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Impacts of Access Control Conversion on Incentives to Use and Performance of High Occupancy Vehicle Lanes

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Impacts of Access Control Conversion on Incentives to Use and Performance of High Occupancy Vehicle Lanes

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Civil Engineering

by

Kasidit Jirotkun

Thesis Committee:

Professor R. Jayakrishnan, Chair
Professor Jean-Daniel Saphores
Professor Michael G. McNally

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Dedication

To my beloved Mom

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Acknowledgments

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Abstract of the Thesis

Impacts of Access Control Conversion on Incentives to Use and Performance of High Occupancy Vehicle Lanes

By

Kasidit Jirotkun

Master of Science in Civil Engineering

University of California, Irvine 2018

Professor R. Jayakrishnan, Chair

Carpool lanes, technically called High Occupancy Vehicle (HOV) facilities, have operated in the state of California for decades; however, the vehicle speeds on HOV facilities have significantly decreased in many locations and now meet the Federal Standard of HOV degradation. Such degradation is found on both types of HOV facilities used in California – with continuous access and with limited access. This study is interested in 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. The Tobit regression model explores the influencing factors involved in the degradation problem. As the results show, the geometric design of the freeway affects the degradation of HOV lanes. In terms of the speed differences, the degraded carpool lanes are still able to offer incentives to the user. On the basis of the time savings analysis, the degraded HOV

lanes are found to have had worsening travel time delays over the years since the conversion, although the general purpose lanes' travel times improved sufficiently to yield a positive overall benefit from the conversion.

Chapter 1: Introduction

1.1 Background

High-Occupancy Vehicle (HOV) lanes, more commonly known as carpool lanes, are a type of managed lanes which requires two or more people in a car traveling on it. The first carpool lane was introduced in New Jersey around 1969 and its use then spread throughout the country. Nowadays, many states in USA such as Texas, Washington DC, Virginia, California, etc. use HOV facilities to handle the growing traffic demand via incentivizing increased passenger occupancy in vehicles and thus reducing the number of vehicles. The incentive for pooling of passengers is a result of the higher speeds expected on such HOV lanes, as compared to the General Purpose (GP) lanes. In the State of California, there are two types of HOV lanes. The first kind are the limited access HOV lanes in which user can enter or exit at the certain access point, which generally operates in the Southern California area. The other kind are the continuous access HOV lanes in which people can get in or get out everywhere along the stretch, are usually found in the Northern California region (Boriboonsomsin and Barth 2008). A comparison of the performance of the two kinds of HOV lanes through a before-and-after study of the conversion of limited access on a freeway stretch to continuous access is the objective of this thesis. The context of the study is the SR-55 freeway in Orange County in Southern California.

1.2 Objective

The 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. The Standard for degradation is included in the legislation [23 U.S.C. 166 (d) (1)] that requires state transportation agencies such as CALTRANS to take alternative measures. The law specifies 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." The minimum operating speed that is specified is 45 miles per hour (FHWA, 2016). The high percentage of degraded facilities mentioned above is clear indication that poor traffic flow performance of the California freeways' HOV lanes requires urgent attention. There is also a need to find the reasons why the degradation percentage is continually increasing in this region. Thus, the purpose of this study is to compare the effect of two different configurations of carpool lanes on a Southern California freeway (the SR-55) using before and after datasets via an exploration of the influence factors that cause the speed degradation phenomenon using pre-and-post data modeling. For degraded HOV lanes, an incentive/disincentive analysis is used to see whether the carpool facilities still provide benefits to users. Then, the time saving measure can tell how much time the travelers can save while using the HOV facilities as opposed to the regular lanes.

1.3 Study Area

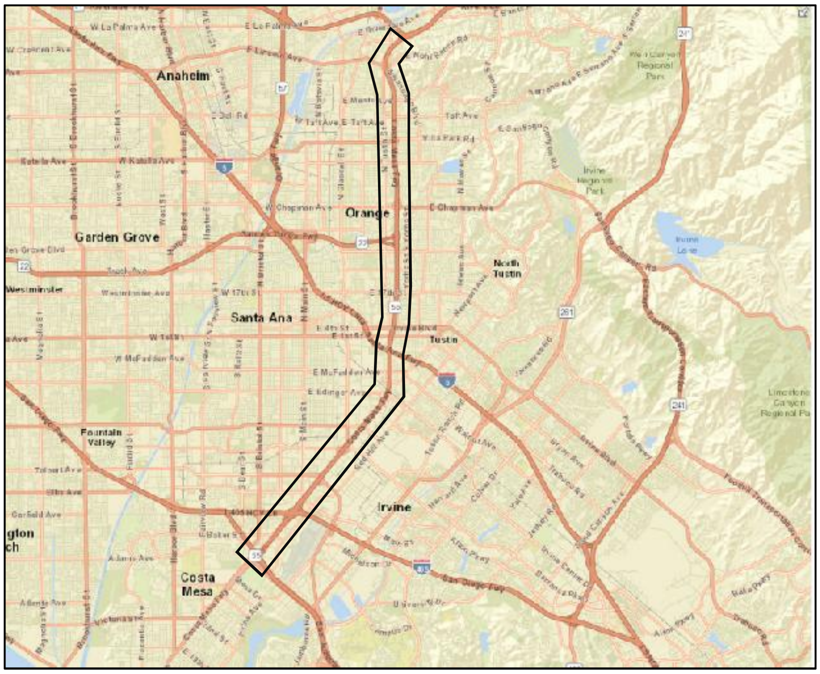

Figure 1: State Route 55 or Costa Mesa Freeway

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 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, so as to compare the before and after performance of the different types of HOV lane access schemes.

The HOV lane is usually the left-most lane on the freeways and two or more people are needed in the car to use this facility in most contexts. The two main types of the carpool lanes used in Orange County and elsewhere are shown in the next two figures, where the lanes with the diamond signs are the HOV lanes).

1) Continuous Access

Figure 2: Continuous Access Carpool Lane

This type of carpool lane uses the same white dashed line as in the striping used between the regular (general purpose) lanes.

2) Limited Access

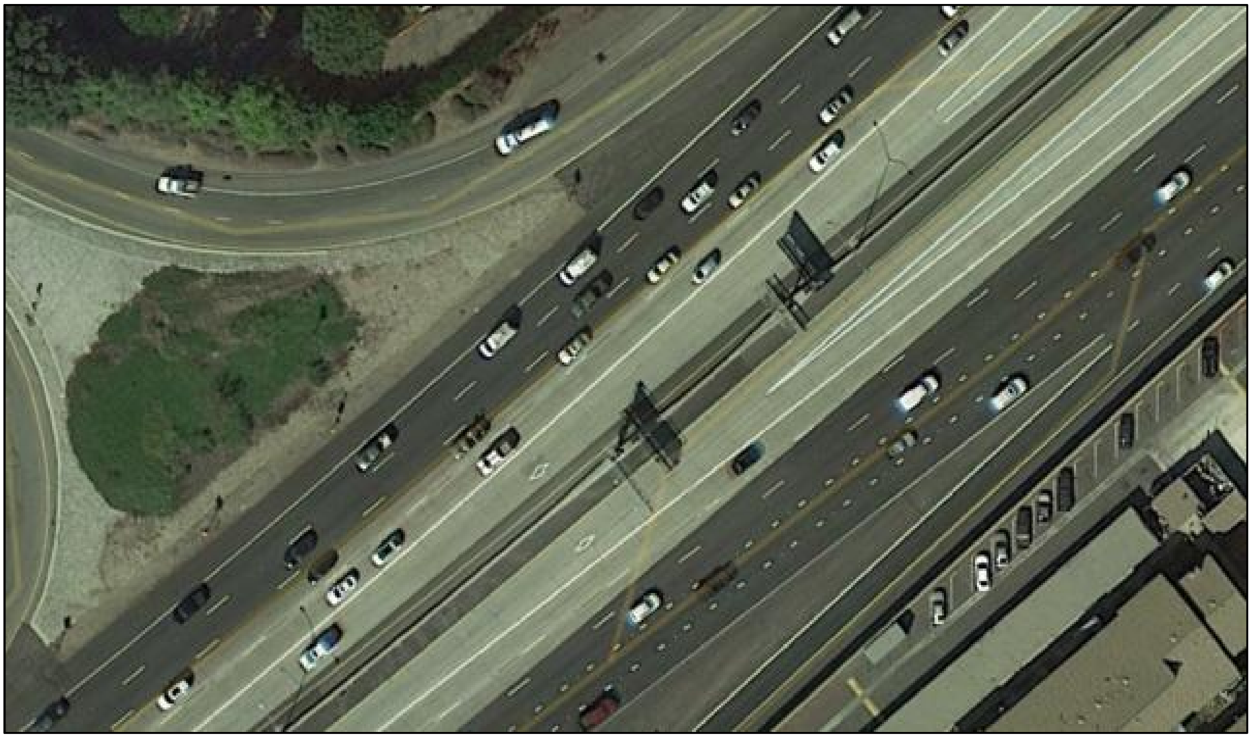

Figure 3: Limited Access Carpool Lane

This type of carpool lane has a solid white line, or a pair of yellow lines that separate it from General Purpose lanes and preventing vehicles changing lanes into it, except at designated stretches where vehicle entry is permitted.

Chapter 2: Literature Review

Various research methods are used to address the effect of carpool lanes. Some researchers try to use the fundamental diagram method to study the relationship between two types of HOV lanes from the existing traffic performance data. Some groups try to develop a model to quantify the variables, such as the road capacity. Besides traffic performance factors, other publications focus on environmental aspects or safety measurements of the carpool lane paper.

Jang et al (2012), utilized the fundamental diagram method to measure the before-after performance comparison between SR-55 and SR-57. According to them, continuous access carpool lanes have better performance during congested periods in which the queue can disappear faster on them, than the restricted access type of carpool lanes. However, there are more lane changes, and more violations happen with continuous access.

The state's HOV lane Degradation Report (Caltrans 2017) pointed out the cross-weaving effects which take place between the HOV lane and the adjacent lanes when people are changing lanes. This consequently leads to a capacity reduction, which depends on the amount of entering flow and the distance between the gore point at the on-ramp and the access point on managed lanes. In the case of limited access, there will be more intense flows in the places that have access points, and they might affect the capacity more, compared to the lighter inflow and outflow along the stretch in the continuous access cases.

As per the Highway Capacity Manual Chapter on Managed Lane Facilities (Wang et al. 2012), data shows that buffer-separated carpool lanes can operate with a lower speed than continuous access lanes, based on the speed-flow relationship. As an example, there will be the case that the slower cars will block the faster cars behind them, thus causing a chain reaction of blockages. However, this situation will not happen much in the continuous access case in which drivers can freely switch lanes to maintain their speed.

In terms of safety, there are different opinions on which type of HOV lane is better. The result of an early study (Newman 1988) shows that restricted-access carpool lanes, especially the ones that are buffer-separated, are safer compared to those with only a dashed line. However, several other research studies show that continuous access leads to fewer accidents, as well. For instance, Jang and Hall (2008) used a continuous risk profiles (CPR) analysis and found that collisions occur more often near the ingress/egress area of limited access carpool lanes. Thus, the geometric design might be an influential factor for accidents occurring on the freeway. Furthermore, (Jang et al. 2009) the collision rate in carpool lanes is related to shoulder width, length of access, and proximity of access to neighboring ramps.

As for the environmental impacts, one simulation-based study (Boriboonsomsin and Barth 2008) concluded that limited access HOV lanes produced more emission because vehicles have a higher chances to accelerate or apply brakes rapidly, as opposed to when they change lanes, which can cause more emission than in the continuous access case.

Even though there are many studies about different aspects of HOV lanes, which type of carpool lane outperforms the other is still debatable, and it is hard to find the right study framework to prove it one way or the other. This is because there are many elements that could affect the results, including location, road geometry and driving patterns.

Moreover, there are only a small number of case studies which compare the performance of these two types of access (Wu et al. 2015).

As mentioned in the introduction, from the California statewide data, the High-Occupancy Vehicle lanes in California are now congested, and 65% of the HOV lanes meet the Federal standards for degradation according to Caltrans. The Federal definition is that "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)." (FHWA, 2016). However, there still is no apparent conclusion about what factors lead to this HOV degradation issue or which types of carpool lanes perform better. Much of the literature referenced above did not focus directly on this aspect, as the legislation that included the Federal standards is more recent.

Chapter 3: Data and Methodology

3.1 Data Collection

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.

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.

3.2 Pre-and-Post Analysis

3.2.1 Tobit Regression

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

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

Where

i = 1,…, N indicates the individual

ε_i = error term

y_i^* = a latent variable

x_i' = 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.

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

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 mi les per hour along this freeway. This is because these kinds of variables will lead to singular ity issues in the model estimation process. The well-known Akaike Information Criterion

(AIC) was used to select between candidate models.

$$A \quad = 2k - 2\ln(L)$$

Where

K = number of independent variables

L = log likelihood

Table 1: The List of 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 2: 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	0.031	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	0.331	0.693	1
Prop_AML_45	0.300	0.224	0	0.031	0.475	0.825
Prop_AML_55	0.371	0.241	0	0.181	0.5	0.9250
Prop_AML_65	0.711	0.269	0	0.525	0.943	1
HOVDisToOffR	0.551	0.595	0	0	0.85	1.9

3.2.2 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

3.2.3 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 3: Access-control Conversion Dates for the HOV facility on SR-55

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

Source: Statewide HOV Lane Inventory Report (January 2017)

3.2.4 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 4: 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 5: 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 6: 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	24.0759350	210.70407	211.09007	4237.1	5.520211	20.09924
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	905.7143	12.9766059	122.45049	105.77735	4700.2	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	243.30692	214.54620	4115.0	5.520019	21.11981
155	9	17	4216.2	237.2	906.4286	-2.8358519	255.31143	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	-36.5344236	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	149.73405	149.12706	3415.1	5.520039	23.25004
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	210.40587	237.99816	4284.4	5.520064	20.57970
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	-54.7951308	230.60565	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.

Chapter 4: Result

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

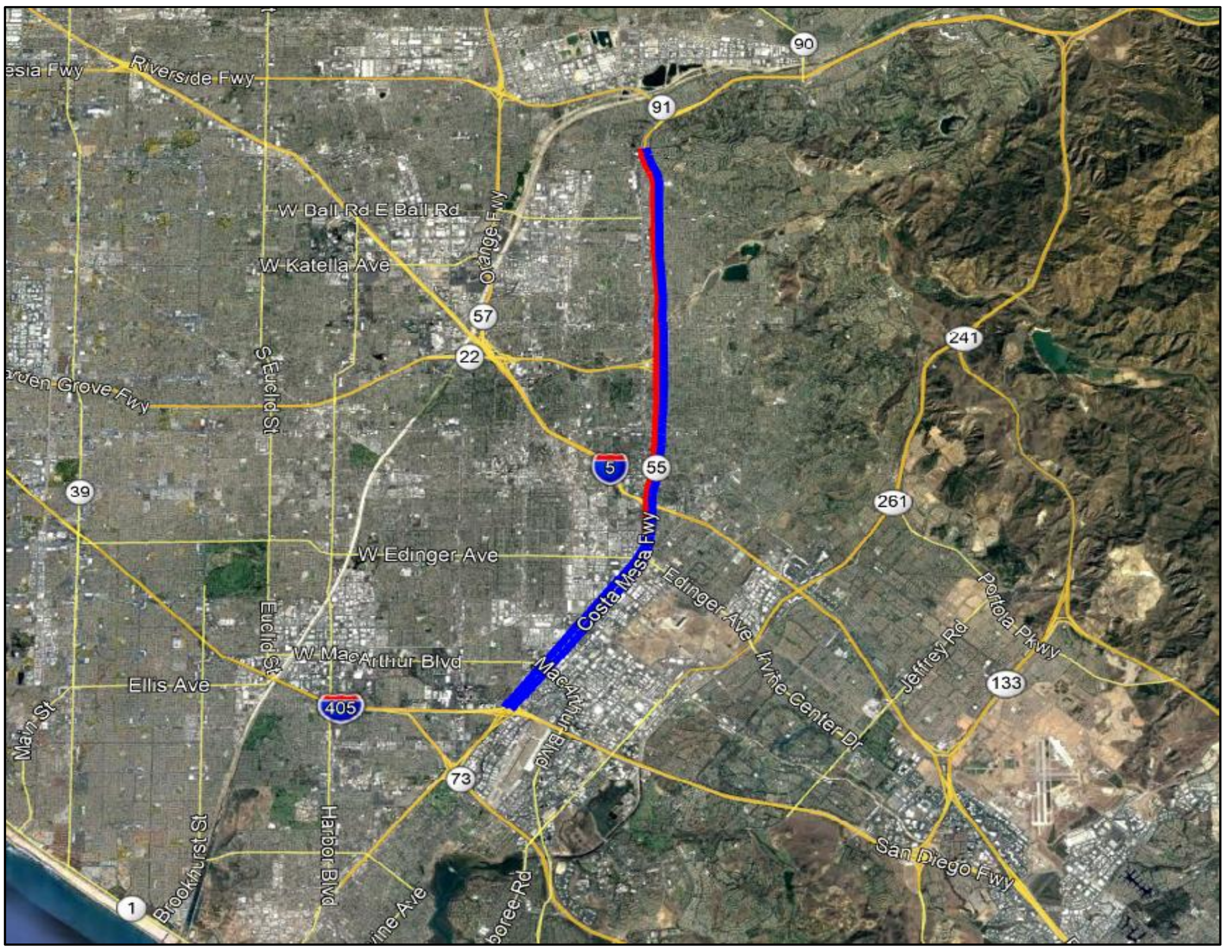

Figure 4: Degradation Status of SR-55 (AM peak Hour)

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 4 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.

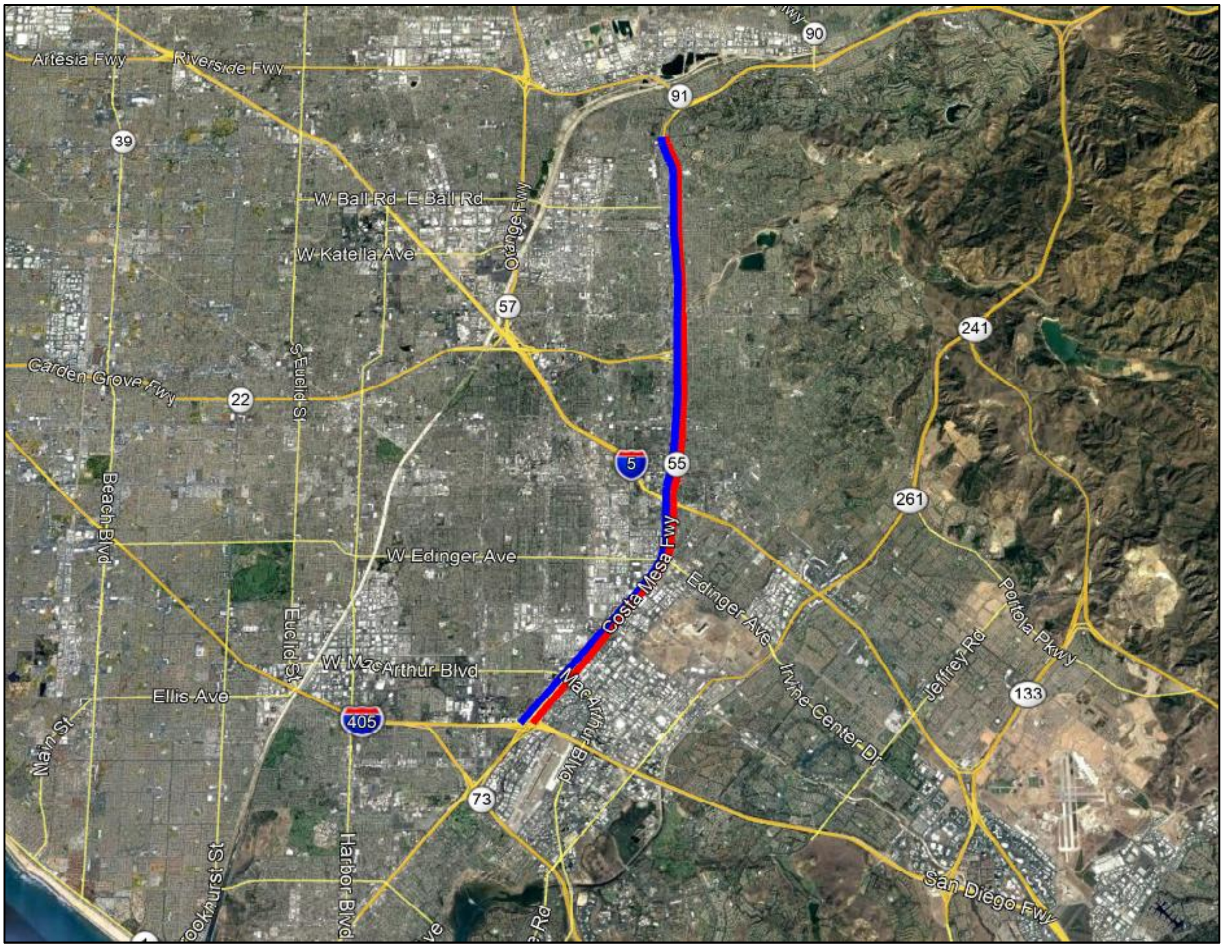

Figure 5: Degradation Status of SR-55 (PM Peak Hour)

As in Figure 5, 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 chapter.

4.1 Multiple Regression Model

Table 7: 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 Table 7, 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 8: 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 table 8, 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 9: 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 sam 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 9 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 behaviors and different intelligent transportation systems, such as those in the Northern California and the Southern California, which applied different strategies while establishing HOV facilities. A further item to consider is what is described in section 4.3 in terms of the changes in the General purpose lanes, which became distinctly better in performance after HOV-conversion to continuous access.

4.2 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.

From the methodology in chapter 3, the incentive and disincentive analysis will be on the basis of the speed difference measure. As can be seen in table 10, 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 10: 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

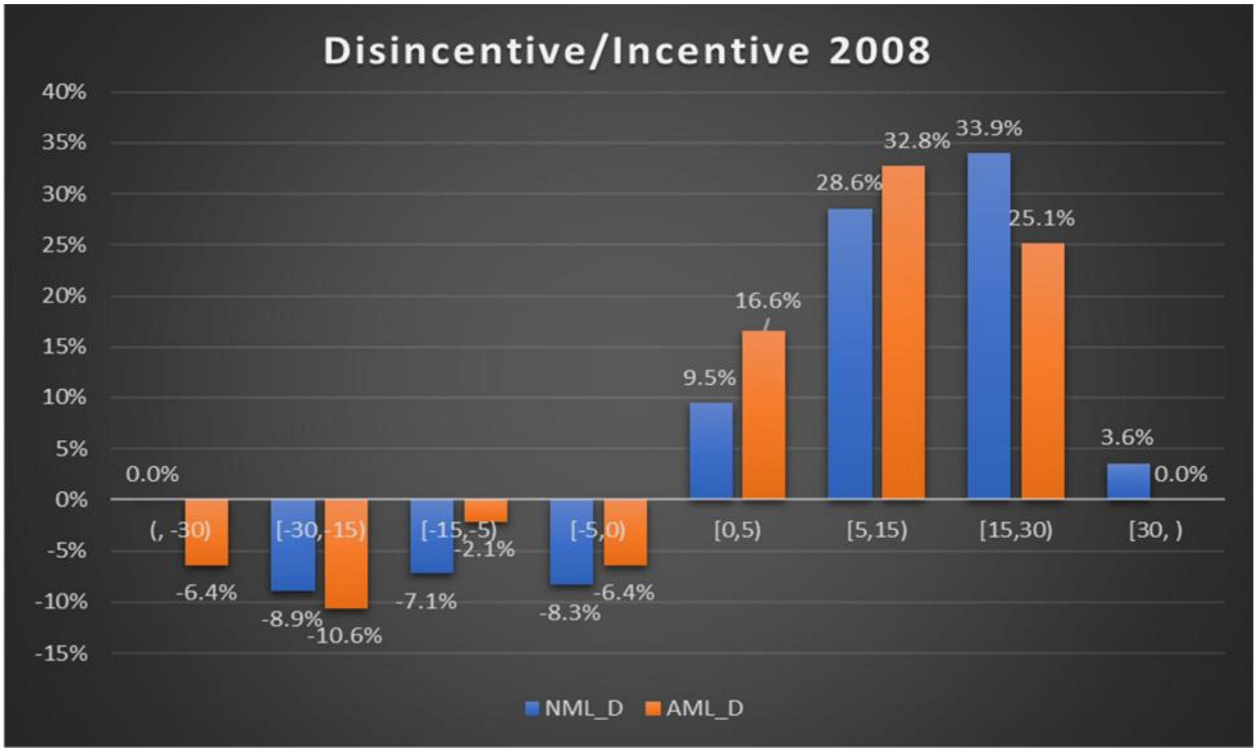

Figure 6: Percentage of Speed Difference in 2008

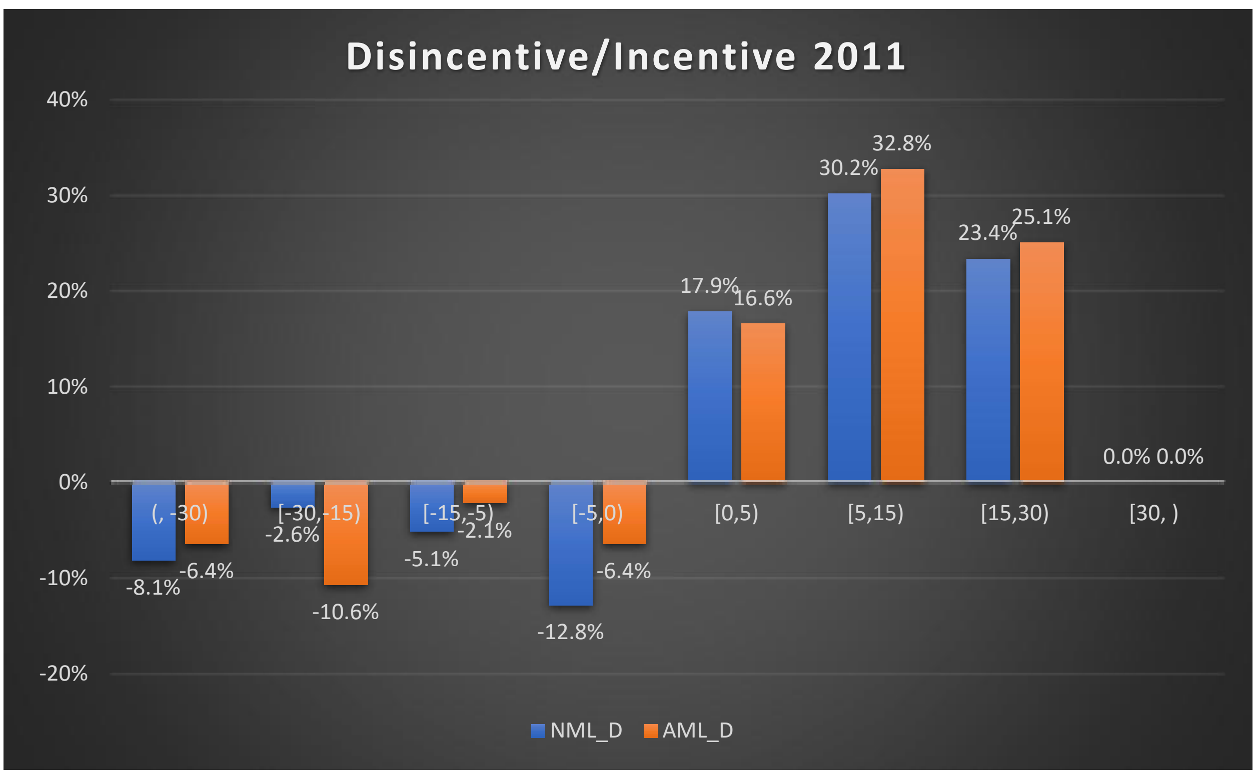

Figure 7: Percentage of Speed Difference in 2011

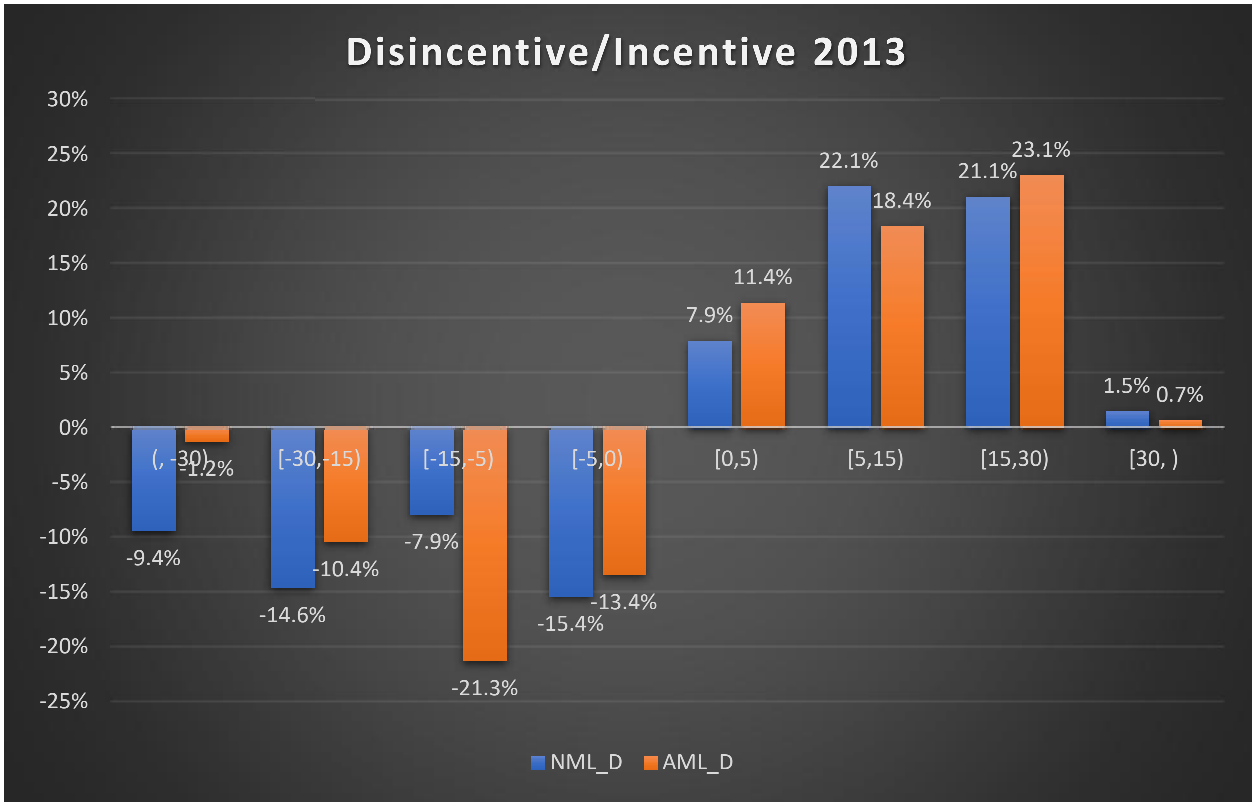

Figure 8: Percentage of Speed Difference in 2013

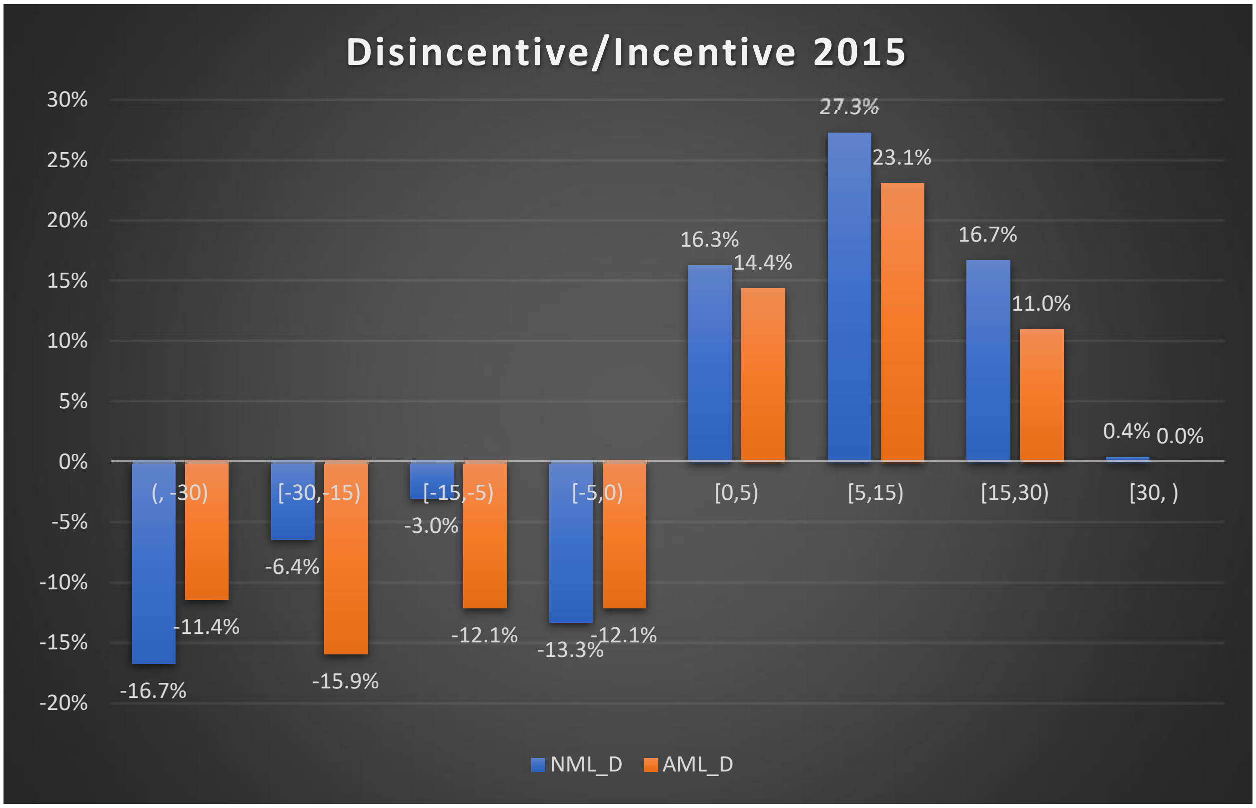

Figure 9: Percentage of Speed Difference in 2015

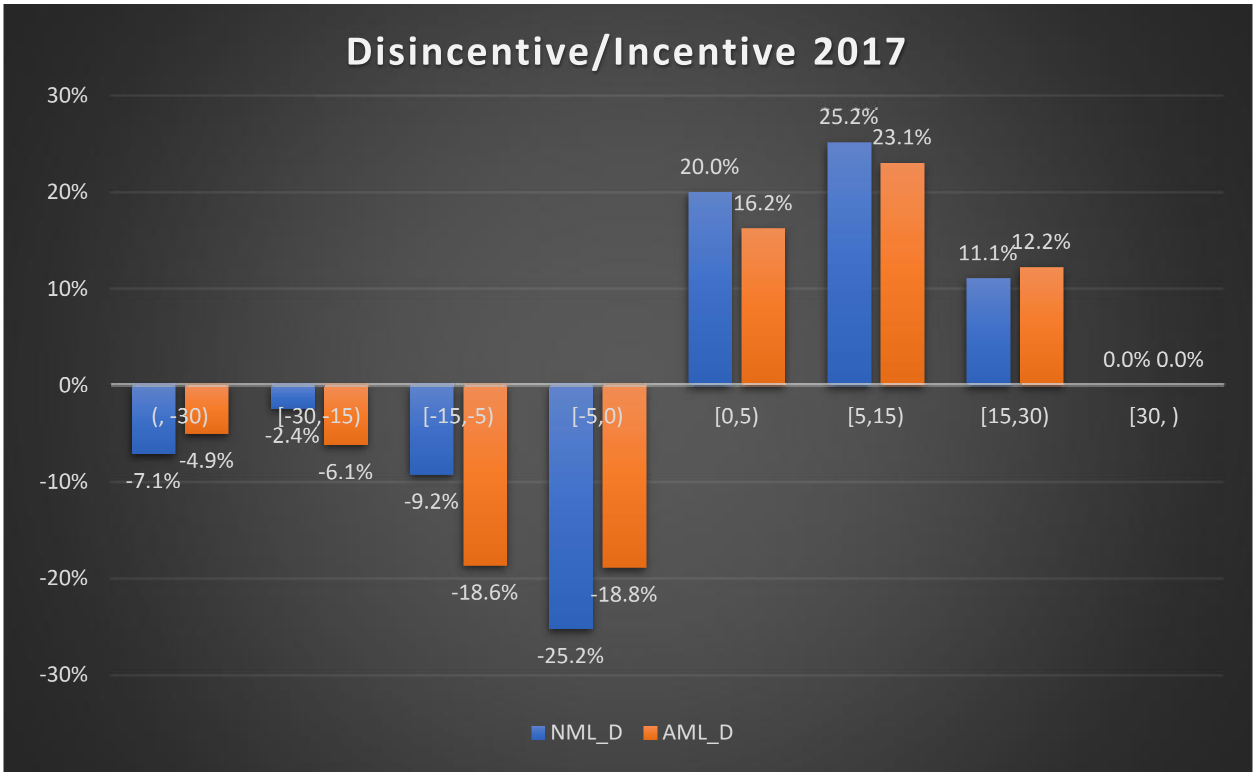

Figure 10: Percentage of Speed Difference in 2017

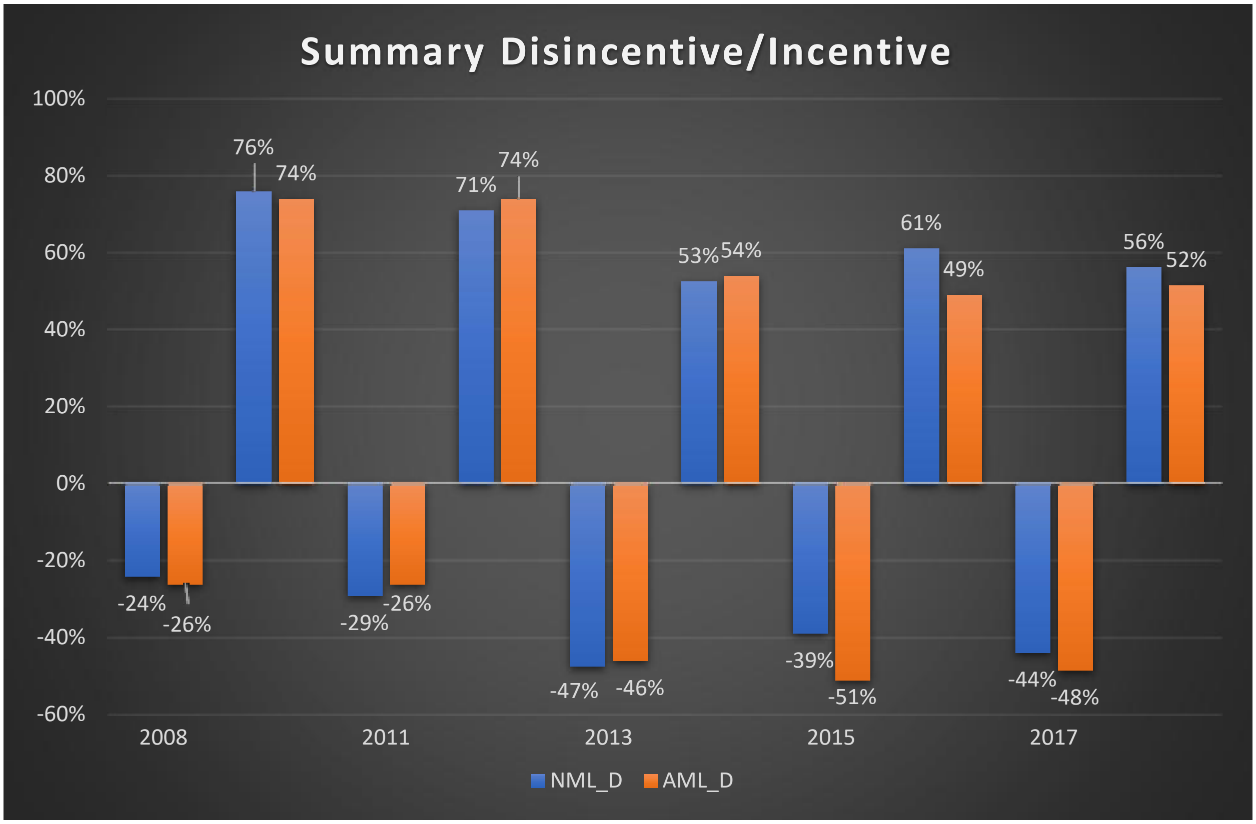

Figure 11: Summary of Percentage of Speed Difference

From Figure 11, 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 the year 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.

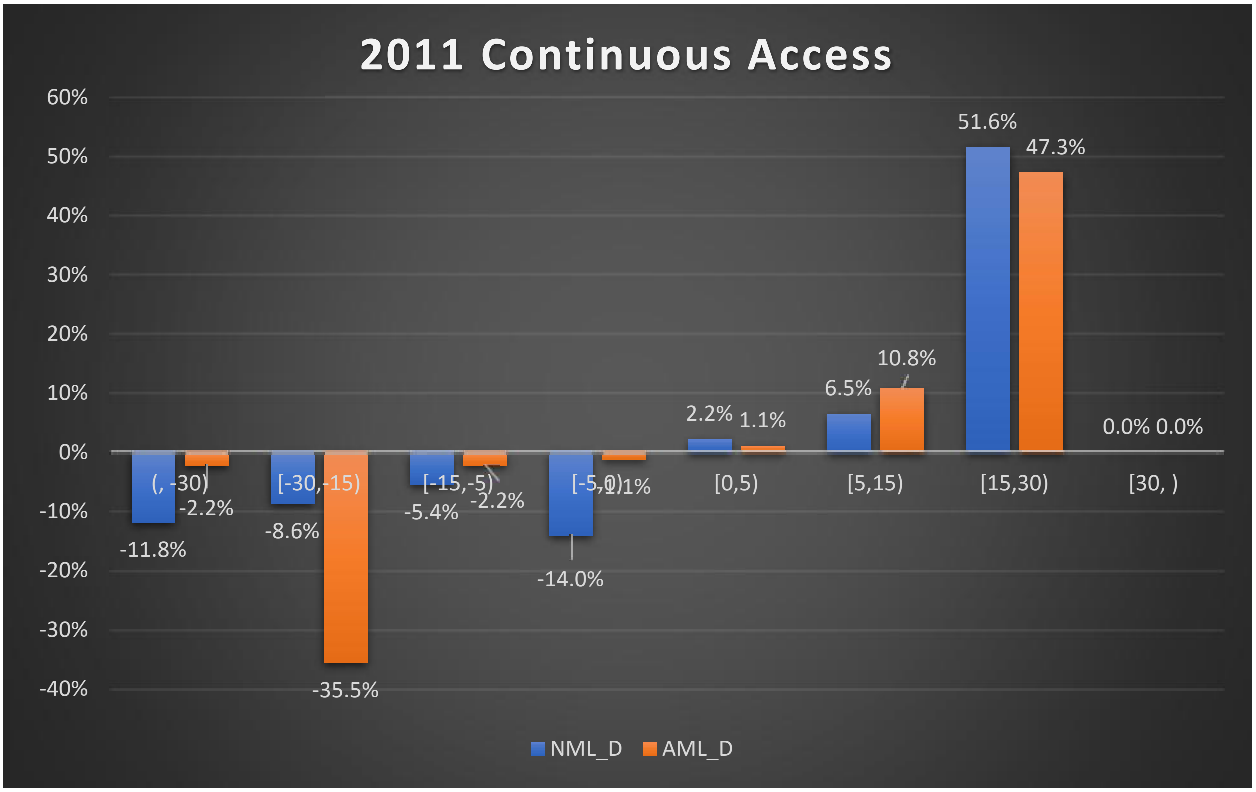

Figure 12: Percentage of Speed Difference in 2011 (Continuous Access Case)

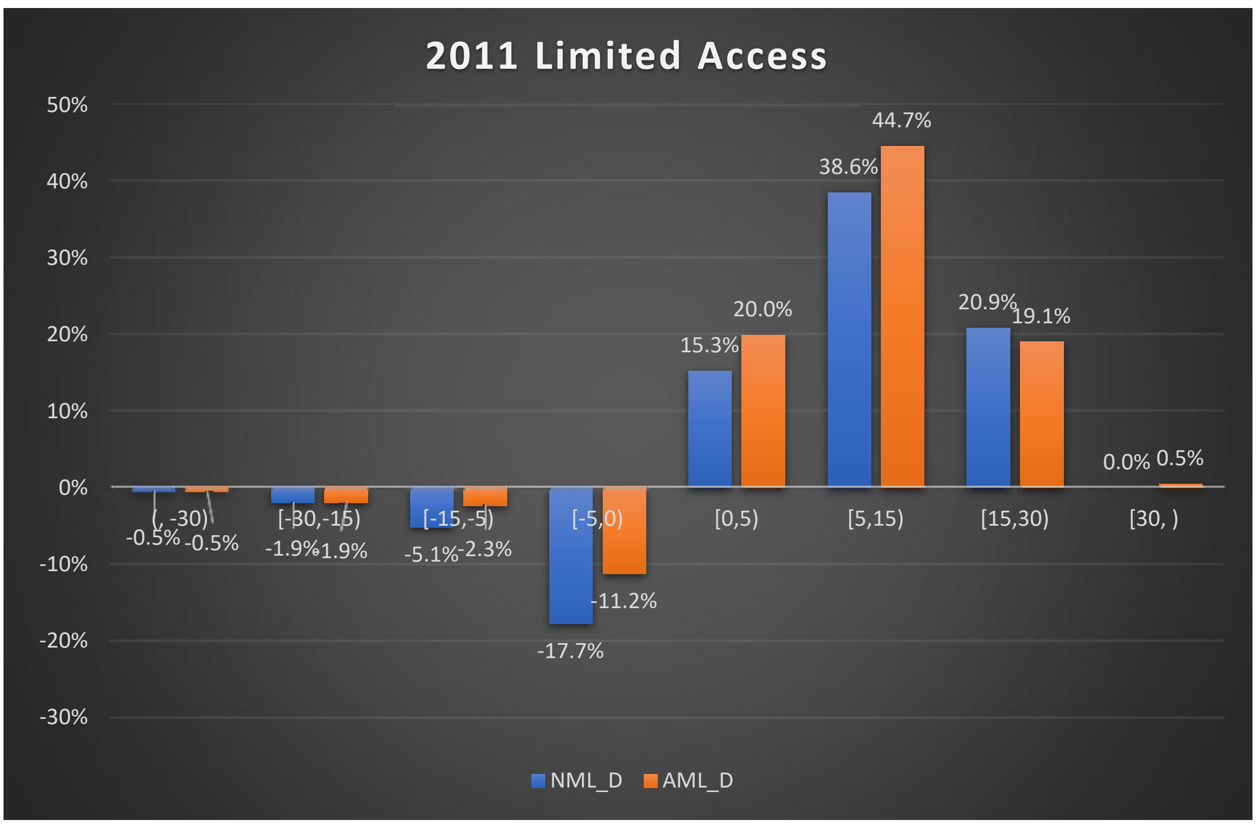

Figure 13: Percentage of Speed Difference in 2011 (Limited Access Case)

Table 11: 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			
[15,30)	51.6%	47.3%	High Incentive			
[30,)	0.0%	0.0%	Extreme Incentive			

Table 12: 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.

4.3 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 13: 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 14: 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 15: Time Savings on HOV lanes on SR-55 (based on travel times per mile)

Year	All Corridors		Degraded Corridors		Vehicle Miles Traveled
	Total Time Saving (s)	%Time Saving	Total Time Saving (s)	%Time Saving	
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 VMT on 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 16: 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

Table 16 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 on the basis of VMTs and not based 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. Further discuss of this is provided in the next chapter with the study conclusions.

Chapter 5: Conclusions and Future Work

This thesis research attempted to study the effect of the conversion of HOV lane access control from limited access to continuous access in a case-study context of the SR-55 freeway in Orange County, California, USA, with a specific focus on the degradation of the HOV lanes. With the speed of HOV lanes having dropped significantly in many places, the degradation of HOV facilities has become a serious concern in California lately, which was the motivation for this study.

The first observation of the study was 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 problematically 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.

A second issue of significance in the above Federal definition of HOV lane degradation is that it is defined completely on the basis of 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. On this aspect, this thesis does indeed throw some light, as the access-control conversion of SR-55 HOV lanes seemed to improve the conditions of the overall traffic even when the HOV lanes themselves became worse in performance.

In terms of the results, On SR-55 route, it looked like the speed of the HOV lanes during peak hours tended to decrease almost every year over the period from before the conversion from continuous-access to limited-access. From the modeling results, access type is a variable which has a relationship with the speed drop on carpool lanes. The results show that there is less speed degradation on the limited access carpool lanes than on the continuous access carpool lanes in our study area. This is admittedly a counter-result to what is found from a statewide analysis, which showed that HOV lanes with continuous access operate better than those with limited access. A closer look at the SR-55 context would reveal that there may be other site-specific reasons for the counter-result.

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. According to the results in chapter 4, the nearest mainline lane or the regular lane that located adjacent to the HOV facilities perform corresponding with 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, is a mistake in the Federal Standard. Nevertheless, the incentive trend is in a downturn from 2008 to 2017. The carpool lanes in the degraded corridors have not been providing much time savings since the access conversion. However, the travel time on regular lanes decreased significantly. So, changing HOV configuration from limited access to continuous access in this study area gave crucial overall benefits to the users. From this standpoint, we can again see that the definition of HOV degradation should not focus on only the HOV lanes. HOV lanes not only put more people in each vehicle but also help smooth traffic on the general purpose lane. However, it does appear that the continuously worsening performance of the SR-55 HOV lanes needs addressing. Ultimately, and perhaps fairly soon, the HOV travelers may recognize that there is no relative benefit in using those lanes; an eventuality that should be avoided. From this standpoint, re-introducing limited access in some portions of the corridor may become necessary.

One reason for why the HOV lane users have continued to use the HOV lane despite the relatively poor performance after conversion may be that they are somewhat captive as users of relatively short HOV stretches on SR-55 in between other crossing freeways, with 4 of them crossing SR-55 over roughly a 15 mile stretch. As the users would like to continue on to better performing HOV lanes on other freeways and use HOV connectors that also are performing much better than the regular freeway connectors, they may be choosing to suffer the disincentive of using the SR-55 HOV lanes after access conversion. An elaborate study of this aspect was beyond the scope of this thesis.

The SR-55 is a relatively rare case of a freeway that has had the HOV configuration changed from limited access to continuous access. There are a few other similar cases in southern California. A conversion from continuous access to limited access is, however, even rarer in California. Not doing a before-and-after case-study comparison case study of such a reverse conversion is thus a limitation of this thesis. Focusing on just one freeway stretch is also a limitation. As a result, the limited data points mays have affected the quality of modeling in this study. It will be worthwhile to embark on a future project in which date is gathered for the same time periods from difference freeways where both types of access control configuration conversions are done, and explore the effects on degradation. More data points from such a study can also decrease variance and relieve the effect of outliers in the model calibration process.

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. Simulated modeling of violation behavior using simple common-sense behavioral models also may yield some insights on the importance of such studies.

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