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Reducing Degradation in High-Occupancy Lanes

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Reducing Degradation in High-Occupancy Lanes

A Research Report from the University of California Institute of Transportation Studies

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Disclaimer

Reducing Degradation in High Occupancy Lanes

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November 2019

R. Jayakrishnan, Professor, Department of Civil and Environmental Engineering, University of California, Irvine

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Executive Summary

HOV lanes in California continue to be congested, with as many as 62% of HOV lane-miles meeting the Federal standards for degradation, which is defined as a condition when a HOV facility has an average operating speed of less than 45mph during peak hours for more than 10% of the time for a consecutive 180-day period.

The broad aims of this project are to identify factors behind degradation and to recommend strategies that mitigate degradation. To that effect, we have undertaken a multi-pronged effort that involves:

- Compilation and fusion of traffic, accident, and geometric data pertaining to HOV lanes in California.
- Creation of new geographic data that classifies all HOV facilities in California based upon their access type (continuous, limited, buffer-1, and so on). This is an extensive effort representing several hundred person-hours, but the final dataset is expected to yield valuable dividends for transportation agencies and researchers interested in mapping the complex relationships between highway geometry and performance in more detail.
- Data analysis of degradation, including with a study of time incentives linked to HOV travel, and how these incentives vary with different threshold speeds as specified in the definition of degradation.
- Accident analysis on HOV lanes to identify pertinent geometric contributing factors.
- Simulation modelling of HOV lanes with various access options and operational strategies.
- HOV-specific analysis from the latest edition of the Highway Capacity Manual to obtain insights on the breakdown of traffic in HOV lanes with different geometries.

Our observations broadly suggest that there exist relationships between HOV facility geometry and performance, though these relationships can be specified with statistical confidence only after an analysis of bigger datasets, encompassing more facilities, and a longer time span. Such an effort is currently underway. Highway Capacity Manual analysis performed on HOV lanes indicates that continuous access managed lanes are superior to buffer-1 managed lanes in terms of maximum flow rates. HCM analysis calls for the need of HOV degradation standards to be defined relative to the performance of adjacent GP lanes, a recommendation also corroborated by our preliminary observations of time-incentives on HOV lanes.

Results obtained from a state-wide analysis show also show that HOV lanes with continuous access operate better than those with limited access.

Based on the speed difference measure, degraded stretches which met the Federal Standard of degradation speed threshold were still found to give some incentives for users compared with the regular lane both nearest mainline lane cases and average mainline lane cases. Once again, we see that an over-emphasis on the HOV lanes' own performance, neglecting the

relative performance vis-a-vis the regular lanes, seems to be an oversight in the Federal Standard. Nevertheless, the incentive trend is on a downturn from 2008 to 2017.

In terms of HOV exemption policy, there exist no studies that link HOV degradation to exemptions provided to ZEV. Furthermore, in the absence of data on the number of ZEV, LEV, and Plugin-Hybrids on various HOV facilities, it is difficult to quantify their effect on HOV degradation

1 Introduction

HOV facilities continue to be an integral part of the transportation infrastructure in California. The underlying premise behind the creation of HOV lanes is that the resulting demand shift from single-occupancy vehicles on the mainline to multiple-occupancy vehicles on the HOV lane would provide societal benefits such as lowered emissions and improved mobility, while at the same time preserving travel time savings relative to mainline lanes. Most HOV lanes in California apply a two-person-or-more (HOV2+) vehicle occupancy criterion for lane access. In the past, other types of vehicles have also been allowed access, such as motorcycles, low-emission vehicles, hybrid or alternative-fuel vehicles, and in some cases single-occupancy vehicles with a toll.

High usage of HOV lanes in California has led to increased traffic on these lanes, to the point where many HOV facilities now meet the Federal standard of *degradation*, which is defined as follows:

"An HOV facility is considered degraded if it fails to maintain a minimum average operating speed 90 percent of the time over a consecutive 180-day period during morning or evening weekday peak hour periods (or both for a reversible facility)."

California continues to lead the nation in developing a clean-energy economy, reducing carbon emissions, and promoting green technologies. One of the policies presumed to incentivize the purchase of zero-emission and hybrid vehicles has been to make them 'exempt' for HOV lanes, even at single occupancy. However, the degradation of HOV lanes can have a negative effect on the decision to purchase ZEVs or hybrid vehicles, which is not desirable.

1.1 Existing Conditions

Degradation of HOV lanes is worsening almost every year. As per the recent Degradation Report by the Department of Transportation in California (CALTRANS, 2017), more than 65% of HOV lanes facilities operated under worse conditions that defined as the Federal Standard and the percentage of degraded facilities is increasing on annual basis in recent years. Around 62% of HOV lane miles in the state of CA were found to be degraded in 2015. Exempted vehicles such as Zero Emission Vehicles and hybrid vehicles account for less than 2% of peak hour HOV lane flows. Geographically, Caltrans District 7 (LA and Ventura County) accounted for the highest share of statewide degraded HOV lane miles in 2014 (36%) followed by District 4 (Oakland) and District 12 (Irvine).

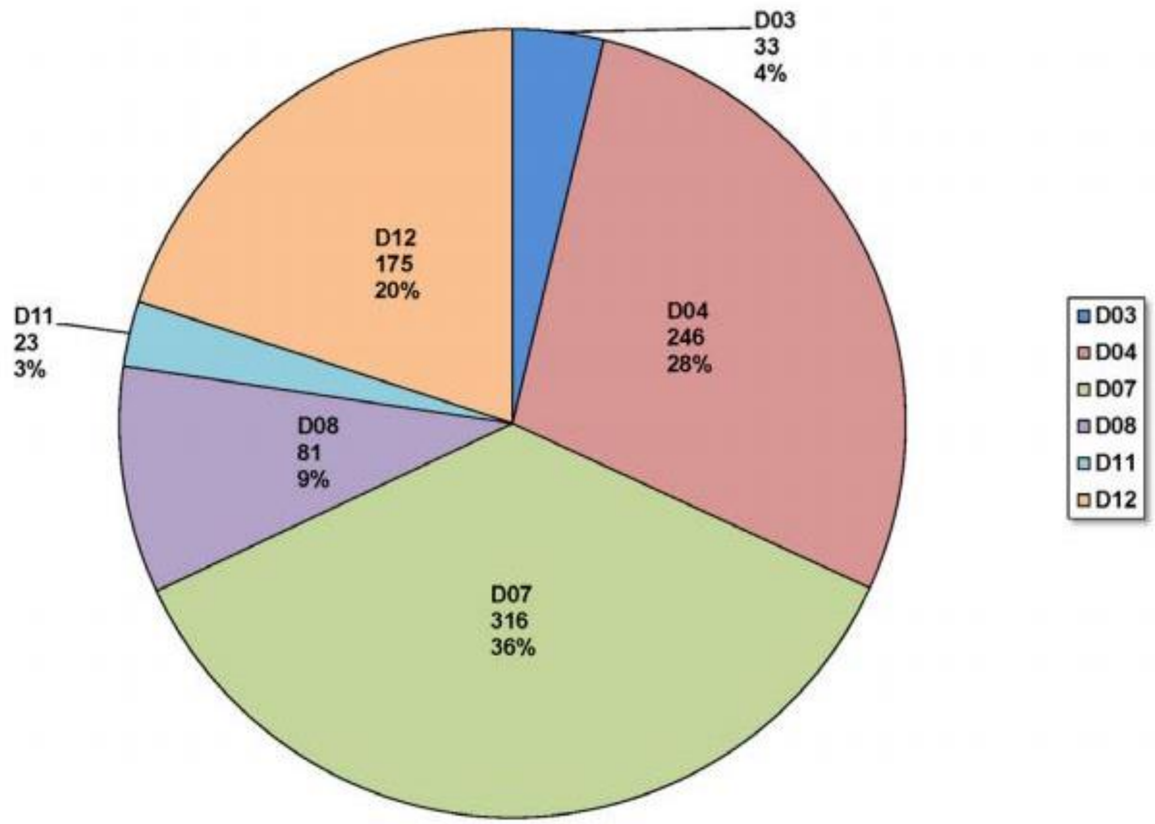


Figure 1.1. Distribution of degraded lanes by District (source: California High-Occupancy Lane Degradation Determination Report, December 1, 2016

Caltrans further classifies degradation of HOV lanes to distinguish between daily recurrent congestion and non-recurrent congestion. Their categorization is as follows:

- Slightly Degraded (Degradation during 3-9 weekdays a month).
- Very Degraded (Degradation during 10-15 weekdays a month).
- Extremely degraded (Degradation more than 15 weekdays a month).

Following are the broad objectives of this study:

- Examining the major factors that lead to HOV degradation.
- Analysis of data obtained from key study areas and locations that help draw inferences between traffic performance on HOV lanes and road geometry.
- Investigating any possible relationships between type of HOV access (continuous, buffer-1, buffer-2, etc.) and design geometry on HOV lane capacity.
- Modeling and simulation of isolated stretches of HOV lanes, with different geometries, and with real-time and static access options.

- Studying the effects of exemptions given to low emission and zero emission vehicle on HOV degradation.
- Recommendations on HOV violation enforcement.
- Identifying best strategies in the policy, technology, and infrastructure domains to reduce HOV degradation.

2 Data Preparation

Data from diverse sources have been compiled for various analysis. In some cases, data have been directly available to use, but in many instances, data creation and synthesis were performed manually. The following are the major sources of data that have been used, broadly divided into highway geometry data and traffic data.

2.1 California Highway Geometry Information

As of 2016, approximately 1500 miles of HOV facilities are in operation, with slightly over 700 miles being Programmed-Proposed, and a approximately 110 miles are under construction in California. The following map shows the location of HOV facilities in the state.

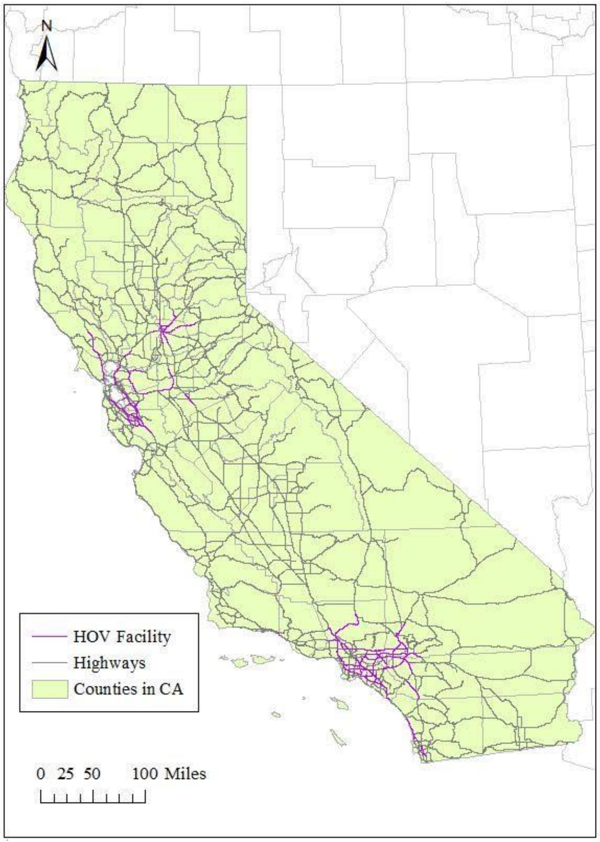


Figure 2.1. Location of HOV facilities in CA

1) State Highway Network (SHN) and Postmile System

Caltrans provides state highway polyline and postmile point feature data which contain various attributes such as county, route, postmile prefix, and postmile suffix. Postmile is defined as “the way that a specific location on a state or federal route is specified within the

Linear Reference System. In a linear reference system, locations are indicated by a distance along a route". The following figure illustrates the schema of the data obtained from Caltrans.

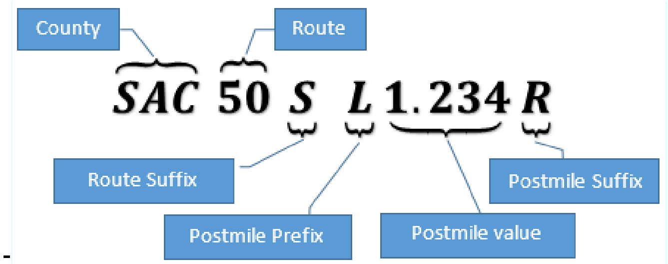


Figure 2.2. Schema for postmile CALTRANS data

2) California High Occupancy Vehicle (HOV) Lanes

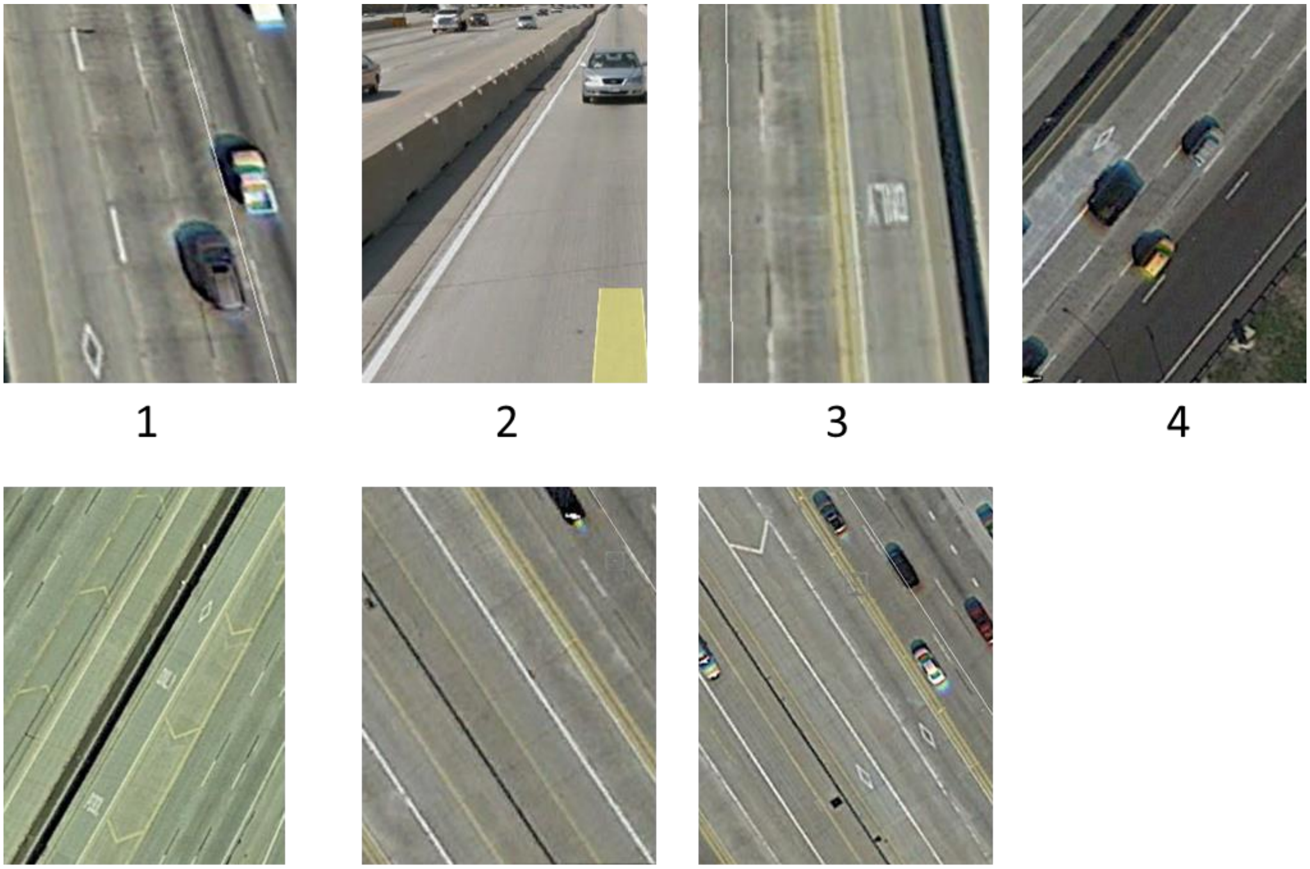
HOV lane feature data represents HOV facilities based on the following characteristics: (a) existing, (b) under construction, (c) programmed, and (d) proposed HOV lanes. High Occupancy Toll (HOT) Lanes information is also available from Caltrans, but has not been used so far in the study.

3) HOV lane geometry information

HOV facilities data provided by Caltrans do not include detailed geometry information e.g. access type (continuous vs. limited), separation type (buffer vs. barrier). Since this information was critical to the objectives of the project, we manually constructed detailed geometry data for HOV lanes for all of California, based upon information gathered from Google Earth satellite imagery and ESRI ArcMap software.

HOV lane geometry can be categorized by the type of marking and separation on HOV facilities. The following spatial feature data was added to the HOV lanes under analysis:

1. Single broken white line – continuous access
2. Barrier – limited access, barrier separation
3. Double solid yellow line – limited access, buffer separation
4. Single solid white line – limited access (crossing is discouraged), buffer separation
5. Wide double solid yellow line – limited access, buffer separation
6. Double solid yellow line & multiple HOV lanes separated with a single solid white line
7. Double solid yellow line & multiple HOV lanes separated with a wide double solid white line



1 2 3 4

5 6 7

Figure 2.3. Types of HOV lanes

2.2 Caltrans Traffic Measurement System (PeMS) Data

A primary data source for this thesis study is the California Performance Measurement System (PeMS) that first began operating in 2001 and receives data from the data centers of all twelve districts (Chen, Varaiya, and Kwon 2005). The PeMS website is a user-friendly interface tool which stores the real-time data and historical data from all the detectors along the freeway system in California. The abundant amount of data from PeMS is useful for researchers to build analysis models to test their assumptions or for practitioners who are interested in collecting information, visualizing them to make data more meaningful such as through graphical forms, or exploring traffic data for analysis in numerous ways.

Since the data came from various sources, data fusion is necessary for building the dataset. VDS (Vehicle Detector Station) ID is the key to match all the datasets together. The speed on the regular lane was assumed to have effects on the HOV lane. Thus, the VDS ID Match list which contains the VDS of HOV lanes and their corresponding mainline lane VDS is the essential item that is necessary to develop the relationship among these nearby sensors. As part of the project, a Python library has been created to automate data collection from PeMS. The library is available to access code and class description, which specifies class definition, parameters, and examples.

1) PeMS Roadway Information

PeMS provides physical characteristics of highway segments based on the location of the stations. We have obtained 44 different attributes for roadways as well as detectors. These data can be acquired from the 'ChangeLog' class in the Python library

2) Performance Data

Average Annual Daily Traffic (AADT) information and other performance data of a specific station during a user-defined time period has been collected. This is represented by the class 'AADT' in the Python library.

California Highway Patrol Incidents data based on absolute postmile of highway segment (class 'CHPIncidents' in the Python library) have been collected. These data represent the total number of incidents on a highway segment with a specific postmile range. It is of limited use in its current state, because it cannot distinguish between incidents occurring on the mainline lanes and HOV lanes. In order to acquire information on incidents only on HOV facilities, CHP incidents data in the PeMS data clearinghouse have been utilized. Other data can be acquired as needed and this list will be updated throughout the project.

2.3 Data Fusion

Data from various disparate sources with different attributes and levels of detail needed to be combined so that they are utilized in data analysis and simulation studies. This is an intricate and cumbersome task, since each dataset has its own unique identification schema, and there aren't any intuitive common keys or attributes that can be used to link these datasets. We have implemented data fusion based on their spatial relationships using ESRI ArcMap software and Python.

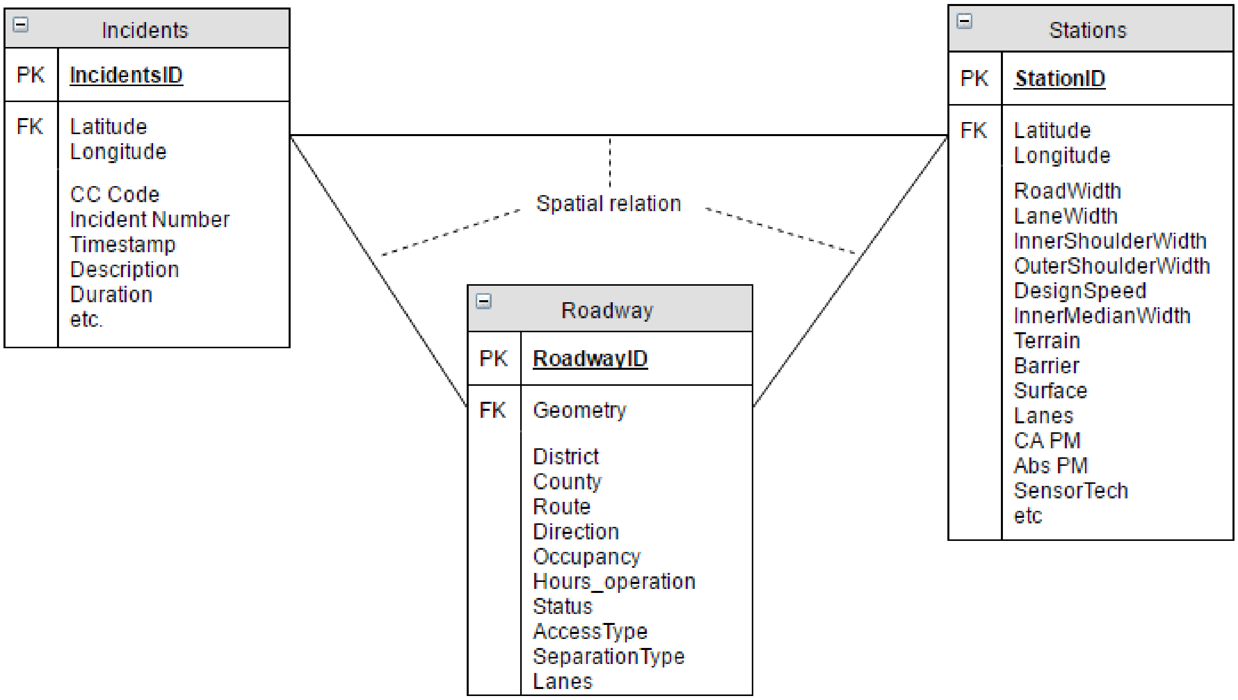


Figure 2.4. Linking performance and road geometry data

3 Accident Data Analysis

The purpose of this analysis was to determine what causal factors, if any, contributed to traffic incidents on HOV facilities. Traffic incidents are events on roads such as car accidents and vehicle breakdowns, traffic hazards, etc. which lead to severe congestion and pose a safety threat to other vehicles on the roadway. Therefore, it is important to understand the relationship between occurrence of traffic incidents and factors such as geometric features of the physical facility and traffic performance.

3.1 Study Area and Data

The area of interest in this analysis encompasses highway HOV facilities in Orange County, CA, with the intention of expanding the study area in future research. The data sources for this study are:

California High Occupancy Vehicle Lane data

1. HOV segment geometry and the corresponding attributes such as highway number and direction, HOV lane occupancy regulation and operation hour, etc.
2. HOV line access type and separation type, manually edited based on Google Earth satellite imagery. This is a labor-intensive process, since there are no available sources of GIS data that have this information.
3. Spatial polyline data, composed of objects that represent sequences of connected line segments.

California Highway Patrol (CHP) Incidents data

1. Incident records representing location of the incident, duration, descriptions, etc. A significant amount of data processing is needed to aggregate records in such a way that the frequency of traffic incidents on each of road segments can be represented as a dependent variable in the regression model.
2. In the mapping software, point data represented by objects that have x and y coordinates.

Caltrans Measurement System (PeMS) Data

1. Annual Average Daily Traffic (AADT) which is a commonly-known variable that has a positive relationship with car accidents.
2. Station information and information of roadway where the station is located, such as location of the station, road, lane, shoulder width, design speed, terrain, etc.
3. Point data representing accidents as recorded by CHP (California Highway Patrol).

3.2 Data Processing

Data fusion is needed to build a single dataset for a regression work. Since datasets from diverse sources have different identification schemes and no attributes in common, we used their spatial relationships to combine them.

3.2.1 CHP Incidents Data & HOV Lane Data

1. The point data (CHP Incidents data based on the location of each incident record) have been projected to the closest line segment (HOV Lane data segmented by a certain distance, e.g. 0.1 mile).

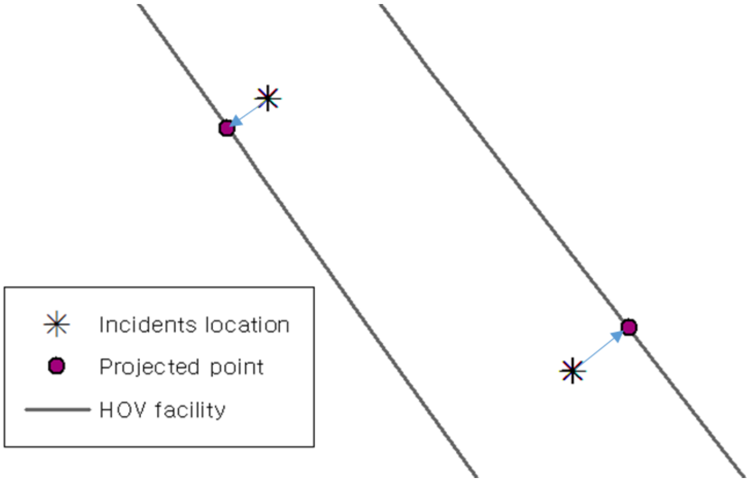
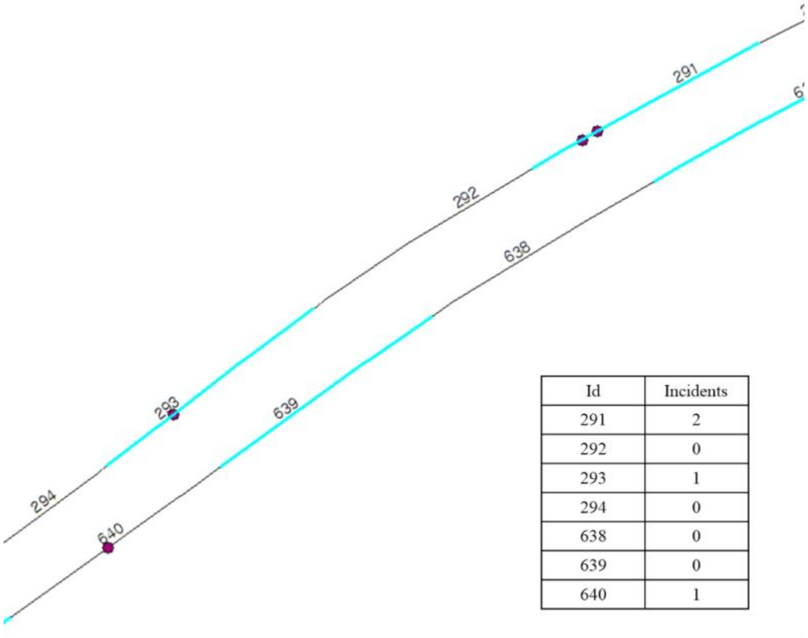


Figure 3.1. Projecting accident data on HOV line segments

2. The frequency of incidents is calculated for each road segment based on the number of points on each line object.



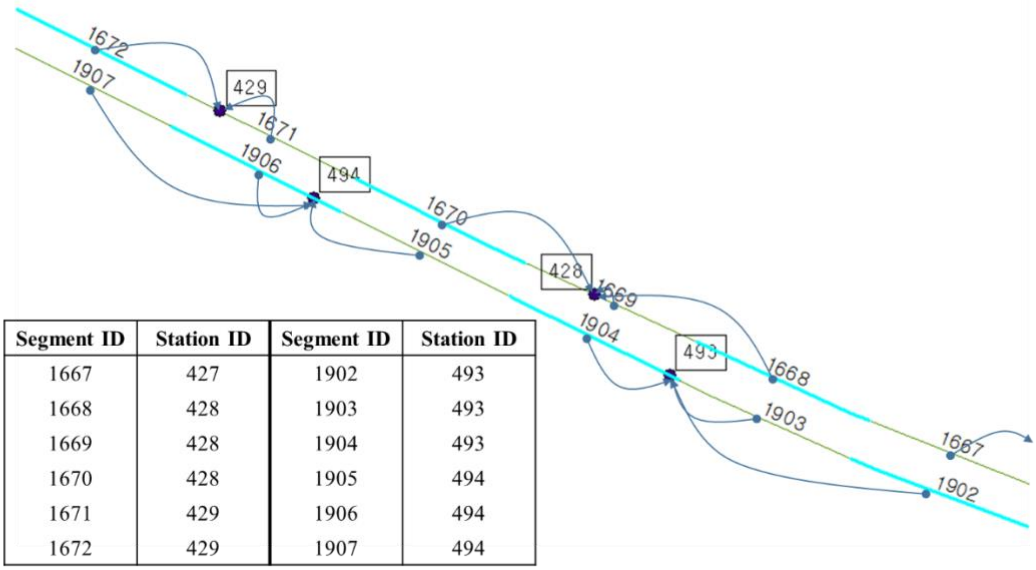
Id	Incidents
291	2
292	0
293	1
294	0
638	0
639	0
640	1

Figure 3.2. Calculating accident frequency on HOV line segments

3.2.2 PeMS Data & HOV Lane Data

Caltrans PeMS provides a variety of performance measures and physical geometry data that is sometimes lacking from HOV Lane data. To enrich our dataset, we assigned the attributes of PeMS data (point data) to the segmented HOV Lane dataset (line data).

Due to the nature of roads, there may be no significant changes in the road geometry between adjacent roads within the 0.1 mile length. Therefore, we assumed that road segments have same characteristics of a station closest to each of them.



Segment ID	Station ID	Segment ID	Station ID
1667	427	1902	493
1668	428	1903	493
1669	428	1904	493
1670	428	1905	494
1671	429	1906	494
1672	429	1907	494

Figure 3.3. Linking point data with segment data

3.2.3 Adding a Kernel Function Using the Incidents Data

Due to recording errors inherent in spatial data, places where frequent incidents occur does not always imply that incidents occur repeatedly on exactly the same location. It is instructive to recast accident data, which is point data, into a probabilistic measure that is a continuous function over the length of road. There are various kernel functions that allow this transformation. We base our kernel function to reflect the assumptions in Atsuyuki Okabe , Toshiaki Satoh & Kokichi Sugihara (2009)[1], a well-known study that introduces a network-based kernel density estimation method and distributes an ArcMap Add-in for this purpose.

---

[1] Okabe, A., Satoh, T., & Sugihara, K. (2009). A kernel density estimation method for networks, its computational method and a GIS-based tool. *International Journal of Geographical Information Science, 23*(1), 7-32.

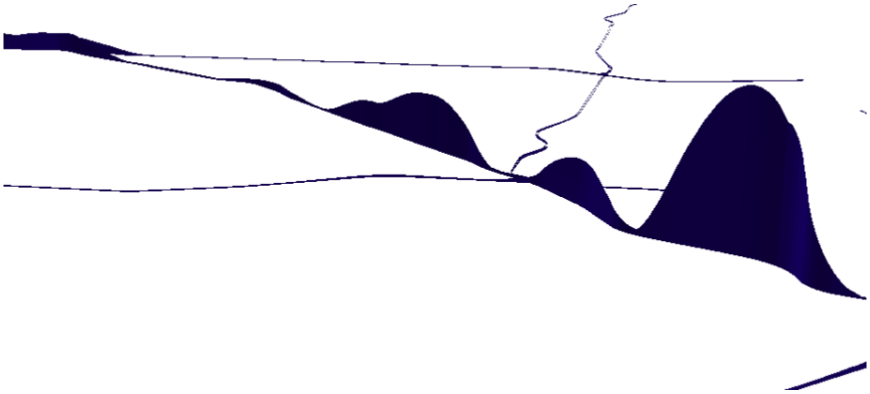


Figure 3.4. Imputing accident density from point data

The ultimate goal of network-spatial analysis is to transform noisy real time traffic data into a visual form that makes it easier for transportation agencies to interact with, and gain insights from, which can then be used for more effective traffic management. We leveraged the existing GIS cyberinfrastructure of Caltrans to create visualization tools that can be quickly deployed by users and projected on applications such as Google maps. A snapshot of an accident web visualization tool for HOV facilities in Southern California is shown below. The purple color denotes accidents on the mainline freeway lanes, and the red color denotes accidents on the corresponding HOV facilities.

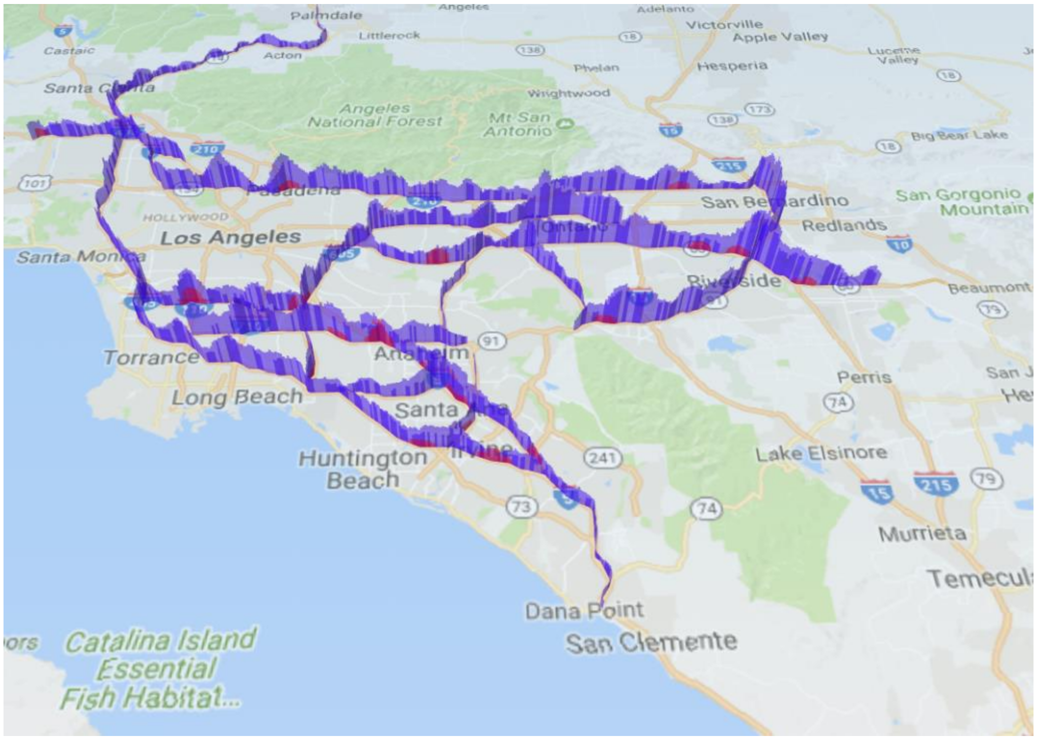


Figure 3.5. Mainline and HOV accident densities in Southern California

3.3 Accident Analysis (Linear Regression)

This study posits a multivariate linear regression model to describe the relationship between traffic incidents and roadway-related attributes. The dependent variable is incidents from the kernel function, as described earlier. The initial explanatory variables contain various geometric variables and AADT. All the variables are converted to log-scale to reduce the scale effect from different measures of variables, except for the dummy variables (access type and separation type).

Table 1: Variables used in the analysis

Name	Description
logZVal	(DV) Kernel density value of the incident frequency
Continuous	(dummy) continuous access
Buffer	(dummy) limited access separated by buffer
Barrier	(dummy) limited access separated by barrier
logRdwid	Road width
logLnwid	Lane width
logInSh	Inner shoulder width
logOutSh	Outer shoulder width
logInMed	Inner median width
logDistoffR	Distance to the nearest front off-ramp
logAADT	Annual average daily traffic

Based on the significance of the variables and Akaike Information Criterion (AIC) value, a measurement for a goodness-of-fit, the subset of explanatory variables was selected from the overall pool of variables described in the table above. As a rule of thumb, if the difference of this statistic of two models is larger than 3, the performance difference of the models was considered significant. Using this methodology, we determined a final model that included only 5 variables (Buffer, Barrier, logRdwid, logInSh, and logInMed). The statistical results are summarized in the table below.

Table 2: Linear regression summary of accident data

Variable	Coefficient	Standard Error	t value
(Intercept)	0.18578	0.10639	1.746
Buffer	0.16329	0.01626	10.04
Barrier	0.81702	0.05184	15.76
logRdWid	-0.25332	0.05813	-4.358
logInSh	-0.29145	0.03588	-8.124
logInMed	0.45064	0.0398	11.322

4 Simulation of HOV Lanes

In this project, we deployed microscopic simulation modelling of HOV lanes for two main objectives:

Evaluation of existing HOV lane conditions on selected freeway geometries (based on latest guidelines on HOV lanes in the Highway Capacity Manual) to assess their performance.

Design and assessment of intelligent approaches on the candidate road stretches to determine and suggest suitable operational alternatives under which HOV facilities can exhibit observable improvements in their operational performance.

4.1 Transmodeler Simulation Model

The use of microscopic simulation to evaluate different HOV lane configurations is specifically appropriate for this study as it can capture traffic flow dynamics and provide more details of vehicle-to-vehicle interactions. TransModeler, the software chosen for this study, simulates the movement of each vehicle every one-tenth of a second. Vehicles can vary in terms of their physical and performance characteristics, and can be custom defined. Acceleration, deceleration, car-following, lane-changing, merging/yielding, and movements at intersections are simulated in detail and are influenced by driver aggressiveness, vehicle characteristics, and road geometry, which can all be user-defined. While default settings are provided for commonly-known behavioral models, it is possible to adjust the parameters. TransModeler can also evaluate dynamic congestion pricing measures and HOT lanes. It also simulates toll plaza operations, including toll (HOT) facilities. Moreover, modified service time parameters in the software makes it possible to model any type of toll payment technology including electronic toll collection facilities.

The above-mentioned capabilities, together, make TransModeler a suitable candidate for studying HOV lane analysis under intelligent control and policy scenarios.

4.2 Intelligent Scenarios

To explore best practices which can address HOV lane degradation, several innovative scenarios have been identified, such as:

- Different geometry contexts
- Dynamic HOV lane
- Priority based HOV lanes
- Intelligent geometry control such as dynamic (time and/or space variable) access points based on real-time traffic conditions.
- Long term vehicle occupancy density credit to access HOV
- Various pricing options (such as Credit-based Congestion Pricing (Kockelman et al., 2005))
- Incentive mechanisms

Although a detailed simulation study of each scenario listed above would be beyond the scope of our current work, we summarize the simulation studies conducted.

4.3 Tested Scenarios

We implemented two different versions of a dynamic HOV lane scenario in TransModeler as preliminary examples. A dynamic HOV lane is an HOV lane that can be converted to a General Purpose lane (GL), based upon specific criteria, and to satisfy a specific MOE.

4.3.1 Scenario A: Occupancy-based Dynamic HOV Lane

In this scenario, a simple network comprising of a freeway segment with one on- and one off-ramp is modeled.

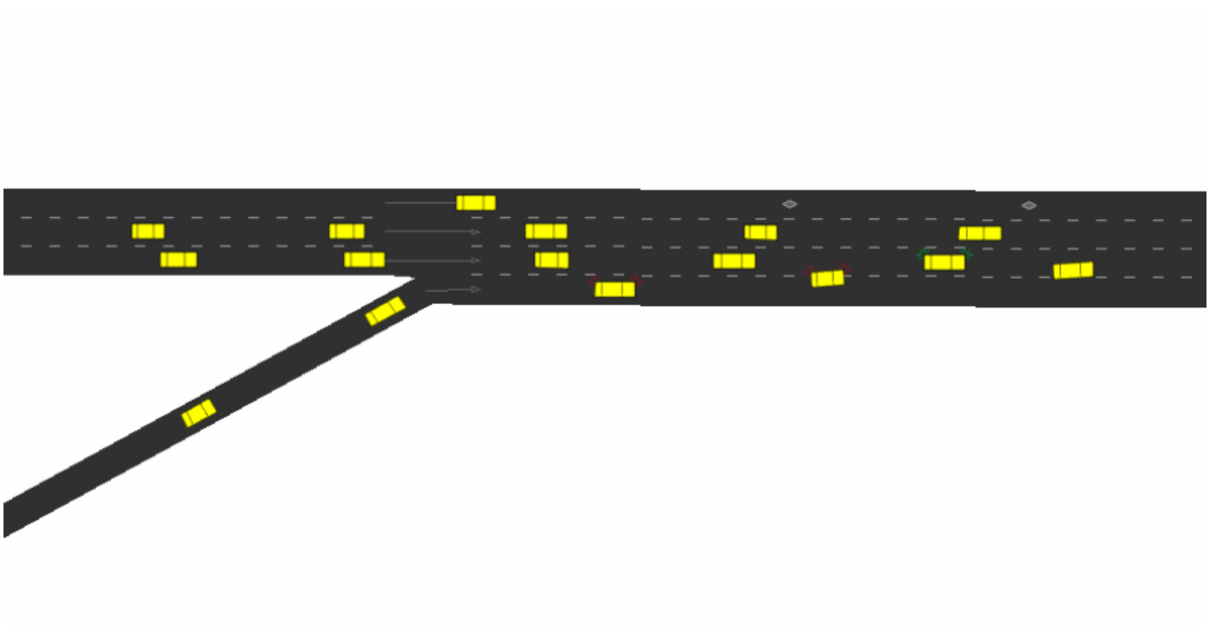


Figure 4.1. Network traffic when the far-left lane is still performing as HOV

The functionality of the far-left lane on the road stretch between the on ramp and off ramp is coded in GISDK as a dynamic HOV lane which is reversible depending on its adjacent GL lane's traffic condition. The logic is that the lane is an HOV by default from the start of the simulation. A detector, located 30 feet behind the on-ramp access point on the freeway's middle lane, continuously measures the occupancy of the middle lane. As soon as the occupancy at that point crosses a certain threshold, the HOV lane converts into General Lane (GL).

The following respectively show snapshots of the network minutes before and after when the HOV changes into GL based on the detector's occupancy rate.

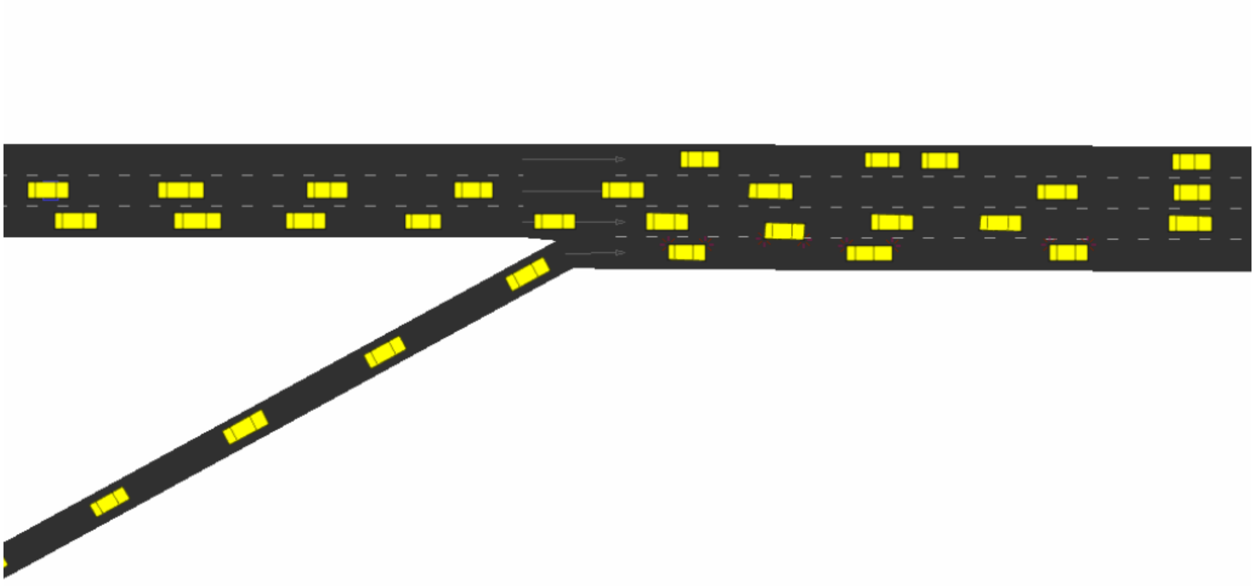


Figure 4.2. Network traffic after the far-left lane changes into General Lane

4.3.2 Scenario B: Speed Based Dynamic HOV Lane

In this scenario, the functionality of the far-left lane on the road stretch between the on ramp and off ramp is coded in GISDK as a dynamic HOV lane which is reversible, depending on two variables:

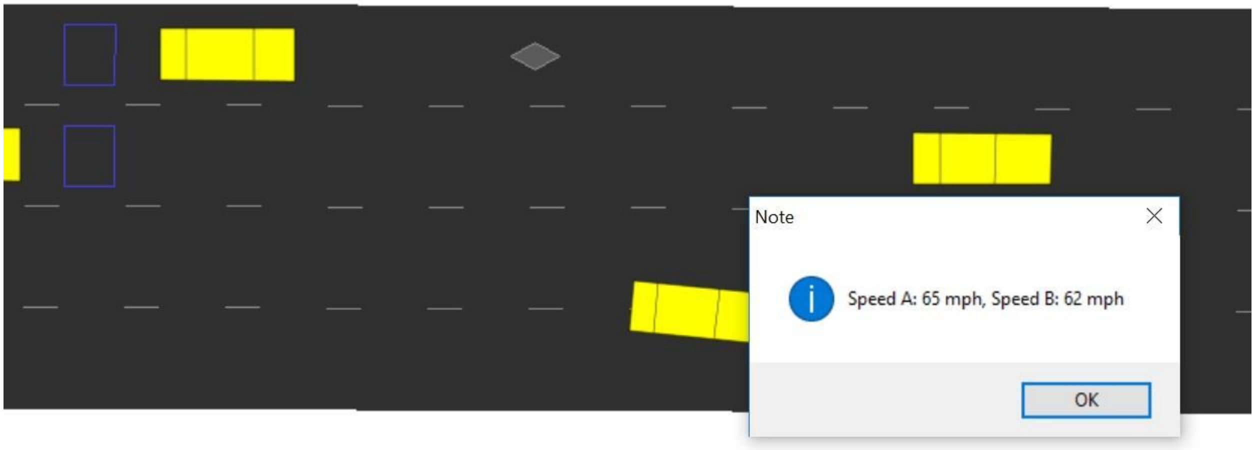
1. Minimum average speed on the that lane (Speed A)
2. Speed difference between the HOV and its adjacent GL (Speed A – Speed B)

The idea behind this approach is that if HOV lane gets congested (here we define it as speed <50 mph) and if the speed on that lane is not more than 8 mph higher than the adjacent GL, then it means the HOV lane is not providing enough incentive as expected. Hence, the HOV lane is converts to a GL. For this purpose, two detectors are located 100 feet after the on-ramp, one on the middle lane (Speed B), and another on the HOV (Speed A) lane. The detectors measure average speeds on the HOV lane and middle lane every 30 seconds. The HOV lane converts into General Lane (GL) when both following conditions are held:

1. (Speed A) <50 mph, and
2. (Speed A -Speed B) < 8 mph.

The following figures show two screenshots of the simulation minutes before and after when the HOV changes into GL based on the speed rates. In Figure 4.3. speed on the left lane and middle lane are respectively 65 and 62 mph. So, because speed on the HOV lane is already higher than 50 mph, the lane is still serving as HOV lane. In Figure 4.4. , although the HOV lane is congested with speed less than 50 mph (Speed A = 48 mph), the lane is still serving as

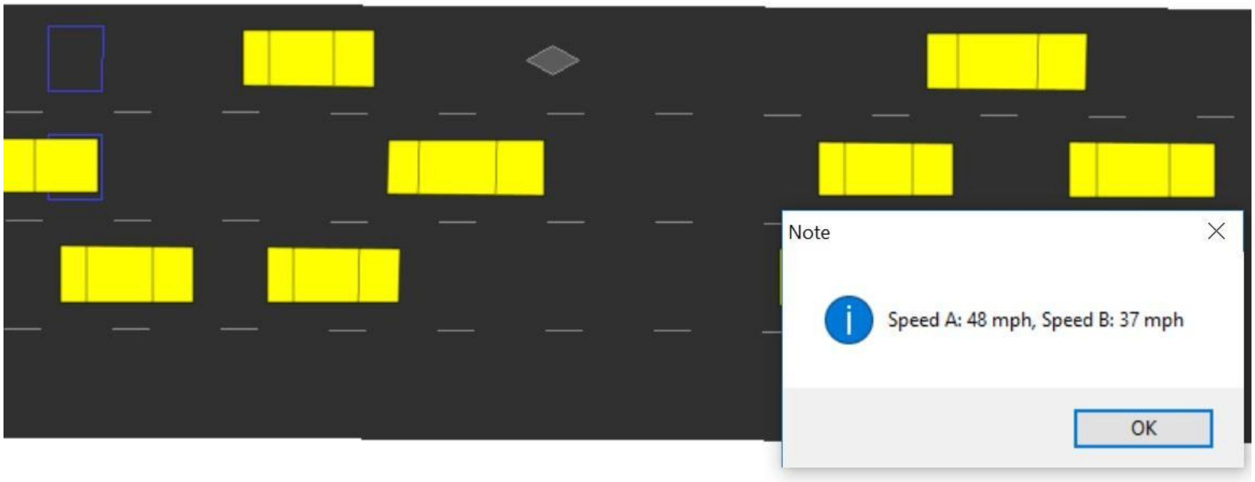
HOV lane because the speed difference between the two lanes is larger than 8 mph as it means it is providing the minimum incentive.



Note

Speed A: 65 mph, Speed B: 62 mph

Figure 4.3. Network traffic when the far-left lane is still performing as HOV since Speed A > 50



Note

Speed A: 48 mph, Speed B: 37 mph

Figure 4.4. Network traffic when the far-left lane is still performing as HOV since (Speed A – Speed B) > 8 mph)

A possible direction of our future work is to examine the safety characteristics of different HOV facilities, based upon their access type (continuous, buffered, barrier, etc.). To our knowledge no microsimulation study has attempted this task, since car-following models embedded in traditional simulation software do not allow for the possibility of vehicle collision. However, there exist probabilistic models such as SSAM (Surrogate Safety Assessment Model), that use vehicle trajectory outputs from standard simulation models and calculate accident probabilities.

5 HOV Data Analysis of Degradation - Orange County Case Study

5.1 Existing Loop Detectors (District 12)

Currently, existing transportation infrastructure in District 12 (Orange County) consists of a total of 560 loop detectors, and 103 dual loop detectors along major freeways (Table 1).

Table 3: District 12 Loop Detectors

Freeway	Total VDS Number	Dual Loop VDS Number
I-5	189	27(16N,11S)
I-405	116	30(15N,15S)
I-605	4	0
I-91	80	6(E)
I-22	69	35(17W,18E)
I-55	44	5(2N,3S)
I-57	58	0
Total	560	103

The figure below depicts the distribution of VDS (Vehicle Detector Station) sensors in District 12. Fig 1 (A) shows that I-5 and I-405 contain the largest proportion of stations, both single and double loop. Double Loop data is mainly available on I-5, I-405 and I-22.

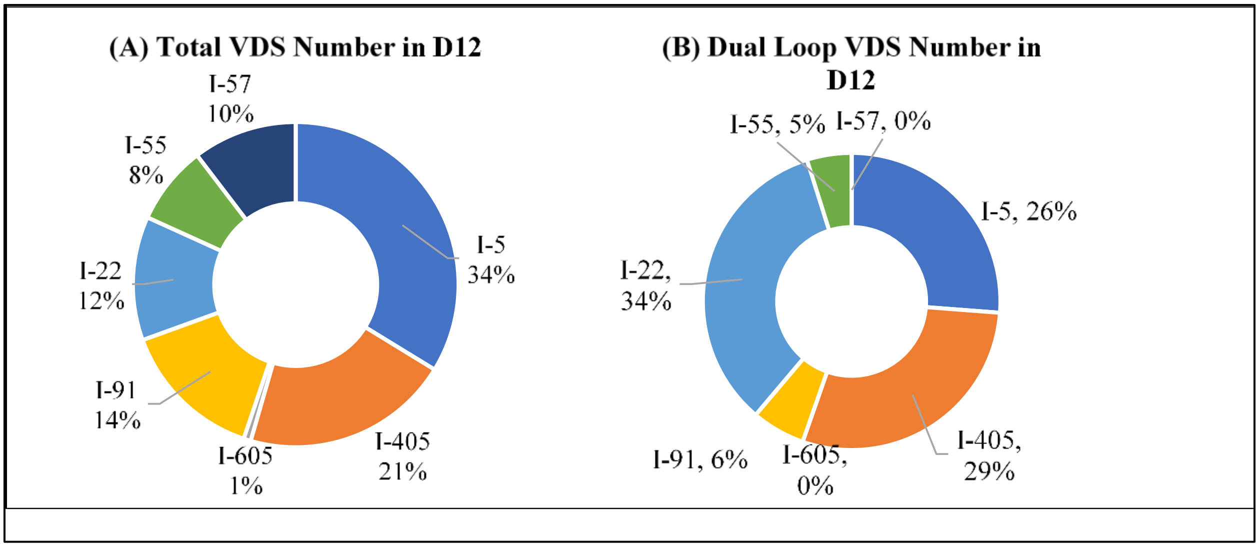


Figure 5.1. Distribution of Detector Stations in District 12

5.2 Modeling for HOV Degraded Speed

The purpose of this analysis is to identify the explanatory variables that statistically influence the speed of the HOV lane, using linear regression models. The explanatory variables selected for these models were chosen based on geometry of HOV lane and observed discrepancies on travel behavior based on these parameters.

5.2.1 Response and Explanatory Variables

(a) Response Variable

The focus of our study is HOV degradation speed, and we use 5min data from PeMs as our data source. "Proportion of time intervals degraded" was chosen as the response variable to represent the HOV degradation. There are 288 five-minute intervals in a 24 hour time period. The number of intervals that are degraded is calculated, and divided by 288 to arrive at the value for the response variable. corresponding to total intervals of 288. Wednesday, Feb 8th, 2017 was chosen as for analysis, with the assumption that it was unbiased by weekend, Monday, Friday, or holiday traffic patterns.

Proportion of time intervals degraded on HOV is:

$$y = \frac{\sum number\ of\ time\ intervals \leq 45mph}{total\ time\ intervals(288)}$$

(b) Explanatory Variable Data Set

Based on Wu, Boriboonsomsin, Barth, and Tadi (2015), a comprehensive list of explanatory variable set for HOV degradation was chosen, as shown in the following table.

Table 4: Explanatory variables in the regression model

Item	Variables
0	intercept
1	Number of Lanes
2	Lane Width
3	Inner Shoulder Width
4	Outer Shoulder Width
5	HOV access type I (1-Continuous, 0-Limited)
6	HOV access type II (1-Buffer, 0-no buffer)
7	Barrier (1-Barrier, 0-no barrier)
8	Distance to the nearest Off Ramp(mi)
9	Surface Type (Bridge Deck/Concrete)
10	Prop.AML= Proportion of Average Mainline Average Speed—45/55/65mph
11	Prop.NML=Proportion of Nearest Mainline Speed—45/55/65mph

Variables 1 to 8 are geometric attributes that represent the HOV stretch. Additionally, item 9 and 10 are speed factors of Mainline (ML). Since the traffic on the mainline lanes tends to influence traffic behaviour on HOV lanes, we posit that it influences HOV lane speed as well. Nearest Mainline speed (proportion) as included as one of the factors. Also, if the average traffic speed is low on Mainline, then eligible vehicles are incentivized to move into HOV lanes. Therefore, the Average Mainline Speed (proportion) is also considered as an explanatory variable.

(c) Data Set

The analysis was performed on two data sets: the whole data set including single and double loop data, and one containing only double loop data.

Three different thresholds of speed for proportion of ML speed were chosen: 45, 55 and 65mph. This is because the degradation degrees have different impact on HOV lane. For example, if the ML speed is much higher than the HOV lane speed, vehicles are not incentivized to change their lane to the HOV lane, and vice versa.

We have six models in total, three for the first data set corresponding to speed thresholds of 45, 55, 65, and the same corresponding models for the second data set.

5.3 Linear Regression Results

Significant variables for speed threshold of 45mph for AML and NML are shown in Table 3 and 4 respectively.

(1) HOV Single & Dual Loop (D12) = 418 Data Points

Table 5: Significant variables for all VDS sensors(D12)

Item	Significant Variables	Pr(>t)	Star
0	intercept	0.000449	***
1	Number of Lanes	0.001082	**
2	HOV access type I (1-Continuous, 0-Limited)	0.001748	**
3	HOV access type II (1-Buffer, 0-no buffer)	0.002193	**
4	Distance to the nearest Off Ramp(mi)	0.047470	*
5	Prop.AML_45mph	1.88e-07	***
6	Prop.NML_45mph	0.008481	**

(2) HOV Dual Loop (D12) = 74 Data Points

Table 6: Significant Variables for Double Loop VDS sensors(D12)

Item	Significant Variables	Pr(>t)	Star
1	Number of Lanes	0.025025	*
2	Inner Shoulder Width	0.001968	**
3	HOV access type I (1-Continuous, 0-Limited)	0.000126	***
4	HOV access type II (1-Buffer, 0-no buffer)	0.000126	***
5-1	Surface Type (Bridge Deck)	0.009320	**
5-2	Surface Type (Concrete)	0.000710	***
6	Prop.AML_45mph	3.18e-05	***
7	Prop.NML_45mph	0.029439	*

From Table 3 and 4, we observe that if we set the same threshold of 45mph for ML speed, there are 6 significant variables for Single & Double Loop data, and 7 significant variables for Double Loop data. They have 5 same significant variables and 3 different variables of Inner Shoulder Width, Distance to the nearest Off Ramp and Surface Type.

We further set the threshold of AML and NML of 55mph and 65mph and compare the results in the following tables.

Table 7: Comparison of Significant Variables for Whole VDS sensors (D12)

	Single & Dual Loop Data – 418 data			
	Significant Variables	**45mph**	**55mph**	**65mph**
1	Number of Lanes	√	√	Δ
2	Inner Shoulder Width			
3	HOV access type I (1-Continuous, 0-Limited)	√	√	Δ
4	HOV access type II (1-Buffer, 0-no buffer)	√	√	Δ
5	Distance to the nearest Off Ramp(mi)	√		
6	Surface Type			
7	Proportion of AML	√	√	
8	Proportion of NML	√	√	√

Ps: symbol Δ means the significance level is 0.1 rather than 0.05.

Table 8: Comparison of Significant Variables for Double Loop VDS sensors(D12)

	Dual Loop Data – 74 data			
	Significant Variables	**45mph**	**55mph**	**65mph**
1	Number of Lanes	√		
2	Inner Shoulder Width	√	√	Δ
3	HOV access type I (1-Continuous, 0-Limited)	√	√	Δ
4	HOV access type II (1-Buffer, 0-no buffer)	√	√	√
5	Distance to the nearest Off Ramp(mi)			
6	Surface Type	√	Δ	√
7	Proportion of AML	√		
8	Proportion of NML	√		√

Ps: symbol Δ means the significance level is 0.1 rather than 0.05.

After comparing the tables above, we can state the following:

(1) From Table 5, common significant variables for the whole data set is: Number of lanes, Continuous or Limited Access Type, Buffer Type, and proportion of NML speed. And the proportion of NML is significant (0.05) among three models, which means the Nearest Mainline Speed do have an impact on HOV speed.

(2) From Table 6, the common significant variables for the double loop data is: Inner Shoulder Width, Continuous or Limited Access Type, Buffer Type, Surface Type and Prop. NML speed (Only two models are significant). Since double loop data set is small, we need more data to validate our hypothesis.

(3) For both double loop data or single & double loop data, the common explanatory factors are: Continuous or Limited Access Type, Buffer Type, Proportion of NML speed.

(4) When the ML speed increases from 45mph to 55mph, and then to 65mph, the number of significant variables decrease. This shows that Mainline traffic has a higher influence on HOV performance when the Mainline speeds are lower.

5.4 Incentive vs. Disincentive Analysis

It is important to validate fundamental assumptions underlying the performance of HOV lanes in relation to Mainline lanes. One such assumption is that the increased speeds on HOV lanes incentivize drivers to carpool and move to HOV lanes. We performed incentive vs. disincentive analysis, both at the aggregate level and at the section level.

From the Federal definition of degradation, an HOV lane is considered as degraded if the average traffic speed during am/pm peak hours is less than 45 mph for more than 10 percent of the time over a consecutive 180-day period. However, there exists no clear explanation as to why a threshold speed of 45mph was chosen. Furthermore, it is not clear to the authors that this threshold should be a static value. We consider a scenario where the mainline traffic speed is 15mph, but the HOV lane speed is 35mph. Clearly, the HOV lane provides an incentive in terms of travel time savings, but according to Federal standards, the HOV lane in this scenario would still be considered degraded.

Five-minute healthy double loop data of HOV lane and corresponding regular lanes speed data were used for the analysis. AM-peak hour was set from 6:00 am to 09:00 am and PM-peak hour from 4:00 pm to 7:00 pm in Orange County District (12). All segments with HOV speed less than 45mph were filtered, and the speed difference between two sets of speed in each 5minute interval was computed. One is the difference between HOV lane speed from Nearest Main Lane Speed (NMLS), the other one being the difference between HOV lane speed and the Average Main Lane Speed (AMLS). Table 7 shows the variable description for incentive and disincentive.

Table 9: Variable Description for Incentive and Disincentive

Variable	Description
HOV_ML_N	Speed Difference between HOV Speed and Nearest ML Speed
HOV_ML_Avg	Speed Difference between HOV Speed and Average ML Speed

5.4.1 Section Data Sample

Two detectors on I-22E were used for single detector analysis on Feb 8th and Feb 15th.

Detector #1: 1215051 (33.775838, -117.901985)

Detector #2: 1214771 (33.773077, -117.907372)

When considering a speed of 45mph as degradation on a specific section of SR22-E, it is of interest to consider speed differential as a measure of incentive/disincentive from using the HOV lane.

This section analysis focuses on the data obtained from two healthy double loop detectors on SR22-E and its corresponding adjacent main line. The analysis was completed using 5-minute data from Wednesday, February 8 and 15, 2017.

The speed differential used for analysis was the difference between the HOV lane speed and the main line speed (HV_Speed – ML_Speed). A positive value for the difference represents an incentive to use HOV lanes, and a negative value for a disincentive. The blue bars represent incentives/disincentives when the HOV lane speeds are compared with the nearest Mainline lane speeds, while the orange bars represent the corresponding values when HOV lanes are compared with the average speeds computed across all Mainline lanes.

Feb 8th: 1215051

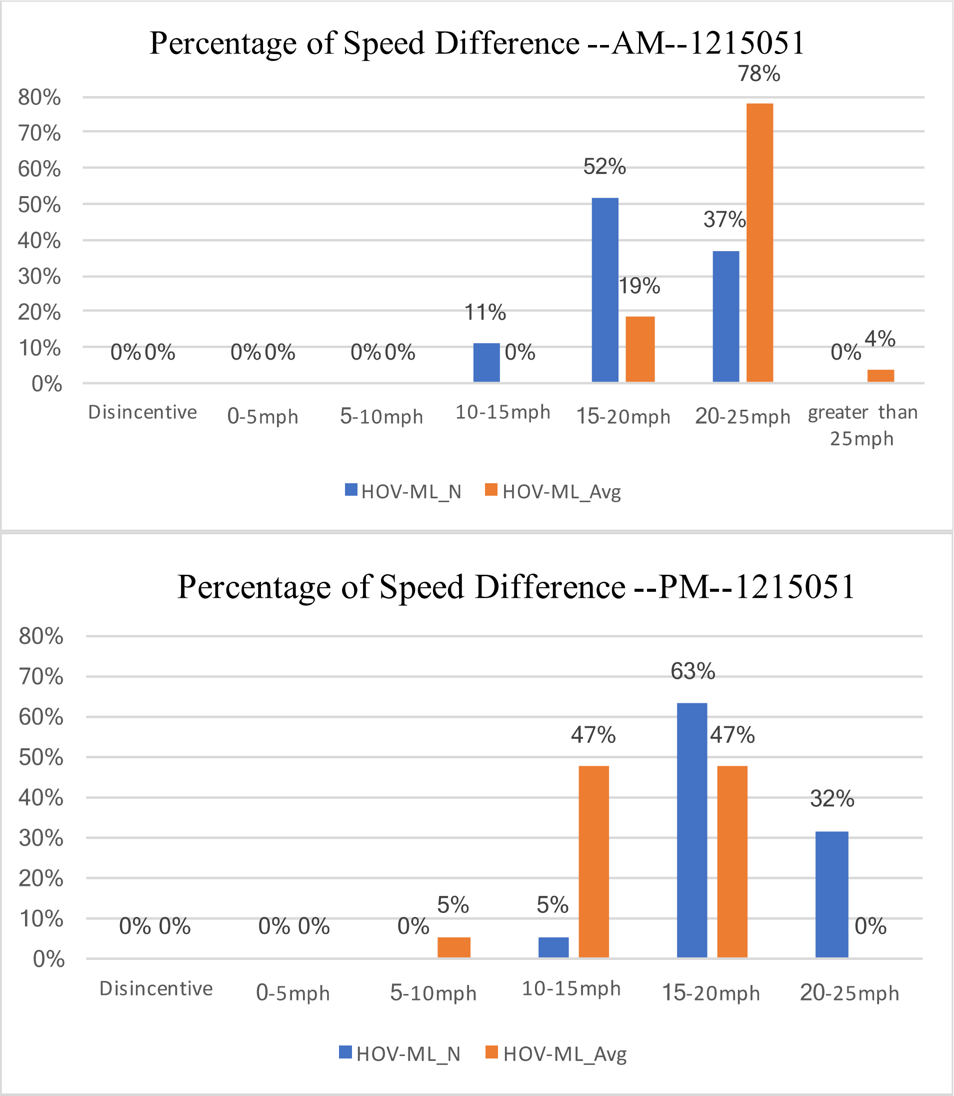


Figure 5.2. Percentage of Speed Difference between HOV and Regular Lane-1215051

Feb 8th: 1214771

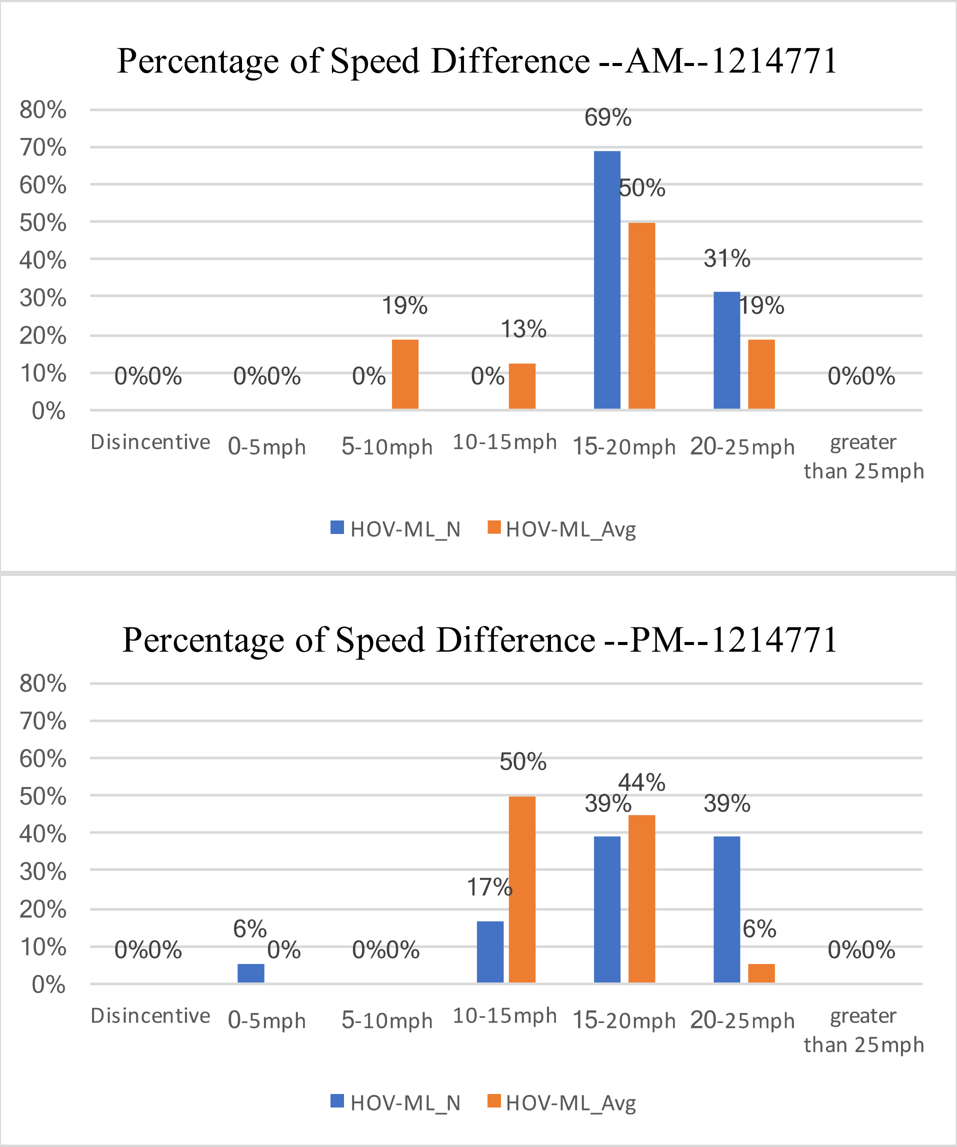


Figure 5.3. Percentage of Speed Difference between HOV and Regular Lane-1214771

Feb 15th: 1215051

5.4.2 HOV Incentives

The following charts depict the percentage of time where incentives were observed under degradation conditions (HOV speeds under 45mph).

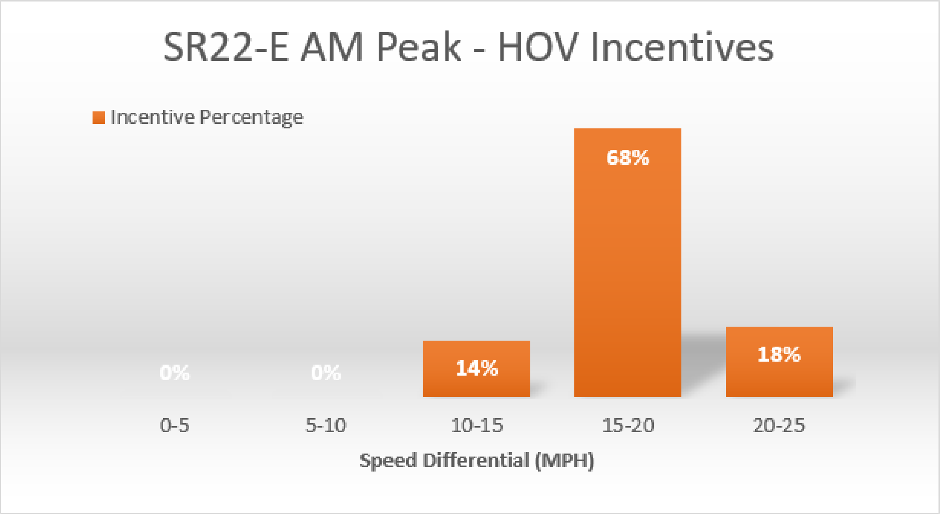


Figure 5.4. Percentage of Speed Difference between HOV and Regular Lane(10.50 AM)

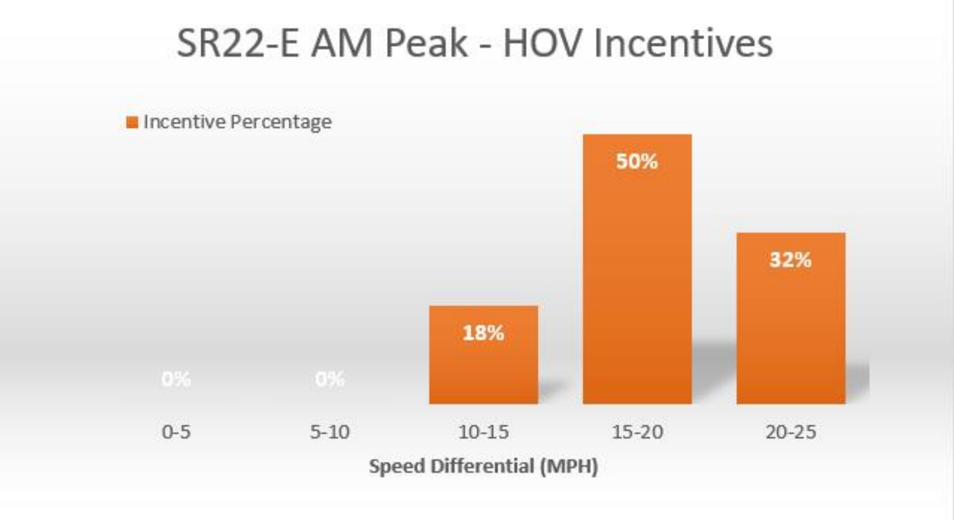


Figure 5.5. Percentage of Speed Difference between HOV and Regular Lane(10.14 AM)

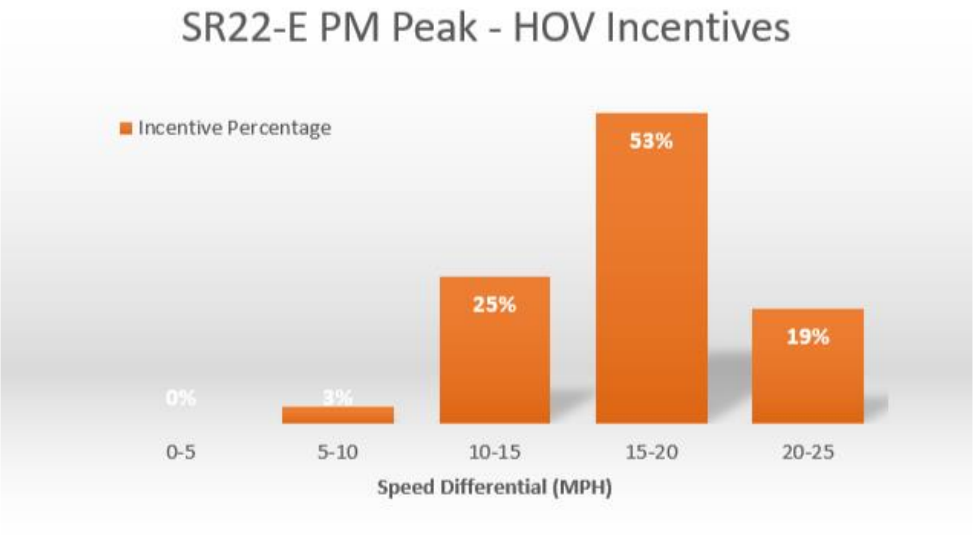


Figure 5.6. Percentage of Speed Difference between HOV and Regular Lane(10.50 PM)

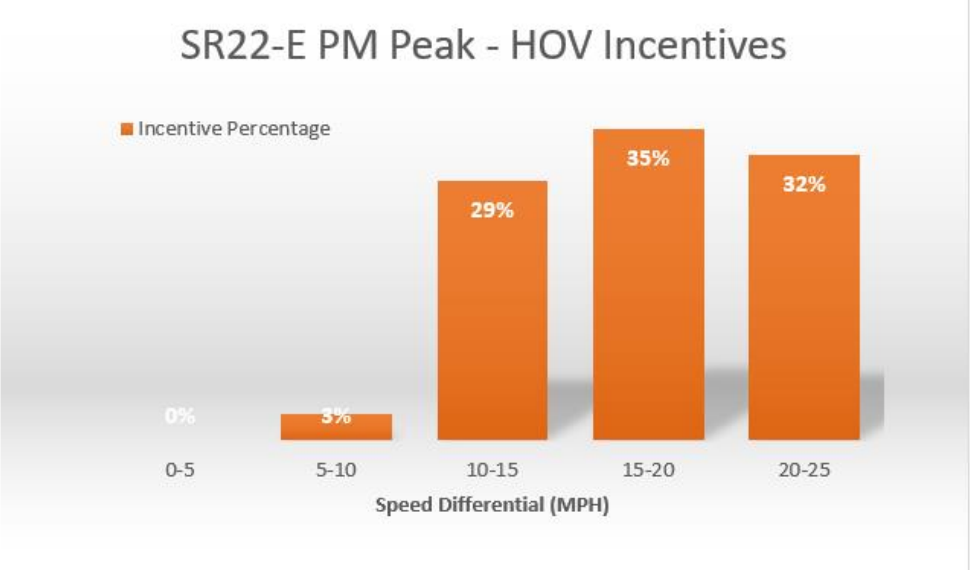


Figure 5.7. Percentage of Speed Difference between HOV and Regular Lane(10.14 PM)

5.4.3 HOV Disincentives

Disincentives, on the other hand, were only observed during the AM peak period under speeds higher than 45 mph.

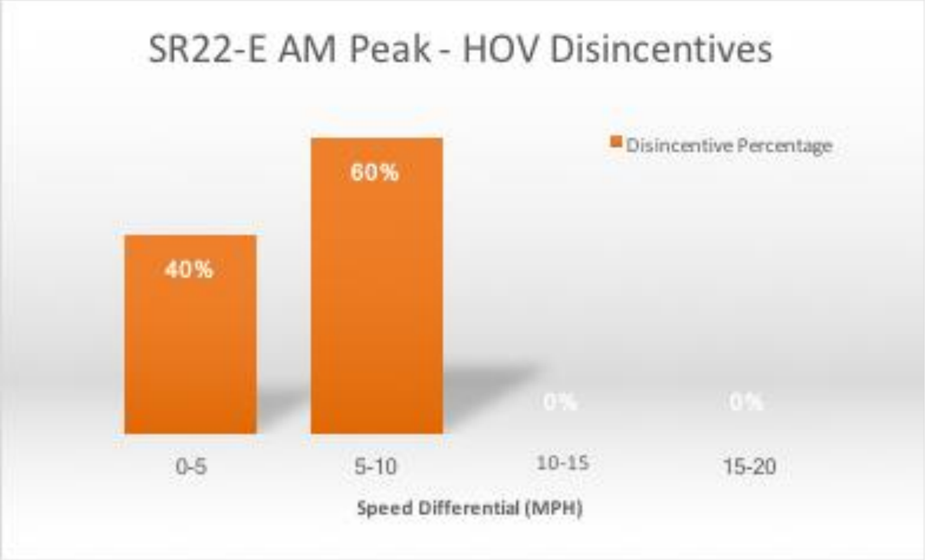


Figure 5.8. Percentage of Speed Difference between HOV and Regular Lane(10.50 AM)

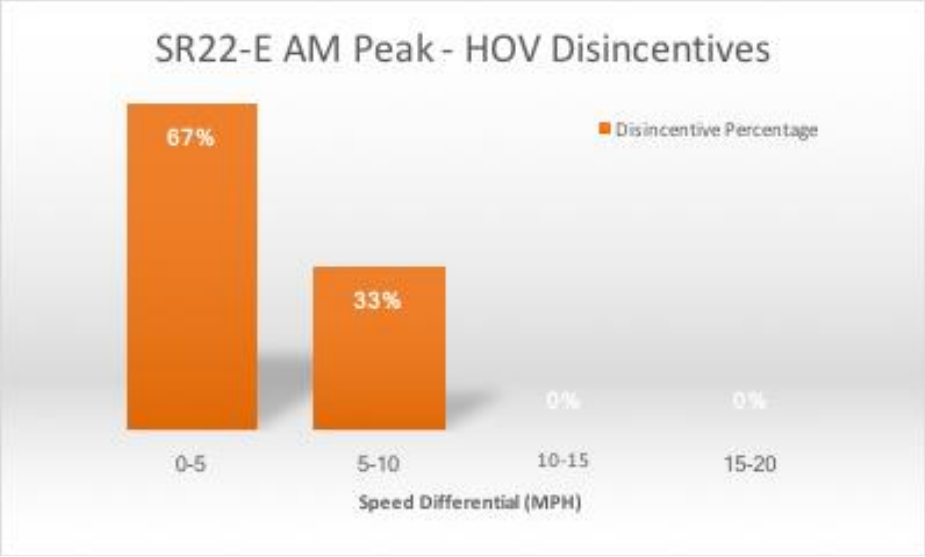


Figure 5.9. Percentage of Speed Difference between HOV and Regular Lane(10.14 AM)

From the two data samples of SR-22 shown in Figure 5.2. to Figure 5.9., we conclude that for this stretch of freeway, February 8 had only incentives for traveling on HOV lanes. The only instance of disincentives was observed during the AM-peak time on February 15.

While a section-based analysis can be useful for a local study, one needs to look at aggregate data from multiple freeways to get a comprehensive view of the overall performance of HOV lanes.

5.4.4 Aggregate Data Analysis

Traffic data from multiple freeways on Wednesday, February 8, 2017 were used for this analysis, with the results shown in Figure 5.10. to Figure 5.15.

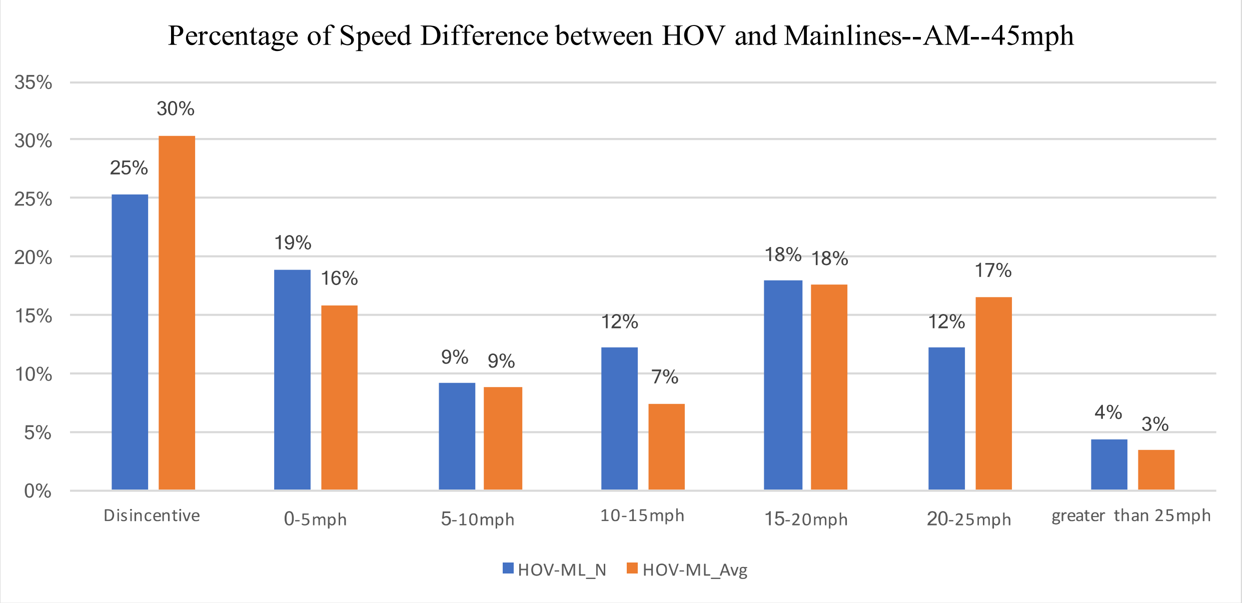


Figure 5.10. Percentage of Speed Difference between HOV and Regular Lanes-AM

From Fig 10, we find that for AM peak hours (6:00-9:00 am), HOV lanes provide an incentive for approximately 70% of the time.

The speed difference between HOV and Nearest Lane is less than 0 for approximately 25% of the time, which means the HOV lane speed is less than Nearest lane speed for approximately 45 minutes. Similarly, for about 34% of the time (62min) HOV speed is significantly greater (beyond 15mph) than the Nearest regular lane.

Also, the speed difference between HOV lane and Average regular lanes follow a similar pattern, with over 30% (54min) less than 0, over 30% (54min) that HOV speed is better than average lane speed, and approximately 38% (68min) time when HOV speed is significantly greater than the average ML.

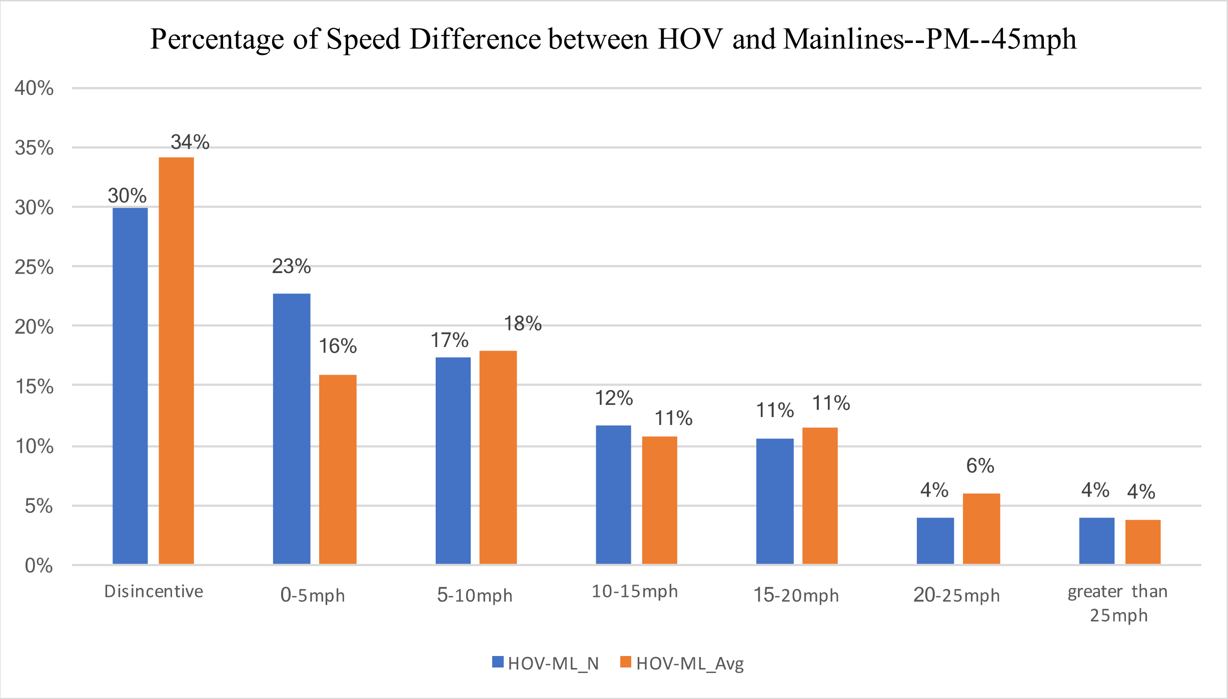


Figure 5.11.Percentage of Speed Difference between HOV and Regular Lanes-PM

For PM peak hours (4:00-7:00 pm) then, speed difference between HOV and both Nearest lane or Average Regular lanes show remarkable agreement, with approximately 30% (55min) time that are a disincentive and 70% of the time an incentive.

The results of degradation threshold as 45mph is shown above, and we find that the HOV lane acts as an incentive for approximately 70% of the time.

We then performed the same analysis, except with different threshold speeds for degradation, and compared the results to determine if HOV lanes show the same levels of incentives and disincentives. Table 8 shows the total number of data points after the HOV data were filtered for various threshold degradation speed.

Table 10: Data counts after Speed Filtering

Filter Speed	35mph	45mph	55mph
AM	93	296	671
PM	363	588	1206

(1) If HOV degradation limit is 35mph

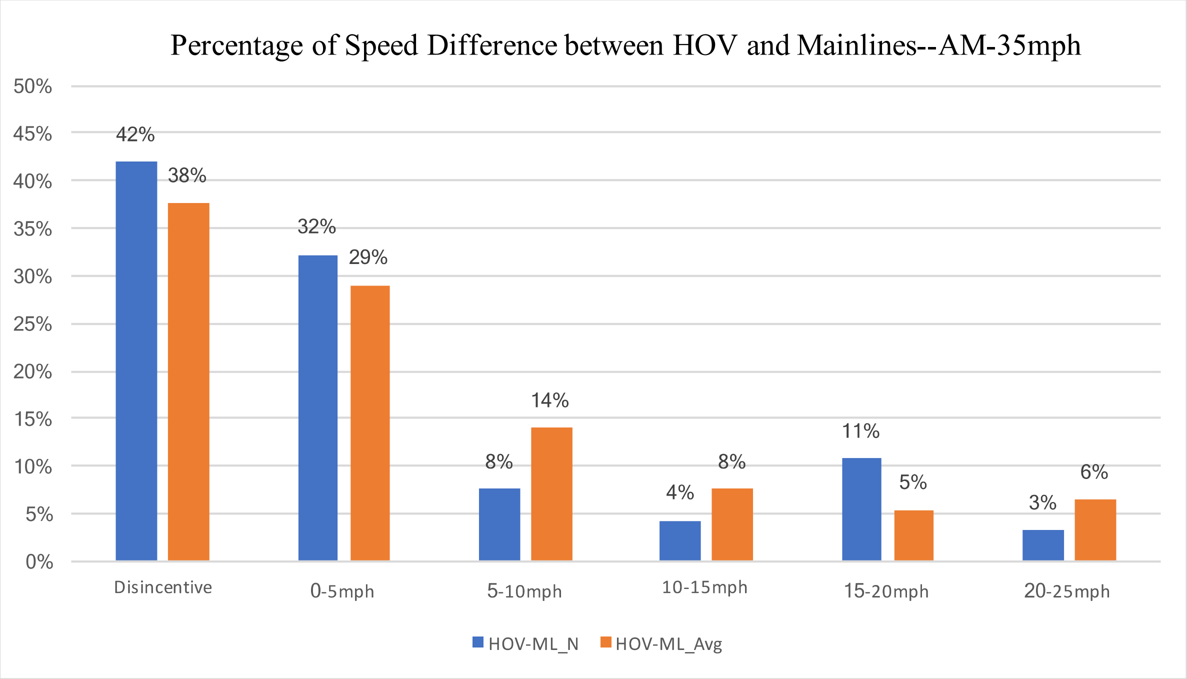


Figure 5.12. Percentage of Speed Difference between HOV and Regular Lanes-AM

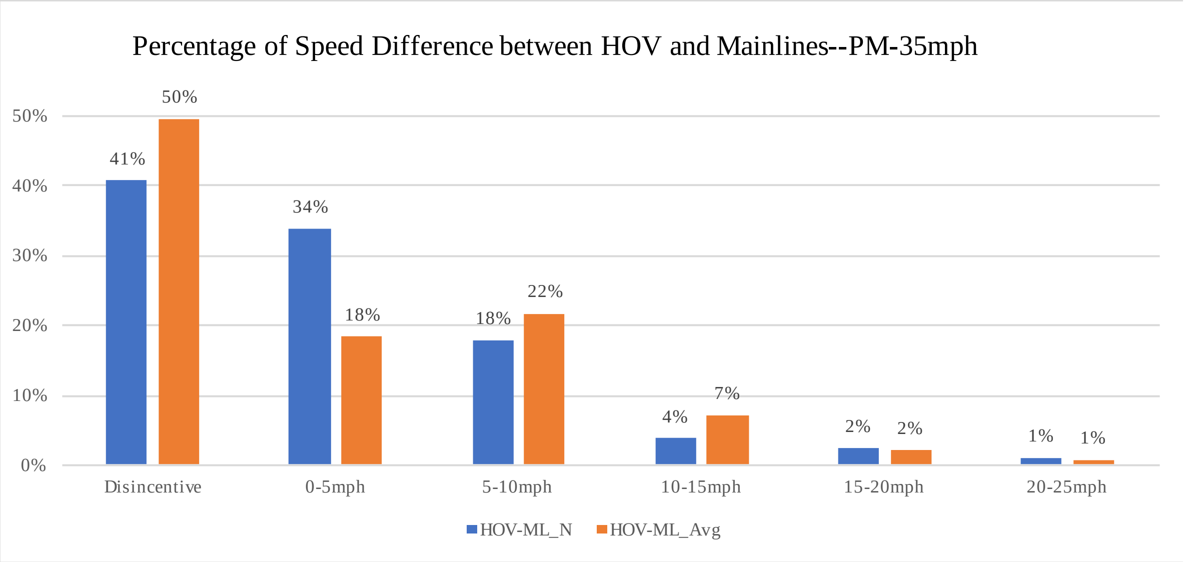


Figure 5.13. Percentage of Speed Difference between HOV and Regular Lanes-PM

(2) If HOV degradation limit is 55mph

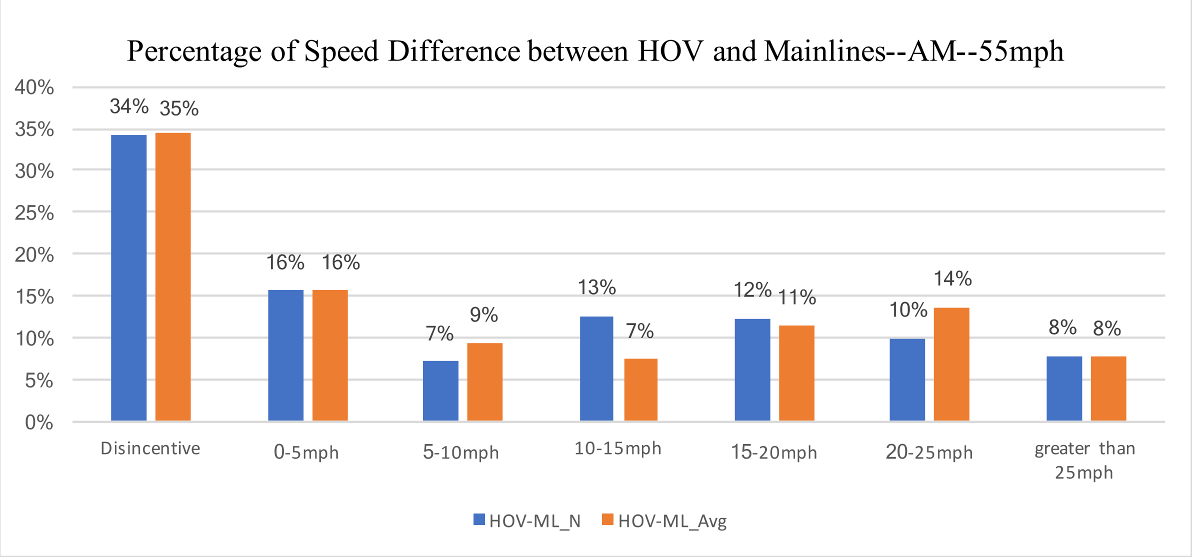


Figure 5.14. Percentage of Speed Difference between HOV and Regular Lanes-AM

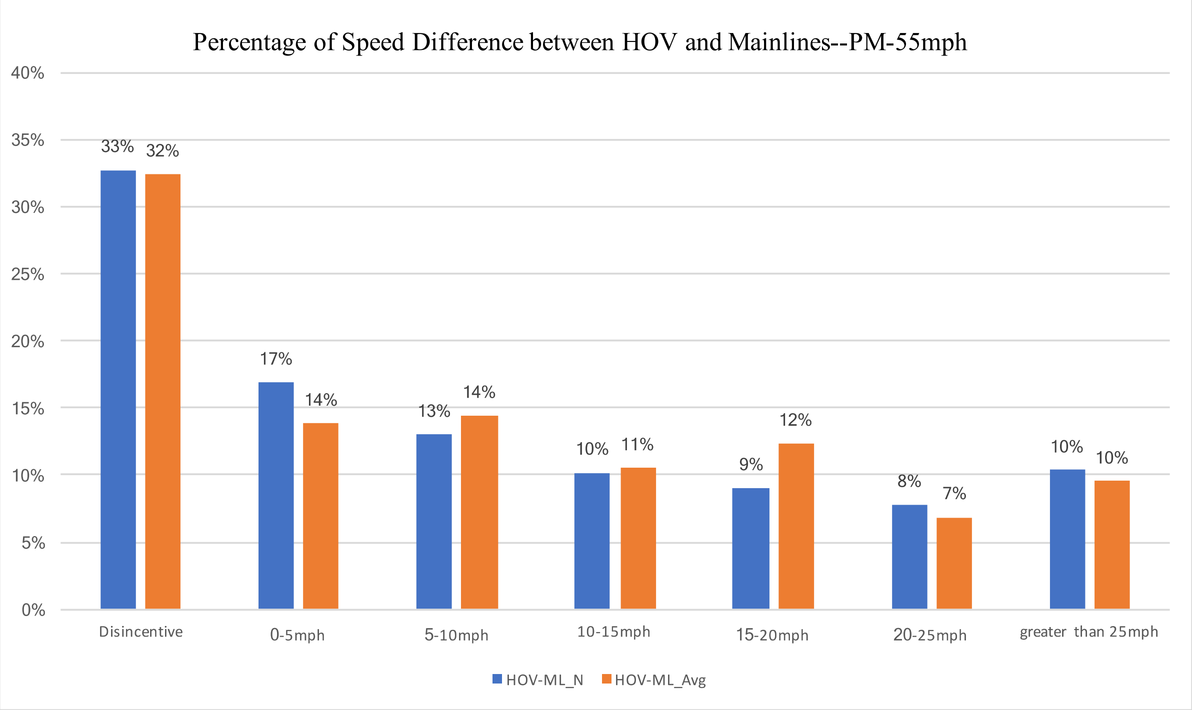


Figure 5.15. Percentage of Speed Difference between HOV and Regular Lanes-PM

After setting 35mph, 45mph, and 55mph as degradation thresholds shown in Table 12 to 15, we find that speed distribution in each degradation threshold is similar in shape, but with different actual percentages in each interval.

Table 11: Incentive and Disincentive Result (with Nearest ML)

	Filter Speed	35mph	45mph	55mph
AM	Incentive	58%	75%	66%
	Disincentive	42%	25%	34%
PM	Incentive	59%	70%	67%
	Disincentive	41%	30%	33%

For AM peak (06:00-09:00am), the percentage times for incentives is highest when the degradation speed set to 55mph, as degradation speed and lowest at 45mph.

For the PM- peak (04:00-07:00pm), the proportion of time for incentives is the highest at 45mph, and lowest at 35mph. We extended the analysis for all HOV facilities in the state. The results are shown in the table below.

6 HOV Lane Degradation Analysis using HCM for Managed Lane Facilities

Federal standards have defined an HOV lane to be degraded if its average speed drops below 45 mph during the peak hour for more than 10% of time over a 180-day period. In 2015 nearly 65% of the HOV lanes in the state of California where found to have varying extent of degradation [CALTRANS, 2016]. However, this analysis does not examine the extent of degradation for different types of HOV lanes. HOV lanes are different based on the number of lanes, the access type and the nature of separation from adjacent General Purpose Lanes. These differences could have a significant impact on the operational characteristics and the capacity of the HOV facilities.

This section examines the application of the newly drafted HCM for Managed Lane facilities in the degradation study of HOV lane facilities.

6.1 Managed Lane Segment - Definition

HCM defines a Managed Lane (ML) segment on a freeway as the one which has distinct operational characteristics in terms of access points, speed, occupancy requirements, tolls etc. compared to the adjacent General Purpose (GP) Lane. A Managed Lane could be either of High Occupancy Vehicle (HOV) Lane, High Occupancy Toll (HOT) Lane or Express Lane. The term Managed Lane(ML) and HOV lane would be used inter-changeably in the rest of this section.

HCM for Managed Lanes broadly classifies Managed Lane segments into the following categories:

1. ML Basic
2. ML On-Ramp
3. ML Off-Ramp
4. ML Weave
5. ML Access Segment (ML-AcS).

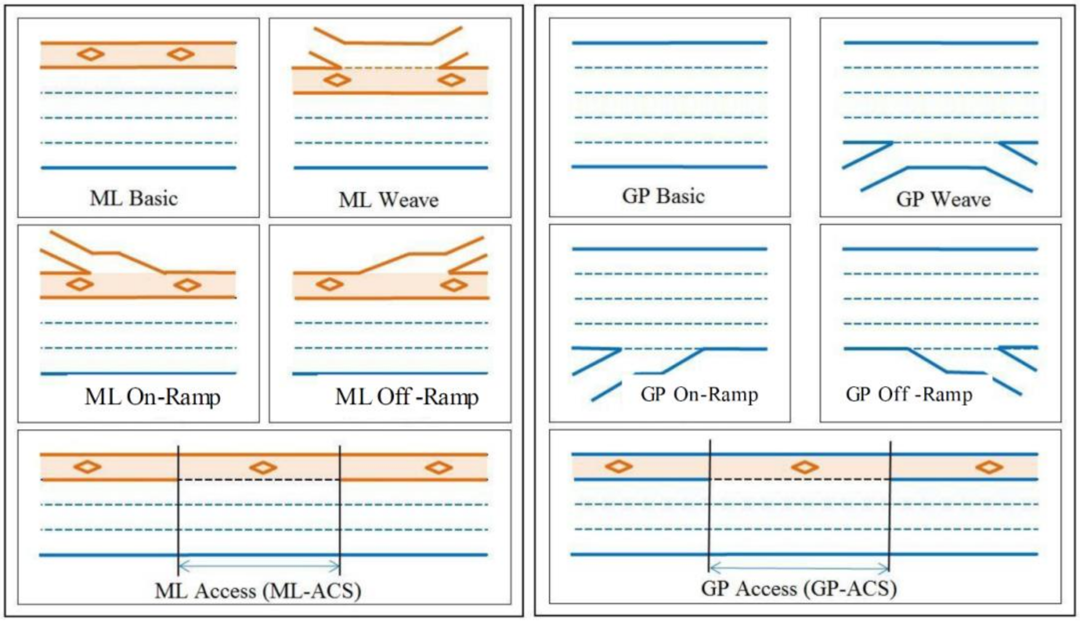


Exhibit 1 Different Segment Types for ML and GP Lanes

Figure 6.1. Classification of Managed Lane Segments [HCM 2010]

The capacity and performance analysis for ML Weave, ML- On-ramp and ML-Off ramp segments are carried out based on the Weaving and Merge-Diverge analysis methods laid out in chapters 12 and 13 of HCM 2010. The capacity analysis for ML Basic and ML Access Segments are specified in the newly drafted Managed Lanes supplementary chapter.

6.1.1 Basic Managed Lane Segments

HCM for Managed Lanes classifies Basic ML segments into the following 5 categories:

1. Continuous Access ML Segment
2. Buffer-1 ML Segment
3. Buffer-2 ML Segment
4. Barrier-1 ML Segment
5. Barrier-2 ML Segment

The following figures show these segments in more detail. These are elaborated in detail in the forthcoming subsection.

Continuous Access ML Segment

A Continuous Access ML Segment refers to single lane ML segments adjacent to General Purpose Lanes in which access between ML and GP Lanes at any point. Entrances and exits to the MLs are unrestricted.

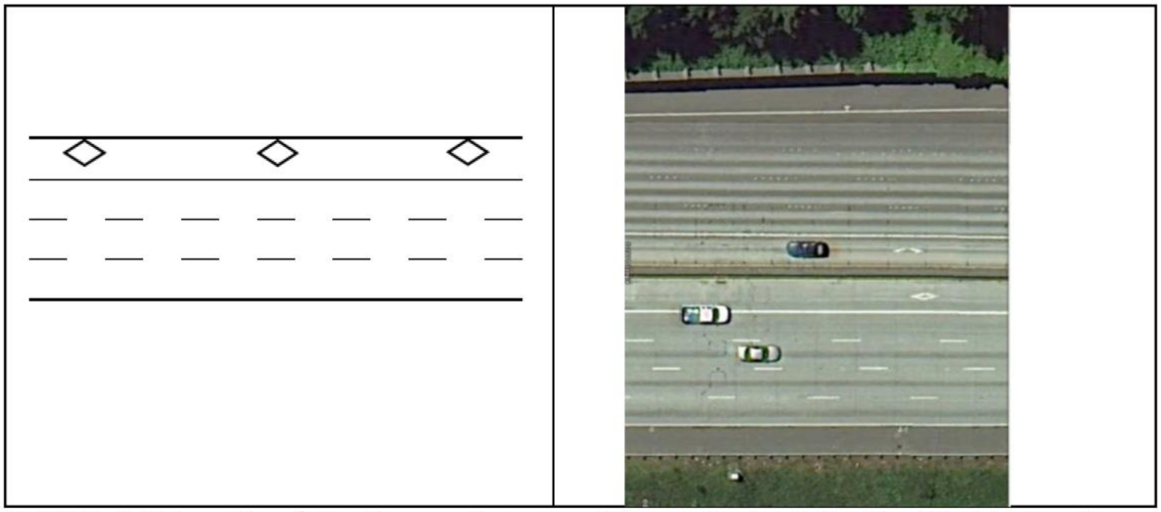


Exhibit 4 Schematic of Continuous Access and Example at I-5 Seattle, Washington (Source: Google Earth)

Figure 6.2. Illustration of a Continuous Access Managed Lane [HCM 2010]

Buffer-1 Managed Lane

A Buffer-1 Managed Lane is an ML segments that are single-laned and run concurrent to GP lanes with intermittent entry and exit points. These ML lanes are separated from the adjacent GP lanes with a striped buffer Figure 6.3. illustrates the configuration of a Buffer-1 Managed Lane.

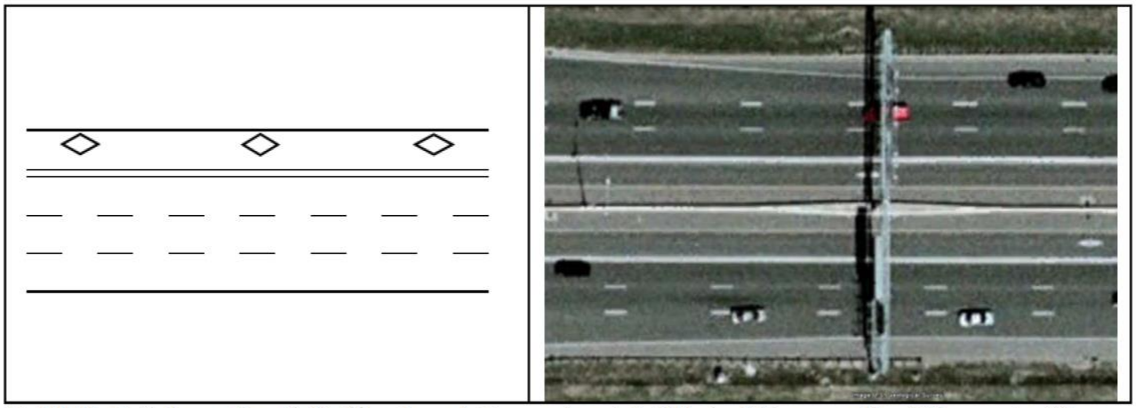


Exhibit 5 Schematic of Buffer 1 and Example at I-394 in Minneapolis, Minnesota (Source: Google Earth)

Figure 6.3. Buffer-1 Managed Lane [HCM 2010]

Buffer-2 ML Segment

A Buffer-1 ML Segment is similar to a Buffer-1 segment except that there are 2 Managed lanes instead of 1. Figure 6.4. illustrates the configuration of a typical Buffer-2 ML Segment.

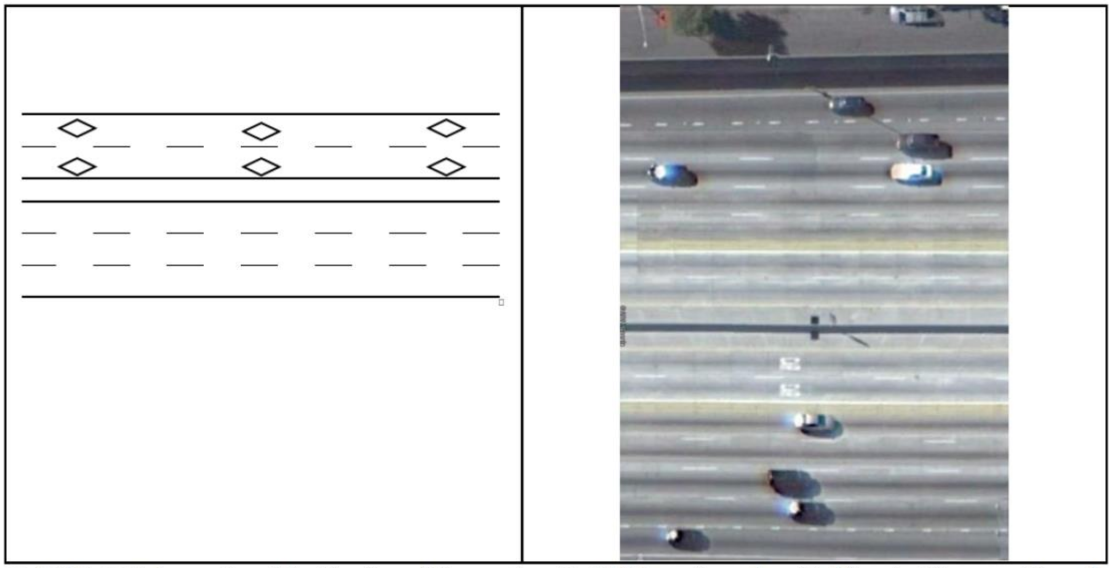


Exhibit 6 Schematic of Buffer 2 and Example at I-110 Los Angeles, California (Source: Google Earth)

Figure 6.4. Buffer-2 ML Segment [HCM 2010]

Barrier 1 ML Segment

A Barrier-1 Basic ML Segment is a single laned ML segment that is separated from the adjacent GP lane by a physical concrete or steel barrier. Figure 6.5. illustrates the configuration of a typical Barrier-1 ML Segment.

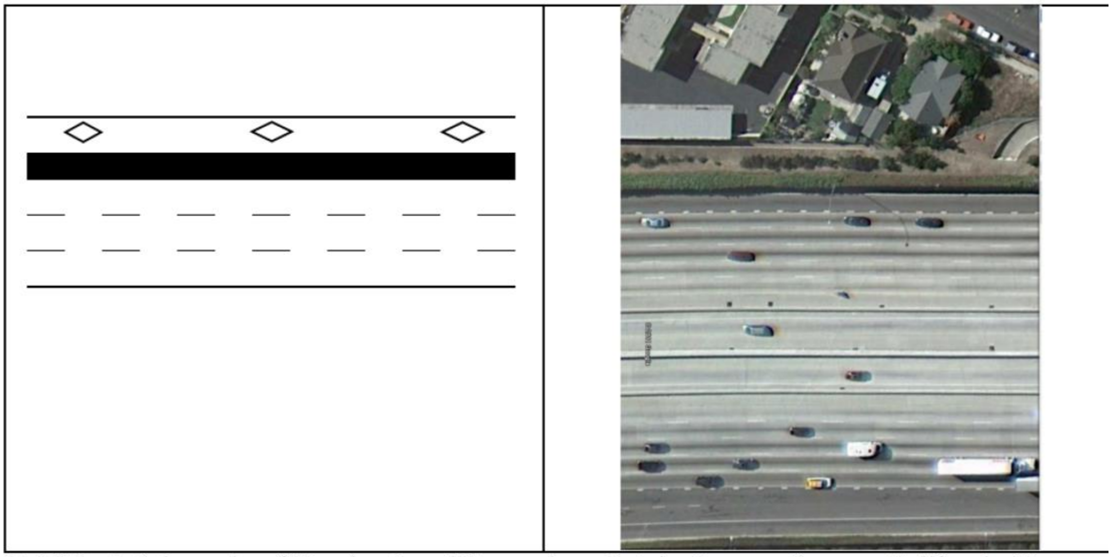


Exhibit 7 Schematic of Barrier 1 and Example at I-5 in Orange County, California (Source: Google Earth)

Figure 6.5. Barrier-1 Basic ML Segment

Barrier-2 ML Segment

A Barrier-2 Basic ML Segment is similar to a Barrier-1 segment except that there are 2 Managed lanes instead of 1. Figure 6.6. illustrates the configuration of a typical Barrier-2 ML Segment.

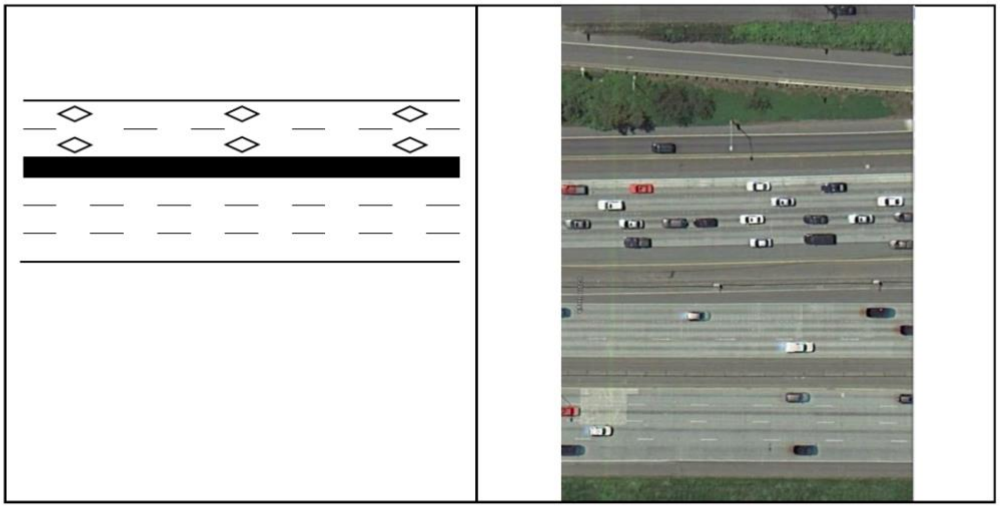


Exhibit 8 Schematic of Barrier 2 and Example at I-5 in Seattle, Washington (Source: Google Earth)

Figure 6.6. Barrier-2 Managed Lane Segment [HCM 2010]

6.2 Speed-Flow relationship for Managed Lane Segments

The speed-flow relationship for Managed Lanes are distinct from that defined for General Purpose Lanes due to the following characteristics that are peculiar to Managed Lanes:

1. Slow car-following effect: Single lane Managed Lane facilities which have restricted access/egress are characterized by the inability of a faster vehicle to overtake a slower vehicle. This leads to a reduction in speed on that lane. This effect is found in Buffer-1 and Barrier-1 Managed Lane segments.
2. Friction effect: The performance of a Managed Lane facility is affected by congestion on the adjacent General Purpose Lane. This is called friction effect. Friction effect is observed in single lane Managed Lane facilities which do not have a physical barrier separating it from the adjacent General Purpose Lane.

Based on the above two performance characteristics unique to Managed Lane facilities, HCM for Managed Lanes defines different Speed-Flow relationships for each category of Basic Managed Lane Segments.

6.3 HOV Lane Degradation: Implications from HCM Analysis

6.3.1 Cut-off Flow rates for HOV lane degradation

As described in the previous section, each category of ML segment has a different speed-flow relationship. Table 1 indicates the cut-off flow rates in pce/hr/lane for each category of ML segment above which the Managed Lane speed drops below 45 mph for different design speeds. Since HOV lane degradation is measured only during the peak hour, Managed Lane segments can be assumed to experience friction effect from the adjacent congested GP lane (Density > 35 pce/mile/lane). Hence the cut-off flow rates have been calculated using the friction effect curves for Continuous Access and Buffer-1 Managed Lane.

Table 12: Cut-off Flow-rates for HOV lane degradation (all flows in pce/hr/lane).

Design Speed (mph)	Continuous Access	Buffer-1	Barrier-1	Buffer-2	Barrier-2
75	1713	1595	1750	1745	2100
70	1630	1515	1700	1655	2050
65	1540	1423	1650	1560	2000
60	1430	1320	1600	1455	1880
55	1290	1214	1475	1335	1760

The above analysis indicates that the cut-off flow rates beyond which an HOV lane enters degradation state is lower for Buffer-1 HOV lanes compared to Continuous Access HOV lanes. This means that a Continuous Access ML can accommodate more vehicle flow before it falls into degraded state. The maximum observed flow rates in Continuous Access HOV lane is higher than that of Buffer-1 HOV lanes due to slow car-following effect described in the previous section. Barrier-2 ML segments have the highest cut-off flow-rates before entering a degraded state.

Due to the difference in operational characteristics for each category of Managed Lane segment, a single standard to define degradation would not be appropriate. Degradation standards for HOV lanes need to be defined separately for each category of Managed Lane segments.

6.3.2 Continuous Access ML vs Buffer-1 ML segment

Continuous Access Managed Lanes and Buffer-1 Managed Lanes form the bulk of HOV lane segments in the state of California, hence it would be appropriate to focus on the degradation in these facilities. These two ML segments have nearly similar geometries and configurations and a conversion from one to the other would involve the least cost. The difference in access to Continuous Access and Buffer-1 ML segments result in a significant difference in operational characteristics which have significant implications for any HOV lane degradation study.

As discussed in the previous section, Buffer-1 Managed Lanes have lower performance in terms of speed and maximum flow-rate compared to Continuous Access Managed Lane segments under all conditions of congestion on adjacent General Purpose lanes. This may indicate that HOV lane degradation could be reduced by converting Buffer-1 Managed Lanes to Continuous Access ML. Buffer-1 HOV lanes also do not offer any safety advantage over Continuous Access MLs as the larger concentration of collisions and higher collision rates were found in Buffered access HOV lanes in California [Jang et al, 2009]. However, Continuous Access Managed Lanes experience greater drop in performance compared to Buffer-1 HOV lane due to friction from adjacent General Purpose lanes. Table 2 indicates the drop in speed on a Continuous Access and Buffer-1 ML segments for different design speeds at cut-off flow rates with and without Friction effect from adjacent GP lane.

Table 13: Speeds at cut-off flow rates for Continuous Access and Buffer-1 HOV lanes (All Speeds in mph)

Design Speed	Continuous Access ML			Buffer-1 ML		
	Without Friction effect	Under friction effect	% Drop	Without Friction	Under Friction	% Drop
75	62.4	45.0	-27.8	58.8	45.2	-23.2
70	60.9	45.1	-26.0	57.2	45.0	-21.4
65	59.2	45.0	-23.9	55.6	45.1	-19.0
60	57.0	45.0	-21.1	53.7	45.1	-16.0
55	54.3	45.1	-16.9	51.2	45.0	-12.1

This data show that drivers in a Continuous Access Managed lane are more likely to expect a vehicle from the adjacent congested GP lane to enter the HOV lane compared to that of a driver in a Buffer-1 Managed Lane. The comparative advantages of Continuous Access and Buffer-1 MLs call for the creation of dynamically changing access points and access types for Managed Lane segments to address HOV lane degradation. Further studies need to be performed to estimate the traffic flow conditions in the Managed Lanes and the adjacent General Purpose lanes to dynamically determine the Managed Lane access type.

6.3.4 Limitations of HCM analysis for Managed Lanes

HCM analysis for Managed Lanes does not apply to ML facilities with design speeds greater than 75 mph or less than 45 mph and to HOV lane designs other than described in the manual. It also does not apply to Managed Lane segments which are over-saturated (LOS F). HCM also does not consider the spillback effect on Managed Lanes close to its termination point. Degradation analysis in these scenarios need to be studies using simulation and other techniques. HCM also does not study the driver behavior with respect to tolls charged for HOT lanes.

The results of the HCM analysis for HOV lanes needs to be validated for each type of Managed Lane segments using field data from PeMS. The HCM analysis indication of superior performance of Continuous Access Managed Lanes over Buffered Access HOV lanes under all conditions needs to be corroborated using simulation. Potential Costs and Benefits of converting Buffer-1 Managed Lanes to Continuous Access HOV lanes in terms of safety and reducing HOV lane degradation needs to be estimated. The effect of adding Passing lanes to Buffer-1 and Barrier-1 ML segments to mitigate degradation due to slow-car following effect needs to be analyzed.

6.4 Conclusions from HCM-based Analysis

The HCM analysis for Managed Lanes was drafted as a supplementary chapter to Highway Capacity Manual 2010 Volume 4. It defined separate operational characteristics for each type of Managed Lane segment. The results indicated a variation in the cut-off flowrates beyond which each type of ML segment enters degradation. The results also indicated a superiority of Continuous Access Managed Lanes over Buffer-1 Managed Lanes in terms of maximum flow rates and speeds. This, along with a high degree of interdependence between HOV lanes and adjoining GP lanes, calls for the need to define specific HOV degradation standards based on the type of HOV lane and in relation to the performance of adjoining GP lanes. Further analysis needs to be done to corroborate the results of the HCM analysis and evaluate the effects of removing the restrictive access to Buffer-1 HOV lanes on degradation.

7 Policy Considerations

7.2 Exempting Zero Emission vehicles

In 2005, 85000 Yellow stickers were initially issued, that allowed Single Occupancy Hybrid Vehicles access to HOV lanes. In 2011 the exemption for hybrid vehicles were discontinued as it was found that hybrid vehicles accounted for as much as 15% of peak hour HOV lane volume in many stretches in California [FHWA, 2014]. Currently, White stickers are issued to Zero-Emission vehicles and Green stickers to Plug-in hybrid vehicles. In September 2016, the cap of 85000 on Green Stickers was removed. Currently, California and Virginia are the only states in the nation that have discontinued the exemption for hybrid vehicles, with the underlying assumption that they are linked to HOV degradation.

Vehicles with Green and White stickers are allowed to use HOV lanes state-wide, however, the exemption policy on HOT lanes and Express lanes varies from case to case, as described below:

1. SR-91 Express Lanes: HOT 3+, Motorcycles and Pure Zero Emission Vehicles (White Sticker: 100% Electric and Hydrogen fuel cell vehicles) free access except in EB direction 4 pm-6 pm weekdays where they get a 50% discount.

2. Metro Express Lanes (LA): I-110: Toll free for HOV 2+, Motorcycles, Zero Emission Vehicles (White stickers) and Plug-in vehicles (Green Stickers)

- I-10: Toll free for HOV 3+, Motor-cycles, Zero Emission and Plug-in hybrids. HOV 2 pays a toll during peak hours.
- Zero Emission Vehicles set FasTrack switch to 3+ and hence there is no way to differentiate between actual HOV3+ and ZEVs from the transponder data.

3. Express Lane on I-15 in San Diego: No tolls for HOV2+, Motorcycles, Green and White Sticker Zero emission vehicles.

4. I-680 and I-880 Express Lanes Bay Area: Toll free for HOV 2+, Motorcycles and Green and White Sticker low emission vehicles. (Source of Data: Respective corridor websites).

It is interesting to note that in Express Lanes with dynamic pricing, when the average speed on HOV lanes falls below 45mph, SOV vehicles are not allowed, however Clean Energy Vehicles and Motorcycles are still allowed access.

Bento et al. [2014] analyzed the effect of the initial Clean Air Vehicle Sticker policy (2005-2011) on HOV lanes in District 7 (Greater LA region). The study focused on social welfare metrics and found that the social cost of allowing Single Occupant Low emission vehicles in HOV lanes far outweighed the social benefits of incentivizing the purchase of low emission vehicles. The volume of traffic on HOV lanes was found to be 30% more than social optimum. The marginal social cost imposed on a carpooler with the entry of a low emission vehicle on the HOV lane was found to vary over space and time. The study concludes by recommending that low emission vehicles not be allowed to use HOV lanes when congestion on HOV lanes is not priced. The study was conducted on the I-10 W HOV lane in LA. However, it was limited in scope as there were no field test validations to confirm the actual number of low-emission vehicles using the facility. The study also did not analyze the effect of the new policy which came to effect from 2012, but stated that since there was no cap on stickers issued under the new policy, congestion was likely to increase.

To our current knowledge, there is no study linking Zero Emission and Low-emission vehicles with HOV lane degradation. So far, more Green and White vehicle stickers have been issued compared to the number of Yellow stickers that were issued to Hybrid vehicles prior to 2011 (and then discontinued, because they were found to degrade HOV lanes). So, the decision to exempt ZEV and Low Emission Vehicles (LEV), while discontinuing the same exemption for regular Hybrid vehicles, can only be justified if the aim of the policy is to incentivize only ZEV and LEV purchase. Data on usage of HOV lanes by ZEV and LEV is not available.

Tal et al. [2013] reported that the HOV exemption program was a significant driver in the Plug-in hybrid vehicle purchase decision by consumers, with as much as 35% of buyers of certain car models citing the HOV lane access sticker program as the primary reason for purchase. Nearly 95% of consumers who purchased these vehicles applied for Clean Air Stickers, and 58% of these people intended to use these vehicles for their daily commute. The average commute length on HOV lanes by consumers incentivized by the HOV lane access program was found to be higher for Plug-in Hybrid Electric Vehicles (Green Stickers) like Plug-in Prius and Volt, compared to fully electric vehicles like Leaf.

The authors discovered that people who use Plug-in Hybrid Vehicles for daily commutes charge their vehicles for shorter duration, but when traveling on HOV lanes, preferred to change the mode of their cars from electric to fossil fuel. The study recommended that stickers and HOV access privileges should be based on battery range of the Plug-in Hybrid, and with some consideration towards actual electric Vehicles Miles Travelled (eVMT), rather than just VMT.

7.2 HOV Operator Survey

In the absence of crucial data relating to HOV performance, vehicular composition, and HOV access geometry, we find it necessary to survey HOV operators across the state to gain insight from their experiences in the field. Most surveys conducted in-state and across the country follow broad lines of inquiry, such as:

1. What are their stated HOV system goals
2. Whether system performance is measured, and if so, what data are collected
3. Whether their HOV system meets their stated objectives
4. Whether they plan to revise their goals in light of new data, and/or policies
5. What operational policy changes have been applied to better meet stated goals

6. If any operational policy changes have been applied, what conditions/data motivated those changes
7. How easy/difficult is it to apply new policy changes in terms of execution. enforcement, public approval, and cost.

7.3 HOV Lane Violation Enforcement

Currently available HOV violation data collected by California Highway Patrol (CHP) are sparse and on their own do not provide a strong basis to make inferences, since checks are done randomly at a few locations on certain days. However, operator surveys make it abundantly clear that they consider lane violations to be significant. State-wide HOV lane violations are up from 10,000 in 2010 to 52,000 in 2015. [CHP, 2017]. Nine counties in Northern California account for nearly half of the total state-wide HOV lane violations in 2015 with violations in some HOV stretches accounting for a staggering 41% of vehicular traffic.

Continual HOV violations reduce the efficiency of HOV and HOT facilities, and lead to lost revenues for transportation agencies. Furthermore, violations erode the public's trust in the efficacy of HOV/HOT to mitigate traffic congestion and encourage carpooling. Thus, effective enforcement is critical to the successful operation of these facilities.

Violation Enforcement System (VES) employed by Express Lanes in California and other agencies throughout the country can only detect violations where the vehicle doesn't have a transponder. It is not capable of detecting vehicle occupancy violations, which account for the majority of HOV violations in the state. Manual enforcement via CHP is still the only enforcement mechanism in place for occupancy violations. While CHP enforcement does yield dividends in terms of dramatically reduced violations, manual enforcement can be costly, and in some cases hazardous for enforcing officers. Additionally, manual enforcement will be difficult to execute in the future, as more complex and real-time lane-access policies are deployed on HOV/HOT facilities. Therefore, there is a need to explore the potential of automated vehicle occupancy verification technologies. Research on Automated Vehicle Occupancy Verification (AVOV) is broadly divided into:

1. Roadside systems:
    - Video
    - Passive Microwave
    - Infrared (most promising, with successful field tests)
2. In-vehicle systems developed with airbag deployment systems
    - Weight sensors,
    - Electric field sensors
    - Optical or near infrared

Note that information transmitted by in-vehicle systems to a roadside reader may pose legal challenges, but with the connected-vehicles concept that has gained much support over the last few years, this issue may not be critical. One significant impediment to relying solely on in-vehicle technologies is that it takes approximately 20 years for newer technologies to fully penetrate car fleets in the US.

With many HOV/HOT strategies explicitly distinguishing between HOV2+ and HOV3+ vehicles, there is an urgent need for automatic identification of *back-seat passengers* in the future. This has proven to be a difficult research to undertake, with many state-of-the-art image-processing algorithms proving to be unreliable outside of controlled environments. To our knowledge, there is one commercial product introduced by Xerox corporation in 2014 that purports to be almost 99% accurate for HOV2 lanes, and 95% for HOV3 lanes. It is unclear if their system has been operational in the field, but if their detection rates are as accurate as claimed, it would be far beyond what any current system has been able to accomplish.

Until in-vehicle technologies mature, however, HOV lane enforcement is expected to be a combination of manual and automatic enforcement, with consideration also given towards self-reporting enforcement strategies.

8 Impacts of Access Control Conversion of Performance: A Case Study

This section describes the pre-and-post comparison of the performance of an HOV facility (the SR-55 freeway in Orange County) with significant degradation, on which the access type was converted from limited to continuous. The comparison uses a Tobit regression analysis, an incentive/disincentive analysis, and a time savings analysis. The study considers the performance in multiple years before and after the conversion, as well. The modeling dataset contained data from the California PeMS (Performance Measurement System) and new data on geometry variables which were manually collected on the two access-control configurations.

8.1 Study Area

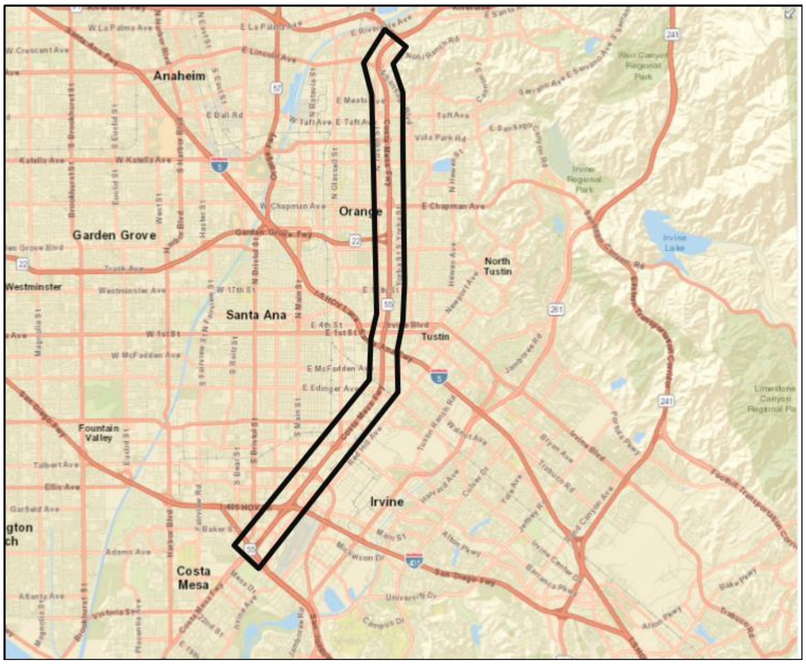


Figure 8.1. State Route 55 (Costa Mesa Freeway)

The SR-55, named the Costa Mesa freeway, starts at Highway 1 in Newport Beach and ends at an East West freeway, the SR91. It is 17.807 miles in length and acts as a North-South corridor traversing Orange County, California. SR-55 is also the first route that got an HOV facility in Orange County, in 1985. The black boundary on Figure 8.1. shows the location of the carpool facilities on SR-55. From the objective points, the pre-and-post analysis was conducted to quantify the degradation of HOV lanes. This location was selected because there were changes made in the configuration of HOV lanes from limited access carpool lanes to continuous access carpool lanes in the recent past. Unlike some researchers who try to measure the effect of limited and continuous carpool lanes from different locations, this study was conducted to illustrate the outcomes at the same location, to compare the before and after performance of the different types of HOV lane access schemes.

8.2 Data Collection

The primary data source for this thesis study is the California Performance Measurement System (PeMS) that first began operating in 2001 and receives data from the data centers of all twelve districts (Chen, Varaiya, and Kwon 2005). The PeMS website is a user-friendly interface tool which stores the real-time data and historical data from all the detectors along the freeway system in California. The abundant amount of data from PeMS is useful for researchers to build analysis models to test their assumptions or for practitioners who are interested in collecting information, visualizing them to make data more meaningful such as through graphical forms, or exploring traffic data for analysis in numerous ways.

In this research, the 5-minute data that obtained from Data Clearinghouse tools provided performance variables such as speed, flow, or vehicle miles traveled (VMT) for each lane at a specific location of each vehicle detector sensor (VDS). For the variables, there are 44 attributes of the physical characteristics of the freeway which can be acquired from the Change-log section. Furthermore, information on different access types, which was manually collected and incorporated into an ArcGIS platform by the HOV research group at the University of California, Irvine (Jayakrishnan, 2017), were also added to the dataset as variables.

Since the data came from various sources, data fusion is necessary for building the dataset. VDS (Vehicle Detector Station) ID is the key to match all the datasets together. The speed on the regular lane was assumed to have effects on the HOV lane. Thus, the VDS ID Match list which contains the VDS of HOV lanes and their corresponding mainline lane VDS is the essential item that is necessary to develop the relationship among these nearby sensors. To examine the degradation of HOV lanes on SR-55, a Tobit regression model analysis, an incentive/disincentive analysis, and a time saving analysis were conducted.

8.3 Pre-and-Post Analysis

8.3.1 Tobit Regression

$$y_i^* = x_i'\beta + \varepsilon_i$$

$$y_i = \begin{cases} a & \text{if } y_i^* < \mathrm{a} \\ y_i^* & \text{if } \mathrm{a} < y_i^* < \mathrm{b} \\ b & \text{if } y_{it}^* \geq \mathrm{b} \end{cases}$$

Where

i = 1,..., N indicates the individual

ε_i = error term

y_{it}^{*} = a latent variable

x_{it}' = independent variables

β = coefficient value

Tobit regression is used when the dependent variable has a fixed boundary whether it is the upper bound, lower bound or both (Tobin, 1952). The Tobit model will help decrease the bias of the estimator due to the concentration of the point censor the dependent variable has. In our case, our dependent variable distribution is not normally distributed but skews to the right. In other words, most of the data points are near the left censor. Since the normality assumption does not hold, multiple regression analysis may not be a proper choice. Under such a case, a Tobit model will help overcome the issue of a model bias. In terms of the model estimation method, Tobit regression uses a maximum likelihood estimator. As in standard linear regression, the intent is to predict the effect of independent variables on the outcome in terms of the dependent variable. Naturally, the significant variables are those that have more reliable influence on the dependent variable.

As the focus of our study is speed degradation on HOV lanes, the speed data during 8:00 am to 9:00 am and 5:00 pm to 6:00 pm were chosen as the AM-peak hour and PM-peak hour, respectively. Furthermore, the proportion of the speed data on HOV lanes from these two peak periods, which were below 45 mph, was utilized as the dependent variable. Though the Federal degradation standards are defined for the fraction of time that an HOV facility operates with speeds below 45 mph for a consecutive 180 day period, it was decided that the fraction of time during a 20 day period is sufficient to determine the factors influencing degradation. In the month-based modeling scheme, the denominator is 40, because there are always a minimum of 20 weekdays or 40 peak hours in one month.

$$\mathrm{Y} = \frac{\sum \text{number of peak period intervals which speed is less than 45 mph}}{\text{Total Time Interval (40)}}$$

From the parameters in the model, some of the independent variables which may have a

dominant observed value was excluded. For example, the design speed limit is 70 miles per hour along this freeway. This is because these kinds of variables will lead to singularity issues in the model estimation process. The well-known Akaike Information Criterion (AIC) was used to select between candidate models.

$$AIC = 2k - 2\ln(L)$$

Where

K = number of independent variables

L = log likelihood

Table 14: Independent Variables Used in the Model

No.	Variables	Definition
1	Road width	The width of the road
2	Lane width	The width of the lane
3	Inner Shoulder Width	The space between median and rightmost lane
4	Outer shoulder width	The space from rightmost lane to the edge of road width
5	Inner Median Width	The width of the median
6	Access1	HOV access type I (1: Continuous Access, 2: Limited Access)
7	Limited	Limited Access Type (0: Continuous Access, 1: Buffered, 2: Barrier, 3: Direct Connector)
8	Buffer	Buffer Type (0: Continuous Access, 1: Two-Yellow-Solid, 2: One-white-solid, 3: Wide Buffer)
9	Access2	HOV access type II (0: 1 lane, 1: Continuous Access, 2: Limited Access)
10	Prop_NML_45	Proportion of time periods when the Nearest Mainline Lane Speed was below 45mph
11	Prop_NML_55	Proportion of time periods when the Nearest Mainline Lane Speed was below 55mph
12	Prop_NML_65	Proportion of time periods when the Nearest Mainline Lane Speed was below 65mph

13	Prop_AML_45	Proportion of time periods when the Average Mainline Lane Speed was below 45mph
14	Prop_AML_55	Proportion of time periods when the Average Mainline Lane Speed was below 55mph
15	Prop_AML_65	Proportion of time periods when the Average Mainline Lane Speed was below 65mph
16	HOVDisToOffR	Distance from the Vehicle Detector Sensor to the nearest off-ramp

Table 15: Statistics on the Variables Used in Model

Variable	Mean	Standard Deviation	Min	Q1	Q3	Max
Proportion_Degradation	0.193	0.198	0	0	0.4	0.55
Road width	51.000	10.148	44	44	56	76
Lane width	11.450	0.618	11	11	12	12.70
Inner Shoulder Width	3.182	2.641	2	2	2	13
Outer shoulder width	8.382	3.601	2	8	10	22
Inner Median Width	9.545	5.430	6	6	14	22
Access1	1.518	0.502	1	1	2	2
Limited	0.518	0.502	0	0	1	1
Buffer	1.064	1.043	0	0	2	3
Access2	1.009	0.991	0	1	2	2
Prop_NML_45	0.280	0.220	0	0.03125	0.45	0.8
Prop_NML_55	0.346	0.240	0	0.1	0.5	0.8750
Prop_NML_65	0.503	0.261	0	0.3312	0.6937	1
Prop_AML_45	0.300	0.224	0	0.03125	0.475	0.825

Variable	Mean	Standard Deviation	Min	Q1	Q3	Max
Prop_AML_55	0.371	0.241	0	0.1812	0.5	0.9250
Prop_AML_65	0.711	0.269	0	0.525	0.9437	1
HOVDisToOffR	0.551	0.595	0	0	0.85	1.9

8.3.2 Tobit Panel Data Model

The Tobit model in the previous section considers the cross-sectional data in three individual years. Panel data is the kind of dataset which has two dimensions: the individual aspect as cross-sectional data, and the time-dependent variations of them as the longitudinal data (Hsiao 2007). Thus, panel data has more variability and a larger degree of freedom than cross-sectional or time-series data alone (Wooldridge 2002). Panel data's structure helps control for the immeasurable effects of the individual objects, such as the heterogeneity of vehicle detector sensors in the study area.

Our dataset contains three different years, namely 2008, 2011 and 2017. To run a Tobit regression model with panel data, the three separated datasets were combined into a panel data form. We observed the data corresponding to the individual Vehicle Detector Sensor (VDS) over the relevant time periods. Then, Tobit regression model was run via the censReg package in the R programming software (Henningsen 2010). The Tobit Panel Data Model is described next.

$$y_{it}^* = x_{it}' + \varepsilon_{it} = x_{it}'\beta + \mu_i + \nu_{it}$$

$$y_{it} = \begin{cases} a & \text{if } y_{it}^* < a \\ y_{it}^* & \text{if } a < y_{it}^* < b \\ b & \text{if } y_{it}^* \geq b \end{cases}$$

Where

i = 1,..., N indicates the individual

t = 1,..., T_i indicates the time period

μ_i = time-invariant individual specific effect

ν_{it} = the remaining disturbance

y_{it}^* = a latent variable

x'_{it} = independent variables

β = coefficient value

8.3.3 Incentive/Disincentive Analysis

This analysis considered the case in which HOV lanes are degraded as per the Federal standard for HOV degradation, with a 45 mile per hour threshold, to see if there is a chance that the HOV lanes are still offering benefits compared to the regular lane. With this intention, the speed difference between the HOV lanes and the regular lanes was computed as the incentive, in the case that the HOV lane speed is higher than the regular lane speed. In contrast, the result will be a disincentive in the opposite case. As for the speed-difference dataset, five-minute speed data during peak periods on the HOV lanes and the corresponding General Purpose lanes are considered. After that, the process of cleaning and setting up the data involved importing the stations' five-minute speed data from the Data Clearinghouse on PeMS, filtering only morning and evening peak periods. This created two variables, an average mainline lane speed difference (AML_D) and the nearest mainline lane speed difference (NML_D) which are used to compare and visualize the level of the speed difference shown by the dataset.

Then, the study on HOV lanes' degraded portions are performed to see the speed difference between HOV lanes and mainline lanes in both of the nearest mainline lanes and average mainline lane cases. So, NML_D is the variable for the speed difference between HOV Speed and Nearest Mainline Lane Speed (NML_D = HOV lane speed − NML lane speed) and AML_D is the variable for the speed difference between HOV Speed and Average Mainline Lane Speed (AML_D = HOV lane speed- AML lane speed).

The incentive of using HOV lanes is when NML_D and AML_D have positive values, which means that the speed in the HOV lane is higher than the comparable mainline lanes. In contrast, the negative value represents the disincentive that the users experience. The graphs in the next chapter illustrate the levels of incentive and disincentive for each dataset.

The datasets included the February speed data from five years (2008, 2011, 2013, 2015 and 2017) on the SR-55 freeway. As per the plans for HOV configuration changes from limited access in the year 2008 to fully continuous access in the year 2011, Caltrans converted the northern part of SR-55 from 17th Street to the Junction of SR91 around July 2008. After that, they replaced the rest of the limited access carpool lane with continuous access around May 2011. The remaining datasets from the year 2013, the year 2015 and year 2017 are used to help capture the trend of incentives and disincentives on the carpool lanes.

Table 16: Access-control Conversion Dates for the HOV facility on SR-55

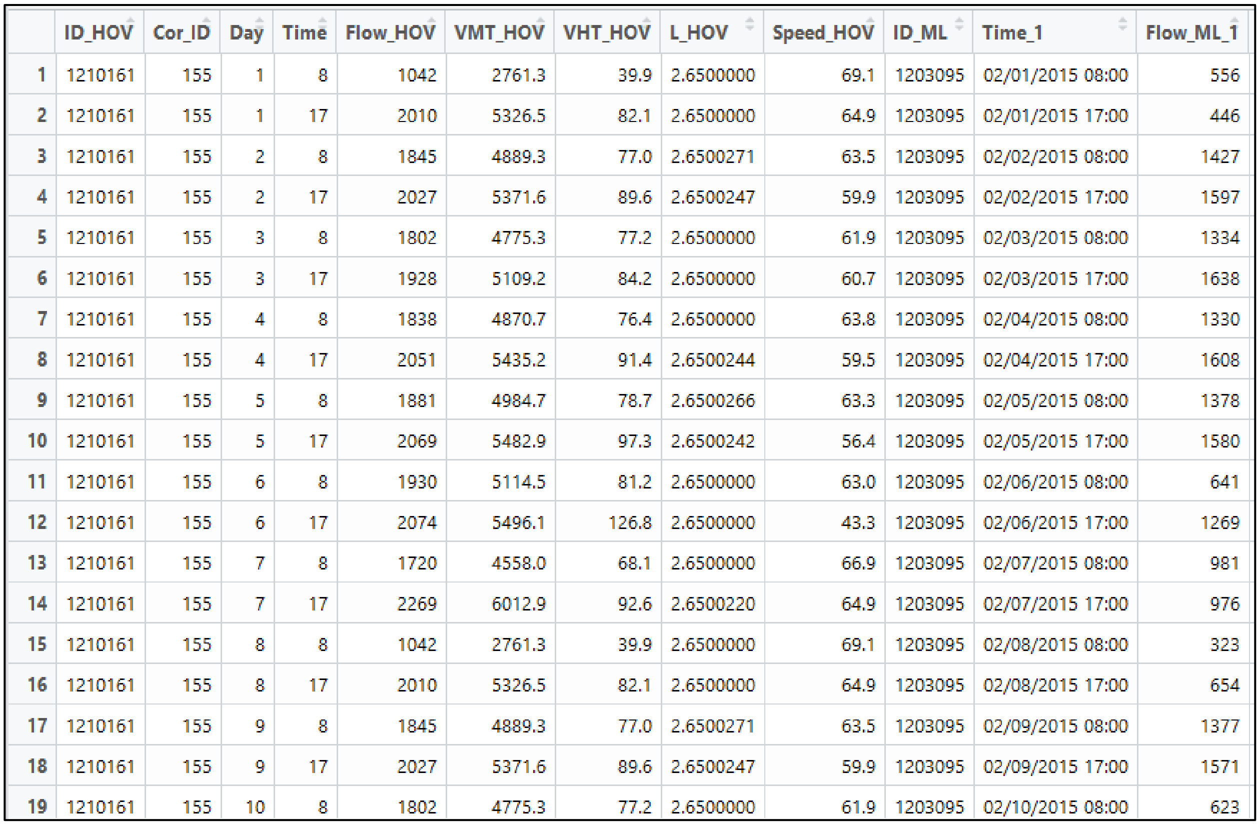
Conversion period	From	To	Start	End	Comments
July 2008	17th St.	Junction of SR-91	11.8	17.8	Convert HOV striping from buffer-separated to continuous access
	Junction of SR-91	17th St.	17.8	11.8	Convert HOV striping from buffer-separated to continuous access
May 2011	Paularino Ave.	17th St.	5.5	11.8	Convert HOV striping from buffer-separated to continuous access
	17th St.	Paularino Ave.	11.8	5.5	Convert HOV striping from buffer-separated to continuous access

Source: Statewide HOV Lane Inventory Report (January 2017)

8.3.4 Time Saving for Degraded HOV Lanes

The time savings for degraded HOV lanes is the variable that shows how much time the users can save when they use these facilities compared to the adjacent regular lane. Also, the results can explain the performance of carpool lanes in the particular year, and help draw clearer conclusions on the contrast between continuous-access carpool lanes and limited-access carpool lanes. Similar to the incentive/disincentive analysis, the amount of time saved are calculated using the performance data from PeMS in February for five years, namely 2008, 2011, 2013, 2015, and 2017. Note that the time savings in this analysis are measured with respect to the nearest General Purpose lane.

Table 17: Dataset Snapshot for Time Saving Analysis



	ID_HOV	Cor_ID	Day	Time	Flow_HOV	VMT_HOV	VHT_HOV	L_HOV	Speed_HOV	ID_ML	Time_1	Flow_ML_1
1	1210161	155	1	8	1042	2761.3	39.9	2.6500000	69.1	1203095	02/01/2015 08:00	556
2	1210161	155	1	17	2010	5326.5	82.1	2.6500000	64.9	1203095	02/01/2015 17:00	446
3	1210161	155	2	8	1845	4889.3	77.0	2.6500271	63.5	1203095	02/02/2015 08:00	1427
4	1210161	155	2	17	2027	5371.6	89.6	2.6500247	59.9	1203095	02/02/2015 17:00	1597
5	1210161	155	3	8	1802	4775.3	77.2	2.6500000	61.9	1203095	02/03/2015 08:00	1334
6	1210161	155	3	17	1928	5109.2	84.2	2.6500000	60.7	1203095	02/03/2015 17:00	1638
7	1210161	155	4	8	1838	4870.7	76.4	2.6500000	63.8	1203095	02/04/2015 08:00	1330
8	1210161	155	4	17	2051	5435.2	91.4	2.6500244	59.5	1203095	02/04/2015 17:00	1608
9	1210161	155	5	8	1881	4984.7	78.7	2.6500266	63.3	1203095	02/05/2015 08:00	1378
10	1210161	155	5	17	2069	5482.9	97.3	2.6500242	56.4	1203095	02/05/2015 17:00	1580
11	1210161	155	6	8	1930	5114.5	81.2	2.6500000	63.0	1203095	02/06/2015 08:00	641
12	1210161	155	6	17	2074	5496.1	126.8	2.6500000	43.3	1203095	02/06/2015 17:00	1269
13	1210161	155	7	8	1720	4558.0	68.1	2.6500000	66.9	1203095	02/07/2015 08:00	981
14	1210161	155	7	17	2269	6012.9	92.6	2.6500220	64.9	1203095	02/07/2015 17:00	976
15	1210161	155	8	8	1042	2761.3	39.9	2.6500000	69.1	1203095	02/08/2015 08:00	323
16	1210161	155	8	17	2010	5326.5	82.1	2.6500000	64.9	1203095	02/08/2015 17:00	654
17	1210161	155	9	8	1845	4889.3	77.0	2.6500271	63.5	1203095	02/09/2015 08:00	1377
18	1210161	155	9	17	2027	5371.6	89.6	2.6500247	59.9	1203095	02/09/2015 17:00	1571
19	1210161	155	10	8	1802	4775.3	77.2	2.6500000	61.9	1203095	02/10/2015 08:00	623

The dataset for this analysis, a snapshot of which is shown in Table 4, is acquired from PeMS (California Performance Management System). Along with this, the HOV research group created the corridor match list to group several VDS into one corridor stretch. As per the dataset, each vehicle detector sensors (VDS) in the ID_HOV column in the dataset has 40 data points which refer to 40 peak-hour periods on the weekdays in February. Apart from the speed in each type of lane, the Vehicle Miles Traveled (VMT) and Vehicle Hours Traveled (VHT) are included in this dataset, so as to calculate the corridor speed. In addition, the traffic flow at each detector station is included in the dataset as an essential factor in estimating the time saving variables for each VDS station.

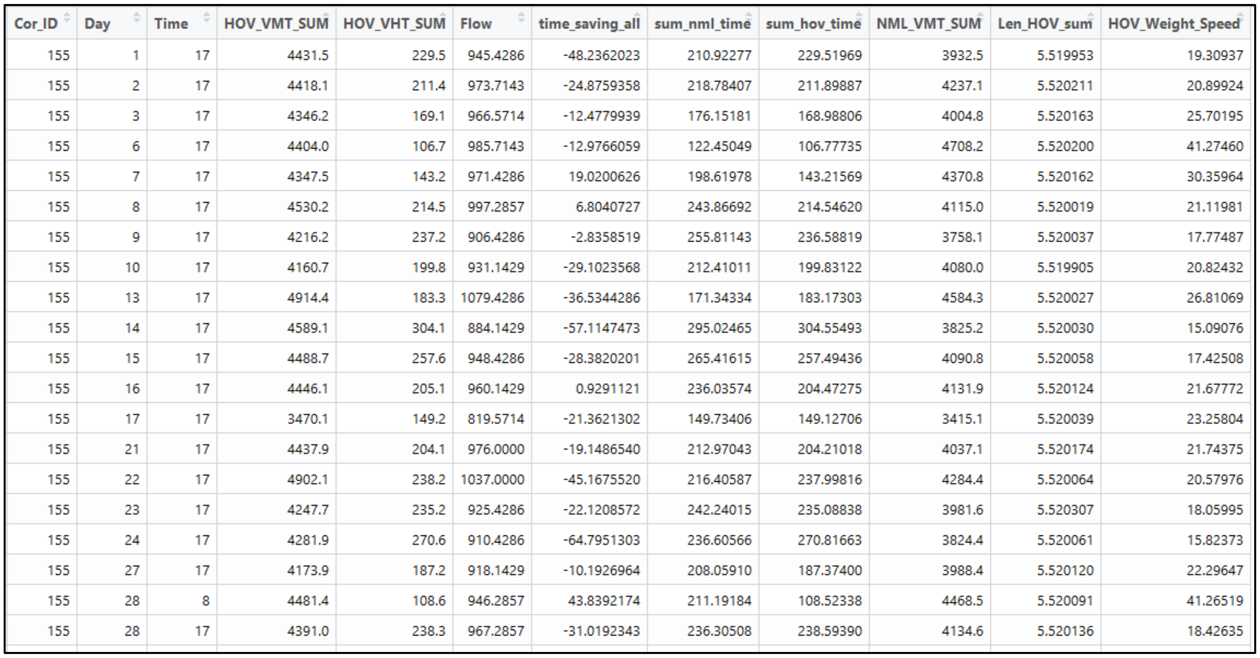
The incentive/disincentive analysis only considers the Vehicle Detector Sensor (VDS) data points to compare the speed-difference between the HOV lanes and General Purpose lanes. If done in that manner, the overall time saving values can be biased because the lengths between detector stations are not identical. The long stretches will automatically have more detectors and will capture more flow than the shorter stretches. To reduce this problem, several VDS were grouped into one corridor, with the corridors being similar in their lengths and the number of associated VDSs. Several variables were defined for the modeling analysis as shown next.

Table 18: Variables used in the Time Savings Analysis

Variables	Expression
HOV_time	$\frac{\text{Length of each VDS on the HOV lane}}{\text{the HOV lane speed}}$
NML_time	$\frac{\text{Length of each VDS on the HOV lane}}{\text{the nearest mainline lane speed}}$
Total time saving	(NML_time – HOV_time)* Flow_HOV
Regular Lane Travel Time	(NML_time)* Flow_ML_1
Corridor_Speed	$\frac{\text{Corridor\_VMT}}{\text{Corridor\_VHT}}$
L_HOV	The length of the HOV lane
L_ML_1	The length of the mainline lane VDS

To begin the calculation process, the HOV_time, NML_time, and Total time savings for each VDS are introduced. After that, every VDS which is in the same corridor is pooled together with the specific date and peak hour period. At the same time, the VMT_HOV, VHT_HOV, Total time saving, and detector length are summed up.

Table 19: Corridor Data for Time Saving Analysis (Example)



Cor_ID	Day	Time	HOV_VMT_SUM	HOV_VHT_SUM	Flow	time_saving_all	sum_nml_time	sum_hov_time	NML_VMT_SUM	Len_HOV_sum	HOV_Weight_Speed
155	1	17	4431.5	229.5	945.4286	-48.2362023	210.92277	229.51969	3932.5	5.519953	19.30937
155	2	17	4418.1	211.4	973.7143	-24.8759358	218.78407	211.89887	4237.1	5.520211	20.89924
155	3	17	4346.2	169.1	966.5714	-12.4779939	176.15181	168.98806	4004.8	5.520163	25.70195
155	6	17	4404.0	106.7	985.7143	-12.9766059	122.45049	106.77735	4708.2	5.520200	41.27460
155	7	17	4347.5	143.2	971.4286	19.0200626	198.61978	143.21569	4370.8	5.520162	30.35964
155	8	17	4530.2	214.5	997.2857	6.8040727	243.86692	214.54620	4115.0	5.520019	21.11981
155	9	17	4216.2	237.2	906.4286	-2.8358519	255.81143	236.58819	3758.1	5.520037	17.77487
155	10	17	4160.7	199.8	931.1429	-29.1023568	212.41011	199.83122	4080.0	5.519905	20.82432
155	13	17	4914.4	183.3	1079.4286	-36.5344286	171.34334	183.17303	4584.3	5.520027	26.81069
155	14	17	4589.1	304.1	884.1429	-57.1147473	295.02465	304.55493	3825.2	5.520030	15.09076
155	15	17	4488.7	257.6	948.4286	-28.3820201	265.41615	257.49436	4090.8	5.520058	17.42508
155	16	17	4446.1	205.1	960.1429	0.9291121	236.03574	204.47275	4131.9	5.520124	21.67772
155	17	17	3470.1	149.2	819.5714	-21.3621302	149.73406	149.12706	3415.1	5.520039	23.25804
155	21	17	4437.9	204.1	976.0000	-19.1486540	212.97043	204.21018	4037.1	5.520174	21.74375
155	22	17	4902.1	238.2	1037.0000	-45.1675520	216.40587	237.99816	4284.4	5.520064	20.57976
155	23	17	4247.7	235.2	925.4286	-22.1208572	242.24015	235.08838	3981.6	5.520307	18.05995
155	24	17	4281.9	270.6	910.4286	-64.7951303	236.60566	270.81663	3824.4	5.520061	15.82373
155	27	17	4173.9	187.2	918.1429	-10.1926964	208.05910	187.37400	3988.4	5.520120	22.29647
155	28	8	4481.4	108.6	946.2857	43.8392174	211.19184	108.52338	4468.5	5.520091	41.26519
155	28	17	4391.0	238.3	967.2857	-31.0192343	236.30508	238.59390	4134.6	5.520136	18.42635

As shown in table 6 for a sample corridor, each corridor (Cor_ID) can potentially have 40 rows that contained 40 peak periods of 20-weekday data points, out of which a filtering steps identifies the rows with the degraded condition (Corridor_Speed <45). Last, we sum all the HOV time savings and overall the nearest mainline lane travel time of different dates and times together. After that, the time saving per vehicle per mile is calculated by dividing the overall time savings by the overall VMT on the carpool lane. Similarly, dividing the total time spent on the nearest mainline lane by its total VMT produces the regular lane travel time per vehicle per mile. Then, we can calculate the HOV time saving with respect to regular lane travel time which will be shown in the next chapter. Moreover, the number of degraded days for each corridor were counted to define the degraded stretches both morning and evening peak hour along the SR-55.

8.4 Case Study Results

Based on the data sets and the model fundamentals shown in the last chapter, data analyses were conducted on data on the SR-55 freeway from before and after the conversion of access-control of HOV lanes from limited to continuous. This chapter describes the results, starting with the analysis of speeds to find the degradation status

The SR-55 has six corridors, three corridors each direction roughly delineated by four crossing freeways (I-405, I-5, SR-22 and SR-91), as defined by Caltrans. Degradation of carpool lanes on SR-55 depends on the on the time period and traffic direction. Figure 8.2. shows the degradation status of each corridor on SR-55 in the morning peak hour period, found based on the HOVs' inability to maintain speeds above 45 mph for 90% of the time (i.e, for 18 or more days out of 20 days that were considered). Note that this is based on the interpretation of the Federally mandated standard by FHWA and Caltrans, which effectively makes a corridor that has degraded conditions for any more than 10% of the days to be considered degraded. For the AM peak hour, the red highlighted line that involves two corridors is the degraded stretch (Southbound direction from SR91 to McFadden Avenue). The blue line is the non-degraded HOV stretches, which consist of three corridors in the northbound direction from I-405 to SR91, and one southbound stretch that is from McFadden Avenue to I-405.

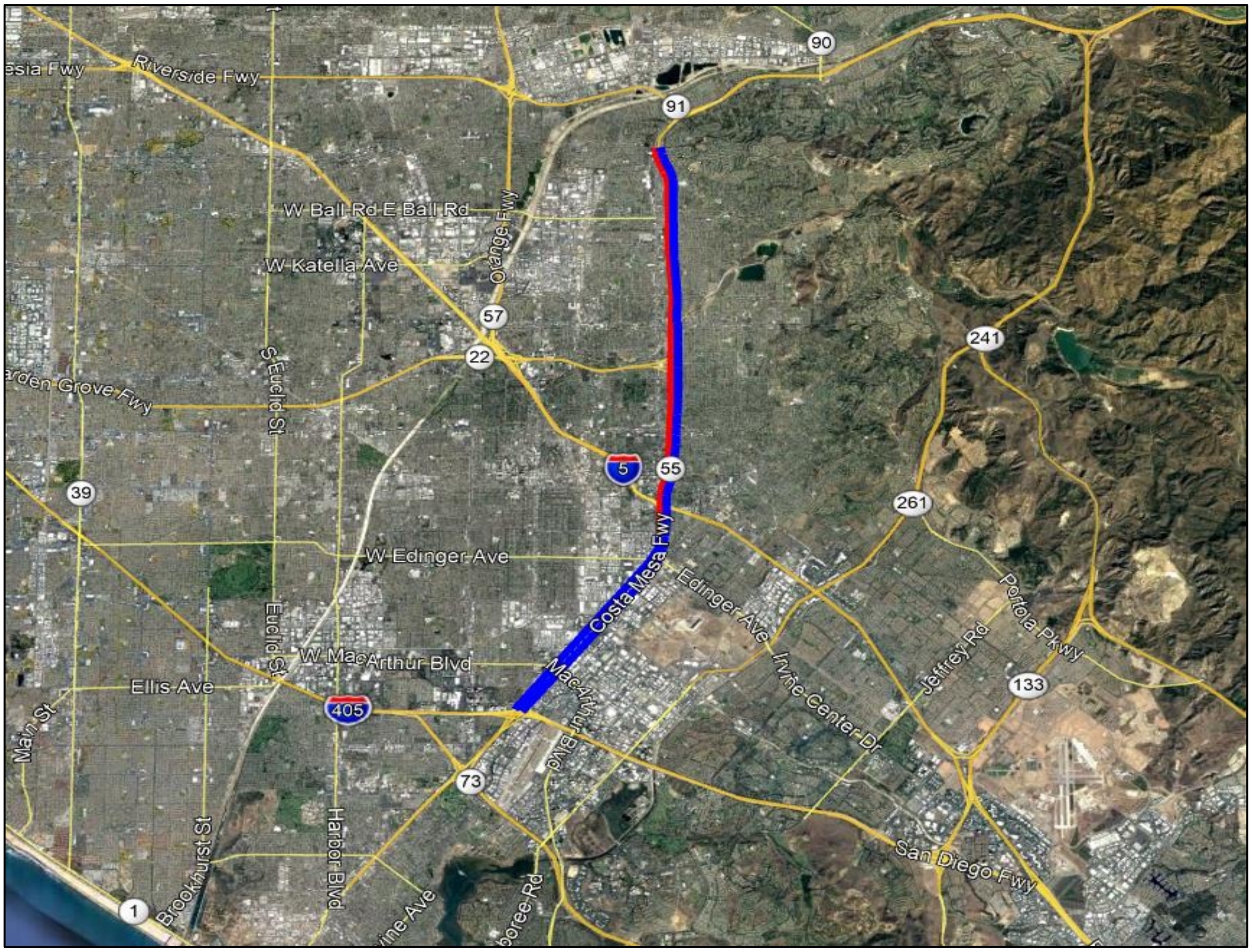


Figure 8.2 Degradation Status of SR-55 (AM peak Hour)

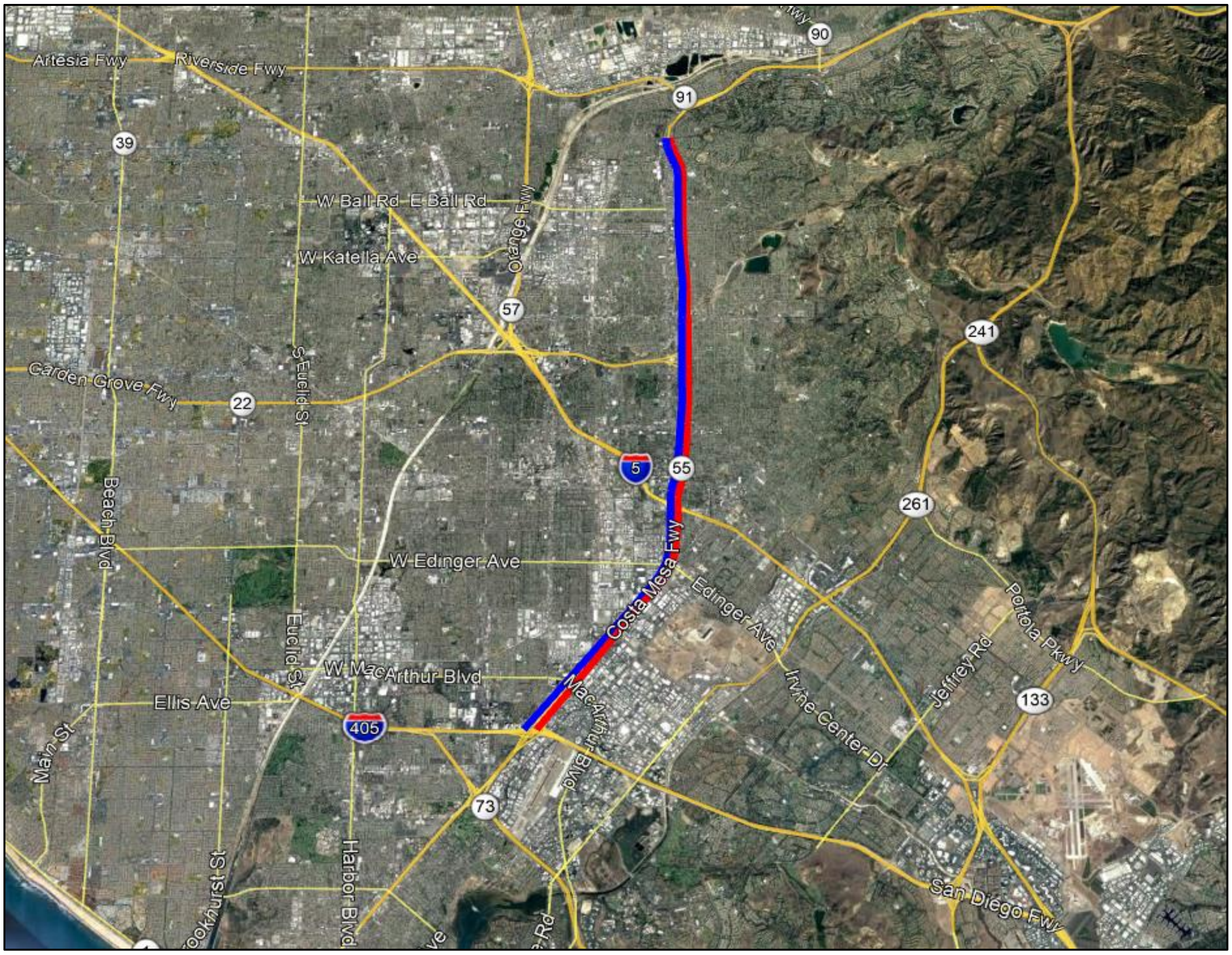
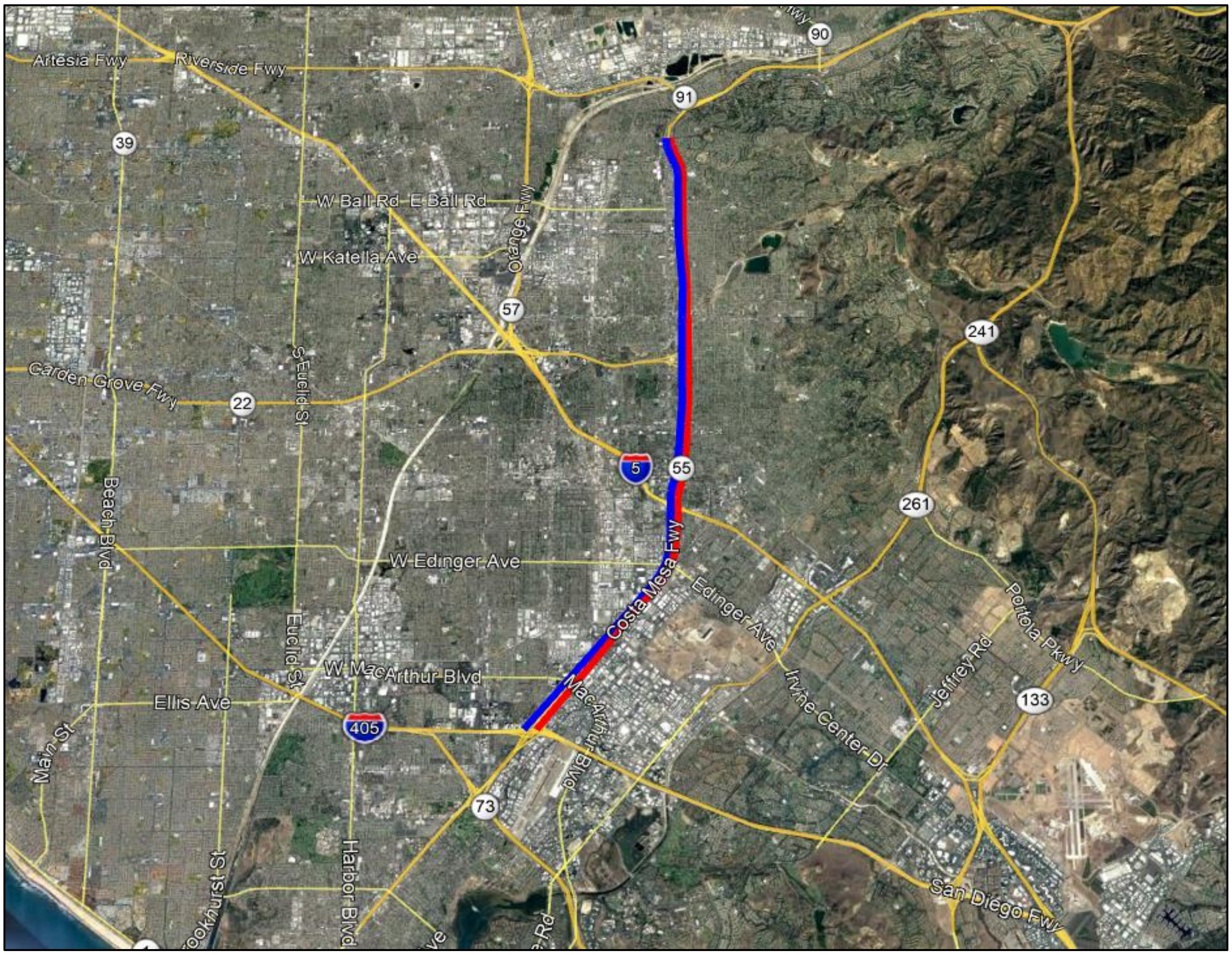


Figure 8.3. Degradation Status of SR-55 (PM Peak Hour)



As in Figure 8.3., the northbound HOV lanes of SR-55 from I-405 to SR-91 is the degraded stretches as shown in the red highlighted line. In contrast, the stretches in the southbound direction are not degraded in the evening peak hour. As a result, the degradation on SR-55 happens in both northbound and southbound direction. As action plans are often suggested on whether to add one more HOV lane, to add more General Purpose lanes, or to convert HOV lanes to HOT (High Occupany Toll) lanes, a careful analysis is needed on the current performance, and the changes before and after the access-control conversion, which is the focus of the remainder of this section.

8.5 Multiple Regression Model

The results obtained from the Tobit regression model are summarized in the following table.

Table 20: Tobit Regression Model Results

Explanatory Variables	2008 Model		2011 Model		2017 Model	
	Estimate	T-value	Estimate	T-value	Estimate	T-value
(Intercept)	-0.690	-0.848	-3.042	-2.154(*)	-1.639	-1.923(.)
Lane Width	0.054	0.7	0.286	2.154(*)	0.173	2.16(*)
Outer Shoulder Width	-0.001	-0.201	-0.018	-1.186	-0.013	-1.735(.)
Inner Shoulder Width	0.026	1.707(.)	0.019	0.847	0.008	0.549
Inner Median Width	-0.014	-1.548	-0.043	-2.767(**)	-0.019	-2.021(*)
PROPORTION_NML_45	0.886	6.163(***)	1.177	4.276(***)	0.566	4.337(***)

From the table we see that the 2008 Model (fully limited access) has two influential variables, as the stars or dots in the parentheses indicate the relative significance of the explanatory variable coefficients. Prop_NML_45 has a strong positive relationship with the response factor. Thus, the degradation of the carpool lane is likely to occur corresponding to the low speed conditions on the nearest mainline lane. For the inner shoulder width, the wider it is, the more the frequency of degradation on the HOV lane, which may appear to be a counter intuitive result; however, as explained next in the case of Lane widths, this could be due to other factors such as where the wider shoulder usually appear on the freeway stretches. The lane width was not of primary importance in the 2008 case, unlike in the latter cases with continuous access.

In terms of the 2011 Model, Lane Width, Inner Median Width, and Prop_NML_45 are the three significant variables. The positive coefficient of Lane Width implies more degradation happening where there is a wider roadway. That is, the stretches with wider a wider lane tend to have more degradation issues on HOV lanes. This is because many stretches which have a wider HOV lane are near the merging area of ramp or the direct HOV-to-HOV freeway connectors. One example is the northbound stretch after the I-405 HOV direct connector joins the SR-55 HOV lane. In addition, the nearest mainline lane and HOV lane under 45 mph behave in the same way in degraded conditions.

For 2017 Model, the Prop_NML_45 is still the most significant variable related to our response variable. So, the nearest mainline lane and HOV lane under 45 miles per hour perform in a similar way. In the case of Lane Width, the large lane causes more degradation on HOV lanes according to the positive value of the coefficient. The Outer Shoulder Width has a negative effect on the degraded proportion. As a result, the narrower the outer shoulder, the more the likelihood of degradation.

The regression results showed that the degradation proportion on HOV lanes has a significant relationship with the degradation proportion on the nearest mainline lane under 45 miles per hour (Prop_NML_45) for all the cases. However, the T-values decrease from before conversion (2008) to after conversion (2017).

Table 21: Tobit Model with Panel Data - Results

Variables	Estimate	Std.error	T-value	Pr(>t)	Significant Level
(Intercept)	-1.062	0.830	-1.28	0.201	
HOVLanes	-0.246	0.482	-0.511	0.609	
Access Type	-0.103	0.050	-2.053	0.040	*
Lane Width	0.137	0.062	2.19	0.028	*
Inner Shoulder Width	0.013	0.013	1.006	0.314	
Outer Shoulder Width	-0.007	0.007	-0.922	0.356	
Inner Median Width	-0.019	0.0067	-2.882	0.004	**
Proportion_NML_45	0.862	0.171	5.039	4.69E-07	***
logSigmaMu	-4.134	7.779	-0.532	0.595	
logSigmaNu	-1.765	0.108	-16.281	<2e-16	***

From the table, our Tobit model has four significant variables, Access Type, Lane Width, Inner Median Width and Proportion of time that the nearest mainline lane operates under 45 miles per hour (Prop_NML_45). Access Type has a negative relationship with the dependent variable which means that the limited access carpool lane seems to be less degraded than the continuous access carpool lane. Next, the wider lane width will lead to more degradation on the carpool lane, which appears to be counterintuitive. However, these places on SR-55 that have large lane width are mostly located near the merging or diverging area of the ramp. Regarding inner median width, the narrower inner median width caused more degradation to happen. Furthermore, the nearest mainline lane behaved in the same way as the HOV lane, which means when the nearest mainline lane was degraded, the speed in the parallel carpool lane was likely to be under 45 mph as well.

Table 22: Statewide Regression Model Results

VARIABLES	Pr(>|t|)	t value	Coefficient
Intercept	***	7.267	0.200
HOVLanes	***	-5.536	-0.133
Limited	*	2.374	0.019
Inner.shoulder.width	*	-2.164	-0.002
Inner.Median.Width		0.945	0.001
AMLPROP_45	***	12.526	0.424
NMLPROP_45	***	5.95	0.201
NMLPROP_65	**	-2.284	-0.042

The statewide regression model analsis was conducted by the HOV research group at the University of California, Irvine, at the same time as this thesis study. The researchers used the whole California region, which contains 6 districts where there are HOV facilities as the study area. Table 6 showed the regression model result at the statewide level, which used data from the PeMS in February 2017. As the regression results show, there are six variables which influence degradation proportion. Some of them are similar to the significant variables in the SR-55 model outcome. As an example, the adjacent HOV lane performs in the same way as the carpool facility. However, the limited access carpool causes more degradation on HOV lanes in the data for all of California. Then, this reverse result showed us that the degradation of the carpool lane could vary with respect to the specific locations. This is possibly because different locations may have distinct driving behavior and different operating characteristics in Northern California and Southern California.

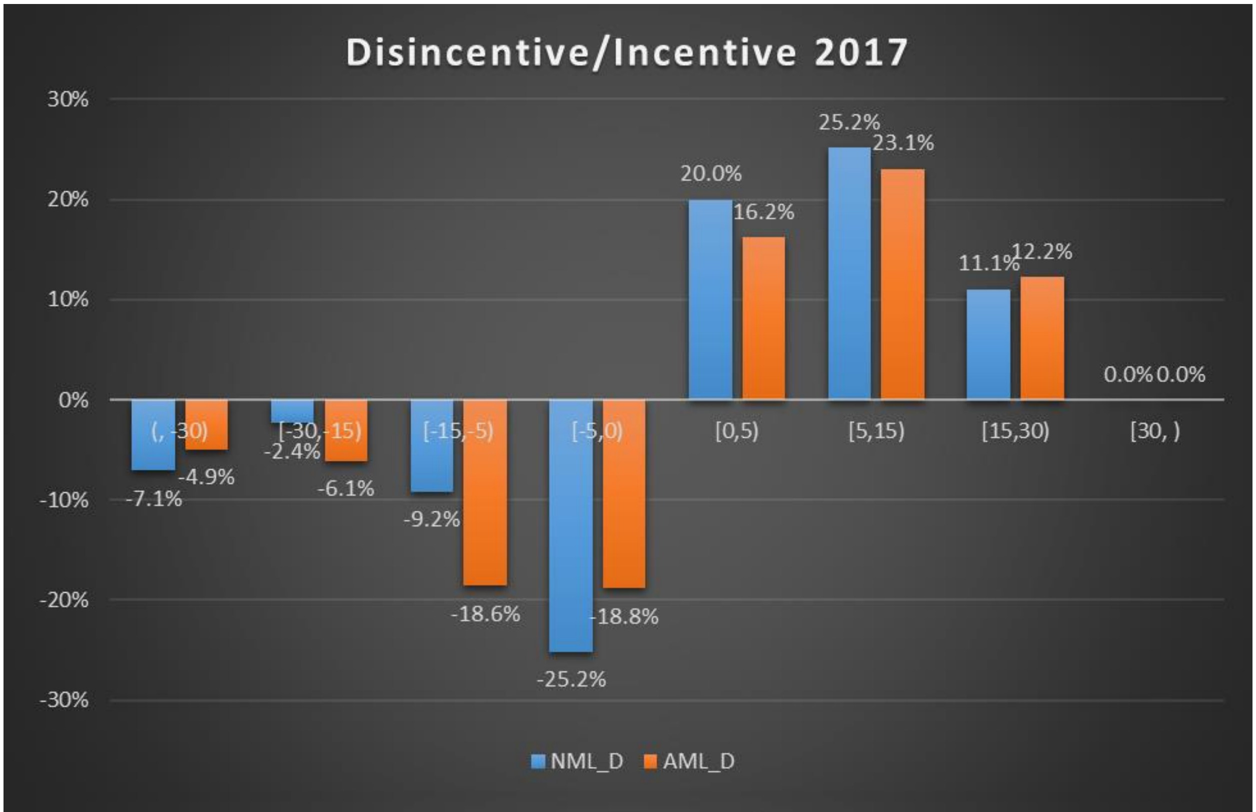
8.6 Incentive and Disincentive Analysis

The Federal standards for HOV degradation were set with a threshold at 45 miles per hour. This analysis will test the assumption that degraded HOV lanes on which the speeds drop below 45 miles per hour may still be offering incentives for HOV usage because their speeds are still greater compared to the General Purpose lanes, via an incentive and disincentive analysis.

The incentive and disincentive analysis is based on the speed difference measure. As can be seen in table 23, the level of incentive/disincentive is categorized by the magnitude of the speed difference in four levels, slight incentive/disincentive, normal incentive/disincentive, high incentive/disincentive and extreme incentive/disincentive. The analysis results are presented as histograms for the different cases. The blue bars in the graphs represent the differences between the HOV lane's speed and the nearest mainline lane's speed (NML_D). The orange bars show the differences between the HOV lane's speed and the average speed on the regular lanes (AML_D).

Table 23: Levels Selected for Incentives/Disincentives

Speed Difference(Mph)	Category
Less than 30	Extreme Disincentive
Between -30 and -15	High Disincentive
Between -15 and -5	Normal Disincentive
Between -5 and 0	Slight Disincentive
Between 0 and 5	Slight Incentive
Between 5 and 15	Normal Incentive
Between 15 and 30	High Incentive
More than 30	Extreme Incentive


Disincentive/Incentive 2017
30%
20%
10%
0%
-10%
-20%
-30%
(, -30)
[-30,-15)
[-15,-5)
[-5,0)
[0,5)
[5,15)
[15,30)
[30,)
-7.1%
-4.9%
-2.4%
-6.1%
-9.2%
-18.6%
-25.2%
-18.8%
20.0%
16.2%
25.2%
23.1%
11.1%
12.2%
0.0%
0.0%
NML_D
AML_D

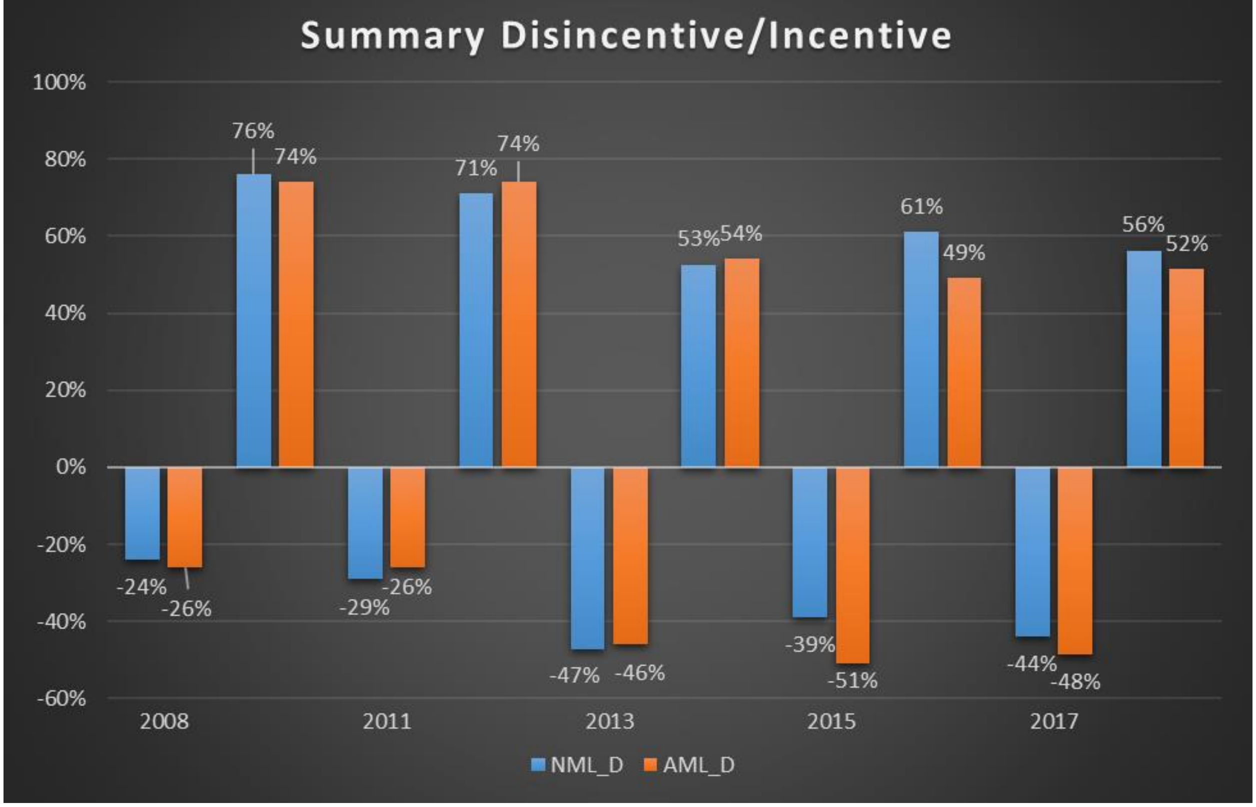

Summary Disincentive/Incentive
100%
80%
60%
40%
20%
0%
-20%
-40%
-60%
2008
2011
2013
2015
2017
-24%
-26%
76%
74%
-29%
-26%
71%
74%
-47%
-46%
53%
54%
-39%
-51%
61%
49%
-44%
-48%
56%
52%
NML_D
AML_D

Figure 8.5. show a summary of the incentive/disincentive results obtained for the year 2017, and for previous years.

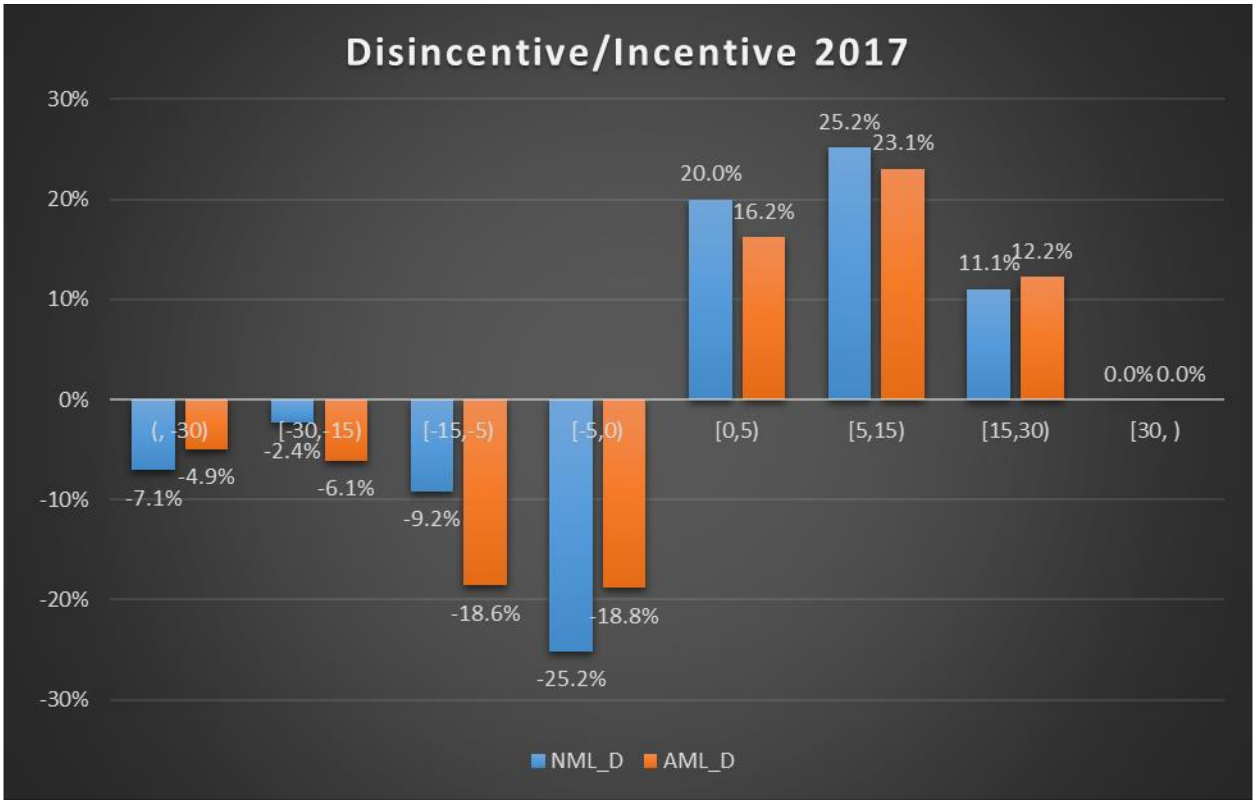


Figure 8.4.Percentage of Speed Difference in 2017

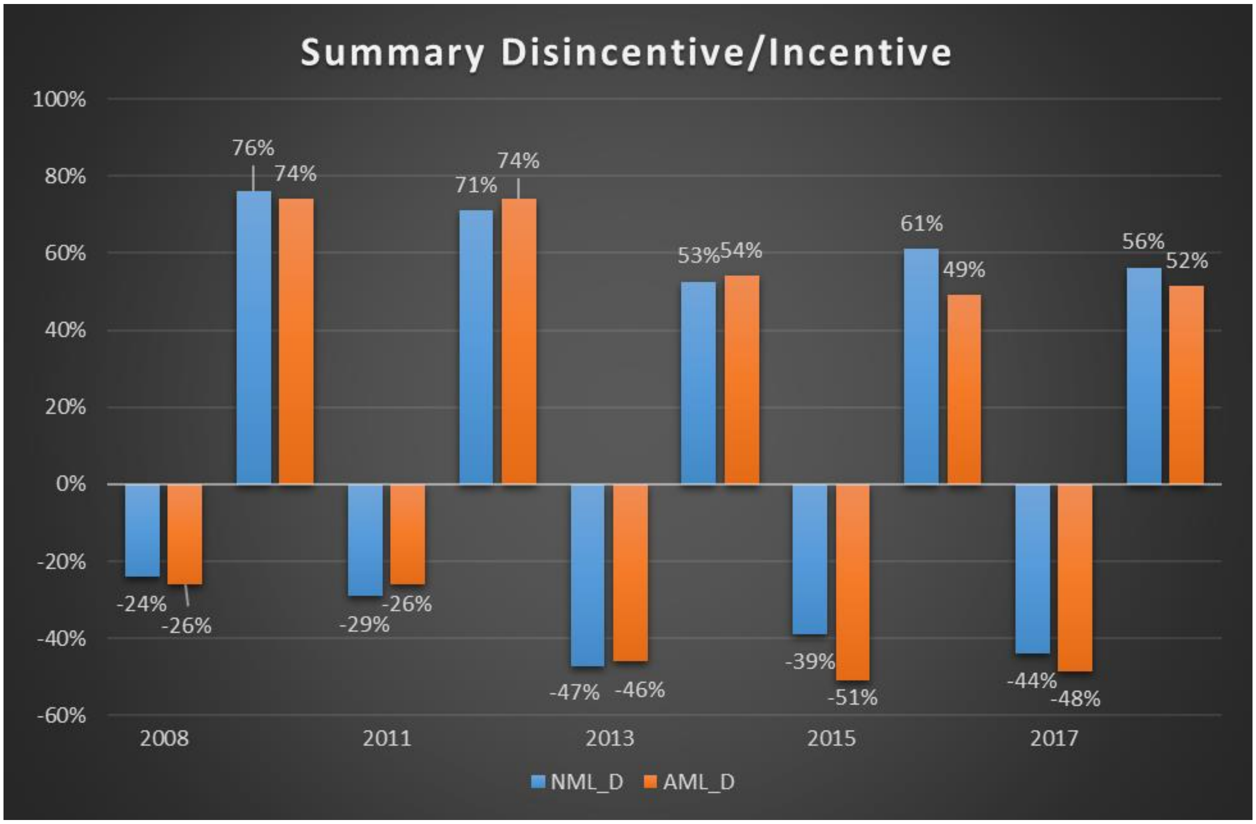


Figure 8.5. Summary of Percentage of Speed Difference

From the figures, we can see that the limited access carpool lane provided the highest incentive level according to the 2008 dataset. However, it can be affected by external factors such as economic conditions. When the northbound of SR-55 was converted to continuous access, the incentive decreased slightly. Then, the data from the year 2013 by when all the carpool lane stretches on this route had become continuous-access stretches showed a significant drop in the speed-difference incentives. The percentage of the incentive on the carpool lane along the SR-55 is in a downtrend, which implies that the speed of carpool lane in this route is now less attractive for people to use the facilities than earlier in 2008. Nonetheless, these degraded stretches still give incentives to the user in some periods of time until the year 2017.

In 2011, the SR-55 had two HOV configurations on the same route in different stretches, as explained before. Hence, it is the chance to evaluate the performance of both types of the carpool lane with the same study time period. For this purpose, the dataset was classified into two groups, the continuous access in the north part and limited access in the south part and tested via the incentive/disincentive analysis.

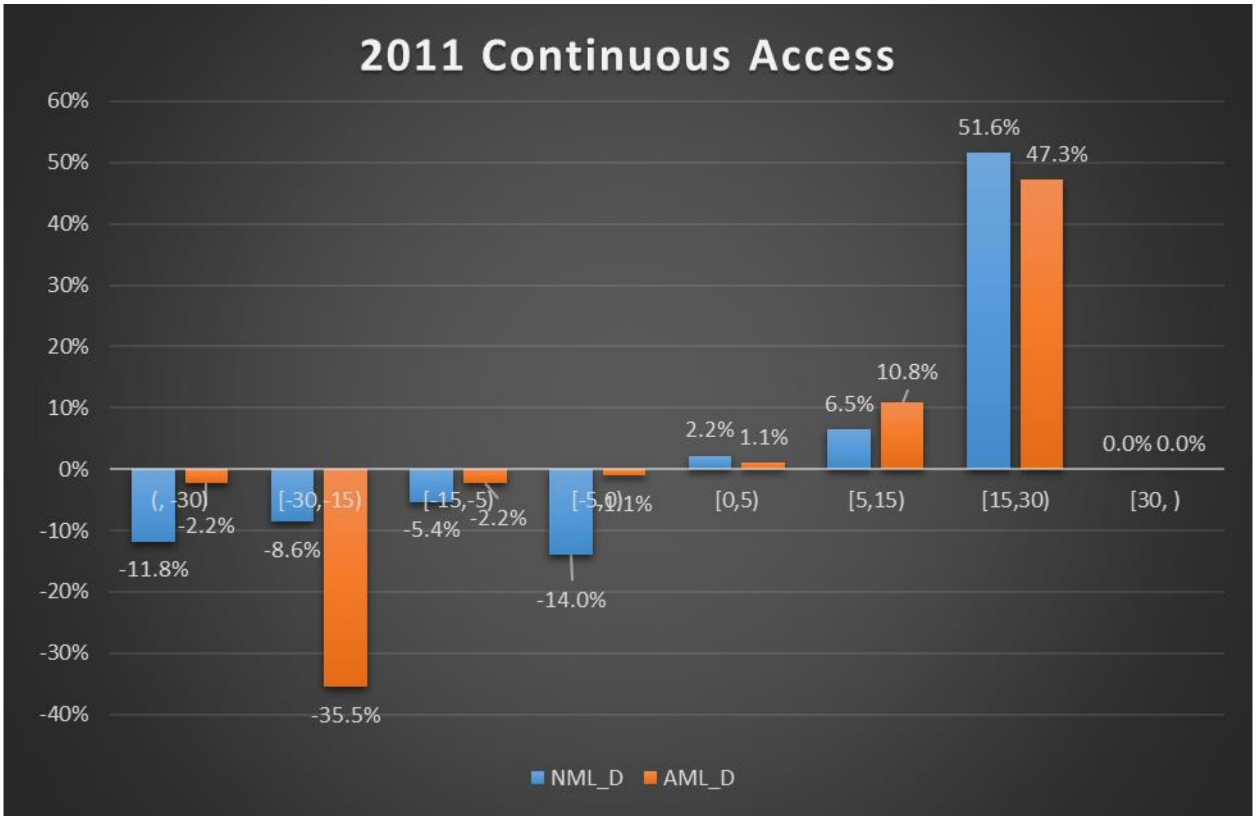


Figure 8.6. Percentage of Speed Difference in 2011 (Continuous Access Case)

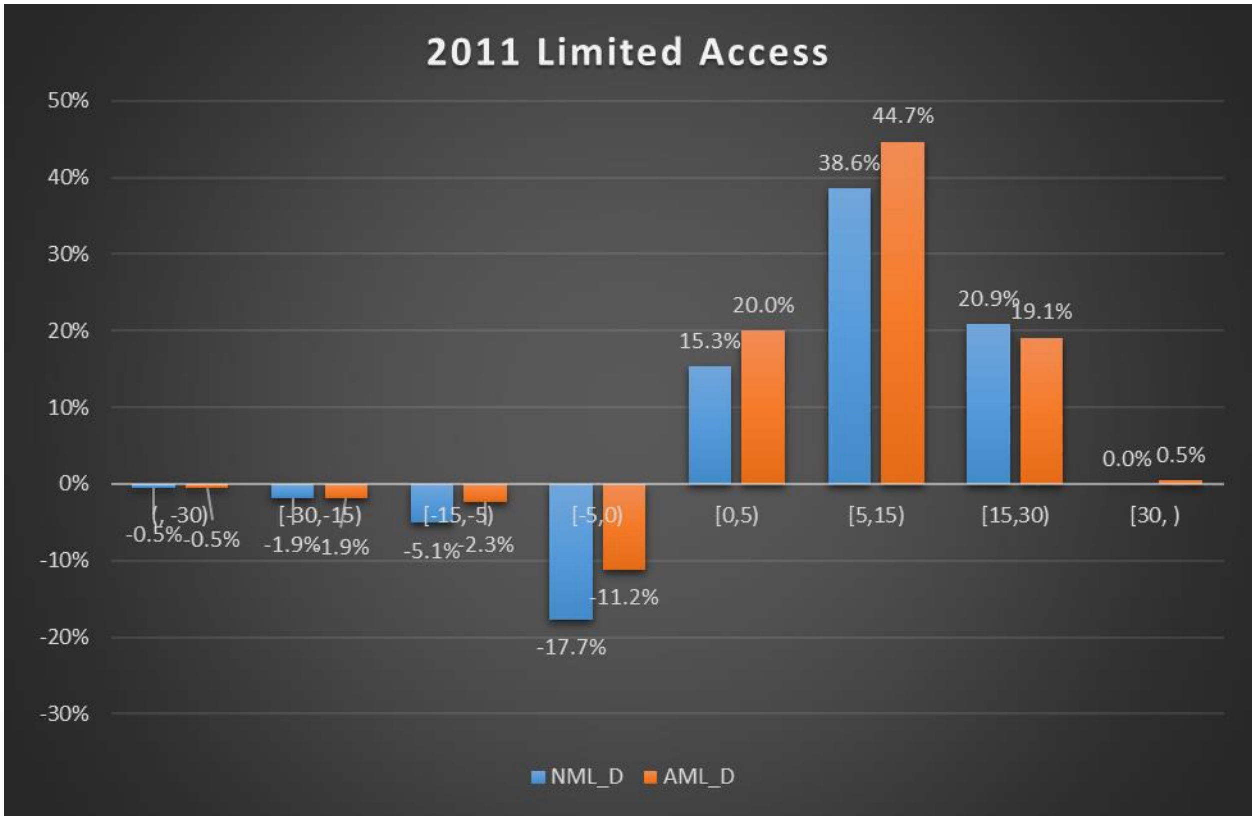


Figure 8.7. Percentage of Speed Difference in 2011 (Limited Access Case)

The numerical results are summarized in the tables below.

Table 24: 2011 Continuous Access

Speed Difference(Mph)	NML_D	AML_D	Category	Total	NML_D	AML_D
(, -30)	-11.8%	-2.2%	Extreme Disincentive	Disincentive	-40%	-41%
[-30,-15)	-8.6%	-35.5%	High Disincentive			
[-15,-5)	-5.4%	-2.2%	Slight Disincentive			
[-5,0)	-14.0%	-1.1%	Not Disincentive			
[0,5)	2.2%	1.1%	Not Incentive	Incentive	60%	59%
[5,15)	6.5%	10.8%	Slight Incentive			

Speed Difference(Mph)	NML_D	AML_D	Category	Total	NML_D	AML_D
[15,30)	51.6%	47.3%	High Incentive			
[30,)	0.0%	0.0%	Extreme Incentive			

Table 25: 2011 Limited Access

Speed Difference(Mph)	NML_D	AML_D	Category	Total	NML_D	AML_D
(, -30)	-0.5%	-0.5%	Extreme Disincentive	Disincentive	-25%	-16%
[-30,-15)	-1.9%	-1.9%	High Disincentive			
[-15,-5)	-5.1%	-2.3%	Slight Disincentive			
[-5,0)	-17.7%	-11.2%	Not Disincentive			
[0,5)	15.3%	20.0%	Not Incentive	Incentive	75%	84%
[5,15)	38.6%	44.7%	Slight Incentive			
[15,30)	20.9%	19.1%	High Incentive			
[30,)	0.0%	0.5%	Extreme Incentive			

Under these circumstances, it can be seen that the restricted access carpool lane that has more than 75 percent of incentive (with respect to both the adjacent mainline lane and average mainline lane) provides more incentive compared to the continuous access carpool lanes which give approximately 60 percent of incentive (with respect tor both the nearest mainline lane and the average mainline lane). However, this result may not be used to derive clear conclusions on the comparison between these two configurations because the incentive could vary depend on the study sites. This caveat is provided here because in the statewide study, the research found a reverse outcome that continuous access is better than limited access. Then, there should be many places which the continuous HOV lanes' benefits outweighs the limited access carpool lanes' benefits.

8.7 Time Savings for Degraded HOV Lanes

From the previous section, we see that the incentives on the degraded carpool lanes are in an extended decline from 2008 to 2017. In other words, the HOV facilities performed worse as the time passed. With the same study period, the time saving value will show how much time the degraded carpool lanes can still provide as benefit to users.

Table 26: Statewide Time Savings on HOV lanes (based on travel times per mile)

Access Type	All Corridors		Degraded Corridors	
	Total Time Saving (s)	%Time Saving	Total Time Saving (s)	%Time Saving
Continuous Access	5.74	6.77%	19.34	13.17%
Limited Access	3.35	4.05%	8.47	6.55%
Total	4.61	5.51%	13.21	9.67%

Table 27: Statewide Travel Times (per mile) on Different Types of Lanes

Access Type	All Corridors			Degraded Corridors		
	HOV Travel Time(s)	Nearest Lane Travel Time (s)	GP Lane Travel Time (s)	HOV Travel Time(s)	Nearest Lane Travel Time (s)	GP Lane Travel Time (s)
Continuous Access	79.02	84.76	85.52	127.51	146.85	145.59
Limited Access	79.31	82.66	88.82	120.75	129.22	134.41
Total	79.09	83.70	87.58	123.41	136.62	137.77

Before going to the SR-55 case, table 13 and table 14 show the statewide time savings results in both the all-corridors case and degraded-corridors case. The results show that the time savings of continuous access HOV lanes outweigh those on the limited access HOV lanes on a statewide analysis. Regarding all-corridors case, continuous access provided 6.77% time savings per mile, compared to 4.05% on limited access. When we consider only the corridors that are degraded, continuous access performs even better with 13.71% travel time saving per mile compared to 6.55% on restricted access HOV lanes.

Table 28: Time Savings on HOV lanes on SR-55 (based on travel times per mile)

Year	All Corridors		Degraded Corridors		
	Total Time Saving (s)	%Time Saving	Total Time Saving (s)	%Time Saving	Vehicle Miles Traveled
2008	-0.89	-1.14%	23.18	15.76%	64,479,708
2011	-0.69	-0.84%	26.82	17.69%	63,450,635
2013	-4.09	-4.87%	10.05	7.43%	62,335,098
2015	-12.05	-17.27%	-4.49	-3.70%	67,376,718
2017	-13.53	-15.60%	-9.00	-6.50%	66,100,012

For the SR-55 case, the time saving results are calculated and shown in table 15. As we can see, the percentage time saved on the HOV lanes has been decreasing from approximately 15.76% in 2008 to -6.50% in 2017 with respect to the mainline lanes' average travel time. That is, the HOVs were operating with worse speeds than the mainline lanes in 2015 and 2017. At the same time, the VMT (vehicle miles traveled) was not significantly different in 2017 when compared to 2008, which alludes to the fact that demand is similar in 2017, even though we can see that it had decreased for a few years, probably due to economic recession a few years ago. In any case, it is rather clear that the time savings for the HOV users have been decreasing after access-control conversion, as time went by, despite the demand in terms of VMTon the SR-55 not changing much.

The above results show that the implementation of continuous access on the SR-55 HOV facility has not helped relieve its degradation. However, this is the contrast of the statewide result we showed earlier that the performance of continuous access HOV lanes is better than of those with limited access. It is important to state right here that it is quite possibly the peculiarities of the SR-55 context that may have caused this, as described next in the examination of the overall (all lanes) travel changes, which indeed indicate that the conversion to continuous access was a success, despite the HOV lanes becoming worse.

Table 29: Travel Times (per mile) on Different Types of Lanes on SR-55

Year	All Corridors			Degraded Corridors		
	HOV Travel Time(s)	Nearest Lane Travel Time (s)	GP Lane Travel Time (s)	HOV Travel Time(s)	Nearest Lane Travel Time (s)	GP Lane Travel Time (s)
2008	78.95	78.07	82.09	123.90	147.08	164.30
2011	82.88	82.19	86.11	124.82	151.65	151.43
2013	88.02	82.93	86.04	125.23	135.29	136.47
2015	81.83	69.78	76.34	126.06	121.57	121.56
2017	100.22	86.69	89.63	147.43	138.43	139.78

The table shows the travel time of different types of lanes on SR-55. As we can see, the access-control conversion has increased the travel time on HOV lanes. The regular (GP, General Purpose) lanes became much better, however, especially on the degraded HOV corridors case, where the GP lanes' average travel times dropped from 164.30 seconds to 139.78 seconds.

The above results bring up an important conclusion that is of relevance in any argument against the Federal legislation that mandates state transportation agencies to take action to address the degradation on HOV lanes. The legislation (23 U.S.C. 166 (d) (1)) confines itself to the HOV lane and its performance while defining degradation, without any reference to the associated mainline lane conditions. As common sense would dictate, and as is evident from the SR-55 case study, HOV lanes and their details such as access-control have a significant effect on the performance of the regular lanes.

One important note on the above results is that the overall benefits were calculated based on VMTs and not on personal miles traveled. The HOV lane vehicles have about twice the occupancy, and thus the negative benefits from the continuous access HOVs are even more significant than in the analysis above. With that in mind, steps may need to be taken to arrest the continued deterioration of the HOV lanes on SR-55.

9 Conclusions

HOV lanes in California continue to be heavily used, with many facilities meeting the Federal standards of degradation. This research report outlined a series of efforts devoted to data analysis for identifying the causes of degradation, modelling of selected HOV stretches with different operational strategies, surveying selected HOV practitioners to supplement our knowledge in the absence of certain data, and creating new geographic datasets that would enable research into linking HOV geometry with traffic performance.

Our first comment is on the definition of HOV degradation, as in the Federal Standards mandated by legislation [23 U.S.C. 166 (d) (1)], which states that an HOV facility “shall be considered to be degraded if vehicles operating on the facility are failing to maintain a minimum average operating speed 90 percent of the time over a consecutive 180-day period during morning or evening weekday peak hour periods.” It is immediately clear that the wording is ambiguous, in that it could mean either “not (operating above minimum speed for 90% of the time)” or “(not operating above minimum speed) 90% of time” – which are entirely different conditions. The first condition could mean that an HOV lane that operates badly for just over 10% of the time but performs acceptably for even up to 90% of the time will still be called degraded, which defies common sense. The second meaning is that the speeds need to be below the minimum for over 90% of the time for it to be called degraded, which would be the counter-extreme case that would make many HOV stretches with extremely poor performance for much of the time to not be called degraded. Caltrans and FHWA use the first definition, and naturally HOV lane degradation would appear to be much worse a problem than it may be. In any case, studying this aspect and suggesting alternate definitions was beyond the scope of this thesis, and only observation of this important issue is being provided here as part of the conclusions.

The Federal definition of HOV lane degradation is based solely on the performance of the HOV lane, and that the legislation requires actions to improve the HOV lane, via alternatives such as implementing HOT (High Occupancy Toll) lanes. Not considering the effect of HOV lanes on the regular lanes’ traffic performance while recommending actions that may negatively affect the overall conditions is also problematic on a first look. Our study on the access-control conversion of SR-55 HOV lanes shows that the conversion itself led to an improvement in traffic conditions overall, even when the HOV lanes themselves became worse in performance.

Results obtained from a state-wide analysis show also show that HOV lanes with continuous access operate better than those with limited access.

In addition, there are some other factors which have an impact on the degradation. Examples are the geometric design, the inner shoulder width, lane width, and inner median width. Additionally, the speeds of the mainline lanes also affect the carpool lane’s conditions, a result that provides evidence for the observation made above on deficiencies in the Federal Standards for HOV degradation. Results show that the nearest mainline lane or the regular lane that located adjacent to the HOV facilities perform similarly to the carpool lane.

Based on the speed difference measure, those degraded stretches which met the Federal Standard of degradation speed threshold were still found to give some incentives for users compared with the regular lane both nearest mainline lane cases and average mainline lane cases. Once again, we see that an over-emphasis on the HOV lanes’ own performance, neglecting the relative performance vis-a-vis the regular lanes, seems to be an oversight in the Federal Standard. Nevertheless, the incentive trend is on a downturn from 2008 to 2017.

It would also be worthwhile to examine the medium and longer term changes in user behavior, in response to access-control conversion. One rather well-known effect is the HOV-violation behavior, which is known to be more in the case of continuous access, than in the case of limited access. The ongoing Caltrans surveys on passenger occupancies within cars on a lane-by-lane basis may throw some light on this aspect.

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