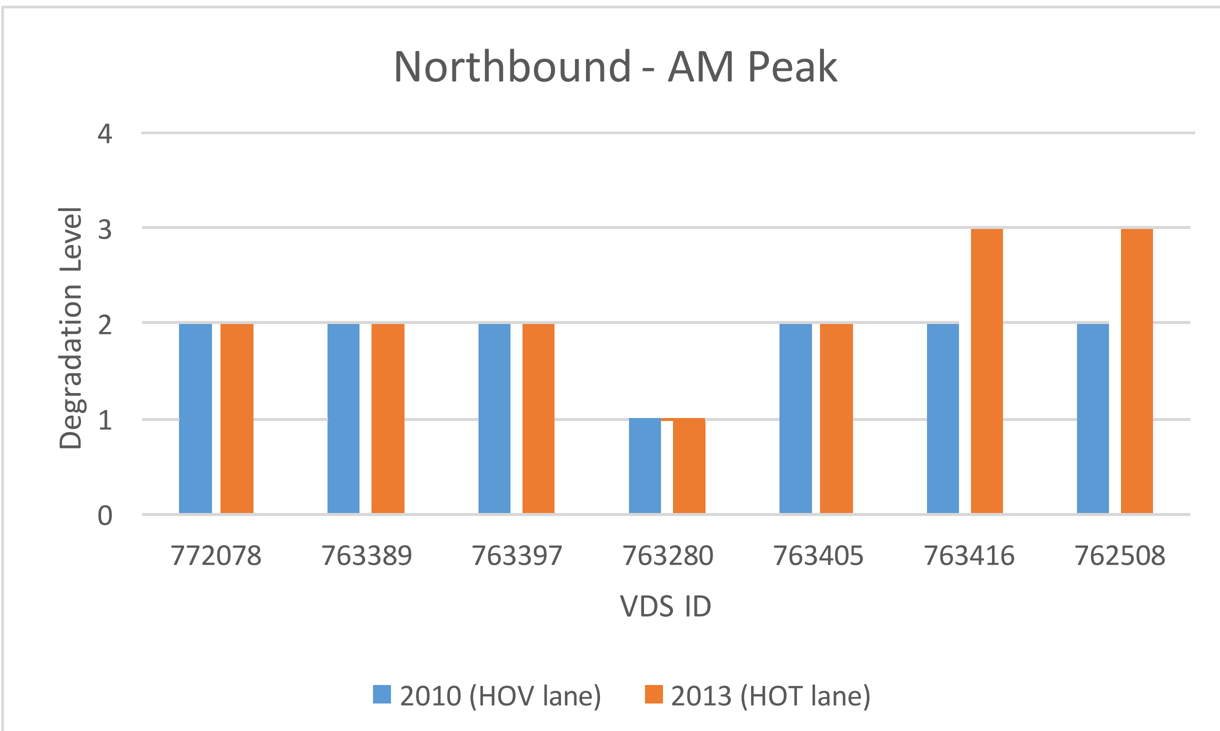


Figure 56. Degradation level of HOV/HOT lane on I-110 NB during AM peak before and after conversion

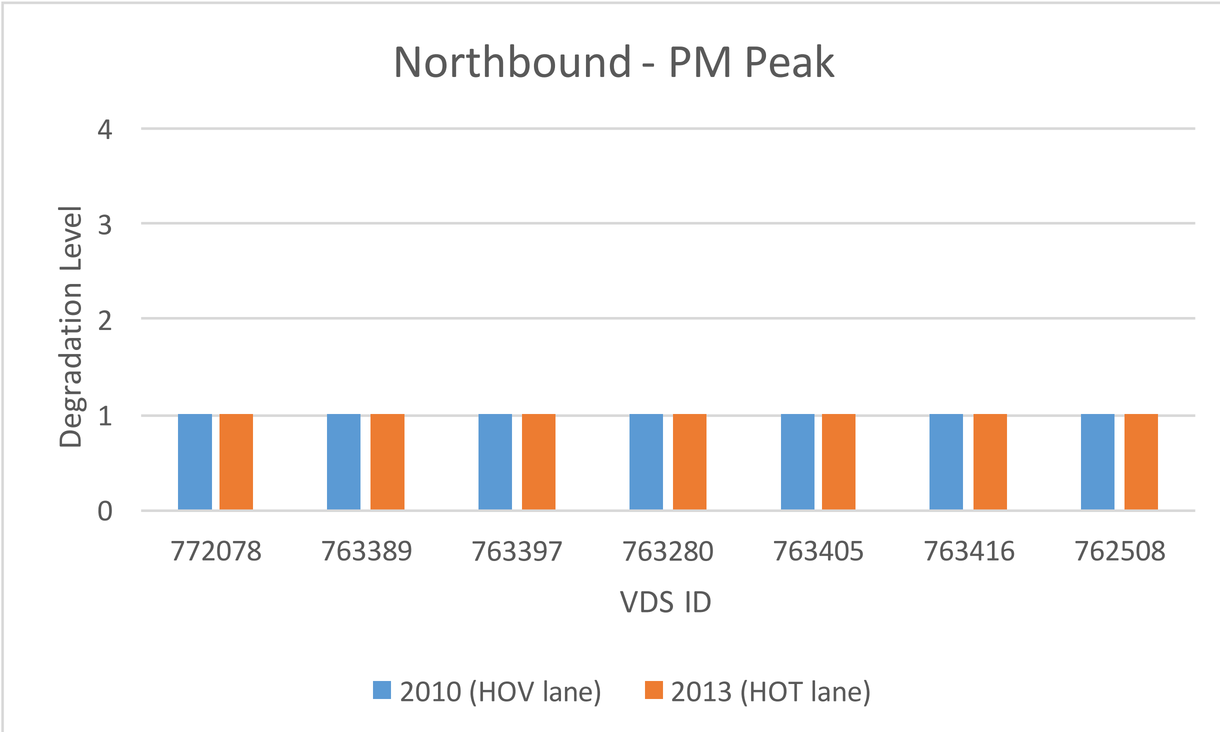


Figure 57. Degradation level of HOV/HOT lane on I-110 NB during PM peak before and after conversion

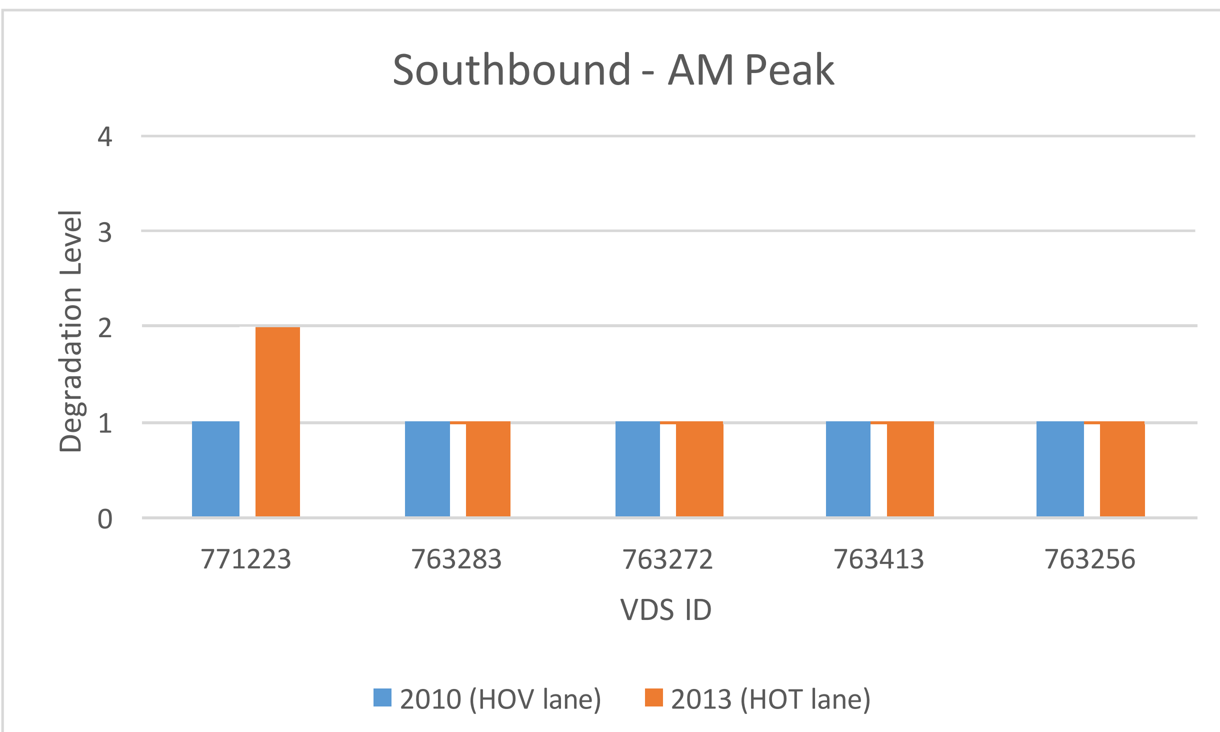


Figure 58. Degradation level of HOV/HOT lane on I-110 SB during AM peak before and after conversion

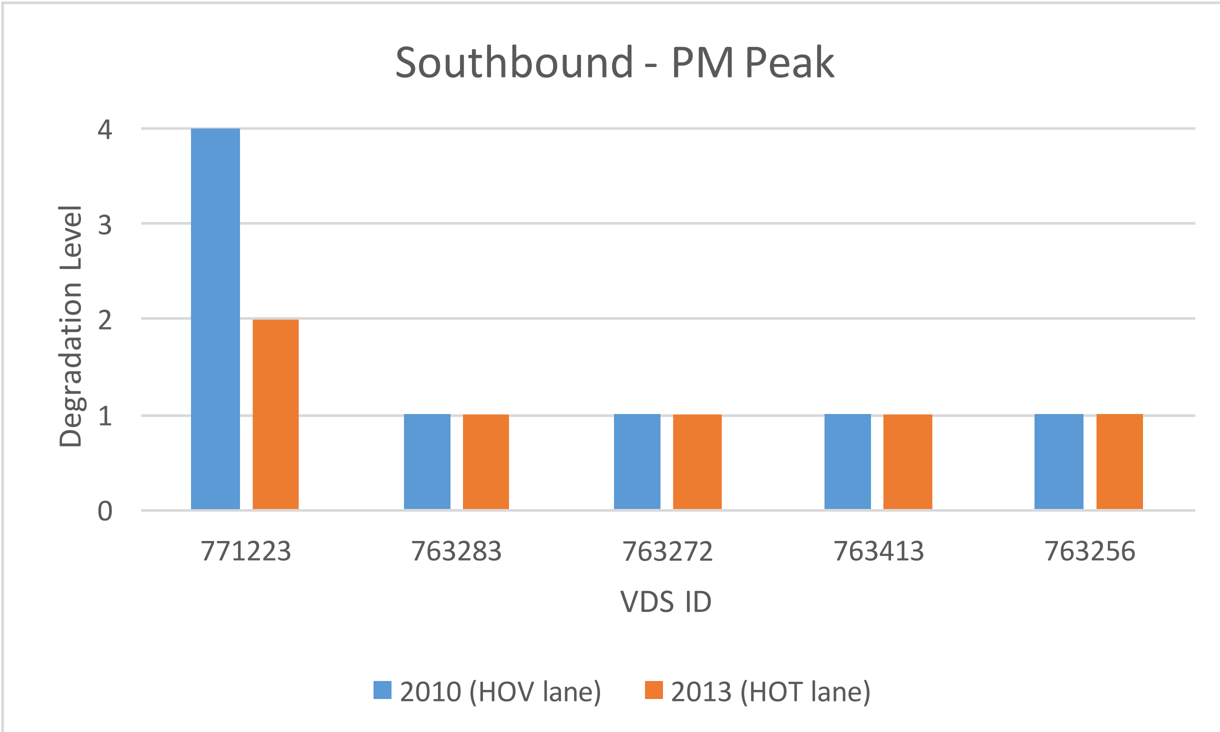


Figure 59. Degradation level of HOV/HOT lane on I-110 SB during PM peak before and after conversion

5. Assessment of Alternative HOV Lane Operational Strategies with Traffic Simulation

To address the HOV lane performance degradation problem, several strategies have been proposed, which can be grouped into four categories—capacity expansion, operational improvement, education, and enforcement. Operational improvement, such as increasing occupancy requirements or converting HOV lanes to HOT lanes has potential to address the degradation issue, but these strategies may impact the travel speed of the vehicles in the MF lane. Education and enforcement strategies, such as increasing public awareness and installing additional signage along the HOV lanes, could be implemented at a low cost, but the potential to address the degradation problem may not be significant. Therefore, capacity expansion strategies such as adding a second HOV lane can be an effective way to alleviate HOV degradation. However, such strategies can be difficult in some areas where there is not much room left to add new travel lanes. In that case, adding a new HOV lane that operates in a contraflow fashion could be a good compromise, especially if peak travel demands in the HOV lanes are tidal, e.g. morning peak congestion in one direction and afternoon peak congestion in the other direction. Because of the relatively higher costs of constructing and operating a contraflow HOV lane than a concurrent HOV lane, it is important to conduct a thorough evaluation of the potential operational improvements of this strategy before an actual implementation. In this task, we conduct such evaluation with a traffic microsimulation tool.

5.1. Study Site Selection

Since this research project is focused on mitigating congestion in HOV facilities, the study site was chosen among the HOV facilities that are under major degradation. Based on the 2019 California High-Occupancy Vehicles Facilities Degradation Report and Action Plan and the discussion with Caltrans staff, the research team selected the HOV facilities on I-215 (between absolute post miles 30 to 35) in Riverside County, as shown in Figure 60, as the study site. The selected freeway segment connects two major cities in Riverside County—City of Riverside and City of Moreno Valley, and is usually heavily congested during both morning and afternoon peak hours. As indicated in the 2018 Degradation Report, the HOV facilities in both directions of this freeway section are extremely degraded, the highest level of degradation status in the report. To further understand the congestion patterns on the freeway section, we checked Google Maps, which provides visualization of typical traffic speed on any chosen days of week as estimated from historical traffic data, as shown in Figure 61.

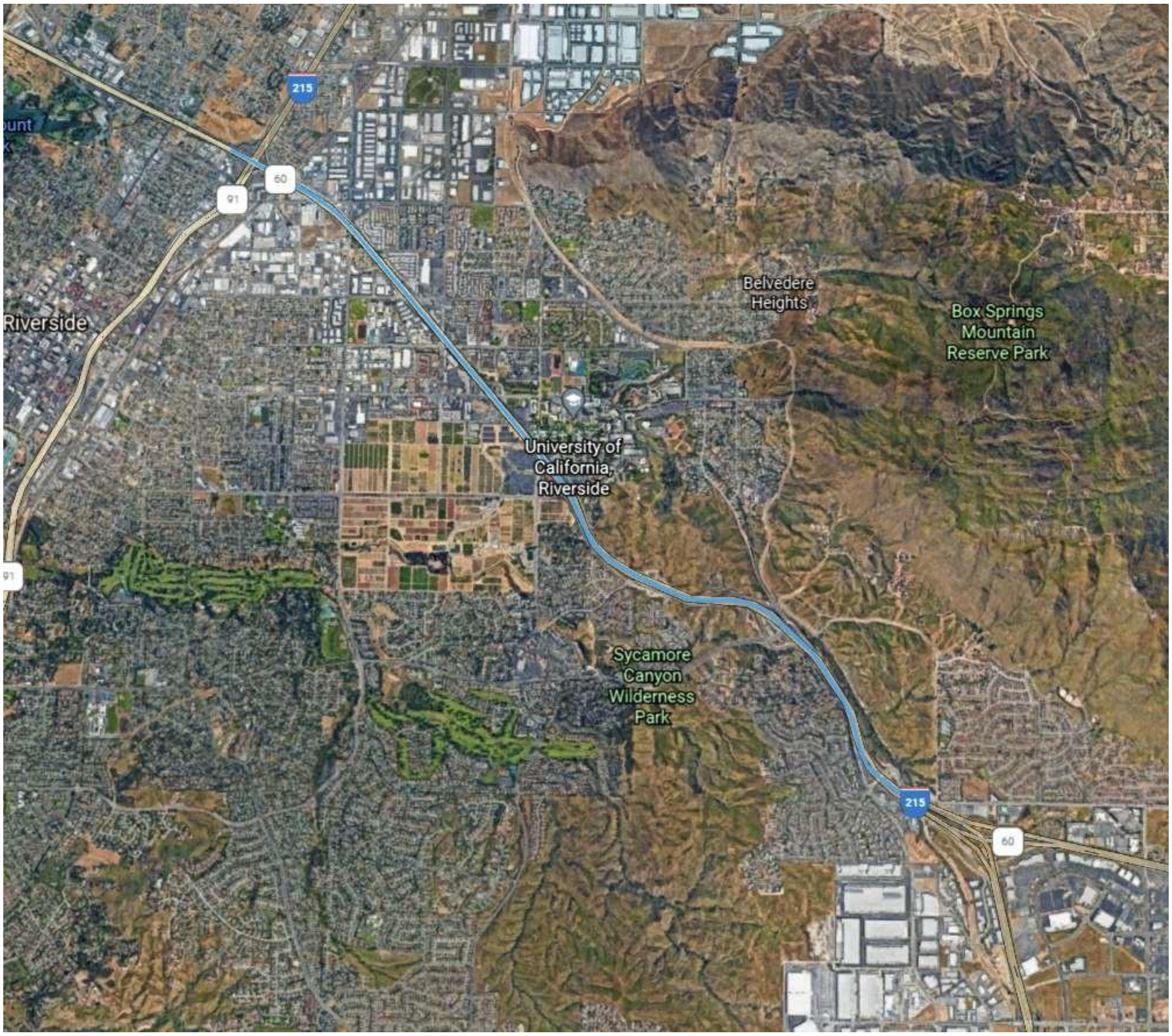


Figure 60. Selected HOV facilities for the study

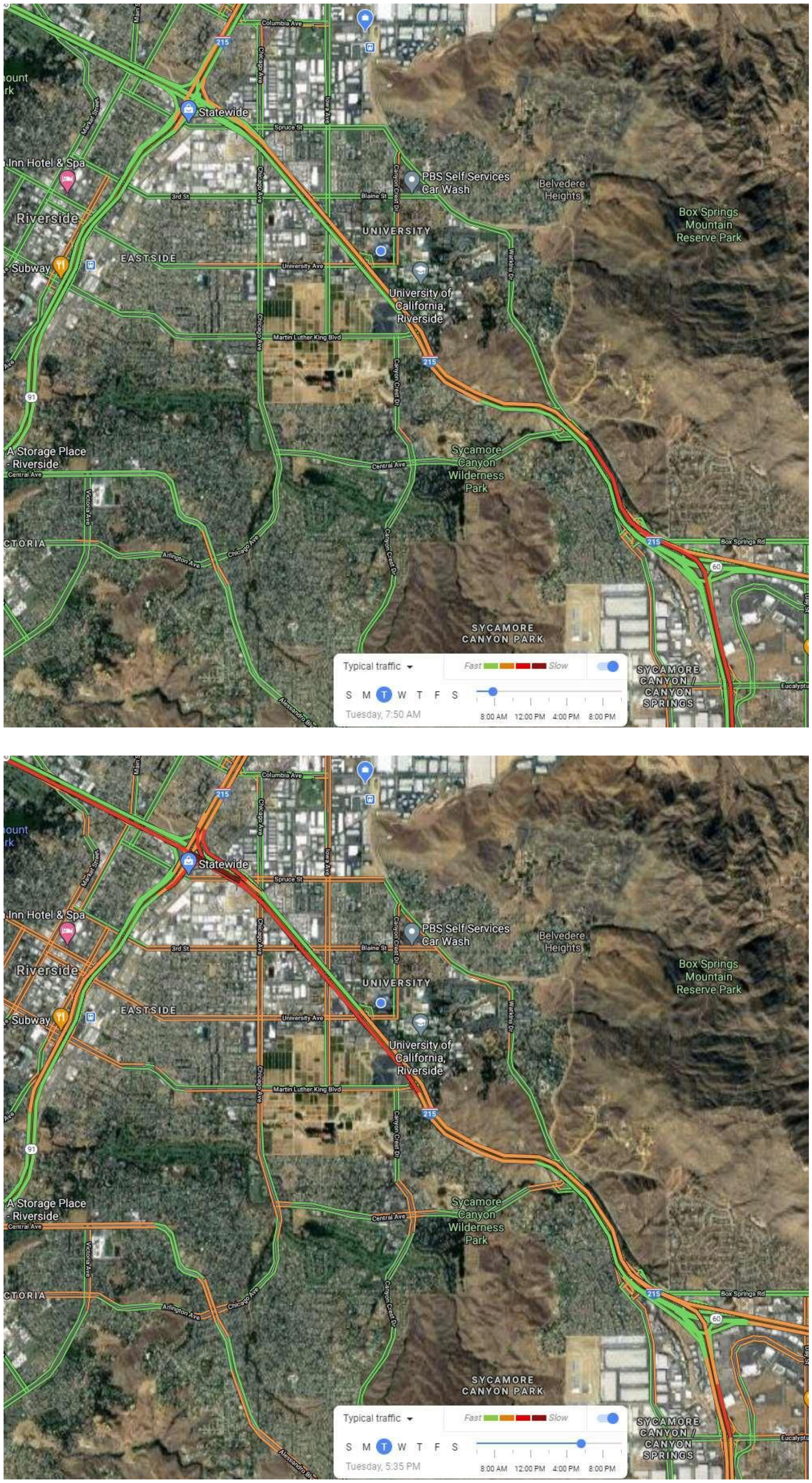


Figure 61. Typical traffic speed on Tuesday during morning peak (top) and afternoon peak (bottom)

As shown in Figure 61, on a typical Tuesday the morning and afternoon peak hours are usually at around 8 a.m. and 6 p.m., respectively. During the morning peak, heavy traffic congestion occurs at the south end of the northbound, near the interchange of SR-60 and I-215 in the City of Moreno Valley. It is gradually relieved along the northbound direction. In the afternoon peak, congestion occurs at the north end of the southbound, near the interchange of SR-60 and SR91 in the City of Riverside, and impacts the north portion of the southbound direction. In the southbound direction, there is also moderate congestion in the south portion of the section.

This pattern of congestion indicates that a majority of the vehicles travels northbound in the morning and southbound in the afternoon, which supports our idea to add a new contraflow HOV lane in the median to increase the capacity of the existing HOV lanes in both travel directions. However, the length of the new HOV lane that should be operated in a contraflow fashion needs to be determined. Specifically, we evaluated two configurations in this task:

1. *Full contraflow HOV lane*: This configuration adds a new contraflow HOV lane along the entire section. This means that the new HOV lane is open to the northbound traffic during the morning peak hours and to the southbound traffic during the afternoon peak hours.

2. *Partial contraflow HOV lane*: This configuration adds a new HOV lane along the entire section, but operates it as a contraflow HOV lane only in the north portion of the section. This means that the north portion of the new HOV lane is operated as a contraflow lane in the same way as the previous configuration. On the other hand, the south portion of the new HOV lane is always used for northbound traffic, essentially forming dual HOV lanes in that direction. The main reason for this configuration is that in the south portion of the study section, the northbound traffic always appears to be more congested than the southbound traffic.

Once the study section had been selected, the research team checked the reliability of the traffic data reported by PeMS from 2018 to 2019 based on the recorded detector health information. We found that during February 2019 the detectors on the freeway section were healthy for over 90% of the time. We then examined the average traffic volume at 5-min intervals and found the period 5:35-6:35 p.m. to have the highest volume. Thus, we selected Tuesday February 12, 2019, as the target day of study for the simulation modeling.

5.2. Simulation Network Coding

Figure 60 shows the 5-mile freeway section of the selected study site. The section has 3 inflow sources from the north end, which are SR-60 eastbound, I-215 southbound, and CA-91 eastbound. The number of lanes on different segments of the study site varies from four to six, with the leftmost lane a full-time HOV lane. The elevation difference between the north end and the south end of the section is 180 m. There are five pairs of off-ramp/on-ramp over the entire section in each direction. PeMS detectors are installed at the on-ramp, off-ramp, and the mainline between pairs of off-ramp/on-ramp, so the inflow and outflow at each ramp could be calculated using the traffic flow data collected from the loop detectors.

As shown in Figure 62, the study site was coded into a simulation network using PTV Vissim, a microscopic multi-modal traffic simulation software. Geographic images from OpenStreetMap were imported as the background to help code the detail of the network, including the curvature of the road segments, merging points of the outermost lanes, and on-ramp/off-ramp locations. Satellite images from Google Maps were also used to verify the locations to make sure that the simulation network was coded as close to the real world as possible. In the simulation network, the left-most lane is designated as the HOV lane, which does not allow any non-HOVs. HOVs are free to use any lanes, but will prefer the lane with less congestion. Therefore, when the mainline starts to get congested, HOVs will start to change into the HOV lanes until both the MF and the HOV lanes are at the same congestion level.

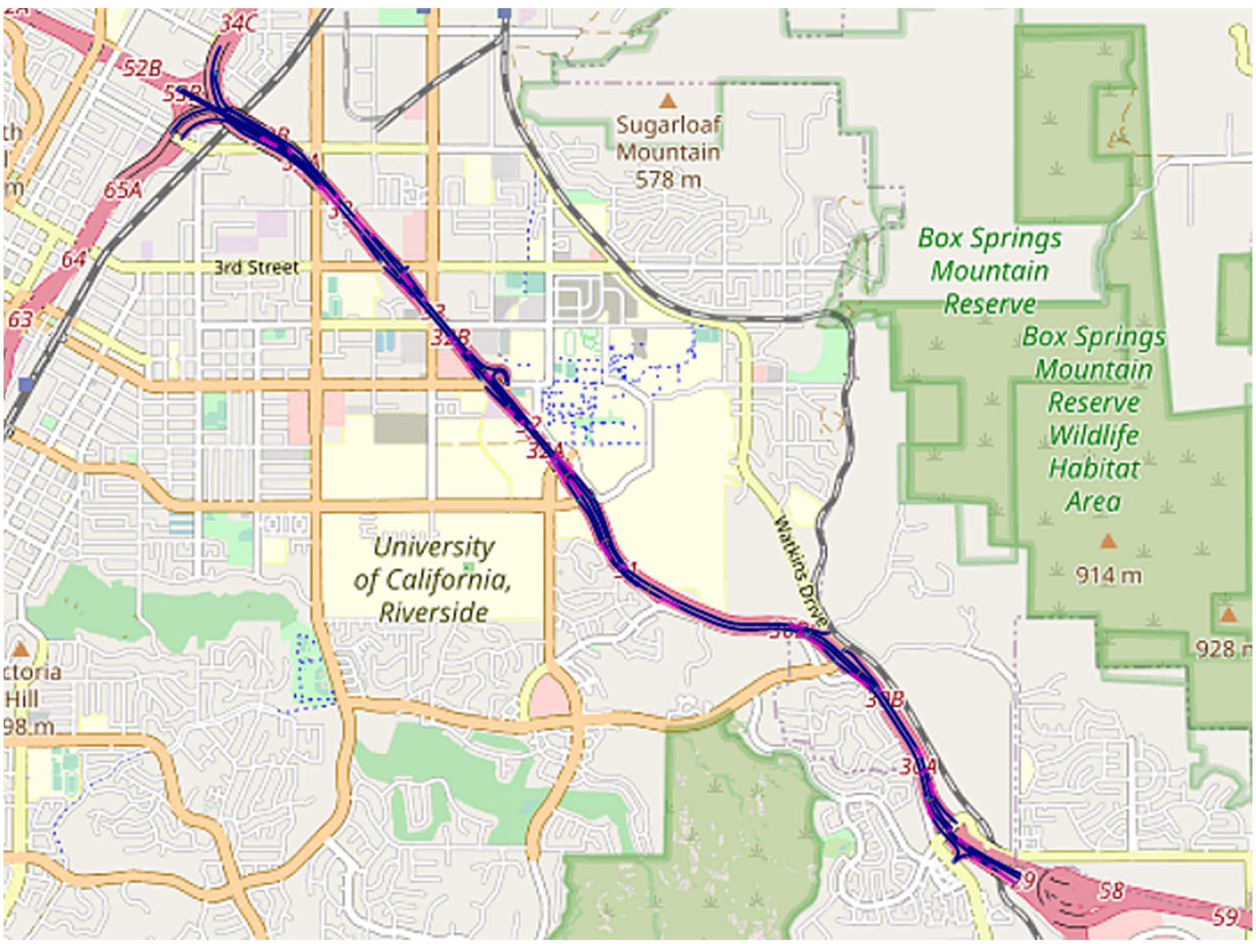


Figure 62. Overview of the entire simulation network in VISSIM

There are three vehicle types in the simulation network, namely HOV-passenger car, SOV-passenger car, and SOV-heavy-duty truck (HDT). SOV-HDTs are only allowed in the two outer lanes with a lower maximum speed as compared to the other two vehicle types. The relative amount of traffic volume for the three types of vehicles was set to be 46.8%, 46.8%, and 6.4%, respectively, based on PeMS data. The afternoon peak hour (17:35-18:35) was selected as the main simulation period, with 35-min warm-up period (to allow time for the vehicles to enter the network) added before the main period and 40-min cool-down period (to allow time for the vehicles to leave the network) added after the main period. The vehicle input flows at each on-ramp are different based on the real-world data in the three periods.

5.3. Simulation Network Calibration and Validation

Network calibration is crucial in simulation studies as the real-world driving behaviors may be different from the simulation result with the default parameters. In this study, we first calibrated the traffic flow data collected from PeMS as some of the loop detectors were non-functional or missing in some lanes. Below shows an example of how we calibrate the data. As can be seen from Table 18, the HOV traffic flow percentage observed at Box Springs Southbound is 0, meaning the data collected is not trustable due to the potential malfunction of the loop detector. We analyzed the location of the detector (shown in Figure 63) and used the confirmed accurate data from the other detectors upstream to estimate the traffic flow of the Box Springs SB stations. Therefore, the HOV traffic flow (q) can be estimated using the equations below:

$$q_{\text{HV,Box Spring SB}} = q_{\text{HV+ML+OR,Central Ave SB}} - q_{\text{FR,+ML,Box Spring SB}} \quad (1)$$

where q represents traffic flow, FR, OR, ML, and HV represent off-ramp, on-ramp, mainline, and HOV respectively, and the traffic flow at a finer resolution is calibrated using the ratio calculated from the hourly data. Figure 64 and Figure 65 show the traffic flow comparison before and after calibration and we can see that the traffic flow no longer has some abrupt changes shown in the original traffic flow map.

Table 18. Traffic Flow Statistics Collected from PeMS

					Traffic Flow hourly		
Abs PM	Location	Type	% Observed		17	18	19
30.29	Box Springs	HV	100.0		1,116.00	1,262.00	1,063.00
30.29	Box Springs	ML	100.0		5,976.00	5,275.00	4,839.00
30.44	Box Springs SB	OR	100.0		318.00	235.00	156.00
30.44	Box Springs SB	ML	100.0		6,554.00	5,919.00	5,548.00
30.44	Box Springs SB	HV	0.0		1,302.00	964.00	698.00
30.44	Box Springs SB	FR	100.0		335.00	293.00	266.00
31.40	Central Ave SB	OR	100.0		1,218.00	947.00	449.00
31.40	Central Ave SB	ML	100.0		6,736.00	5,949.00	6,044.00
31.40	Central Ave SB	HV	100.0		1,564.00	1,451.00	1,244.00

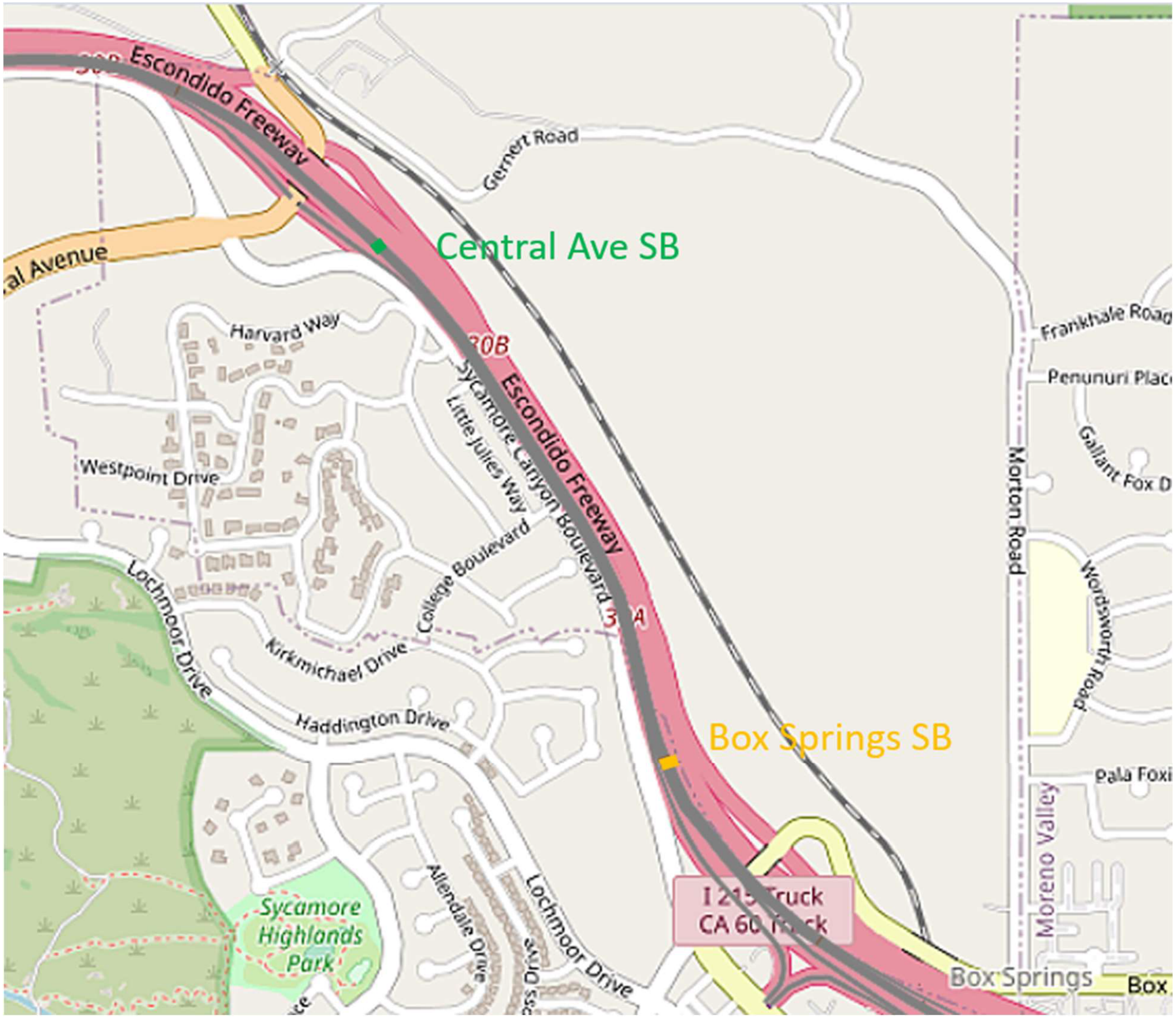


Figure 63. Location of the loop detectors on I-215 southbound

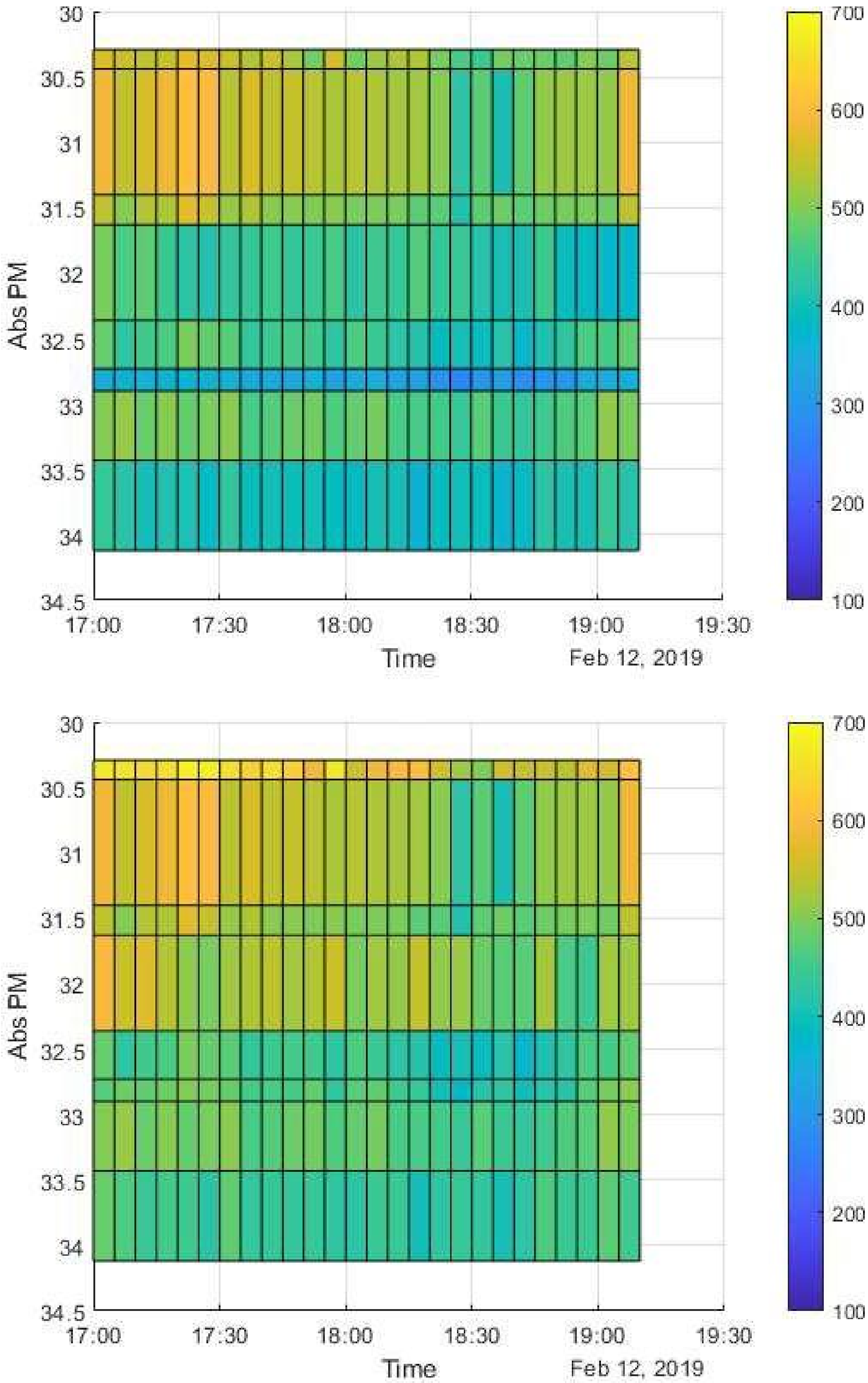
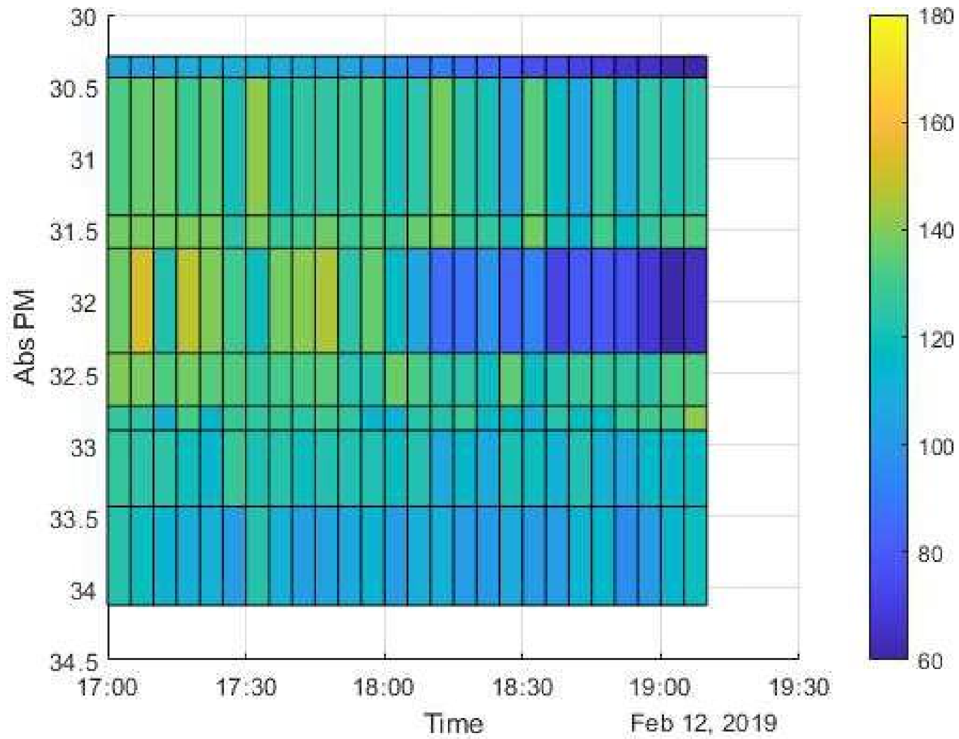


Figure 64. (Top) Original MF traffic flow and (bottom) calibrated MF traffic flow on I-215 southbound



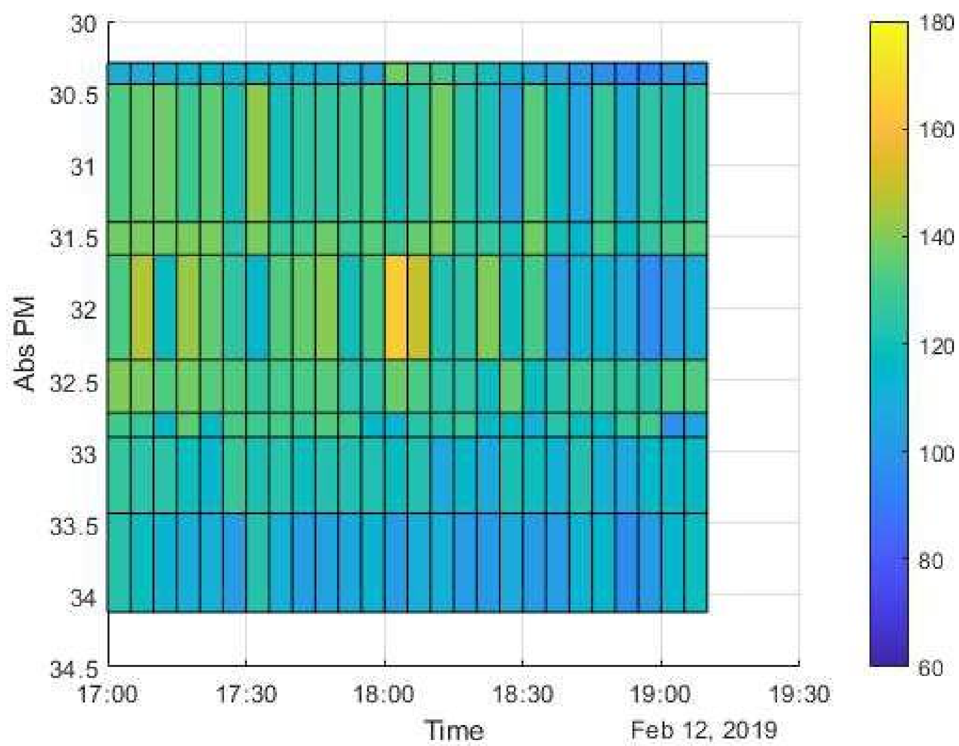


Figure 65. (Top) Original HOV traffic flow and (bottom) calibrated HOV traffic flow on I-215 southbound

Then, the link-level parameters, such as Link Behavior Type and Link Gradient, were adjusted based on the real-world location of the link in the segment. Lastly, a brute-force search algorithm was conducted by running a for loop on a selected range of global parameters, including car following headway time and lane change safety reduction factor. The best set of global parameters was chosen based on the minimum hourly traffic flow difference. The final values of the headway time and safety reduction factor for the Merge link type were set to be 1.8s and 0.4, respectively. And the same set of values for the Freeway link type were set to be 1.7s and 0.6, respectively.

We then used the Caltrans guidelines [Dowling et al., 2002] to validate our model quantitatively. Geoffrey E. Havers (GEH) statistic and traffic flow error calculated using the data collected from each loop detectors (9 ML detectors and 9 HOV detectors on Southbound, 8 ML detectors and 8 HOV detectors on Northbound) are shown in Table 19. The GEH statistic is calculated using the following equation:

$$GEH = \sqrt{2(q_s - q_o)^2 / (q_s + q_o)} \qquad (2)$$

where q_s is the simulated flow and q_o is the observed flow. As shown in the table, over 85% of all the cases are in the acceptable range for each criterion. And the GEH statistics of total link flows is smaller than 5. The results verify that the simulated traffic network has been successfully calibrated according to the real-world traffic.

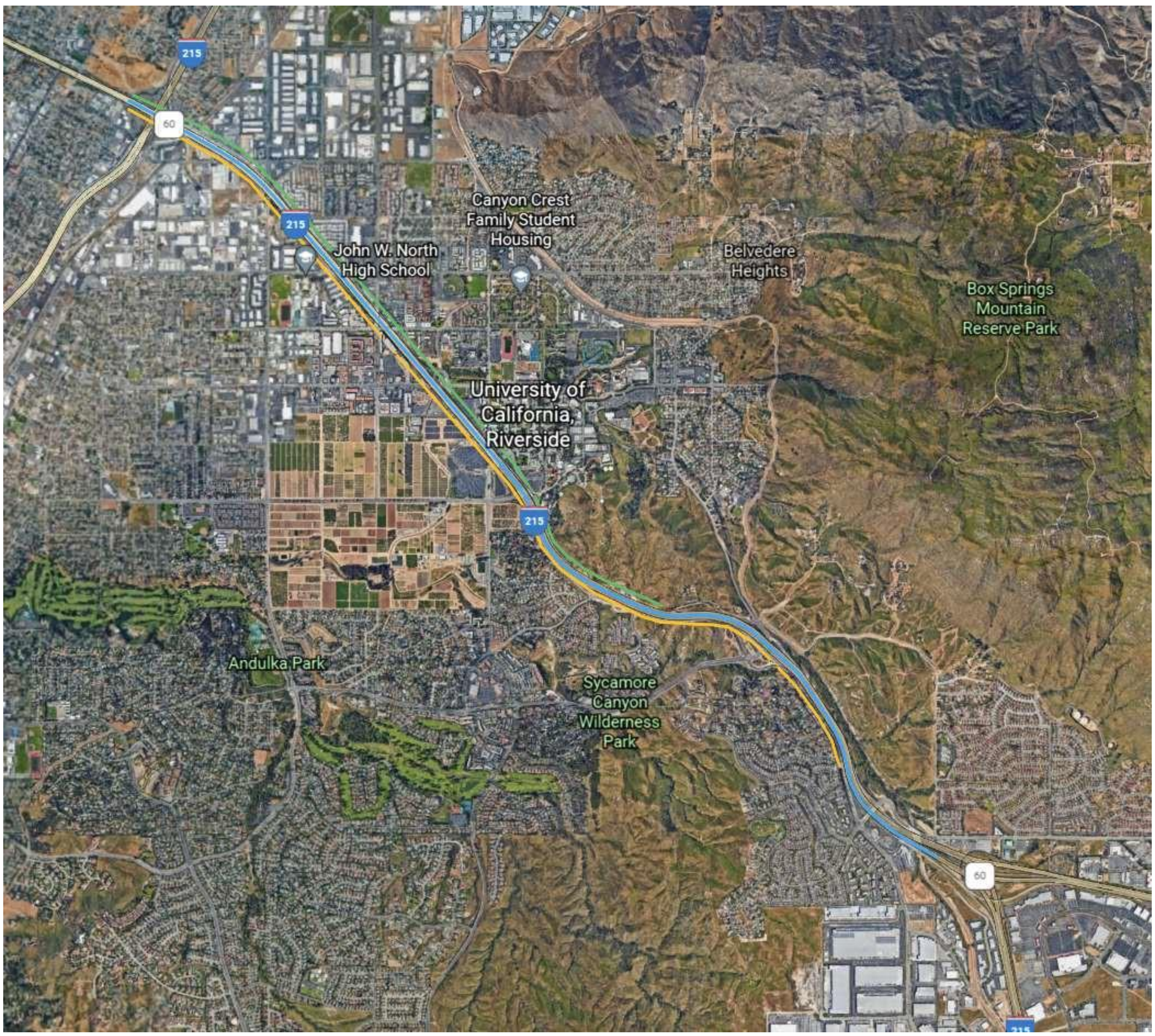
Table 19. Summary of validation targets and results

Criteria and Measures	Acceptability Targets	Validation Results
Hourly flows: simulated versus observed		
Individual link flows		
Within 100 veh, for flow <700 veh	>85% of all cases	100% of 0 cases
Within 15%, for 700 veh < flow <2700 veh	>85% of all cases	88.2% of 17 cases
Within 400 veh, for flow >2700 veh	>85% of all cases	88.2% of 17 cases
Total link flows-within 5%	All accepting links	0.203%
GEH statistics-individual link flow (GEH<5)	>85% of all cases	88.2% of 34 cases
GEH statistics-total link flows (GEH<4)	All accepting links	0.687
Visual audits		
Individual link speeds		
Visually acceptable speed-flow relationship	To analyst’s satisfaction	Satisfied
Bottlenecks		
Visually acceptable queuing	To analyst’s satisfaction	Satisfied

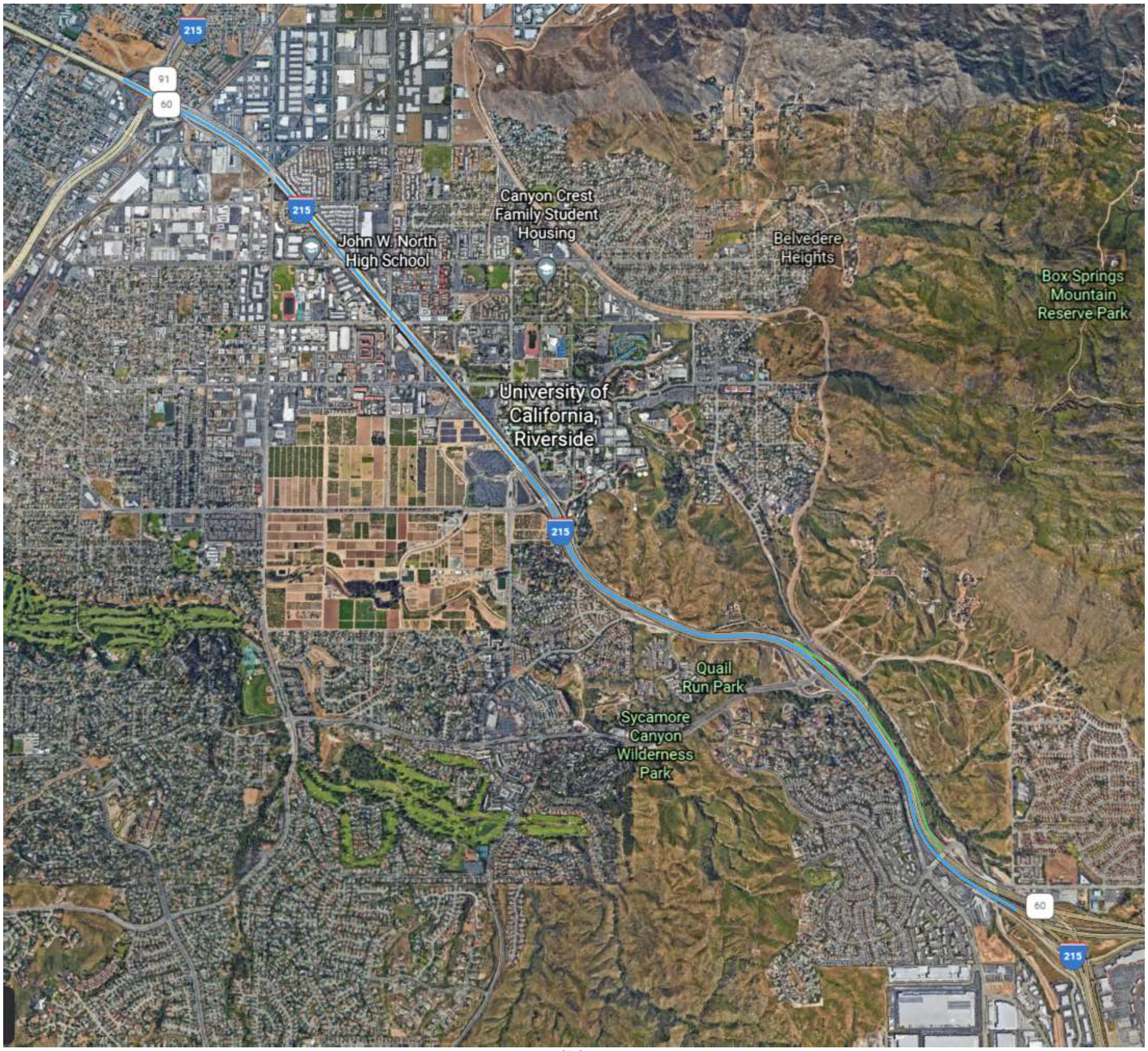
After the optimal set of parameters have been identified, we also tested other seed numbers and picked a total of 5 seeds that satisfied the criteria to increase the number of samples. As mentioned in Section 5.2, we also coded two other simulation networks of the same freeway section—one with a new full contraflow HOV lane, and another one with a new partial contraflow HOV lane. We added the new HOV lane to the median of the freeway section and applied the verified parameters from the baseline simulation network to the new simulation networks. More details and results comparison are provided in the next section.

5.4. HOV Lane Performance Evaluation

We applied the full and partial contraflow HOV lane configurations to reduce traffic congestion and increase vehicle throughput in HOV lanes on the selected section of I-215. As shown in Figure 66(a), within the 5.1-mile study section of I-215 (labeled in blue), the lengths of the full contraflow HOV lane (labeled in yellow) and the partial contraflow HOV lane (labeled in green) are 4.6 miles and 3.5 miles, respectively. That means the dual HOV lanes on I-215 northbound, labeled in green in Figure 66(b), are 1.1 miles. The ending location of the partial contraflow HOV lane for southbound traffic was chosen to be the location that is usually free of congestion according to the typical traffic speed maps. Also, the merging point of the dual HOV lanes for northbound traffic was picked specifically to be away from the existing on-ramp merging or off-ramp splitting areas so as to avoid interfering with those weaving traffic.



(a)

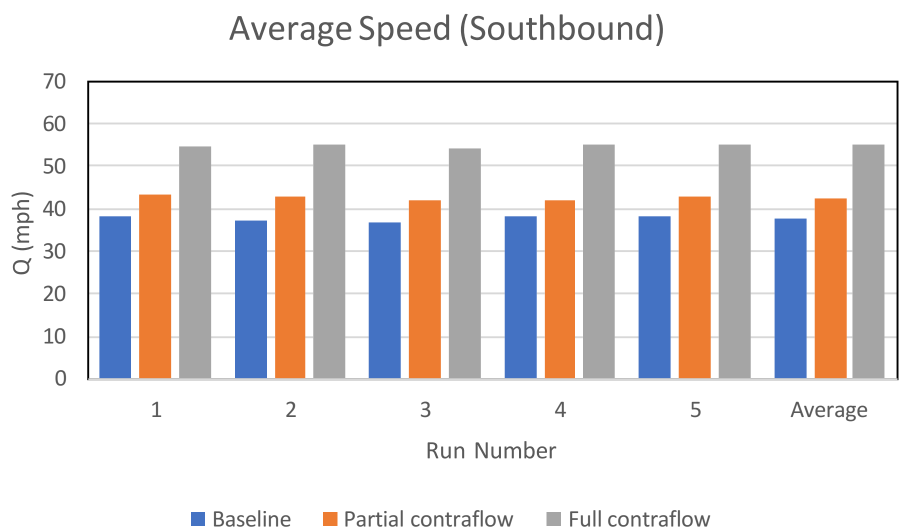


(b)

Figure 66. Map of baseline, PC, and FC HOV lanes in (a) southbound direction and (b) northbound direction

Five simulation runs with different seed numbers were made in each of the baseline, partial contraflow (PC) HOV, and full contraflow (FC) HOV networks. The evaluation metrics including vehicle miles traveled (VMT), vehicle hours traveled (VHT), average travel speed (Q = VMT/VHT), and average vehicle delay were obtained and compared among the different networks, as shown in Figure 67 and Figure 68 and summarized in Table 3. The vehicle delay is defined as the duration of delay caused by the queues formed in the congestion.

According to the Figure 67 and Figure 68, the baseline network performs the worst in terms of average travel speed and average vehicle delay. In the southbound direction, the FC configuration has the least delay and the highest average travel speed in all the simulation runs, while the PC configuration performs better than the baseline but worse than the FC configuration. In the northbound direction, a similar increase in average travel speed and a decrease in average vehicle delay can be observed when comparing the baseline and the PC networks. Note that the FC configuration does not apply to the northbound direction since both directions cannot have an extra HOV lane at the same time and only the afternoon peak period is simulated.



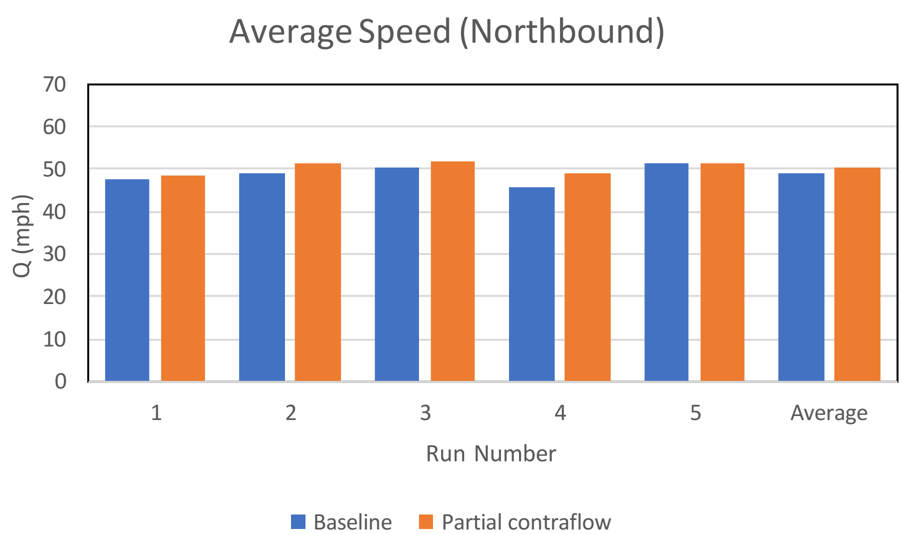
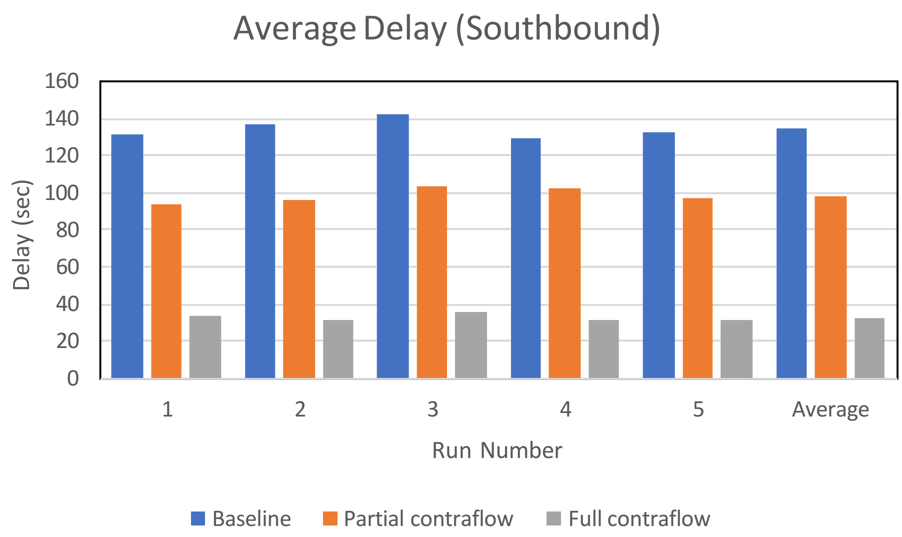


Figure 67. Average travel speed in southbound (top) and northbound (bottom) directions



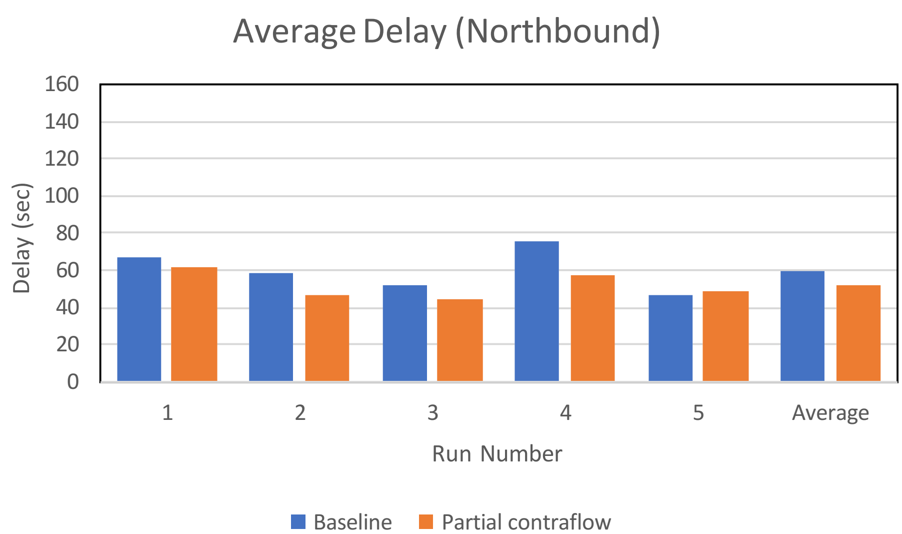


Figure 68. Average vehicle delay in southbound (top) and northbound (bottom) directions

Table 20 provides the average values of the performance metrics from all five simulation runs. The values are provided separately for each travel directions of the freeway and combined. As can be seen from the table, in the southbound direction, the average travel speed of the freeway with additional FC HOV lane is 46% and 30% higher than that of the freeway with no additional HOV lane and the freeway with additional PC HOV lane, respectively. The average delay of the freeway with additional FC HOV lane is also reduced by 76% and 67%, respectively. In the northbound direction, the average travel speed of the freeway with additional PC HOV lane is 3% higher than that of the freeway with no additional HOV lane. And the average delay of the freeway with additional PC HOV lane is also reduced by 14% compared with the freeway with no additional HOV lane. When we combine the two directions and evaluate them together, the FC configuration outperforms the PC configuration with an increase in average speed of 14% and a decrease in delay of 42%.

Table 20. Comparison of performance metrics among different HOV lane configurations

	Southbound			Northbound		Combine		
Network	Baseline	PC	FC	Baseline	PC	Baseline	PC	FC
VMT (mile)	39,566	39,796	39,895	31,938	31,650	71,504	71,446	71,833
VHT (hour)	1,048	934	726	654	628	1,702	1,562	1,380
Q=VMT/VHT (mph)	37.8	42.6	55.0	48.8	50.4	42.0	45.7	52.1
Delay (s)	134.6	98.3	32.8	59.7	51.7	101.0	77.4	45.0

To better visualize the effect of the additional HOV lane on traffic speeds, Figure 69, Figure 70, and Figure 71 show the HOV lane and MF lane speeds of all detectors in the baseline, PC HOV, and FC HOV networks, respectively. As can be seen from the figures, most of the traffic speeds in the baseline drop below 30 mph in both the HOV and MF lanes of the study section between postmile 31.5 to 34.0. On the other hand, there is little congestion in the FC HOV network, while the PC HOV network has some severe congestion at around postmile 32.0 where the dual HOV lanes end. In general, the additional HOV lane reduces traffic congestion on the study freeway section, not only in the HOV lanes but also in the MF lanes. The congestion reduction in the HOV lanes can help alleviate or even eliminate the issue of performance degradation in these HOV facilities. For instance, the FC HOV configuration increases the average travel speed in the southbound HOV facility from 37.8 mph to 55.0 mph, which is enough to lift this HOV facility out of the degradation status.

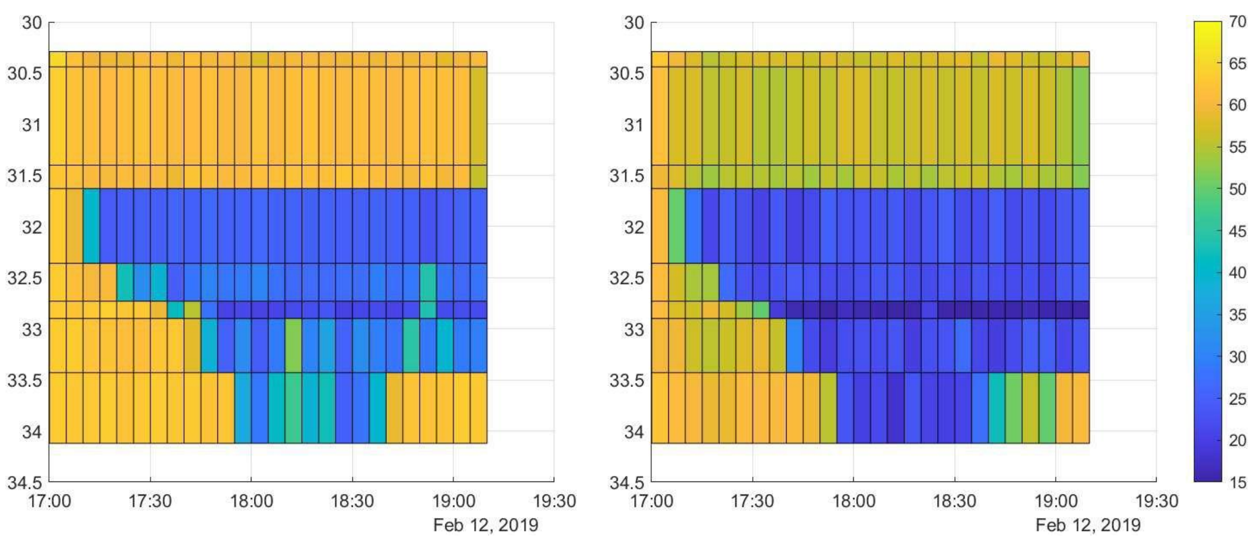


Figure 69. Traffic speed in southbound for (left) baseline HOV lane and (right) baseline MF lanes

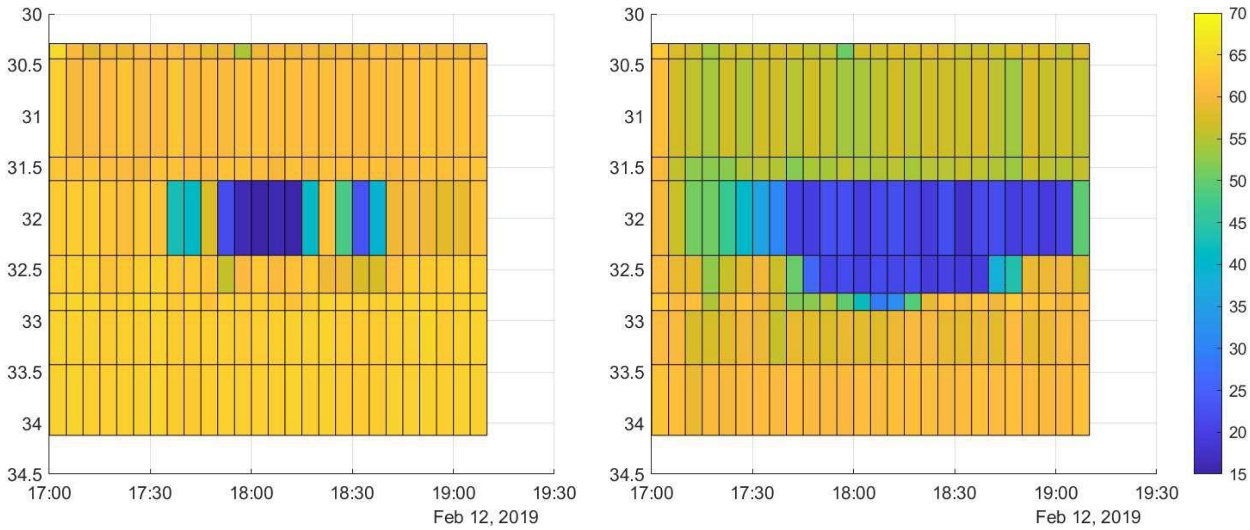


Figure 70. Traffic speed in southbound for (left) PC HOV lane and (right) PC MF lanes

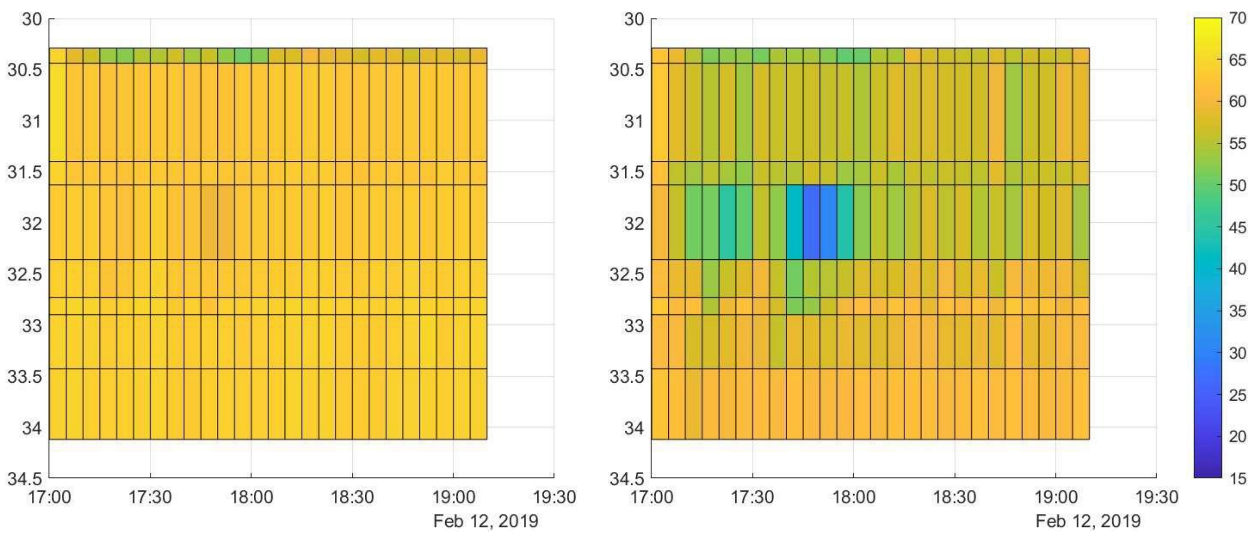


Figure 71. Traffic speed in southbound for (left) FC HOV lane and (right) FC MF lanes

6. Conclusions and Recommendations

In California, the majority of HOV facilities are operated with a single HOV lane and the minimum occupancy requirement of two (i.e., HOV2+). This operational strategy has historically provided satisfactory performance for the most part. However, with the increase in travel demand and the introduction of more clean air vehicles over the last decade, some HOV facilities have become congested and failed to meet the Federal requirement of maintaining the average operating speed above 45 mph. According to the 2019 California High Occupancy Vehicle Facilities Degradation Report and Action Plan, 26% and 40% of the 1,302 HOV lane-miles monitored in the morning and afternoon peak hour periods were degraded, with approximately 46% of the degraded facilities in the afternoon peak hour period experiencing extreme levels of degradation. While the number of degraded HOV facilities dropped significantly during the beginning of the COVID-19 pandemic, it has increased again since June 2020 and recently reached a level similar to that prior to the pandemic. Therefore, alternative operational strategies for mitigating congestion in HOV facilities need to be considered and their effectiveness evaluated in order to understand their potential for addressing the HOV lane performance degradation issue in California.

In this research project, the research team first reviewed the method for analyzing HOV lane performance degradation, and examined how different variations in the analysis method would impact the resulting performance degradation determination. Also, we explored an alternative approach for determining HOV lane performance degradation that is based on the speed differential between HOV and MF lanes. In addition, we conducted a performance evaluation of several alternative HOV operational strategies using a combination of travel demand modeling and traffic simulation. Key findings from these research efforts and recommendations for future research or implementation are summarized in the following sections.

6.1. HOV Lane Performance Degradation Analysis

Impacts of Variations in Analysis Method

The research team analyzed the performance degradation of HOV facilities on SR-91 in District 8 with three variations in the analysis method: 1) changing peak hour analysis periods from one hour to three hours, 2) re-segmentation of HOV facilities for analysis, and 3) exclusion of incident-affected speed data from the analysis.

The results of changing the peak hour analysis windows from one hour (8-9 am and 5-6 pm for morning and afternoon peaks, respectively) to three hours (6-9 am and 3-6 pm) were mixed. In cases where the real peak did not sustain for a longer period than one hour and the previously considered 1-hour window did not capture the true peak, the 3-hour peak consideration worsened the degradation determination. Conversely, in cases where the previously considered 1-hour window did capture the true peak, then the degradation determination for the corresponding 3-hour window was milder. In general, widening the peak hour analysis window from one hour to three hours can help capture the true peak period. Therefore, it is recommended that the analysis windows of three hours be used, especially for HOV facilities in urban areas where the peak traffic tends to sustain for longer than one hour.

The results of re-segmenting HOV facilities for performance degradation analysis indicate that segmentation is an important consideration. Analysis segments need to be picked carefully to not project the impacts of localized congestion over a disproportionate length of the HOV facility. In this research, the research team re-segmented the selected HOV facilities on SR-91 in District 8 into 5-mile segments using major interchanges as the break points. This allows the geometric characteristics and traffic patterns within each segment to be fairly consistent for most of the segments. This also means that congested locations tend to be grouped together in one analysis segment instead of being spread over multiple analysis segments, helping reduce the number of analysis segment considered to be degraded. It is recommended that other HOV facilities in the state be re-segmented with a similar approach for the performance degradation analysis.

The results of excluding incident-affected speed data from the degradation analysis show that the frequency of degradation for almost all the analysis segments drops. The drops were generally more pronounced for the segments that were more congested. This is somewhat expected as incidents partly contributed to the congestion on these segments. These results imply that some of the degraded HOV segments could benefit from incident management strategies. It is recommended that the impacts of traffic incidents on HOV lane performance degradation be monitored over time to identify HOV segments that are consistently affected by incidents for possible investment in traffic incident management program.

Alternative Approach for Determining HOV Lane Performance Degradation

The current approach for determining HOV lane performance degradation requires the HOV lane to maintain the average operating speed above 45 mph. However, this approach does not take into account the overall traffic condition on the freeway, and thus, does not reflect the primary objective of HOV lanes in providing travel time savings over the corresponding MF lanes. The use of this fixed speed threshold may force HOV facility operators to adopt more restrictive HOV eligibility criteria in order to reduce the HOV lane traffic. However, such policies may shift a significant amount of traffic onto the MF lanes, potentially worsening the congestion in these lanes.

In this research, an alternative approach for determining HOV lane performance degradation was introduced. It is based on the ‘speed differential’ measure, which is defined as the difference in average operating speed between the HOV lane and the adjacent MF lane. Although the current method for determining HOV lane performance degradation that is based on a fixed speed threshold is a legislatively approved process, the speed differential measure can be used as a complementary indicator of HOV lane performance when the overall travel demand on the freeway facility is very high, which makes it difficult to maintain the average operating speed of 45 mph. It is recommended that this measure be calculated and reported in the future in order to provide a comprehensive picture of the performance of HOV facilities in California.

6.2. Assessment of Alternative HOV Lane Operational Strategies

The research team conducted a performance evaluation of several alternative HOV operational strategies. These include: 1) increasing the minimum occupancy requirement from HOV2+ to HOV3+; 2) deploying dual HOV lanes; 3) reducing HOV lane usage by clean air vehicles; 4) converting HOV lanes to HOT lanes; and 5) adding contraflow HOV lane in the median. The first three strategies were evaluated using the SCAG regional travel demand model. The fourth strategy was evaluated using historical speed data from PeMS. The evaluation of the last strategy was conducted in a traffic microsimulation tool. A summary of evaluation results is given below.

Increasing Minimum Occupancy Requirement from HOV2+ to HOV3+

A 16-mile section of SR-91 in Riverside County was selected as a case study. The increase in minimum occupancy requirement from HOV2+ to HOV3+ in this case study was focused on the afternoon peak period (3:00 PM to 7:00 PM) in the eastbound direction. In addition to the baseline scenario, four other scenarios were simulated that represent different levels of SR3+ that are converted from the existing SR2 or DA vehicles on the corridor. The modeling results show that there would be a significant increase in HOV lane speed (from 55 mph to 68 mph) for the scenario where no additional SR3+ carpool is formed, but the HOV lane speed increase would be less for the scenarios where some additional SR3+ carpools are formed. These results suggest that increasing the minimum occupancy requirement from HOV2+ to HOV3+ would result in an immediate congestion relief and travel speed improvement in the HOV lane in the near term. However, the HOV lane speed could drop again once HOV3+ carpools are formed over time. For this specific case study, it was also found that the increase in minimum occupancy requirement from HOV2+ to HOV3+ would not impact the speed in the MF lanes.

Deploying Dual HOV Lanes

This strategy is applicable where there is enough space to add a second HOV lane to the existing one. Based on this constraint, a 36-mile section of SR-14 between the interchange with I-5 and Palmdale Blvd in Palmdale was selected as a case study. There is one existing HOV lane in each direction that operates with the HOV2+ minimum occupancy requirement. The HOV lanes are in operation part-time—during 5-9 a.m. for the southbound direction and during 3-7 p.m. for the northbound direction. The modeling results show that the average HOV lane speed in both directions would improve significantly after deploying dual HOV lanes. In the northbound direction, the average HOV lane speed would increase from 49 mph to 65 mph. In the southbound direction, it would increase from 52 mph to 65 mph. In addition, the traffic flow improvements as a result of deploying dual HOV lanes would also eliminate the bottlenecks on the case study section in both directions as well. In the northbound direction, the minimum HOV lane speed would improve from 28 mph to 57 mph. In the southbound direction, it would improve from 33 mph to 59 mph.

Reducing HOV Lane Usage by Clean Air Vehicles

California has had the clean air vehicle (CAV) decal program since 2004. As the number of CAV decals issued increases, the number of single-occupant CAVs in HOV lanes will also increase. This in turn can impact the performance of the HOV lanes. To assess the impact of reducing HOV lane usage by CAVs on HOV lane performance, a modeling of roadways in Orange county (District 12) was conducted as a case study. Three scenarios were modeled—CAV Doubled, CAV Halved, and CAV Eliminated. As the impact of reducing or eliminating HOV lane usage by CAVs on HOV lane performance would vary by corridor depending on the prevalence of HOV lane-eligible CAVs on the corridor before the change, the average impact for the entire county is reported. The modeling results show that doubling the number of CAV decals from the baseline would decrease the average operating speed in the HOV lanes by 2.1% on average. On the other hand, halving the number of CAV decals from the baseline would increase the speed in the HOV lanes by 2.2% on average. Lastly, eliminating all the CAV decals (i.e., ending the CAV decal program) would increase the speed in the HOV lanes by 5.7% on average.

Conversion of HOV Lane to HOT Lane

There are several HOT facilities in California, some of which have been in operation for many years. This presents an opportunity to assess the effectiveness of HOV-to-HOT lane conversion in addressing HOV lane performance degradation based on real-world data. In this research, the HOT lanes in both directions of I-110 in Los Angeles county were selected as a case study. Speed data from PeMS were used to determine the degradation level of the different segments of these HOT lanes for periods before the lane conversion (July 1 to December 31, 2010) and after the lane conversion (July 1 to December 31, 2013). The PeMS data were available and valid for seven segments in the northbound direction and five segments in the southbound direction. The comparison results show that the degradation level for a majority of these segments remained the same after the conversion to HOT lane. The degradation level for three segments actually increased during the morning peak period whereas the degradation level for one segment decreased during the afternoon peak period.

Adding Contraflow HOV Lane

As discussed earlier, deploying dual HOV lanes can be an effective way to alleviate HOV lane performance degradation. However, such strategy can be difficult in areas where there is not enough space to add a second HOV lane to the existing one in both directions. In that case, adding a new HOV lane that operates in a contraflow fashion could be a good compromise, especially if peak travel demands in the existing HOV lanes are tidal, e.g. morning peak in one direction and afternoon peak in the other direction. In this research, a 5-mile section of I-215 in Riverside County was selected as a case study for evaluating the effectiveness of this strategy. The evaluation was conducted in a traffic simulation tool where a contraflow HOV lane was added to the freeway section, and the simulated traffic performance was compared to that of the baseline condition. The simulation was conducted for the afternoon peak period, during which the peak direction is southbound. The simulation results show that the addition of the contraflow HOV lane would increase the average speed in the southbound HOV facility from 38 mph to 55 mph, which is enough to lift this HOV facility out of the degradation status. Although not simulated, it is expected that this strategy would also result in an improvement in average speed in the northbound HOV facility during the morning peak period.

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Appendix A:

HOV Facility Degradation Sorted by Cumulative Degradation Score (2013-2017)

District	Route	Direction	Begin County	Begin Post Mile	End County	End Post Mile	Degradation Score					Sum Score
							2013	2014	2015	2016	2017	
7	91	EB	LA	R6.400	LA	R11.167	4	4	4	4	4	20
7	105	WB	LA	R10.145	LA	R6.172	4	4	4	4	4	20
7	210	EB	LA	L29.568	LA	R33.827	4	4	4	4	4	20
7	210	WB	LA	R38.395	LA	R33.827	4	4	4	4	4	20
7	405	NB	LA	19.546	LA	24.388	4	4	4	4	4	20
7	405	SB	LA	19.546	LA	14.703	4	4	4	4	4	20
12	55	EB	ORA	R6.000	ORA	R9.761	4	4	4	4	4	20
12	5	NB	ORA	R25.097	ORA	29.703	4	4	4	4	4	20
4	85	SB	SCL	R19.005	SCL	R14.210	4	3	4	4	4	19
4	101	SB	SM	6.6	SM	1.876	4	3	4	4	4	19
4	237	EB	SCL	R6.241	SCL	9.5	4	3	4	4	4	19
7	10	EB	LA	25.464	LA	31.2	4	4	4	3	4	19
7	10	EB	LA	45.33	LA	48.26	3	4	4	4	4	19
7	91	EB	LA	R11.167	LA	R15.933	3	4	4	4	4	19
7	105	EB	LA	R2.200	LA	R6.173	3	4	4	4	4	19
7	110	EB	LA	16.933	LA	20.5	3	4	4	4	4	19
7	170	SB	LA	R17.505	LA	R14.500	4	4	3	4	4	19
7	210	EB	LA	R38.396	LA	R42.964	3	4	4	4	4	19
7	210	WB	LA	R33.827	LA	L29.568	3	4	4	4	4	19
7	405	NB	LA	14.703	LA	19.546	3	4	4	4	4	19
7	405	SB	LA	43.758	LA	38.915	3	4	4	4	4	19
7	605	SB	LA	R12.420	LA	R8.280	3	4	4	4	4	19
8	215	SB	RIV	40.646	RIV	R38.300	3	4	4	4	4	19
12	91	WB	ORA	0.841	ORA	R0.000	3	4	4	4	4	19
12	405	EB	ORA	9.929	ORA	14.779	3	4	4	4	4	19
3	99	SB	SAC	R24.300	SAC	20.167	2	4	4	4	4	18
3	99	SB	SAC	20.168	SAC	16.034	2	4	4	4	4	18
4	80	WB	ALA	6.423	ALA	1.9	2	4	4	4	4	18
4	101	SB	SCL	44.978	SCL	40.254	2	4	4	4	4	18
4	101	SB	SCL	R21.724	SCL	R17.000	2	4	4	4	4	18
4	880	NB	SCL	8.7	ALA	3.089	2	4	4	4	4	18
4	880	NB	ALA	12.321	ALA	19.3	2	4	4	4	4	18
7	105	EB	LA	R6.173	LA	R10.145	2	4	4	4	4	18
7	210	EB	LA	R33.827	LA	R38.396	2	4	4	4	4	18
7	405	NB	LA	9.861	LA	14.703	2	4	4	4	4	18
7	405	NB	LA	38.915	LA	43.758	2	4	4	4	4	18
7	405	NB	LA	43.758	LA	48.6	3	3	4	4	4	18
7	405	SB	LA	26.4	LA	24.388	4	4	3	3	4	18
7	405	SB	LA	14.703	LA	9.861	2	4	4	4	4	18
8	60	EB	SBD	R0.000	SBD	R4.987	2	4	4	4	4	18
8	210	EB	SBD	0	SBD	4.933	2	4	4	4	4	18
8	215	SB	RIV	43.3	RIV	40.646	2	4	4	4	4	18
12	405	EB	ORA	14.779	ORA	19.628	2	4	4	4	4	18
12	405	WB	ORA	19.628	ORA	14.779	2	4	4	4	4	18
12	405	WB	ORA	9.929	ORA	5.08	2	4	4	4	4	18
3	99	NB	SAC	16.031	SAC	20.165	3	4	4	3	3	17
4	80	EB	ALA	2.5	ALA	6.552	1	4	4	4	4	17
4	80	EB	CC	2.582	CC	6.634	2	3	4	4	4	17
4	80	WB	CC	2.923	ALA	6.423	2	3	4	4	4	17
4	85	SB	SCL	R23.800	SCL	R19.005	4	2	3	4	4	17

District	Route	Direction	Begin County	Begin Post Mile	End County	End Post Mile	Degradation Score 2013	2014	2015	2016	2017	Sum Score
4	101	NB	MRN	3.8	MRN	8.323	4	4	4	4	1	17
4	237	EB	SCL	3	SCL	R6.241	2	3	4	4	4	17
4	280	SB	SCL	10.439	SCL	6.879	3	3	3	4	4	17
4	280	SB	SCL	6.879	SCL	L4.700	4	2	3	4	4	17
4	580	EB	ALA	10.485	ALA	R7.800	2	4	3	4	4	17
4	880	NB	ALA	7.705	ALA	12.321	2	3	4	4	4	17
7	10	EB	LA	42.4	LA	45.33	2	4	4	4	3	17
7	14	NB	LA	R24.800	LA	R29.281	1	4	4	4	4	17
7	118	EB	LA	R7.600	LA	R11.400	3	3	3	4	4	17
7	134	EB	LA	4.428	LA	R8.855	1	4	4	4	4	17
7	405	SB	LA	4.842	LA	0	1	4	4	4	4	17
8	10	EB	SBD	4.95	SBD	9.9	1	4	4	4	4	17
11	5	NB	SD	R34.600	SD	R38.500	1	4	4	4	4	17
12	55	WB	ORA	13.539	ORA	R9.761	1	4	4	4	4	17
12	5	NB	ORA	29.703	ORA	34.302	1	4	4	4	4	17
12	5	SB	ORA	38.901	ORA	34.302	4	3	4	3	3	17
12	57	SB	ORA	R22.500	ORA	18.6	2	3	4	4	4	17
4	80	EB	CC	6.634	CC	9.9	3	2	3	4	4	16
4	85	SB	SCL	R14.210	SCL	9.59	2	2	4	4	4	16
4	87	NB	SCL	0.2	SCL	3.748	3	3	3	4	3	16
4	101	SB	SCL	40.254	SCL	R35.534	2	2	4	4	4	16
4	280	NB	SCL	L4.700	SCL	6.879	3	3	3	3	4	16
4	680	NB	CC	R8.100	CC	R11.900	2	3	4	4	3	16
4	680	SB	CC	R18.579	CC	16.3	4	3	3	3	3	16
4	680	SB	ALA	R6.980	ALA	M2.385	4	3	3	3	3	16
7	5	NB	LA	42.389	LA	R45.600	4	2	3	4	3	16
7	10	WB	LA	25.464	LA	20.904	3	4	3	3	3	16
7	210	EB	LA	R42.964	LA	R47.532	2	3	3	4	4	16
7	210	WB	LA	L29.568	LA	R25.000	3	3	3	3	4	16
7	405	NB	LA	0	LA	4.842	2	3	3	4	4	16
7	405	SB	LA	38.915	LA	34.073	2	2	4	4	4	16
7	405	SB	LA	24.388	LA	19.546	2	3	3	4	4	16
7	605	NB	LA	R8.280	LA	R12.420	3	3	3	4	3	16
7	605	SB	LA	R16.560	LA	R12.420	2	2	4	4	4	16
8	91	EB	RIV	R0.000	RIV	4.266	4	4	4	3	1	16
8	215	NB	RIV	R38.300	RIV	40.646	2	2	4	4	4	16
11	5	NB	SD	R30.700	SD	R34.600	4	2	4	3	3	16
12	5	SB	ORA	34.302	ORA	29.703	3	4	3	2	4	16
12	57	NB	ORA	18.6	ORA	R22.500	1	3	4	4	4	16
12	91	EB	ORA	5.361	ORA	R9.859	3	2	3	4	4	16
12	91	WB	ORA	R9.870	ORA	5.356	2	4	4	3	3	16
12	405	WB	LA	0.3	ORA	19.628	4	3	3	3	3	16
4	85	NB	SCL	9.59	SCL	R14.210	4	2	3	3	3	15
4	101	SB	MRN	18.9	MRN	12.846	3	3	3	3	3	15
4	280	NB	SCL	6.879	SCL	10.439	4	2	3	4	2	15
4	880	SB	ALA	13.009	ALA	8.164	2	3	3	3	4	15
7	110	WB	LA	20.5	LA	16.933	3	1	4	4	3	15
7	210	EB	LA	R47.532	LA	R52.100	2	3	3	4	3	15
7	405	SB	LA	9.861	LA	4.842	2	2	3	4	4	15
7	605	NB	LA	R12.420	LA	R16.560	3	4	3	3	2	15
12	55	EB	ORA	R9.761	ORA	13.539	2	3	3	3	4	15
12	5	NB	ORA	20.497	ORA	R25.097	4	3	3	3	2	15
12	57	SB	ORA	18.6	ORA	14.7	2	2	3	4	4	15
12	405	EB	ORA	5.08	ORA	9.929	4	3	3	3	2	15
4	87	NB	SCL	3.748	SCL	7.297	3	3	3	3	2	14

District	Route	Direction	Begin County	Begin Post Mile	End County	End Post Mile	Degradation Score					Sum Score
							2013	2014	2015	2016	2017	
4	101	NB	SCL	R35.534	SCL	40.254	2	3	3	3	3	14
4	101	NB	SCL	40.254	SCL	44.978	3	2	3	3	3	14
4	101	SB	SM	1.876	SCL	49.702	4	2	3	3	2	14
4	237	WB	SCL	R6.265	SCL	3	2	2	3	3	4	14
4	680	NB	CC	R3.898	CC	R8.100	3	2	3	3	3	14
4	880	SB	ALA	17.855	ALA	13.009	2	3	3	3	3	14
7	10	WB	LA	20.904	LA	17	4	4	2	2	2	14
7	91	EB	LA	R15.933	LA	R20.700	2	4	3	2	3	14
7	91	WB	LA	R15.933	LA	R11.167	1	3	3	4	3	14
7	105	WB	LA	R14.117	LA	R10.145	4	2	2	3	3	14
7	134	WB	LA	4.428	LA	0	3	2	2	3	4	14
7	210	EB	LA	R25.000	LA	L29.568	2	4	4	2	2	14
7	210	WB	LA	R42.964	LA	R38.395	2	3	2	3	4	14
7	405	NB	LA	4.842	LA	9.861	3	2	2	3	4	14
7	405	SB	LA	34.073	LA	30.7	3	2	3	2	4	14
8	60	EB	RIV	10.266	RIV	15.413	1	3	4	4	2	14
8	210	EB	SBD	4.933	SBD	9.867	1	2	3	4	4	14
12	55	EB	ORA	13.539	ORA	17.3	3	2	3	4	2	14
12	57	NB	ORA	14.7	ORA	18.6	1	2	3	4	4	14
3	99	NB	SAC	20.166	SAC	R24.300	3	2	3	3	2	13
4	80	EB	ALA	6.552	CC	2.582	2	2	3	3	3	13
4	85	NB	SCL	R14.210	SCL	R19.005	3	2	2	3	3	13
4	85	NB	SCL	R19.005	SCL	R23.800	4	1	2	3	3	13
4	101	NB	SON	15.2	SON	18.4	3	2	2	3	3	13
4	280	NB	SCL	10.439	SCL	14	2	2	3	3	3	13
7	10	WB	LA	31.2	LA	25.464	3	3	3	2	2	13
7	105	EB	LA	R14.117	LA	R18.090	4	4	2	1	2	13
7	110	EB	LA	13.367	LA	16.933	2	2	3	3	3	13
7	134	EB	LA	0	LA	4.428	2	2	3	3	3	13
8	91	EB	RIV	13.022	RIV	17.4	1	2	4	2	4	13
11	15	NB	SD	M12.000	SD	M15.900	3	3	3	1	3	13
12	55	WB	ORA	17.3	ORA	13.539	3	3	3	2	2	13
12	5	SB	ORA	29.703	ORA	R25.096	1	2	2	4	4	13
12	57	SB	ORA	14.7	ORA	10.8	1	3	3	3	3	13
12	405	EB	ORA	19.628	LA	0.3	3	2	2	3	3	13
4	4	WB	CC	R20.088	CC	R15.800	4	2	2	2	2	12
4	85	NB	SCL	4.795	SCL	9.59	2	2	2	3	3	12
4	87	SB	SCL	7.297	SCL	3.748	2	2	2	3	3	12
4	101	NB	SCL	30.81	SCL	R35.534	2	2	2	3	3	12
4	101	SB	SCL	49.702	SCL	44.978	3	1	2	3	3	12
4	880	NB	ALA	3.089	ALA	7.705	2	2	3	2	3	12
4	880	SB	ALA	22.7	ALA	17.855	2	2	3	3	2	12
4	880	SB	ALA	3.318	SCL	8.7	2	2	2	3	3	12
7	5	NB	LA	39.4	LA	42.389	4	2	2	2	2	12
7	10	EB	LA	20.904	LA	25.464	4	4	1	1	2	12
7	60	EB	LA	R26.725	LA	R30.450	2	2	2	3	3	12
7	60	WB	LA	R26.725	LA	R23.000	4	2	2	2	2	12
7	91	WB	LA	R20.700	LA	R15.933	2	2	3	3	2	12
7	405	NB	LA	24.388	LA	26.4	2	2	2	2	4	12
8	10	EB	SBD	0	SBD	4.95	3	2	2	2	3	12
8	91	WB	RIV	8.644	RIV	4.266	3	4	2	2	1	12
8	215	NB	RIV	40.646	RIV	43.3	4	2	2	2	2	12
12	22	WB	ORA	R4.368	ORA	R0.700	4	3	1	2	2	12
12	91	EB	ORA	R0.000	ORA	0.864	0	4	0	4	4	12
12	405	EB	ORA	0.23	ORA	5.08	3	2	2	2	3	12

District	Route	Direction	Begin County	Begin Post Mile	End County	End Post Mile	Degradation Score					Sum Score
							2013	2014	2015	2016	2017	
12	405	WB	ORA	14.779	ORA	9.929	4	2	2	2	2	12
3	80	WB	SAC	13.903	SAC	M9.400	2	2	3	2	2	11
4	4	WB	CC	24.4	CC	R20.088	4	1	2	2	2	11
4	80	WB	CC	7.446	CC	2.923	3	2	2	2	2	11
4	237	WB	SCL	9.5	SCL	R6.265	4	2	1	2	2	11
4	680	NB	CC	R18.800	CC	20.3	3	2	2	2	2	11
4	880	NB	ALA	R34.700	ALA	R35.400	3	3	1	2	2	11
4	880	SB	ALA	8.164	ALA	3.318	2	2	2	2	3	11
7	60	WB	LA	R30.450	LA	R26.725	2	2	2	2	3	11
7	170	NB	LA	R17.505	LA	R20.510	1	4	2	2	2	11
8	60	EB	SBD	R4.987	RIV	R0.017	1	3	0	4	3	11
8	60	WB	RIV	R0.017	SBD	R4.987	2	2	0	3	4	11
8	91	EB	RIV	4.266	RIV	8.644	3	4	1	1	2	11
4	101	NB	SCL	R26.448	SCL	30.81	4	1	1	2	2	10
4	280	SB	SCL	14	SCL	10.439	2	1	2	2	3	10
7	60	EB	LA	R23.000	LA	R26.725	2	2	2	2	2	10
7	110	EB	LA	9.8	LA	13.367	2	2	2	2	2	10
7	110	WB	LA	16.933	LA	13.367	2	2	2	2	2	10
7	118	EB	LA	R3.800	LA	R7.600	2	2	2	1	3	10
7	605	NB	LA	R4.140	LA	R8.280	3	2	2	1	2	10
12	22	EB	ORA	R4.368	ORA	R8.036	1	2	2	2	3	10
12	22	EB	ORA	R8.036	ORA	R11.600	1	2	2	2	3	10
12	91	EB	ORA	0.864	ORA	5.361	2	2	2	2	2	10
12	91	WB	ORA	5.356	ORA	0.841	2	2	2	2	2	10
3	80	WB	PLA	0	SAC	13.904	2	2	2	1	2	9
4	85	SB	SCL	9.59	SCL	4.795	2	1	2	2	2	9
4	101	NB	SCL	44.978	SCL	49.702	2	1	2	2	2	9
7	14	NB	LA	R29.281	LA	33.812	1	1	2	3	2	9
7	14	NB	LA	42.775	LA	R47.256	2	2	2	1	2	9
7	14	SB	LA	R29.281	LA	R24.788	1	2	2	2	2	9
7	134	WB	LA	R13.300	LA	R8.872	1	2	2	2	2	9
7	210	WB	LA	R47.532	LA	R42.964	2	1	2	2	2	9
8	10	WB	SBD	9.9	SBD	4.95	1	2	2	2	2	9
8	10	WB	SBD	4.95	SBD	0	3	1	1	2	2	9
8	91	WB	RIV	4.266	RIV	R0.000	2	3	2	1	1	9
8	210	WB	SBD	9.867	SBD	4.933	1	2	2	2	2	9
12	22	WB	ORA	R11.600	ORA	R8.036	1	1	2	2	3	9
12	5	NB	ORA	34.302	ORA	38.901	1	1	2	2	3	9
7	14	SB	LA	33.812	LA	R29.281	2	1	1	2	2	8
7	105	WB	LA	R18.090	LA	R14.117	2	1	1	2	2	8
7	118	WB	LA	R11.400	LA	R7.600	1	2	2	1	2	8
8	91	EB	RIV	8.644	RIV	13.022	1	1	1	2	3	8
8	91	WB	RIV	13.022	RIV	8.644	1	1	2	2	2	8
8	210	WB	SBD	14.8	SBD	9.867	1	1	2	2	2	8
12	55	WB	ORA	R9.761	ORA	R6.000	1	1	2	2	2	8
12	57	NB	ORA	10.8	ORA	14.7	2	1	1	2	2	8
3	50	EB	SAC	16.312	SAC	20.123	2	1	1	1	2	7
7	5	SB	LA	R45.600	LA	42.389	1	2	1	1	2	7
7	14	NB	LA	33.812	LA	38.293	1	1	1	2	2	7
7	105	EB	LA	R10.145	LA	R14.117	2	1	1	2	1	7
7	110	WB	LA	13.367	LA	9.8	2	1	1	2	1	7
7	170	SB	LA	R20.510	LA	R17.505	1	1	2	1	2	7
8	60	WB	SBD	R4.987	SBD	R0.000	1	2	0	2	2	7
8	71	SB	SBD	R8.300	SBD	R4.150	1	1	1	2	2	7
8	91	WB	RIV	17.4	RIV	13.022	1	1	1	2	2	7

District	Route	Direction	Begin County	Begin Post Mile	End County	End Post Mile	Degradation Score					Sum Score
							2013	2014	2015	2016	2017	
11	15	NB	SD	M19.800	SD	M23.700	0	1	2	2	2	7
12	405	WB	ORA	5.08	ORA	0.23	1	1	2	2	1	7
3	80	EB	SAC	M9.399	SAC	13.902	1	1	1	1	2	6
3	80	EB	SAC	13.902	PLA	0	1	1	1	1	2	6
4	87	SB	SCL	3.748	SCL	0.2	1	1	1	1	2	6
4	101	NB	SON	18.4	SON	21.6	1	1	1	1	2	6
4	101	SB	SON	21.6	SON	15.2	1	1	1	1	2	6
4	680	SB	CC	R11.900	CC	R9.248	1	1	1	1	2	6
7	10	WB	LA	45.33	LA	42.4	1	1	1	1	2	6
7	118	EB	LA	R0.000	LA	R3.800	1	1	1	1	2	6
7	134	WB	LA	R8.872	LA	4.428	1	1	1	2	1	6
7	605	NB	LA	R0.000	LA	R4.140	1	1	1	1	2	6
7	605	SB	LA	20.7	LA	R16.560	1	1	1	1	2	6
8	210	EB	SBD	9.867	SBD	14.8	1	1	1	1	2	6
8	210	WB	SBD	4.933	SBD	0	1	1	1	1	2	6
11	15	NB	SD	M15.900	SD	M19.800	0	1	2	1	2	6
11	15	NB	SD	M23.700	SD	M27.600	0	1	1	2	2	6
12	5	SB	ORA	43.5	ORA	38.901	1	1	1	1	2	6
7	14	NB	LA	38.293	LA	42.775	1	1	1	1	1	5
11	15	SB	SD	M27.600	SD	M23.700	0	1	1	1	2	5
12	22	EB	ORA	R0.700	ORA	R4.368	1	1	1	1	1	5
12	22	WB	ORA	R8.036	ORA	R4.368	1	1	1	1	1	5
12	5	NB	ORA	38.901	ORA	43.5	1	1	1	1	1	5