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16. ABSTRACT

Managed lanes, including High-Occupancy Vehicle (HOV) lanes, are an integral part of California's freeway systems. Guidelines developed by Caltrans for HOV lanes indicate that the operation of an HOV facility is closely linked to the design of the facility, the traffic demand in the freeway corridor, and the geographic distribution development as well as the associated travel patterns in the region. Traditionally, HOV lanes have been designed with either limited access or continuous access control. Under this research, researchers developed a new design of HOV access control that combines the advantages of the two existing designs. In the new design, called partially limited access, continuous access is generally provided along the majority of HOV facilities in order to achieve higher travel speed while buffers are strategically placed on selected freeway segments (e.g., recurrent bottlenecks, ramp areas) to mitigate the impact of weaving maneuvers, thus accommodating higher throughput, on those segments. The operational performance of the partially limited access control in traffic microsimulation environment was also evaluated. The traffic microsimulation results for the case study of California State Route (SR)-210 showed that the partially limited access control increased the throughput and decreased the delay of the freeway as compared with the limited access and continuous access controls. The results show the overall network efficiency of the freeway with partially limited access HOV facility was 21% and 6% higher than that of the freeway with limited access and continuous access HOV facilities, respectively. Results also show that the buffers designed with a weaving distance per lane change of 600 ft. (instead of the existing 800 ft. guidelines) had the best operational performance in terms of average travel speed.

17. KEY WORDS HOV, bottlenecks, guidelines, limited access, throughput, delay, weaving, mixed-flow (MF) lanes, corridor, limited access, continuous access, performance, microsimulation, PeMS, vehicle-miles-traveled (VMT), passenger-miles-traveled (PMT), speed-flow, bottleneck, striping, buffer, on-ramp, weave, capacity, simulation, conclusions	18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161	
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FINAL REPORT

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List of Acronyms

BRT	Bus rapid transit
Caltrans	California Department of Transportation
GA	Genetic algorithm
HDT	Heavy-duty truck
HOT	High-occupancy toll
HOV	High-occupancy vehicle
HSIS	Highway Safety Information System
LDT	Light-duty truck
MDT	Medium-duty truck
MF	Mixed-flow (lane)
MnDOT	Minnesota Department of Transportation
MUTCD	Manual on Uniform Traffic Control Devices
PeMS	Performance Measurement System
PMT	Passenger miles traveled
TASAS	Traffic Accident Surveillance and Analysis System
VMT	Vehicle miles traveled
VHT	Vehicle hours traveled

Executive Summary

Managed lanes, including high-occupancy vehicle (HOV) lanes, are an integral part of California's freeway systems. Traditionally, HOV lanes have been designed with either limited access or continuous access control. Over the last several years, the performance of limited access and continuous access HOV facilities in terms of safety, mobility, environment, enforcement, etc. have been extensively compared through empirical and simulation studies. The findings from these previous studies imply that the two existing designs have both advantages and disadvantages.

In this research, the research team developed a new design of HOV access control that combines the advantages of the two existing designs. In the new design, called *partially limited access*, continuous access is generally provided along the majority of HOV facilities in order to achieve higher travel speed while buffers are strategically placed on selected freeway segments (e.g., recurrent bottlenecks, ramp areas) to mitigate the impact of weaving maneuvers, thus accommodating higher throughput, on those segments. We also evaluated the operational performance of the partially limited access control in traffic microsimulation environment.

In the development of the new HOV access control design, the HOV cross-weave effect upstream of off-ramps was first analyzed. Then, a method for determining the location and length of buffers in the partially limited access control was developed and applied to the study site on SR-210 E in Southern California. Next, the operational performance of the new design was compared with the performance of limited access and continuous access designs in a well-calibrated traffic microsimulation network of SR-210 E. Finally, a sensitivity analysis of the operational performance of the partially limited access design with respect to buffer length was also conducted.

The results revealed that HOV cross-weave flow had tangible effect on the capacity of MF lanes upstream of off-ramps. Three influential factors, i.e., HOV cross-weave flow, number of MF lanes, and length of buffer were analyzed. It was found that placing a buffer (with appropriate length) before an off-ramp could reduce the HOV cross-weave effect, keeping the capacity of MF lanes at a high level.

The methodology for designing partially limited access control for HOV facilities was developed based on the following criteria: (1) to reduce HOV cross-weave effect; (2) to improve HOV lane utilization; and (3) not to violate existing HOV design guidelines. In general, a freeway segment can be divided into four portions: (1) between off-ramp and on-ramp, (2) downstream of on-ramp, (3) basic segment, and (4) upstream of off-ramp. For partially limited access HOV lanes, buffers should be placed upstream of off-ramps, as illustrated in Figure ES-1, as long as the buffer length could satisfy other requirements of the existing HOV design guidelines. Note that the existing guidelines of the California Department of Transportation recommend the weaving distance per lane change of 800 ft.

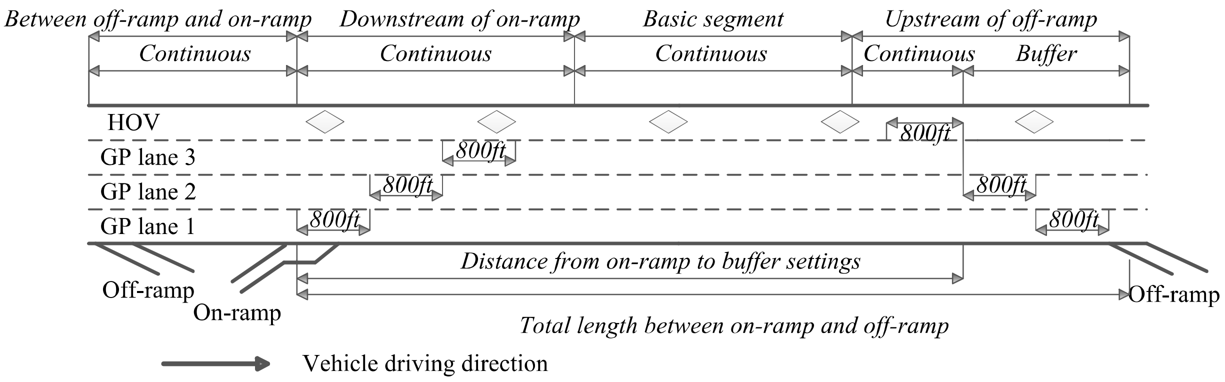


Figure ES-1. Partially limited access design for freeway HOV facilities

The traffic microsimulation results for the case study of SR-210 E showed that the partially limited access control increased the throughput and decreased the delay of the freeway as compared with the limited access and continuous access controls. As a result, the overall network efficiency of the freeway with partially limited access HOV facility was 21% and 6% higher than that of the freeway with limited access and continuous access HOV facility, respectively. For the sensitivity analysis of buffer length, buffers designed with a weaving distance per lane change of 600 ft had the best operational performance in terms of average travel speed.

It should be noted that these results and findings are based mostly on simulation, and an evaluation of the operational performance of a freeway with partially limited access HOV facility in real world is warranted in the future. As part of the future work, other types of performance, such as safety and environmental sustainability, of the partially limited access design should also be evaluated in comparison with the two existing designs. Also, the weaving distance per lane change should be further investigated with the consideration of many site-specific factors, such as level of service and number of MF lanes.

1. Introduction

1.1. Background

California has the most extensive managed lane system in the nation, approximately 40% of the total managed lane miles, the majority of which are high-occupancy vehicle (HOV) facilities. Today over 1,550 lane-miles of HOV facilities are either operational or under construction, with another 560 lane-miles being programmed or proposed by the California Department of Transportation [Caltrans, 2014a]. In essence, HOV facilities have been and will continue to be an integral part of the California freeway system. Therefore, it is necessary for Caltrans to ensure that these facilities are operated in a way that meet their purposes of improving mobility, trip time reliability, and air quality.

Caltrans Division of Traffic Operations has developed guidelines for planning, design, and operations of HOV facilities [Caltrans, 2003]. The guidelines indicate that the operation of an HOV facility is closely linked to the design of the facility, the traffic demand in the freeway corridor, and the geographic distribution development as well as the associated travel patterns in the region. For example, in areas that experience regular periods of congestion for many hours of the day, full-time HOV operations with restricted access is favored to maximize opportunities for HOV utilization and travel time savings, thereby providing incentives to rideshare and relieve the rate of congestion. On the contrary, in areas where commute patterns generally consist of short definable peak periods and clear directional flows, part-time, peak period HOV operations are preferred. With part-time operations, HOV lanes ideally should look like general purpose lanes to minimize the potential for motorist confusion when they are open to general-purpose traffic. Thus, it is preferred that access into and out of HOV lanes operating part time not be restricted.

The College of Engineering - Center for Environmental Research and Technology (CE-CERT) at the University of California Riverside completed research studies *"High Occupancy Vehicle (HOV) System Analysis Tools – District 8 HOV Facility Performance Analysis"* and *"Evaluation of SR-60 Before and After HOV Lane Conversion"* [Boriboonsomsin et al., 2013]. In these studies, the operational performance of limited access and continuous access HOV facilities was extensively compared. The results reveal that: a) buffer-separated HOV facilities are better at regulating traffic flow, which results in higher freeway throughput while b) contiguous HOV facilities are more likely to spread out lane changes, which allows traffic to maintain higher travel speed. These results imply that an alternative design in geometric configuration of HOV facilities where continuous access is generally provided along a freeway to achieve higher travel speed while buffers are strategically placed on selected freeway segments (e.g., bottlenecks, ramp merges) to accommodate higher throughput on those segments may result in better overall operational performance than the existing designs. Figure 1-1 shows the configuration of the new HOV access control design, called *partially limited access*, in comparison with the two existing HOV access control designs.

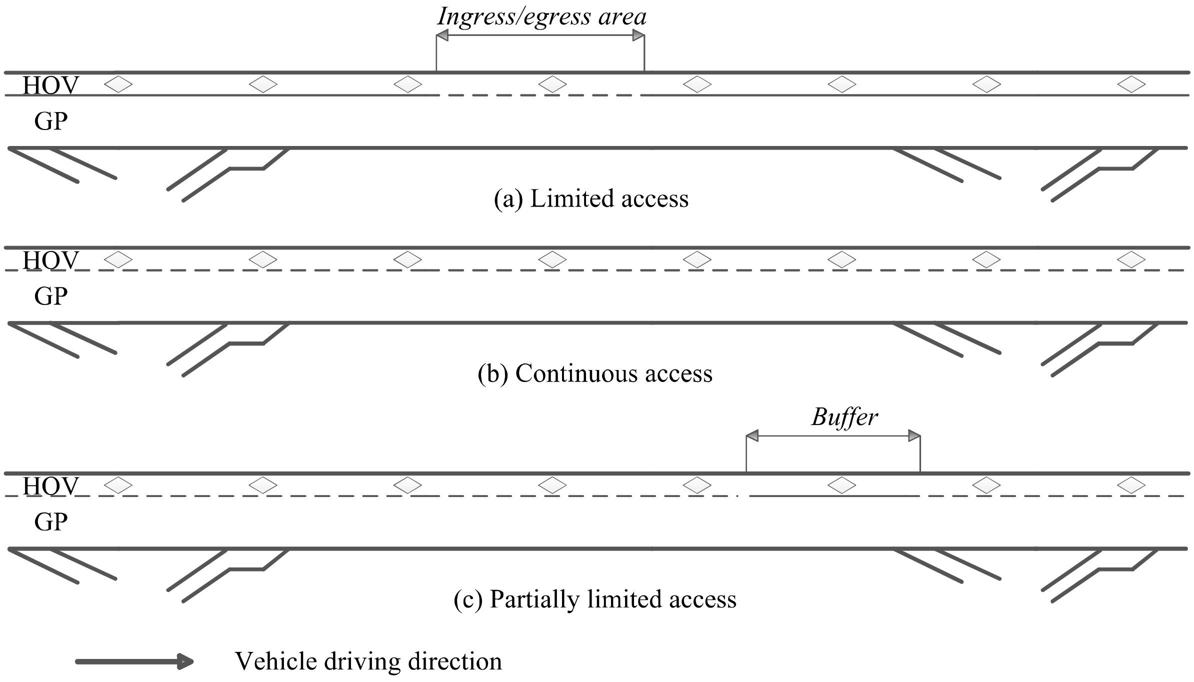


Figure 1-1. Different access control of HOV lane

1.2. Objectives

The objectives of this research are to: 1) evaluate the operational performance of HOV facilities with the partially limited access configuration in relative to those with the existing configurations, and 2) develop guidelines for designing HOV facilities with the partially limited access configuration. The products from this research are expected to enable Caltrans to improve the operational performance of HOV facilities in the state through innovative design of the facilities.

1.3. Report Organization

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

- Chapter 2 summarizes the information gathered from the literature and case study review on HOV lane performance and operation characteristics.
- Chapter 3 describes the methodology that was developed for designing partially limited access HOV facilities.
- Chapter 4 presents the evaluation results of the operational performance of partially limited access HOV facilities based on traffic microsimulation.

- Finally, Chapter 5 provides conclusions of this research and recommendations for future research.

- Additionally, the report contains an appendx at the end that provide supplemental information regarding the methods and results of the research.

2. Literature and Case Study Review

This chapter provides a summary of findings from literature and case study review. While there is a very large body of literature related to HOV lane, we focused our review effort on the evaluation of operational performance of HOV facilities with different types of access control.

2.1. HOV Lane Performance Evaluation

The effectiveness of HOV lane has been the subject of much research and discussion for many years. Many states, including California, have implemented HOV performance monitoring programs and conducted a performance evaluation of their HOV facilities periodically (e.g., [Nee et al., 2004], [Perrin et al., 2004], [Zilliacus et al., 2005]). One purpose of monitoring and evaluating the performance of an HOV lane is to determine if the facility is meeting its goals and objectives.

HOV performance measures that are commonly used include vehicle volume, vehicle occupancy, speed, and travel time [Henderson, 2003]. One particularly important performance measure is average operating speed, on which a consideration whether an HOV facility is degraded or not is based, according to a federal guidance [Federal Highway Administration, 2012a]. A minimum average operating speed is defined as 45 miles per hour (mph), for an HOV facility with a speed limit of 50 mph or greater, and not more than 10 mph below the speed limit for a facility with a speed limit of less than 50 mph. 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).

In California, the effectiveness of HOV lanes was reviewed and discussed in the report by the Legislative Analyst Office in 2000 [California LAO, 2000]. The report suggested that although HOV lanes in California appeared to have a positive impact on carpooling (in terms of increasing person-moving capacity), they were operating at only two-third of their vehicle-carrying capacity. Following this legislative report were two HOV lane performance evaluation studies conducted in Southern California (i.e., [Parsons Brinckerhoff Inc., 2002]; [Southern California Association of Governments, 2004]). Key findings from each study are listed in Table 2-1. Some of the concurrent findings in favor of HOV lanes from these two studies include:

- The general public understands and supports HOV lanes.
- In general, HOV lanes provide travel time savings.
- HOV lanes do encourage ridesharing.
- HOV lanes are well-utilized, with many operating at near capacity during peak periods.
- Violation rates are well below the threshold for concern.

Table 2-1. Findings from HOV lane performance evaluation studies in Southern California

Los Angeles County (Parsons Brinckerhoff Inc., 2002)	**San Bernardino, Riverside, and Orange Counties (Southern California Association of Governments, 2004)**
• Nearly everyone (88%) supports HOV lanes, and 64% agree that HOV lanes reduce congestion. • All HOV lanes save time. Although the travel time savings varies by route, they can add up. • HOV lanes are effective. All but one (Route 170) of the existing freeway HOV routes exceed the minimum operating threshold of 800 veh/hr/ln. • HOV lanes are used all day every day. On many routes, off-peak demand represents 30-50% of peak hour demand. • HOV lanes encourage people to switch from driving alone. Over 50% of carpoolers previously drove alone. • HOV lanes are a good public investment. Most residents (82%) support the use of a portion of sales tax revenues for transit-related highway improvements like HOV lanes. • Many HOV lanes are full and have no capacity to sell. They are carrying between 1,200 and 1,600 veh/hr/ln during peak periods. • HOV lanes are important to bus transit. One-third of transit riders surveyed would most likely discontinue riding the buses if they were no longer able to travel in the HOV lanes. • Violation rates are 0-1% on most routes. The maximum rate found is only 3% • HOV lanes can help air quality. They generate about half the emissions per person-mile than the other MF lanes on a freeway. • A majority of carpoolers (82%) uses HOV lanes to save travel time rather than other reasons.	• General public (76%) understands and strongly supports HOV lanes. • Introduction of HOV lanes on freeways has been followed by a gradual growth of ridesharing and an increase in the life span of carpooling and vanpooling arrangements. • Existing HOV lanes are well utilized, with most operating near full capacity during the peak periods. • With the exception of a few instances, HOV lanes provide time savings ranging from 1 to 15 minutes to rideshare vehicles per trip. • There is no evidence that HOV Lanes are subject to a greater accident rate than other freeway lanes. The installation of direct HOV-to-HOV connectors almost universally reduced accident rates in the vicinity of the affected intersections. • Violation rates average 1.2%, well below the 10% level identified as a threshold for concern. • Transit operations currently contribute relatively little to person movement on the HOV lanes. • Current occupancy requirement are adequate at this time. Based on modeling results, regional VMT, VHT, and average speed are all optimized with a 2+ occupancy requirement. • Continued 24/7 operation of HOV lanes is supported and warranted as congestion and peak spreading continue to grow. • Public surveys express a preference for HOV lane separations from MF lanes.

It is often difficult to evaluate and compare HOV lane performance as a lump sum because HOV lanes can have significantly different characteristics. Key characteristics that affect overall operations of an HOV lane include: a) whether it is part-time or full-time, b) vehicle occupancy requirement (i.e., 2+ or 3+ occupancy) and exemptions (e.g., low-emission and energy-efficient vehicles), c) enforcement, d) access control (i.e., limited access or open access), and e) lane separation (i.e., whether lanes have a buffered separator or not), among others. In the following section, we focus our literature review on HOV lane performance with respect to access control, which is closely related to the subject of this research.

2.2. Limited Access versus Continuous Access

An interest in comparing the performance of limited access versus continuous access HOV facilities in California dated back a number of years. In a 2002 study for the Orange County Transportation Authority, advantages and disadvantages of both types of HOV facilities were assessed under various criteria including cost, safety, operation, violation, etc. [Parsons Brinckerhoff Quade and Douglas, Inc., 2002]. A summary is provided in Table 2-2.

The assessment was based in part on anecdotal evidences as HOV performance data were very limited at that time. Since then, there has been significant improvements to data and research tools that has enabled more objective HOV studies. For example, the Caltrans Performance Measurement System (PeMS) has been an important data source for numerous freeway operation studies. In addition, research tools such as traffic microsimulation as well as video cameras and image processing software have been increasingly used for a variety of traffic studies.

In the past decade, there have been many studies in California that compare the performance between limited access and continuous access HOV facilities over the past decade. This section reviews some of these studies with a focus on the comparison of operational performance between the two types of HOV access control. In addition, a cursory review on the comparison of safety and environmental performances between the two types of HOV access control are also provided.

Table 2-2. Advantages and disadvantages of limited access and continuous access HOV facilities [Parsons Brinckerhoff Quade and Douglas, Inc., 2002]

Criterion	Limited Access	Continuous Access
Cost	• Buffers add cost. If right-of-way is available, cost is lower; if constrained or structured, costs are higher. • No incremental cost to restrict access at project outset. • Re-striping and re-signing cost to change once open.	• Lack of buffer reduces right-of-way cost and impervious surface needs. • Re-striping and re-signing cost to change once open.
Safety	• No systematic impact on accident rate, compared to effect of traffic dynamics and facility design. • Concentrates merging and weaving at designated areas, reduces merging between access points. Impact is location specific.	• No systematic impact on accident rate, compared to effect of traffic dynamics and facility design. • Queued general-purpose traffic can maneuver into HOV lane unexpectedly, creating perception of accident danger.
Isolation from general-purpose congestion and incidents	• Minimized impact in HOV lane from incidents and congestion in general-purpose lane. • HOV traffic flow can be further enhanced by combining benefits of left-side shoulders, direct access ramps, bus service.	• HOV lane users can gain access to all general-purpose ramps. • HOV volumes can spike at congestion hot spots as HOV traffic shifts into the HOV lanes. • HOV lane may appear underutilized except when freeway is congested.
Impact on general-purpose traffic	• If designed well, weaving can be concentrated where adequate capacity exists. • Direct access further reduced weaving to access HOV lane.	• Weaving is distributed along an entire corridor. • Concentrated weaving at inappropriate locations or inadequate weave distance exacerbates bottlenecks.
Violation rates and enforceability	No significant difference is known. Requires: • Adequate space for enforcement activity, and • Adequate enforcement budget.	
Regional consistency	• Buffer and access treatments should be consistent with adjacent facilities. • Isolated buffer and access treatment variations may be appropriate when a facility does not connect to other HOV facilities.	
Compatibility with HOV and transit operation	• May be desired in anticipation of future HOT lane or BRT operation. • Direct access can be provided to further reduce bus weaving.	• Most appropriate when HOV lanes are used for general-purpose at some times.

2.2.1. Operational Performance

Wu et al. [2011] conducted a comparative study of the operational performance of the two types of HOV facilities at the route level based on 6-months' traffic data from more than 700 vehicle detector stations. The study revealed that the ingress/egress areas in limited access HOV facilities could trigger the formation of bottlenecks along HOV lanes. The speed on HOV lanes and the speed differential between the HOV and mixed-flow (MF) lanes are statistically greater in continuous access HOV facilities than in limited access HOV facilities. The analyses on speed-flow probability histograms indicate that the mode speed (which appears most frequently) of HOV lane is significantly higher while the mode flow of HOV lane is lower for freeways with continuous access HOV facilities. The mode speed and mode flow of MF lanes are similar regardless of the access type. Furthermore, statistical analyses show that some performance measures at the route level, including space mean speed and vehicle-miles-traveled (VMT) share of the HOV lanes, are significantly different for HOV facilities with the different access controls. Continuous access HOV facilities have higher space mean speed but lower VMT share of the HOV lane.

Du, et al. [2012] investigated the impacts of collisions in HOV lane on the performance of HOV facilities with different access controls. Based on 5-minute loop detector data and HOV lane collision records from 17 study routes in 2008, the real-world collision-induced impacts were estimated by the following steps: 1) synchronizing HOV lane collision-related information from PeMS and the Traffic Accident Surveillance and Analysis System (TASAS); 2) identifying the collisions' impacts based on the traffic data; and 3) calculating the collision-induced delays. The statistical analysis results implied that the impacts of collisions in HOV lane on the travel delays in both the HOV and the adjacent MF lanes are smaller for continuous access HOV facilities (but not statistically significant at 5% level).

Jang, et al. [2012] compared the operational performance of HOV facilities with four different operation policies: 1) part-time continuous access, 2) full-time limited access, 3) full-time continuous access, and 4) part-time limited access. The performance of selected study sites were analyzed based on the data from HOV annual reports and PeMS. The performance metrics selected for comparison included speed differential between the HOV lane and MF lanes as well as VMT and passenger-miles-traveled (PMT) ratio which measures the utilization level of HOV lane by vehicle-miles and by person-miles, respectively. Based on the data samples of selected HOV facilities, it was found that continuous access HOV lanes have greater speed differentials and a little higher PMT ratio, but also higher variations in VMT and PMT.

Du, et al. [2013] extracted lane change data with high spatial and temporal resolution from videos taken from overpasses at multiple locations in Riverside, California. They investigated lane changing behavior on freeways with the different types of HOV access controls. In addition, those lane change data were correlated with flow and lane occupancy data for each freeway lane from PeMS. The results revealed that limited access HOV facilities have a shorter time gap when the subject vehicles moved out of the HOV lane. Also, most of the lane changes on limited access HOV facilities occurred within the first half of the ingress/egress areas.

Boriboonsomsin et al. [2013] simulated traffic on a section of SR-91 in Riverside County, California, with each type of the two HOV access controls. The results indicated that the freeway with either limited access or continuous access HOV lane tends to have similar average travel speeds (less than 2 mph different) when there is no congestion. When traffic gets moderately congested, the freeway with continuous access HOV lane has higher overall average travel speeds. This is partly because HOVs in the MF lanes can move into the continuous access HOV lane as soon as the traffic in the MF lanes starts to get congested in order to take advantage of the higher speed in the HOV lane. In the case of the freeway with limited access HOV lane, the HOVs must slow down and move along the queue until they reach the next ingress/egress area before getting into the HOV lane.

Wu, et al. [2015] developed a statistical framework for comparing the empirical capacity of freeway with the different types of HOV facilities based on regression analyses using California statewide dataset as a case study. Two data sources were utilized to set up the regression models. Empirical capacity determined from PeMS was the response variable, while most of the explanatory variables were obtained from the federal's Highway Safety Information System (HSIS). The results consistently indicated that freeway segments with limited access HOV facilities would have higher overall capacity than those with continuous access HOV facilities, given that everything else being equal.

In a recent study by Qi, et al. [2015], a unique set of second-by-second vehicle trajectory data were collected from all the vehicles on the same freeway segment of SR-60 in Moreno Valley, California, before and after a conversion of the HOV lane from limited access to continuous access. Using a Kalman Filter smoothing algorithm, the raw vehicle trajectory data were cleaned before lane change statistics were calculated. The result not only shows that the time gaps of lane changes are statistically larger for continuous access HOV facilities, which is consistent with the findings in previous research (e.g., [Du et al., 2013]), but also suggests some new findings. For example, the HOV utilization before and after the conversion was almost the same.

2.2.2. Safety Performance

Based on data from selected HOV facilities in California, Newman, et al. [1988] pointed out that the barrier-separated design outperformed the buffer-separated one in terms of safety, and that continuous access HOV facilities operated least safely. No significant speed differential between the HOV and the MF lanes (<10 mph) was observed. Also, no apparent relationship between HOV utilization and the rate of HOV lane related accidents was evident. However, these conclusions were based on specific conditions of the studied HOV facilities, such as traffic demand, public opinion, etc.

Chung et al. [2007] applied historical accident data from a number of freeway corridors in California to illustrate the lane-by-lane collision distribution. By comparing the safety performance between the two types of HOV lanes, they concluded that the restriction on the entrances and exits of the HOV lanes could cause more intense and challenging lane-changing actions. Consequently, a greater proportion of collisions would likely occur near those locations.

Jang, et al. [2009] evaluated the safety performance of both continuous access and limited access HOV facilities in California. The results showed that the collision rate (in terms of number of collisions per million VMT) of continuous access HOV lanes is statistically smaller than that of limited access ones. Traffic volume and geometric factors, such as shoulder width, total width, length of access, and the proximity of the access to its neighboring ramps, were identified to be important explanatory variables for the collision characteristics (frequency, location, and type) in HOV facilities.

2.2.3. Environmental Performance

Very few HOV studies have considered environmental performance, in terms of vehicle fuel consumption and emissions, of HOV lanes (e.g., [Boriboonsomsin and Barth, 2006]). Even fewer studies compare the environmental performance between the limited access and continuous access controls.

Boriboonsomsin and Barth [2008] used an integrated traffic microsimulation and modal emissions modeling tool to analyze the emission impacts of HOV lanes. Under various scenarios with different levels of vehicle demand and percentage of HOVs in the traffic mix, it was found that a freeway with continuous access HOV lane consistently produces lower levels of pollutant emissions compared to if the same freeway has limited access HOV lane. This is primarily due to the highly concentrated weaving maneuvers that take place on the dedicated ingress/egress sections on the freeway with limited access HOV lane, which cause relatively higher frequency and magnitude of acceleration and deceleration events, resulting in higher emissions on these sections of the freeway.

2.3. Operational Characteristics of HOV Lanes

The presence of HOV lane on a freeway makes freeway operations more complex. It introduces another flow of traffic that not only have significant interactions with but also have different characteristics from the main flow of the freeway. In many cases, standard freeway operational analysis tools and techniques do not apply to HOV lanes. In this section, some of the topics related to operational characteristics of HOV lanes are presented.

2.3.1. Smoothing Effect

Intuitively, one may presume that an introduction of HOV lane would induce more lane changes, especially by HOVs that get on the freeway trying to enter the lane as well as HOVs that exit the lane in order to get off the freeway. Consequently, there would be more disruption to traffic flow in the MF lanes resulting in reduced freeway throughput.

However, some research studies have shown that that is not always the case. In some cases, the presence of HOV lane has little to no adverse impact on the traffic flow in the MF lanes.

A simulation model developed in Menendez and Daganzo [2007] showed that an HOV lane implementation diminishes the lane changing behavior between the HOV lane and the adjacent MF lane. That results in smoother traffic flow across all lanes even when the HOV lane is underutilized. This model assumes that the drivers are aggressive, rational, consistent, and myopic. Their decisions are made in each discrete time interval. The lane-changing behaviors are categorized into three types: mandatory time-related (T-changes), mandatory space-related (S-changes), and optional (O-changes). T-changes correspond to the lane changes of SOVs from the median lane to the adjacent lane right after the HOV actuation in the case of part-time HOV operation. S-changes correspond to the lane changes when vehicles enter or exit the freeway. O-changes are made by drivers that would like to switch to the faster lane if the speed difference between the HOV and MF lanes exceeds a certain value.

Based on the assumptions and parameters above, Menendez and Daganzo [2007] modeled the operational impact of HOV lane under three scenarios. First, the model was applied to a 4-mile, 4-lane ring road with an HOV lane. Entering vehicles were added only when there were sufficient gaps, and exiting vehicles were removed from the traffic stream so that no bottleneck was generated during the simulation. This scenario showed that the capacity of the MF lanes is reduced, at most 450 vehicles per hour per lane (vphpl), as the HOVs cross the MF lanes when entering and leaving the freeway. When the system is under-saturated, the HOV lane has little impact on the MF lanes. Under the saturated condition (but before a bottleneck is formed), the HOVs have a negative impact on vehicles in the MF lanes as those vehicles have to make gaps for the HOVs to make lane changes. This can be considered as a drawback of HOV lanes.

Under a merge bottleneck scenario, another test was conducted on a 1-lane on-ramp merging into a 4-lane freeway with an HOV lane. It showed that the average discharge flow across all MF lanes stabilized at 2,050 vphpl for all HOV flows varying from 0 to 2,000 vphpl. Noticeably, if the HOV restriction was removed, the average discharge flow for the MF lanes would decrease slightly to 1,950 vphpl. This test implied that although the disruption effect of HOVs on MF lanes still exists, the discharge flow of the MF lanes can be well compensated by reduced number of lane changes from MF lanes to the median (HOV) lane. Under a diverge bottleneck scenario, the HOV lane has little effect on the capacity no matter if it is on the branch of larger or smaller flow.

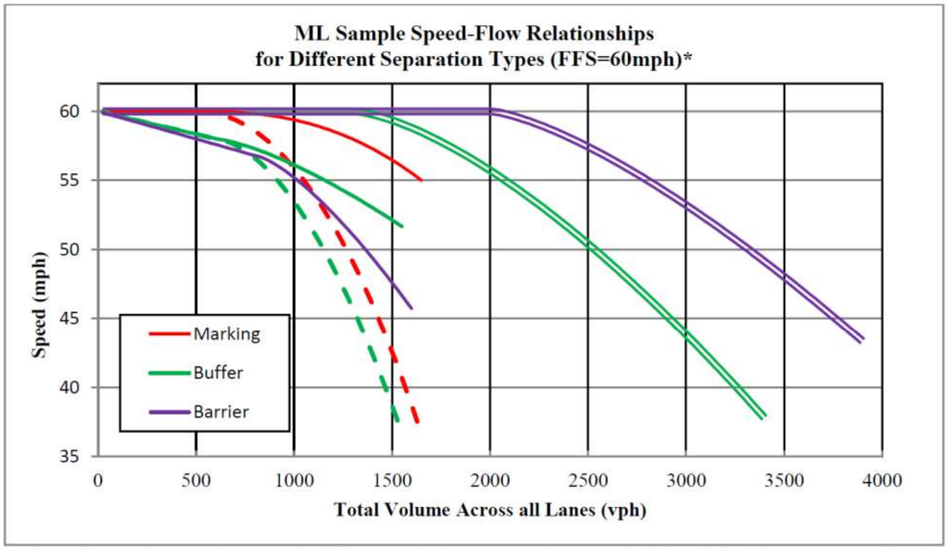
Cassidy et al. [2010] validated this “smoothing effect” of HOV lane using video data collected at I-880 N in Hayward, California. At this study site, the median lane is reserved for carpools on weekdays during the morning peak from 5:00 to 9:00, and afternoon peak from 15:00 to 19:00. Vehicle count data from the videos showed that the flow in the median lane dropped around 15:00 due to the actuation of HOV lane. However, the total flow for all lanes remained steady at about 7000 vph. Considering the underutilization of the HOV lane, it meant the flow rate of the MF lanes actually increased. This phenomenon can be explained by the reduction in lane changing rates in the MF lanes. For the MF lane that is adjacent to the HOV lane, the lane changing rate reduced from 1,280 times/hr/km before 15:00 to 990 times/hr/km after 15:00. The lane changing rate of the middle MF lane also decreased after the HOV actuation. The rightmost MF lane was not affected during that period. In summary, the smoothing effect was contributed by the reduction in the number of lane changes in the two MF lanes adjacent to the HOV lane.

2.3.2. Frictional Effect

Many researchers have studied the interactions of traffic flow between the HOV and the MF lanes. Jang and Cassidy [2012] pointed out two major reasons for the possible slow speed in HOV lanes: high demand for HOV lane itself or slow speed in the adjacent MF lane. This was supported by the field data from I-80 W in Berkeley, California, where the HOV lane speeds fell below 45 mph for more than 40% of the operating times. The time series of speed showed that a reduction of speed in the adjacent MF lane will cause a reduction of speed in the HOV lane, with about 2 minutes of lag. In Liu et al. [2011], such impedance on the speed of HOV lane from the adjacent MF lane is referred to as "frictional effect". This effect occurs when the HOV drivers observe the congested traffic in the adjacent MF lane and feel uncomfortable to pass those slow vehicles rapidly without adequate barrier separation. It results in reduced total flow across all lanes.

Figure 2-1 shows the speed-flow relationships of various types of managed lanes [Wang et al., 2012] including those under the influence of the frictional effect. Each speed-flow curve is based mainly on data collected from several states in the U.S. Data generated by calibrated micro-simulation models are used to supplement the types of managed lanes that are scarce or impractical to gather data from the field. For the continuous access design (labeled "Marking" in the figure), the frictional effect is significant, causing a large drop in total flow across all lanes. For the barrier-separated design, there is no frictional effect. For the buffer-separated design, the effect is somewhere in between. On the other hand, Figure 2-1 also shows the effect that a single HOV lane with buffer or barrier separation has on the car following behavior of HOV drivers. As passing is prohibited for HOVs under this circumstance, the HOV drivers tend to leave a larger headway from the vehicle in front than usual. This results in a significant drop in total flow across all lanes as well as reduced speed even under low volume conditions.

Although the limited access design (either with buffer or barrier separation) suffers less from the frictional effect, Cassidy and Kim [2015] suggested that the access points are prone to become bottlenecks, especially when traffic in the MF lanes is heavily congested. Under this condition, the HOVs in the MF lanes will likely want to use the HOV lane for higher speed. The lane changes will then be heavily concentrated within the short access point. Queues will be formed and the discharge flows for both the HOV and MF lanes will be reduced. The authors studied the bottleneck around an access point on I-210 E in Southern California. Video data showed that an increase in traffic volume was accompanied by the disproportionate increase in the leftward lane-changing count. The average bottleneck duration was 0.7 hour and the discharge flow in the MF lanes was reduced by 6.6%.



* Single lines refer to one-lane ML facilities, double lines to two-lane ML facilities; dashed lines correspond to the speed-flow relationship under *friction effect* conditions

Figure 2-1. Speed-flow relationships for various types of managed lanes [Wang et al., 2012]

2.3.3. Dual HOV Lanes

Wang et al. [2012] studied several freeway facilities with dual HOV lanes, including the buffer-separated dual HOV lanes on a portion of I-110 in Los Angeles, California, the barrier-separated reversible express lanes on I-5 in Seattle, Washington, and the barrier-separated dual HOT lanes in a 3-mile portion of I-394 in Minneapolis, Minnesota.

The dual HOV lanes system would increase the capacity of the HOV lanes. As shown in Wang et al. [2012], if the free-flow speed is 65 mph, the capacity of buffer-separated dual HOV lanes system will be 1,750 passenger cars per hour per lane (pcphpl), based on the 99.5th percentile value. This value is greater than the capacity of continuous access single HOV lane (1,700 pcphpl), buffer-separated single HOV lane (1,600 pcphpl), and barrier-separated single HOV lane (1,700 pcphpl). For barrier-separated dual HOV lanes, the capacity is never reached. The highest observed value is around 1,800 pcphpl. One reason for the higher capacity in dual HOV lane facilities is that there is no “snail effect” where slow HOVs prevent other HOVs from traveling faster as there is no passing lane. On dual HOV lane facilities, these slower vehicles can be passed. The two curves with double lines Figure 2-1 represent the speed-flow relationships of dual HOV lanes for a free-flow speed of 60 mph. This figure shows that the added HOV lane helps maintain the free-flow speed when the freeway segment is under-saturated, and increases the capacity of the freeway segment under congestion.

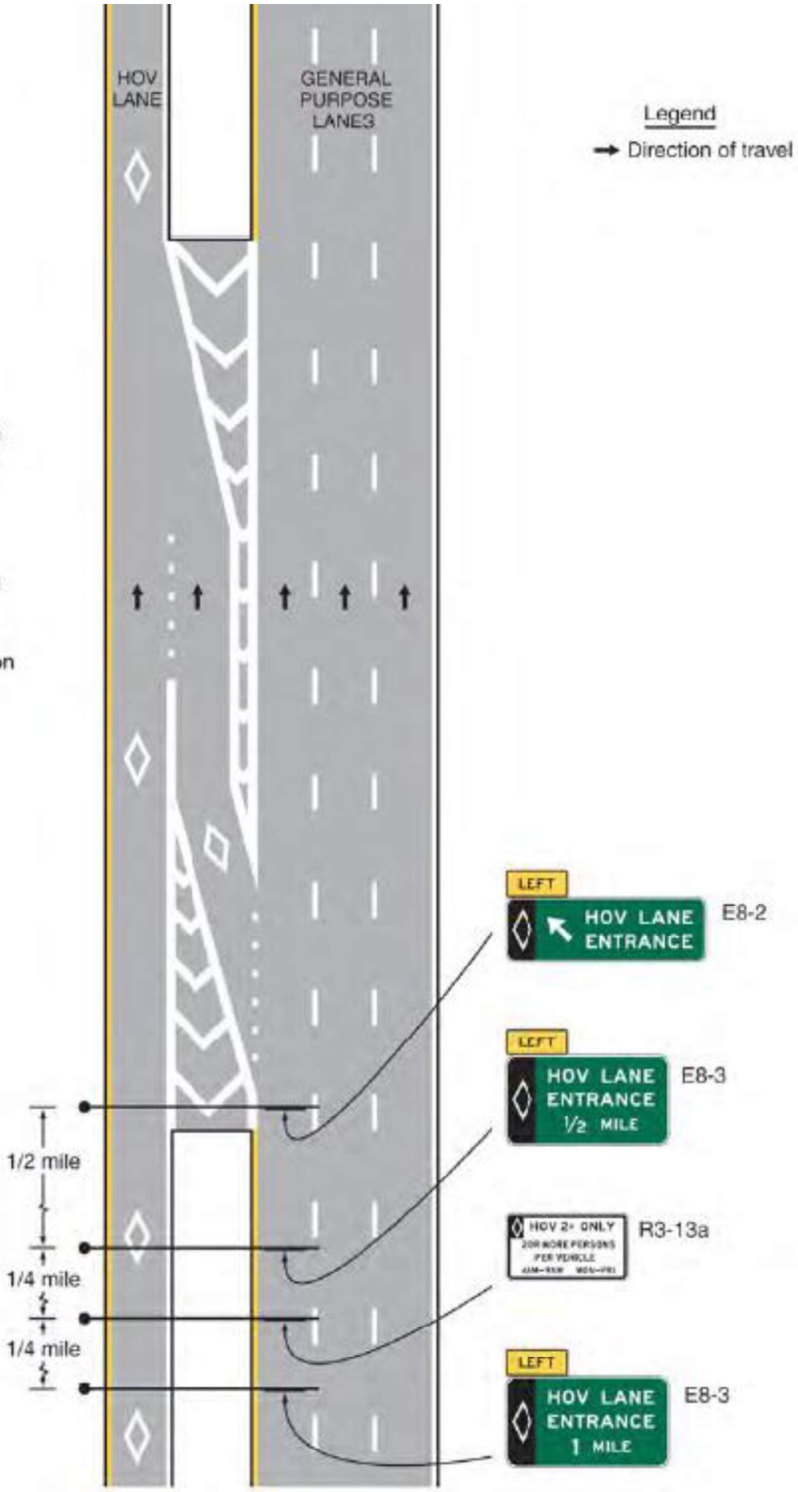
Dual HOV lanes are also implemented in Northern California as part of the US-101 Auxiliary Lanes Project. According to Fehr & Peers [2009], a second HOV Lane was to be added between SR-85 and Oregon Expressway/Embarcadero Road interchange for both northbound and southbound. The measures of effectiveness in 2015 and 2035 were forecasted. In 2015, the dual HOV lanes would effectively alleviate the bottleneck for the southbound, and reduce the queue length for the northbound bottleneck significantly. In 2035, although bottleneck would be inevitable for both directions, the additional HOV lane could substantially reduce travel times and delays.

2.3.4. Signing and Striping Requirements for HOV Lanes

The federal Manual on Uniform Traffic Control Devices, or MUTCD, provides detailed guidelines for meeting the signing, striping, and pavement marking requirements of HOV lanes, one type of preferential lanes in the manual [Federal Highway Administration, 2012b]. Depending on the purpose of either enforcement (regulatory) or guidance (warning), a variety of HOV facility related signing, striping, and pavement markings are provided in different tables and figures in the manual. In addition, the specifications of signage and markings may vary with the access control (e.g., contiguous, buffer-separated, or barrier-separated) and the relative location of the facility (e.g., beginning, intermediate entry/exit, or end). For example, Figure 2-2 and Figure 2-3 show signing guidelines for an intermediate entry to and egress from a barrier- or buffer-separated HOV lane, respectively.

Based on the federal MUTCD and other publications, Caltrans has developed its own version of California MUTCD [Caltrans, 2014b]. For HOV facilities, the majority of standards and parameters conform to those in the federal MUTCD, but some detailed designs may be modified to meet the state's specific needs. For example, Figure 2-4 presents pavement markings for buffer-separated HOV lanes modified for use in California. Detailed information on signage and markings for HOV lanes in California is included in the Caltrans' high-occupancy vehicle guidelines for planning, design, and operations [Caltrans, 2003].

One consideration in the signing and striping of HOV lanes is the access control. For limited access HOV lanes, the current policy of Caltrans is that access openings should have a minimum length of 2,000 ft, and that a minimum of 800 ft per lane change should be provided between the opening and the nearest freeway entrance or exit ramp. These lengths should also be utilized at the beginning and ending of managed lanes.



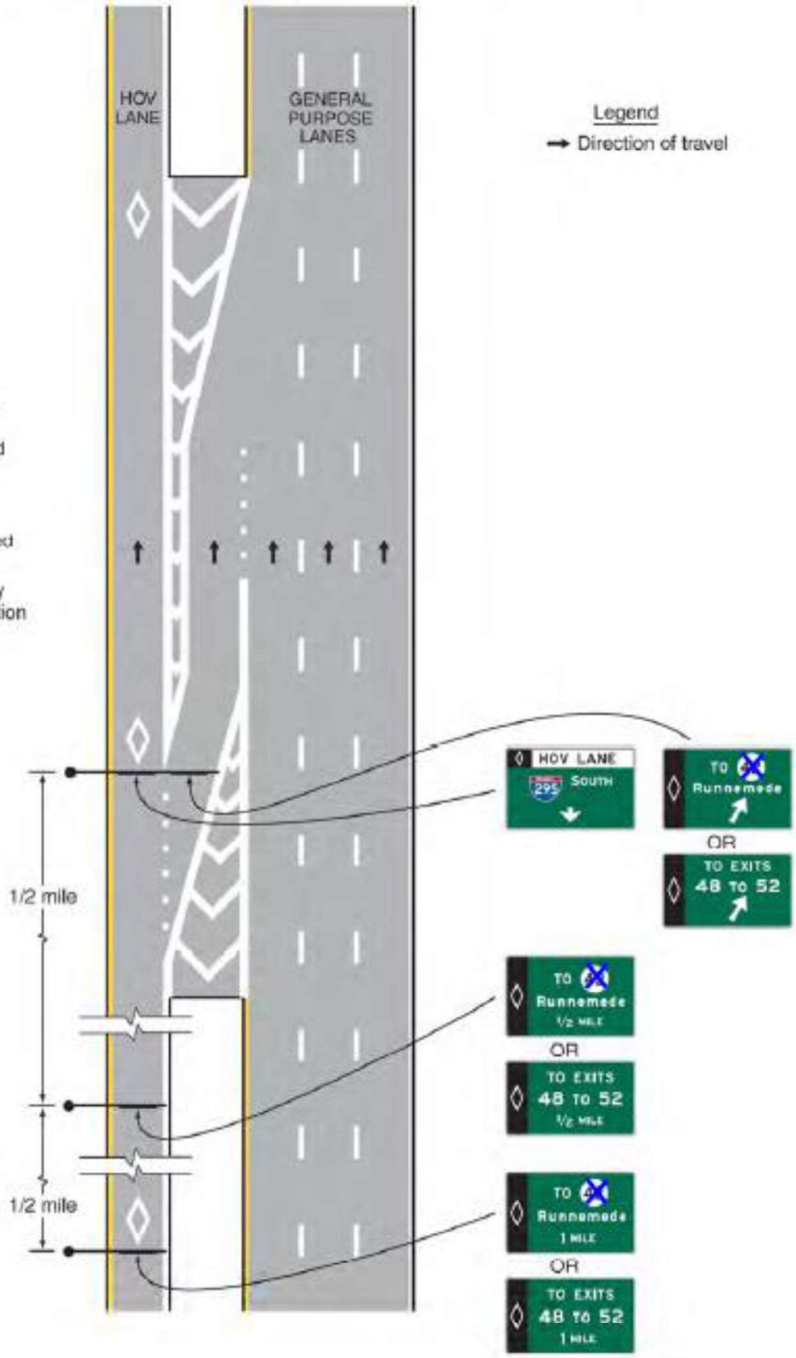
Notes:

1. For access to an HOV lane on the right-hand side, the same signing sequence would be used with adjustments made to sign messages
2. Geometry is for illustrative purposes only; use locally applied geometric criteria
3. The minimum vehicle occupancy requirement and hours of operation on the sign may vary for each facility
4. See Chapter 3D for pavement markings.
5. Warning signs are not shown

Figure 2-2. Signage for intermediate entry to a barrier- or buffer-separated HOV lane [Federal Highway Administration, 2012b]

Notes:

1. For an exit on the left-hand side from an HOV lane, the same signing sequence would be used with adjustments made to sign messages
2. Geometry is for illustrative purposes only; use locally applied geometric criteria
3. The minimum vehicle occupancy requirement and hours of operation on the sign may vary for each facility
4. See Sections Chapter 3D for pavement markings
5. Warning signs are not shown



Note: For Guide Sign Assemblies use California State Route (G28-1(CA)) and US Route (G26-1(CA)) shields.

Figure 2-3. Signage for intermediate egress from a barrier- or buffer-separated HOV lane [Federal Highway Administration, 2012b]

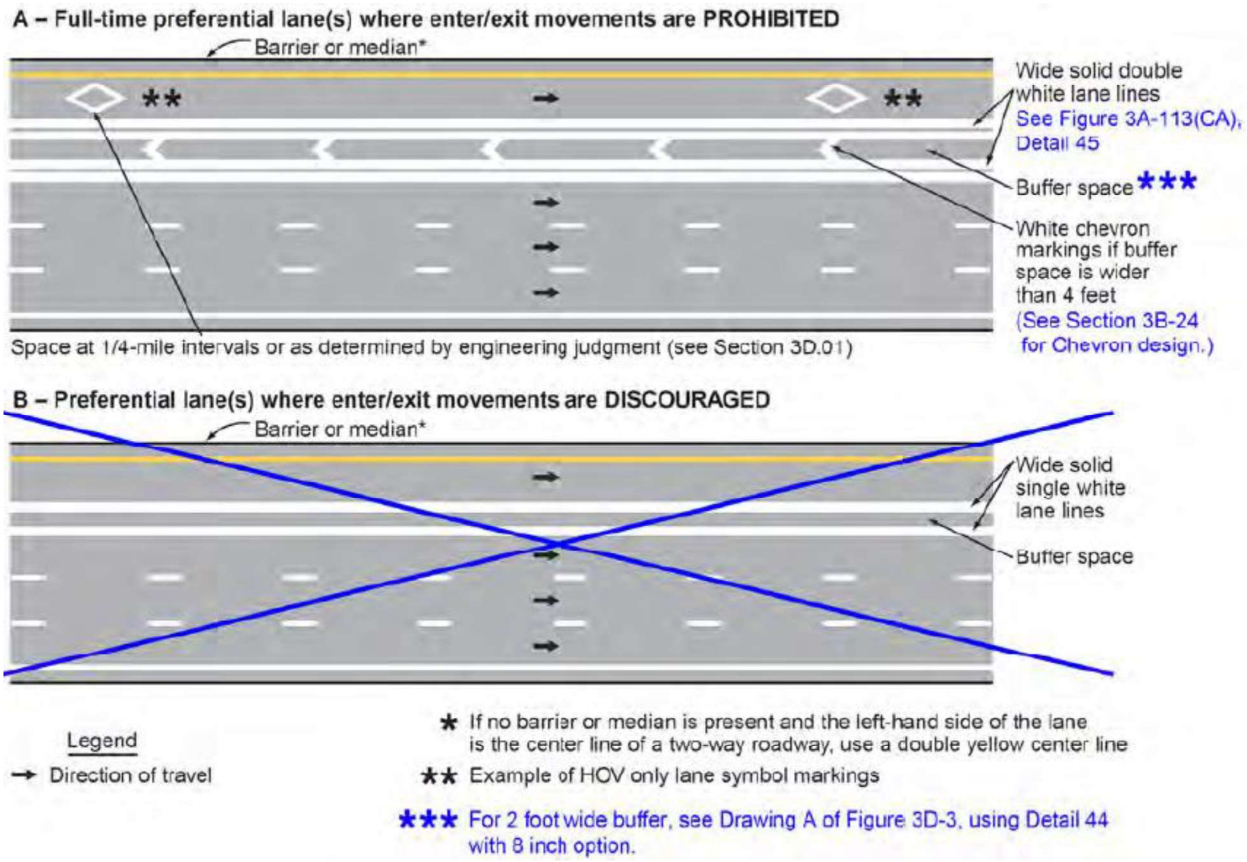


Figure 2-4. Pavement markings for buffer-separated HOV lanes in California [Caltrans, 2014b]

2.4. Case Studies

Based on the literature review on HOV lane operational performance, the limited access and continuous access HOV lanes are found to have the following key characteristics.

- Limited access HOV lanes would provide higher freeway throughput across all lanes if everything else being equal [Wu et al., 2015]. They also suffer less frictional effect from the slower speed in the adjacent MF lane [Jang and Cassidy, 2011; Wang et al., 2012]. However, they may be prone to have bottlenecks at ingress/egress locations, especially when MF lanes are congested [Wu et al., 2011; Cassidy and Kim, 2015].

- Continuous access HOV lanes would provide higher average freeway speed when MF lanes are congested as HOVs are not hold back from entering the HOV lanes [Boriboonsomsin et al., 2013]. They are also less likely to have disrupted traffic flow as lane changes are more spread out and less aggressive with larger time gap and clearance distance [Du et al., 2013; Qi et al., 2015].

These findings make a case for a new design of HOV lane configuration where continuous access is generally provided along the freeway to achieve higher travel speed while buffers are strategically placed on selected freeway segments (e.g., bottlenecks) to accommodate higher throughput on those segments, as shown in Figure 1-1. It is expected that this “partially limited access” design would result in a better overall operational performance of the freeway than the existing limited access and continuous access designs. This section presents a few case studies of HOV lane implementations whose access control is similar to the partially limited access design.

2.4.1. SR-55 HOV Lanes in Orange County, CA

Traditionally, HOV lanes in Southern California were mostly implemented with the limited access design. In the last several years, Caltrans District 12 has converted a portion of its HOV lanes from the limited access design to continuous access. However, there are a few locations on the continuous access HOV facilities in the district that a single white solid stripe was used to discourage lane changes between the HOV lane and the adjacent MF lane. These locations are either at the beginning or at the end of freeway-to-freeway HOV connectors. Although the single white solid stripe does not prohibit motorists from making lane changes, it is felt that the stripe has been effective at reducing the number of lane changes, perhaps due to the motorists’ misunderstanding of the legal meaning of the single white solid stripe [Haber and Pham, 2015].

One of the locations is on SR-55 near E McFadden Ave, shown in Figure 2-5. The start and end points for the single white solid stripes for both northbound and southbound directions are marked on the map in the figure. For northbound, the HOV lane diverges into 2 lanes, the left one going to I-5 and the right one staying on SR-55. The single white solid stripe starts ahead of this road sign so that this diverge is not disrupted by the MF lanes. It switches to a broken stripe after the lane to I-5 is separated by concrete barrier. For southbound, the HOV lane from I-5 and the HOV lane on SR-55 merge at the area shown in the upper right photo in Figure 2-5. The single white solid stripe starts ahead of the merging area to ensure that this merge is not disrupted by the MF lanes. It switches to a broken stripe after the two HOV lanes merge completely.

Another location is on SR-55 near the off-ramp to MacArthur Blvd. In the northbound direction, the starting and ending points of the single white solid stripe are marked on the map in Figure 2-6. The HOV traffic on SR-55 merges with the HOV traffic from I-405 right after the start of the single white solid stripe. The single white solid stripe is used to discourage the entry from the adjacent MF lane so as not to disrupt the merge. It is also used to discourage the late exit of HOV vehicles to reach the off-ramp to MacArthur Blvd.

Figure 2-5. SR-55 near E McFadden Ave

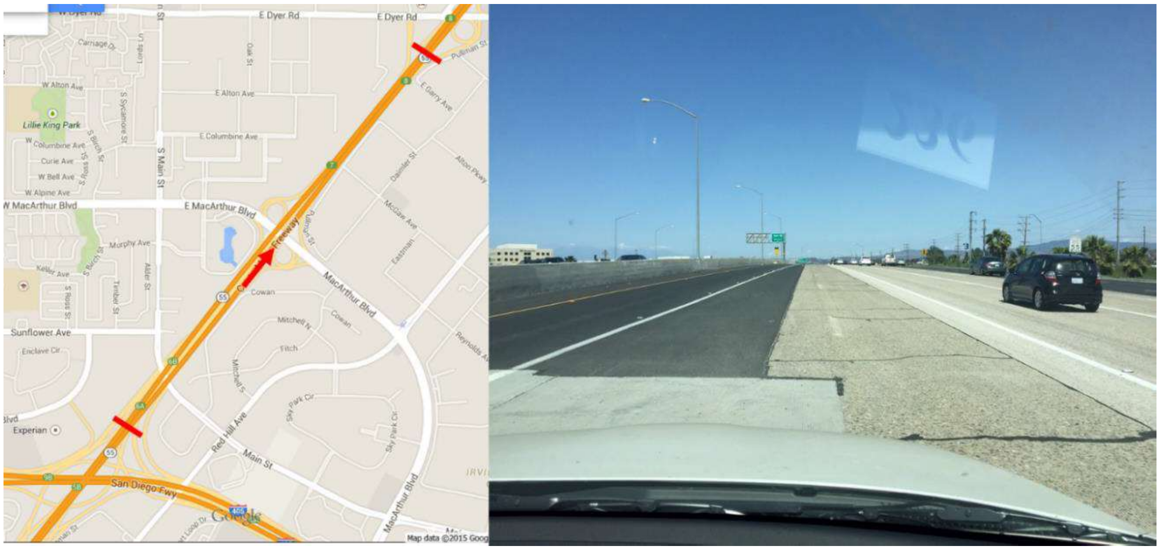


Figure 2-6. SR-55 near the off-ramp to MacArthur Blvd

2.4.2. SR-237 Express Lanes in Santa Clara County, CA

Located in the heart of the Silicon Valley, SR-237 continues to experience saturated operating conditions during peak commute hours, resulting in traffic back-ups in the morning on the freeway approach from southbound I-880 and from local street approaches from Calaveras Boulevard and McCarthy Boulevard to westbound SR-237; and in the evening along eastbound SR-237 itself, along the mainline on SR-237 from Lawrence Expressway to North First Street [Parsons Brinckerhoff Inc., 2010]. As part of the near-term congestion relief program by the Santa Clara Valley Transportation Authority (VTA) in coordination with Caltrans, the connector ramps at the SR-237/I-880 interchange were converted from HOV lanes to express lanes in 2012 as the first phase of the SR-237 Express Lanes Project (Figure 2-7). The express lanes in both directions are operated on weekdays during 5-10 a.m. and 3-7 p.m.

Figure 2-8 shows the SR-237 express lanes around the SR-237/I-880 interchange. Two photos were taken from the east side and west side of the N McCarthy Blvd overpass. It can be observed from the figure that the express lanes and the adjacent MF lanes are separated by double solid white stripes, a portion of which also includes a 2-ft buffer zone. According to Caltrans District 4 engineers, both drivers and local government officials prefer the more flexible access into and out of the express lanes provided by the continuous access design. However, the buffer was placed to minimize weaving maneuvers around the SR-237/I-880 interchange in order to mitigate the queue spilling back onto I-880 southbound or SR-237 eastbound during the peak hours. Based on field observations, it was felt that the buffer has been effective [Seriani and Ma, 2015].

Figure 2-7. SR-237 express lanes [Santa Clara Valley Transportation Authority, 2015]

(a) Looking toward eastbound

(b) Looking toward westbound

Figure 2-8. Buffered sections on SR-237 express lanes

2.4.3. HOT Lanes in Minneapolis, MN

The Minnesota Department of Transportation (MnDOT) has implemented and operated HOT lanes (nicknamed “MnPASS”) for many years. I-394 became the first freeway in Minnesota with HOT lanes in May 2005. The HOV lanes on this freeway were converted into HOT lanes by equipping the lanes with sensors and leasing transponders to SOVs. Approximately 65% of the facility have access control, where HOV lanes are separated from MF lanes by double white solid lines. As the majority of the traffic on this freeway is originated from three interchanges, including I-494, TH-169, and TH-100 (see Figure 2-9), the I-394 HOT lane access points are designed to accommodate the traffic from those interchanges. The locations of the access points are established based on a criterion of 1,800 ft per lane change to ensure safe lane changes to enter or exit the HOT lanes [Kary, 2015].

The violation rate dropped dramatically from 30% to less than 5% after converting to HOT lanes, as some of the violators became customers and the toll revenue funded the increased enforcement. The limited access control prevents lane jumping and requires fewer transponder readers. However, it concentrates all weaving movements at the access points, which sometime causes disruption on the MF lanes. Some negative feedback has been received from the travelers as the limited access control prohibits them from entering the HOT lane at any point. Particularly, bus drivers on I-394 have complained that the slow MF lanes ahead often prevented them from entering the HOT lanes. They sometime had to wait 2,000 ft or so in the queue before they reached the access point and could get into the HOT lane. MnDOT has plans to convert the HOT lanes on I-394 from limited to continuous access in 2016 as part of a pavement resurfacing work [Kary, 2015].

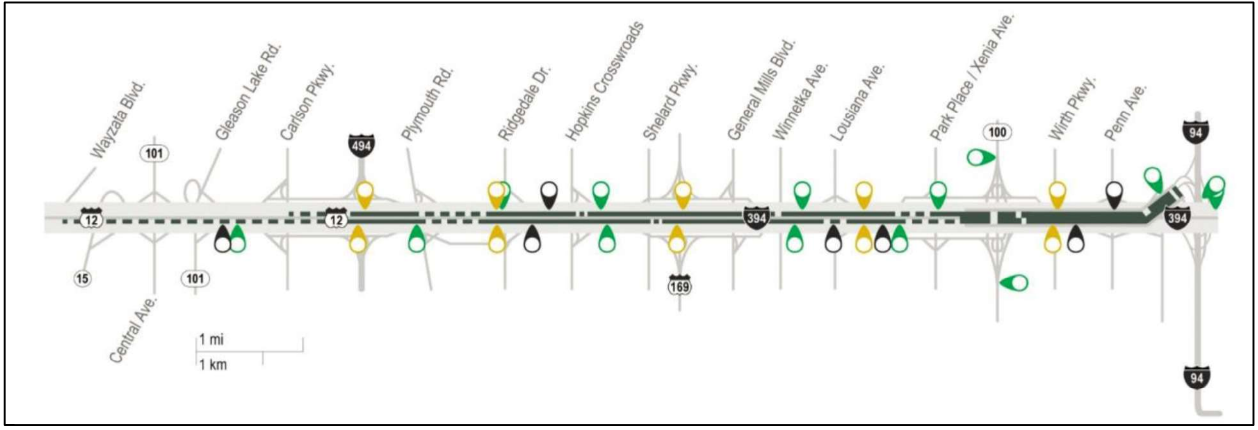


Figure 2-9. I-394 corridor (source: Minnesota Department of Transportation [2014])

On the other hand, HOT lanes on I-35 W—the second in Minnesota—was implemented with the continuous access design as the interchange density is high and the freeway entrance ramps are closely spaced (see Figure 2-10). Lane changes between the HOT and adjacent MF lanes are allowed everywhere except for a few specific locations. Access is only restricted within the major freeway interchanges of Hwy 62, I-494, and Minnesota River Bridge. With the continuous access design, toll transponder readers are placed approximately every 1-1.5 miles. Generally, they are placed about 3,000 ft past an entrance ramp [Kary, 2015].

For the river crossing section between Black Dog and 106th St, the NB HOT lane is separated from the MF lanes with a 2-ft buffer and double white solid stripes. For the SB direction, as there is no room for the buffer and double white striping after adding the HOT lane, the continuous access design was used. The use of different access control designs in opposite directions of the freeway also allows the Minnesota Department of

Transportation to compare the performance of limited versus continuous access designs under similar conditions. In general, travelers are more satisfied with the continuous access design as they can move in and out at any time [Kary, 2015].

In the future, more HOT lanes will be constructed with the continuous access design. However, the limited access design may be implemented at some locations as needed over time to maintain smooth traffic flow in the HOT lane [Kary, 2015].

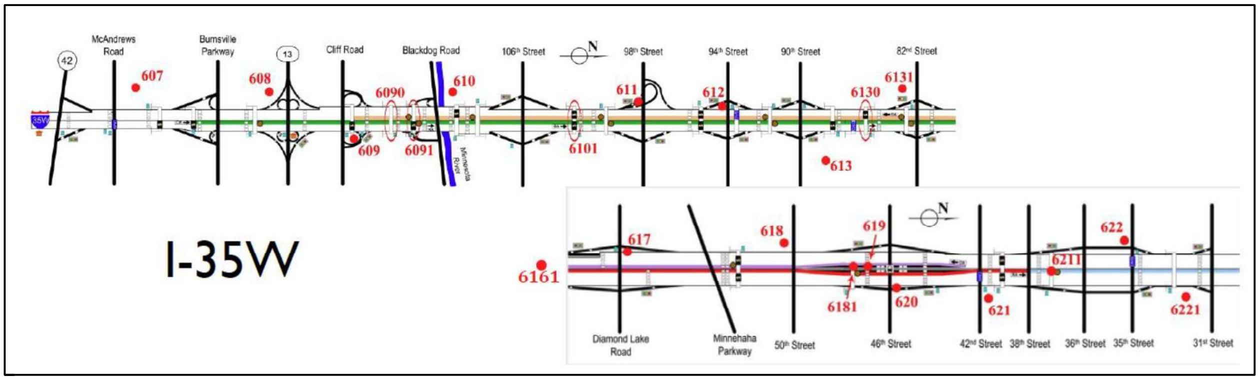


Figure 2-10. I-35 W corridor (source: Minnesota Department of Transportation [2014])

2.4.4. Concluding Remarks from the Case Studies

The three case studies reviewed in this report represent HOV/HOT lane implementations whose access control is similar to the partially limited access design. In all of them, access is restricted in the vicinity of major interchanges in order to reduce weaving in these areas. While the specific implementations are different—the one on SR-55 uses a single white solid stripe while the one on SR-237 uses a 2-ft buffer zone, it is anecdotally observed that such access restriction has been effective at reducing number of lane changes.

Presumably, the reduction in number of lane changes would result in improved traffic flow in those areas. Thus, the observations from the case studies support the notion that the “partially limited access” design of HOV facilities would result in a better overall operational performance of the freeway than the existing limited access and continuous access designs. In the remainder of this project, the research team will work to validate this notion. In addition, we will develop a set of guidelines for implementing partially limited access HOV lanes in the field and a set of analytical methods which can be used to analyze other HOV lane configurations in the future.

3. Partially Limited Access Design

3.1. Design Concept

Previous studies reveal that: a) buffer-separated HOV facilities are better at regulating traffic flow, resulting in higher freeway throughput [Wu et al., 2015]; b) continuous HOV facilities are more likely to spread out lane changes, allowing traffic to maintain higher travel speed [Boriboonsomsin and Barth, 2006; Boriboonsomsin et al., 2013]. The partially limited access design is aimed to take advantage of both existing HOV access designs by placing buffers at proper locations. When designing a partially limited access HOV facility, one should keep in mind the following design objectives: (1) to reduce the negative impact of HOV-related lane changes; (2) to improve HOV lane utilization and (3) to not violate any existing guidelines for designing HOV facilities.

In general, a freeway segment can be divided into four areas: 1) between off-ramp and on-ramp, 2) downstream of on-ramp, 3) basic freeway segment, and 4) upstream of off-ramp, as shown in Figure 3-1.

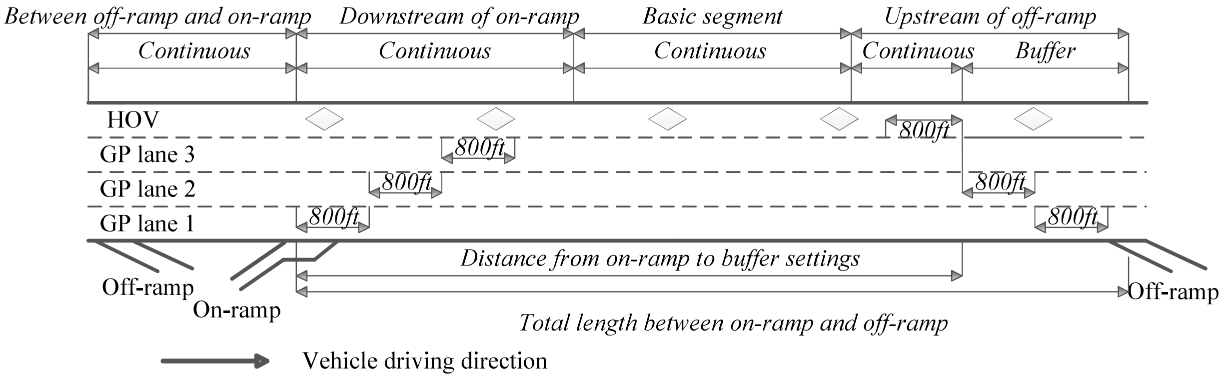


Figure 3-1. Partially limited access design for freeway HOV facilities

- For the areas between off-ramp and on-ramp as well as the basic freeway segment, there is usually little to no HOV cross-weave flow that could negatively affect the capacity of the MF lanes. For these areas, allowing continuous access to and from the HOV lane would likely result in higher HOV lane utilization, compared with limiting the access, as HOVs will be able to move into the HOV lane without restriction. This is especially true for HOVs traveling in MF lanes that start to get congested. Once those HOVs realize the comparatively higher travel speed in the HOV lane, they can try to move into the HOV lane right away. This will not be possible with the limited access design as the HOVs will have to go through the congested traffic in the MF lanes until they reach an ingress/egress zone before they can move into the HOV lane.

- For the downstream area of on-ramp, it would also be better to allow continuous access to and from the HOV lane. In mild to moderate traffic, the HOV lane utilization would likely be higher because HOVs that just enter the freeway from the on-ramp can safely make lane changes and merge into the HOV lane in a relatively short time. And when the traffic is congested, it has been shown through both simulation and field observation that the continuous access does not cause significant HOV cross-weave effect that reduces the capacity of the MF lanes [Liu et al., 2012]. This is because the HOVs that just enter the freeway from the on-ramp will be afforded flexibility in terms of where and when they get into the HOV lane. On the other hand, in the limited access design, if the ingress/egress zone is located in the downstream area of the on-ramp too close to the on-ramp, then HOVs that enter the freeway will face a challenge of making consecutive lane changes to get into the HOV lane before they miss the ingress/egress zone.

Taking as an example an HOV that enters a freeway with an HOV lane from an on-ramp. If the MF lanes are very congested but the HOV lane is in free-flow, then in theory this vehicle should move into the HOV lane immediately to take advantage of the higher travel speed. However, under such traffic condition, it will be challenging for this HOV to get into the HOV lane for two reasons. First, as the MF lanes are congested, it will be difficult for the vehicle to move from the rightmost lane to the leftmost lane of the MF lanes. Second, after the vehicle has reached the MF lane adjacent to the HOV lane after multiple lane changes, it will still not be easy to get into the HOV lane as the speed difference may be too high for a safe lane change. Thus, this HOV may miss the first ingress/egress zone if it is located too close to the on-ramp. Figure 3-2 shows an example of the impedance on HOV cross-weave due to traffic congestion in MF lanes.

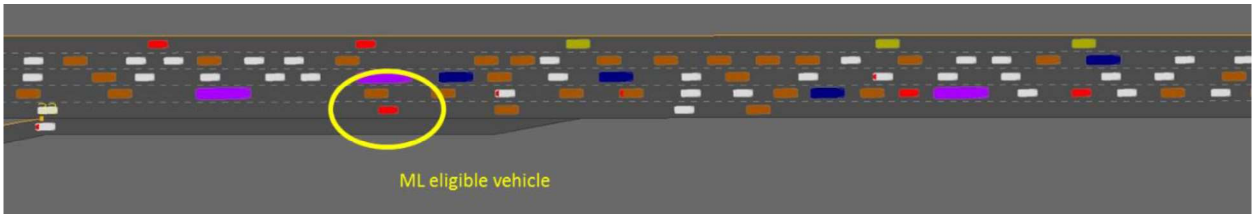


Figure 3-2. The impedance on HOV cross-weave due to traffic congestion

- For the upstream area of off-ramp, as HOVs that want to exit the freeway will have to make multiple lane changes to take the exit ramp, these mandatory lane changes could negatively impact traffic flow in the MF lanes, especially if many of them are concentrated over a short distance. Therefore, it may be beneficial to place a buffer before the off-ramp to disallow or discourage lane changes in the last minute, which often are aggressive and could disrupt traffic flow in the MF lanes. We further describe the reasoning of placing buffers upstream of off-ramps and the optimal design of buffer length in the next section.

3.2. Cross-Weave Effect Upstream of Off-Ramp

Compared with the limited access design, the continuous access design would likely lead to higher HOV lane utilization due to HOVs having more flexibility in terms of where to get in or out of the HOV lane. But in the upstream area of off-ramp, having too much of that flexibility may result in some HOVs making aggressive, last-minute lane changes too close to the off-ramp in order to exit the freeway. This would result in the HOV cross-weave effect which, if substantial enough, could reduce the throughput of the MF lanes in the area upstream of the off-ramp, increase delay, and potentially break down the traffic flow. Therefore, in the partially limited access design of HOV facilities, it would be beneficial to place a buffer immediately upstream of an off-ramp to prevent or at least alleviate such HOV cross-weave effect.

In this section, we present a simulation study to quantify the HOV cross-weave upstream of off-ramps. Simulation test scenarios are first introduced. Then, Van Aerde's curve [Van Aerde, 1995] is applied to estimate freeway capacity using the Genetic Algorithm (GA). Finally, simulation results are analyzed to quantify the HOV cross-weave effect in terms of the amount of freeway capacity drop in relation to buffer length, cross-weave flow, and the number of MF lanes.

3.2.1. Simulation Test Scenarios

We coded a simulation network of a generic freeway section in PARAMICS where a buffer is placed immediately upstream of an off-ramp up to the gore point of the off-ramp, as shown in Figure 3-3. The total length of this simulation network is 13,000 ft or 2.5 mi (4 km). Eleven vehicle detector stations were placed across all MF lanes starting at the point at 4,000 ft through the point at 7,500 ft. The distance between two adjacent detectors is 350 ft. The reason for this detector placement plan is that in a normal condition, there are vehicles in the MF lanes wanting to exit the freeway, which could also result in freeway capacity drop near the off-ramp. Traffic volume and speed data were collected by the eleven vehicle detector stations over 15-minute intervals during the simulation period, which were then used for freeway capacity estimation.

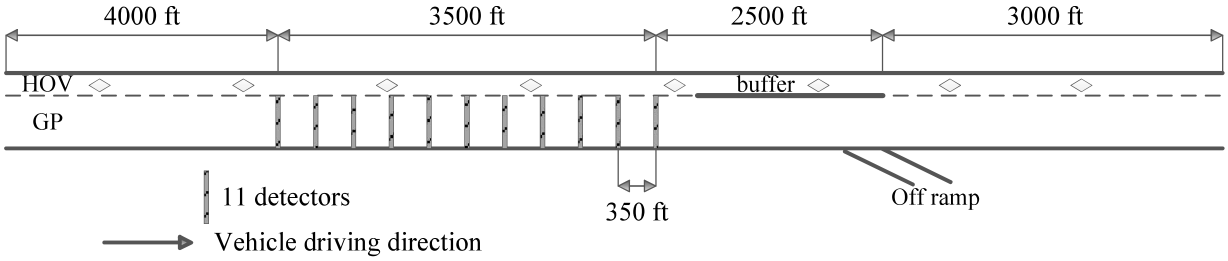


Figure 3-3. Simulation test scenario for HOV cross-weave effect

In this simulation network, only one vehicle type (i.e., passenger car) was used in order to simplify the freeway capacity estimation (no need to convert other vehicle types to passenger car equivalence). The values of driving behavior model parameters such as mean reaction time and mean target headway were taken from the previously calibrated SR-210 E simulation network present earlier. Three influential factors were included in the sensitivity analysis of the HOV cross-weave effect as follows:

1. *HOV cross-weave flow* – 0, 100, 200, 300, 400, and 500 pcphpl
2. *Number of MF lanes* – 2, 3, and 4
3. *Buffer length* – 0, 1,500, 2,500, and 3,500

The number of HOVs entering the simulation network through the HOV lane was set to be 1,400 pcphpl based on field observations of SR-210. The number of vehicles entering the simulation network through the MF lanes varies from 1,200 to 2,400 pcphpl with 200 pcphpl increments. We also assumed that the number of vehicles in the MF lanes taking the off-ramp is 150 pcphpl. In addition, three different seed numbers were used to capture the stochastic variability of simulation results. In the end, 216 simulation runs (6 cross-weave flows × 3 numbers of MF lanes × 4 buffer lengths × 3 seed numbers = 216) were made.

3.2.2. Capacity Estimation Approach

With the data points collected from the eleven vehicle detector stations in the simulation, a Van-Aerde's curve that represents the speed-flow relationship was used to estimate the freeway capacity. The same type of curve was used in the research of HOV cross-weave effect downstream of on-ramps [Liu et al., 2012]. The functional forms of the curve are given in Eq. (3-1) and (3-2).

$$d = \frac{1}{c_1 + \dfrac{c_2}{S_f - S} + c_3 \times S} \tag{3-1}$$

$$q = d \times S = \frac{S}{c_1 + \dfrac{c_2}{S_f - S} + c_3 \times S} \tag{3-2}$$

where d is traffic density (veh/mile); q is traffic volume (pcphpl); S is traffic speed (mph); S_f is free flow speed (mph); c_1 is a constant representing the fixed distance headway (mile); c_2 is a constant representing the first variable headway (mile^2/h); and c_3 is a constant representing the second variable headway (h). These three constants can be calculated by the following equations:

$$m = \frac{2 \times S_c - S_f}{(S_f - S_c)^2} \tag{3-3}$$

$$c_2 = \frac{1}{d_j \times (m + \dfrac{1}{S_f})} \tag{3-4}$$

$$c_1 = m \times c_2 \tag{3-5}$$

$$c_3 = \frac{-c_1 + \frac{S_c}{q_c} - \frac{c_2}{S_f - S_c}}{S_c} \tag{3-6}$$

where S_c is speed-at-capacity (mph); q_c is capacity (pcphpl); and d_j is jam density (veh/mile).

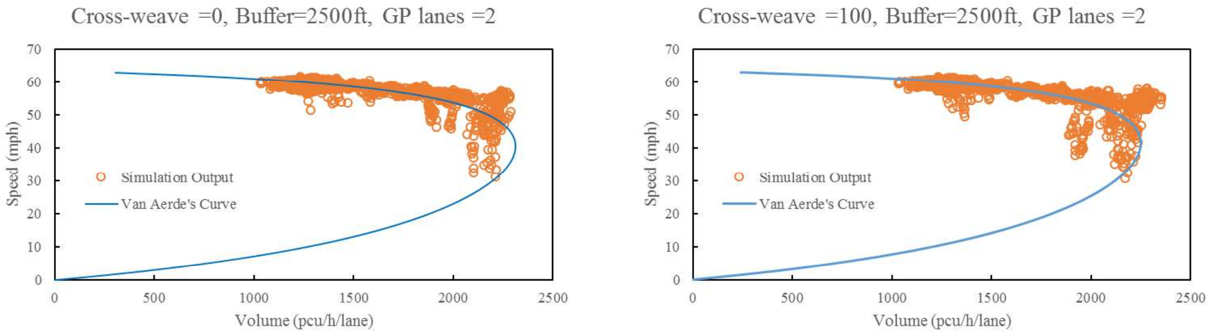
The Genetic Algorithm (GA) is applied to estimate the four parameters. The number of population sizes is 10, the maximum number of iterations is 2000, and the values of probabilities of crossover and mutation operations are 0.8 and 0.005, respectively. Based on the limited speed of freeway and the calibrated fundamental diagram using real-world data as shown in High Capacity Manual 2010, the ranges of these four parameters are: $S_f \in [60, 65]$, $S_c \in [45, 55]$, $q_c \in [1800, 2400]$, and $d_j \in [170, 200]$. The function of fitness is based on the calculated errors between simulated data points and estimated data points given by

$$Fitness = \sum_i \left\{ \left(\frac{q_i - \hat{q}_i}{\tilde{q}} \right)^2 + \left(\frac{d_i - \hat{d}_i}{\tilde{d}} \right)^2 \right\} \tag{3-7}$$

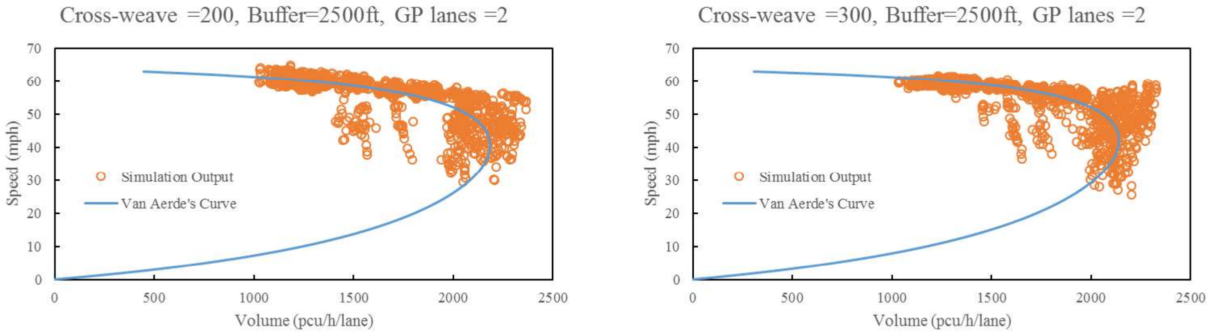
where q_i is simulated flow; $\hat{q}_i$ is estimated flow using Eq. (3-2); $\tilde{q}$ is simulated average flow; d_i is simulated density using the equation of q_i/S_i; S_i is simulated speed; $\hat{d}_i$ is estimated density; and $\tilde{d}$ is simulated average density.

3.2.3. Simulation Results

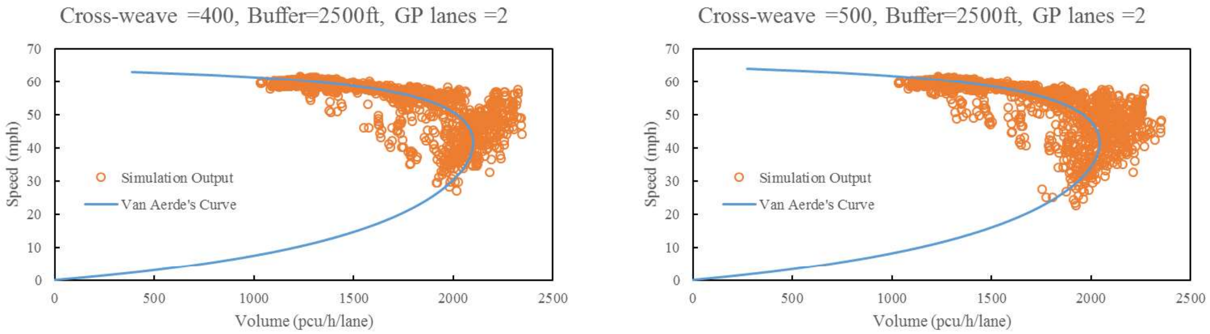
The speed-flow diagram can be drawn with the Van Aerde's curve to estimate the freeway capacity. In this report, we only show the speed-flow diagram results for the scenarios of two MF lanes with the buffer length of 2,500 ft and cross-weave flow ranging from 0 pcphpl to 500 pcphpl (see Figure 3-4).



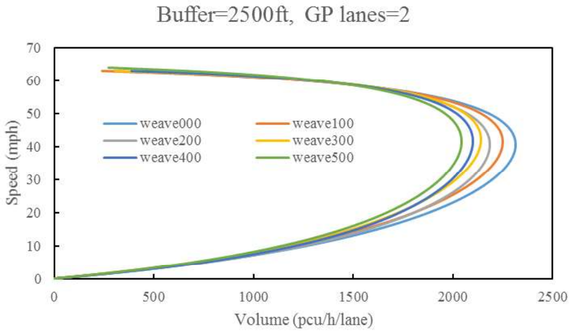
(a) Cross-weave flow=0 pcphpl **(b) Cross-weave flow=100 pcphpl**



(c) Cross-weave flow=200 pcphpl **(d) Cross-weave flow=300 pcphpl**



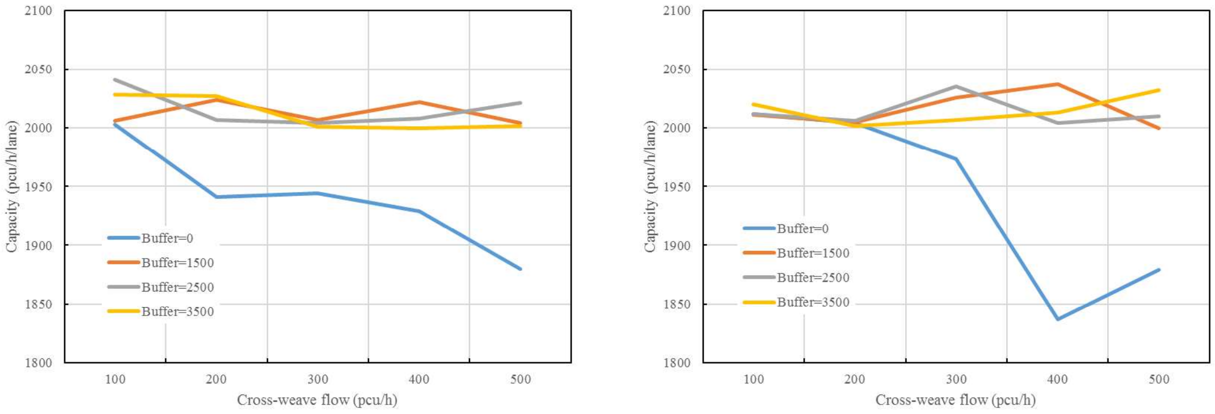
(e) Cross-weave flow=400 pcphpl **(f) Cross-weave flow=500 pcphpl**



(g) Van Aerde's curves for different cross-weave flow scenarios

Figure 3-4. Speed-flow plots and Van-Aerde's curve fitting for 2 MF lane scenarios

As can be seen in Figure 3-4, due to the cross-weave effect upstream of the off-ramp, the freeway capacity shows a decreasing trend from 2,300 pcphpl to 2,000 pcphpl with the increase of HOV cross-weave flow from 0 to 500 pcphpl. Figure 3-5 presents the freeway capacity values of 3 MF lanes and 4 MF lanes scenarios under different HOV cross-weave flows and buffer lengths. The results reveal that placing a buffer immediately upstream of the off-ramp can help maintain the level of freeway capacity. For the different lengths of buffer, the freeway capacity values are around 2,020 pcphpl.



(a) Three MF lanes

(b) Four MF lanes

Figure 3-5. Freeway capacity as a function of cross-weave flow and buffer length

In summary, with the increase of HOV cross-weave flow, the freeway capacity shows a decreasing trend (e.g., Figure 3-4(g) and Figure 3-5 with no buffer). And the freeway capacity upstream of off-ramp increases slightly as the buffer length increases. The results reveal that HOV cross-weave flow has a tangible negative effect on the freeway capacity upstream of off-ramp, and placing a buffer immediately upstream can help mitigate that effect.

3.3. Partially Limited Access Design Methodology

As discussed in the previous section, placing a buffer immediately upstream of an off-ramp can help mitigate the HOV cross-weave effect. However, the buffer length should be as short as possible to allow for a highest HOV lane utilization. And for safety reasons, Caltrans's HOV design guidelines recommend providing a per lane change weaving distance (l_{min}) of at least 800 ft [Caltrans, 2011]. Based on the diagram in Figure 3-1, in the case of three MF lanes an HOV in the HOV lane needs to make two lane changes within the boundary of the buffer to take the exit ramp. Therefore, the buffer should be longer than l_{min} x (N_{MF}-1) ft, where N_{MF} is the number of MF lanes. On the other hand, an HOV that just enter the freeway needs to make three lane changes to get into the HOV lane, thus requiring a minimum distance from the on-ramp to the buffer of l_{min} x N_{MF}.

In summary, the following steps can be used to design partially limited access HOV lanes based on geometric characteristics of the freeway:

1. If an on-ramp and the next off-ramp are far enough from each other, a buffer should be placed immediately upstream of the off-ramp. The buffer length can be determined using the following equations:

$$L_{buffer} = l_{min} \times (N_{GP} - 1) \quad when \; (L_{tot} - L_{buffer}) \geq l_{min} \times N_{GP} \qquad (3\text{-}8)$$

$$L_{tot} \geq l_{min} \times N_{GP} + L_{buffer} = l_{min} \times N_{GP} + l_{min} \times (N_{GP} - 1) = l_{min} \times (2 \times N_{GP} - 1) \qquad (3\text{-}9)$$

   where L_{tot} is the total length from on-ramp to off-ramp, and $N_{MF} \geqslant 2$.

2. If an on-ramp and the next off-ramp are too close to each other, i.e., L_{tot} cannot meet the minimum length required by Eq. (3-8), continuous access should be provided for that segment due to its operational flexibility for HOVs.

4. Simulation-Based Evaluation

As part of the project, the research team conducted a simulation study to evaluate the operational performance of the partially limited access control and compare it to that of the limited access and continuous access controls. This chapter describes the work performed and provides a summary of findings.

4.1. Study Site Selection

To select the study site, we first selected four selected freeway sections in Caltrans District 8 based on suggestions of the Caltrans Project Panel. These freeway sections are listed below:

1. SR-210 between LA County Line and I-15
2. SR-210 E between I-15 and I-215
3. SR-60 E between I-15 and I-215
4. SR-91 E between Pierce St and Adams St

For each freeway section (in both directions), we analyzed 3-month historical data in either the fourth quarter of 2014 or the first quarter of 2015 in order to identify bottleneck locations. We checked the average speed (in mph) at each 5-minute time interval of a day for each Mainline/HOV PeMS station on both weekdays and weekends. If the lowest speed for a station was below 45 mph, that position was considered as a bottleneck and the corresponding time for that lowest speed was also recorded. If there were several consecutive bottlenecks on a freeway, we combined them as one big bottleneck. For each direction of each section, we summarized the bottlenecks (both Mainline and HOV, weekdays and weekends) in a table, and showed their locations in one or two figures. The speed contour maps on weekdays for both Mainline and HOV lanes were also plotted. The results are compiled and given in Appendix A.

Based on the results of the bottleneck analysis as well as other considerations, the research team, in consultation with the Caltrans Project Panel, selected the section of SR-210 E between LA County Line and I-15 as the study site. It has multiple bottlenecks throughout the afternoon peak period. Additionally, the limited access HOV lane on this freeway section was already programmed for restriping to continuous access control within the timeline of this research project, and the schedule for the restriping was far out enough that would allow the research team to complete the design of partially limited access control. The idea was that the HOV lane on the study site could then be restriped into partially limited access control (instead of continuous access control) for the purpose of conducting field operation test of the new design.

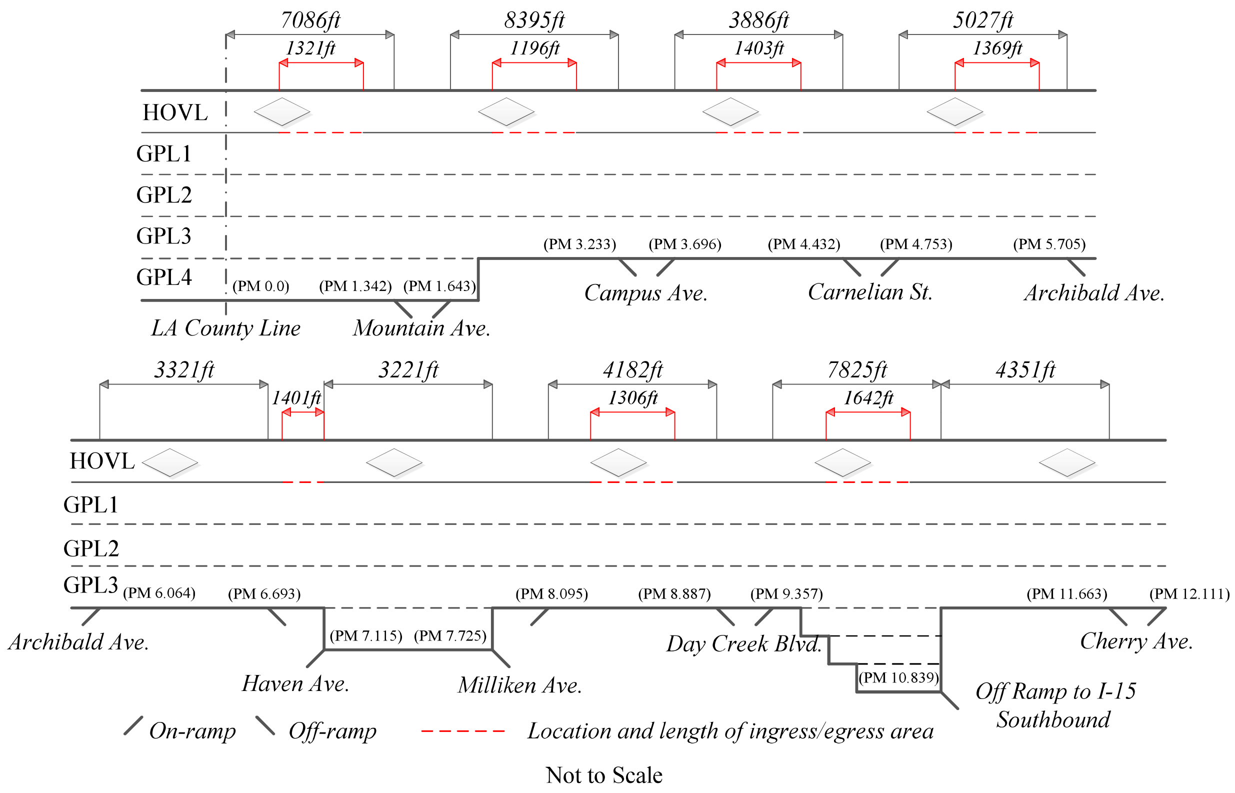
Once the study site had been selected, the research team checked the reliability of traffic data as reported by PeMS over a period of 6 months based on sensor health records. We found that February 2015 had the best record with more than 90% of the sensors being in good condition throughout the month. We then examined the average hourly traffic volume in this month and found the period of 4-6 p.m. to have the highest volume. Thus, we selected this time period for the simulation modeling.

4.2. Simulation Network Coding

Figure 4-1(a) shows a 13-mile (21-km) section of SR-210 E between Los Angeles County Line and I-15 in San Bernardino County, which was used as the study site. The number of lanes on different segments of the study site varies from four to five. The leftmost lane is a full-time HOV lane with limited access control. There are nine pairs of off-ramp/on-ramp with the interspacing distance between consecutive pairs of off-ramp/on-ramp ranging from 3,000 ft to approximately 8,200 ft, as shown in Figure 4-1(b). Note that the interspacing distance is measured from the gore point of an on-ramp to the gore point of the next off-ramp downstream. On the study site, there are seven ingress/egress areas as depicted by the red dashed lines in Figure 4-1 (b). The length of these ingress/egress areas ranges from about 1,200 ft to about 1,600 ft. Six of the ingress/egress areas are located between an on-ramp and the next off-ramp downstream while the other one is located between an off-ramp and the next on-ramp downstream. Note that the eastbound direction was used for the simulation study and methodology development. In the later part of this task, the developed methodology was also applied to the westbound direction.

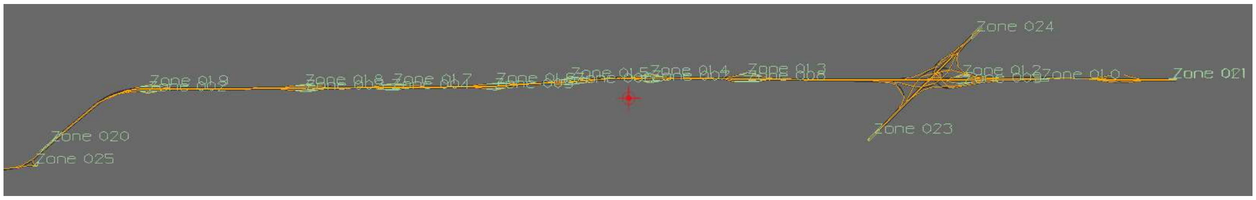
The study site is coded into a simulation network in PARAMICS which is a traffic microsimulation software tool [Quadstone Paramics, 2016]. High-resolution satellite images from Google Map were imported into PARAMICS as background images to aid the coding of details of the simulation network, such as degree of curvature of curves, locations of ramp merge and diverge. As the existing SR-210 E freeway corridor has limited access HOV lane, we coded the HOV and MF lanes as separate links along the segments that have a buffer between the HOV and the adjacent MF lanes. On the other hand, we coded the HOV and MF lanes as a single link for the ingress/egress areas. The overview of the entire simulation network and the zoom-in view of subsections are shown in Figure 4-2.

(a) Map of the study site, SR-210 E from Los Angeles County line to I-15 interchange

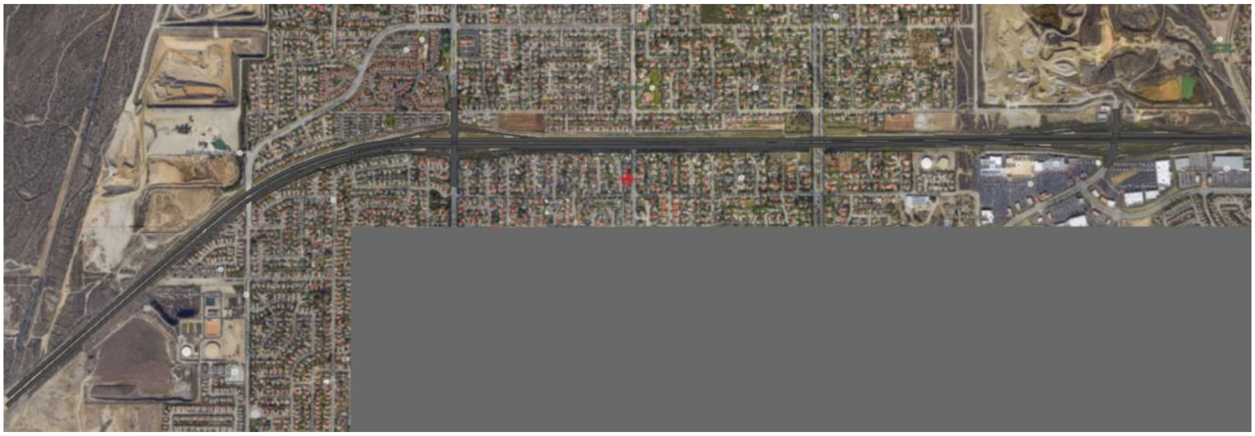


(b) Geometric diagram of the study site

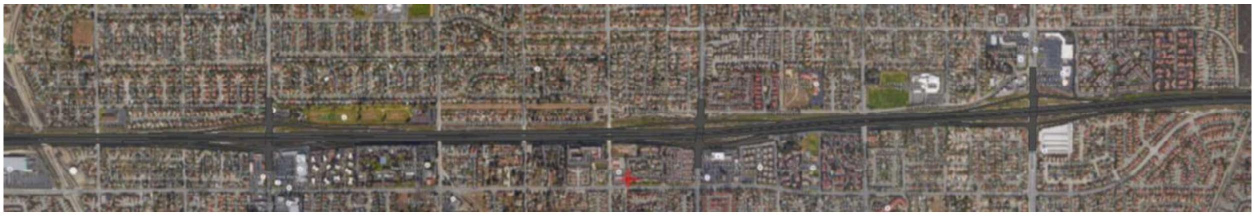
Figure 4-1. Map and geometric diagram of the study site



(a) Overview of the entire simulation network



(b) LA county line to Colonies Crossroads



(c) Colonies Crossroads to Rochester Ave

(d) Rochester Ave to I-15 interchange

(e) I-15 interchange

Figure 4-2. Simulation network of the study site

There are six vehicle types in the simulation network, namely HOV-passenger car, HOV-Light Duty Truck (LDT), single-occupancy vehicle (SOV)-passenger car, SOV-LDT, SOV-Medium Duty Truck (MDT) and SOV-Heavy Duty Truck (HDT). We developed two origin-destination (OD) matrices; one for HOVs and the other for SOVs. In the HOV OD matrix, passenger cars and LDTs account for 57.4% and 42.6%, respectively. In the SOV OD matrix, the proportion of the four vehicle types are 50.7% passenger car, 37.5% LDT, 6.4% MDT, and 5.4% HDT, respectively. Note that the percentages of different vehicle types are based on the fleet of Riverside County. The afternoon peak hour (16:30-17:30) was selected as the simulation period, with 45 minutes added to the beginning as a simulation warm-up time.

4.3. Simulation Network Calibration and Validation

Network calibration is very important to simulation studies as drivers in different areas may have different driving behaviors, which results in different traffic characteristics. In this study, we first used the Estimator tool in PARAMICS to estimate the two OD matrices based on flow data measured by loop detectors of PeMS. Then, the freeway capacity of the study site was calibrated by adjusting global parameters, such as mean target headway and mean driver's reaction time. Lastly, link-level parameters such as link cost factor were fine-tuned in order to satisfy network calibration criteria [Dowling et al., 2002]. After completing the network calibration, the final values of the mean target headway and mean driver's reaction time for this study site are both 0.95. The link cost factor for HOV lane is 0.8 while the value for MF lanes is 1.0.

Data from 26 loop detectors (13 detectors on HOV lane and 13 detectors on MF lanes) were used to validate the calibrated simulation network. As shown in Table 4-1, the simulated flow values are very close to the observed flow values, all within +/-10%. In terms of speed, it was found that most of the simulated speed values are within +/-15% of the observed speed values. These results indicate that the simulated traffic matches reasonably well with that observed in the real world.

One of the validation criteria for calibrating traffic microsimulation network is based on the Geoffrey E. Havers (GEH) statistic. The GEH statistic is calculated using the following equation:

$$\mathrm{GEH} = \sqrt{2 \times (q_s - q_o)^2 / (q_s + q_o)} \qquad (1)$$

where q_s is the simulated flow and q_o is the observed flow. Table 4-2 summarizes the model validation results in comparison with the targets suggested by the Caltrans guidelines [Dowling et al., 2002]. The results affirm that the simulated traffic has been satisfactorily calibrated to the actual traffic in the real world.

The suggested method for validating a calibrated simulation network is to compare the simulation results against the fundamental traffic flow relationships [Dowling et al., 2002]. Figure 4-3 shows the speed versus flow diagram based on the data points from the calibrated simulation network. It follows the expected fundamental diagram and closely matches the diagram based on real-world observation. This validates the simulation network.

Table 4-1. Validation results of the calibrated simulation network of SR-210 E

(a) HOV lane

VDS ID	Lane Type	Post mile	Observed Flow (veh/hr)	Simulated Flow (veh/hr)	Flow Diff. (%)	Observed speed (mph)	Simulated Speed (mph)	Speed Diff. (%)	GEH
819614	HOV	53.839	1333	1423	7%	34.97	36.21	4%	2.43
809349	HOV	54.939	1440	1356	-6%	38.58	43.83	14%	2.24
809210	HOV	55.239	1440	1354	-6%	38.01	40.44	6%	2.31
819600	HOV	55.739	1440	1351	-6%	40.47	40.14	-1%	2.37
809250	HOV	55.739	1430	1348	-6%	40.56	38.54	-5%	2.20
809258	HOV	56.129	1409	1446	3%	45.16	52.07	15%	0.98
809171	HOV	57.139	1380	1442	4%	61.33	52.05	-15%	1.64
819539	HOV	57.539	1417	1388	-2%	63.70	67.41	6%	0.78
808988	HOV	59.239	1363	1395	2%	40.88	43.72	7%	0.86
808994	HOV	59.839	1366	1367	0%	43.71	35.28	-19%	0.02
809071	HOV	60.439	1342	1349	0%	47.35	42.27	-11%	0.18
816193	HOV	61.239	1321	1371	4%	54.13	54.43	1%	1.37
809125	HOV	62.439	1315	1406	7%	54.81	49.96	-9%	2.48

(b) MF lanes

VDS ID	Lane Type	Post mile	Observed Flow (veh/hr)	Simulated Flow (veh/hr)	Flow Diff. (%)	Observed speed (mph)	Simulated Speed (mph)	Speed Diff. (%)	GEH
819613	MF	53.839	4408	4240	-4%	21.40	21.66	1%	2.56
809211	MF	54.939	4727	4559	-4%	35.16	39.59	13%	2.46
819599	MF	55.239	4592	4549	-1%	36.06	34.02	-6%	0.63
809252	MF	56.129	4299	3935	-8%	35.90	32.02	-11%	5.67
819552	MF	56.539	4513	4554	1%	36.50	34.95	-4%	0.61
809287	MF	57.139	4540	4315	-5%	34.18	29.49	-14%	3.38
809172	MF	57.539	5034	5084	1%	48.15	46.50	-3%	0.70
809022	MF	59.439	4534	4345	-4%	39.87	42.43	6%	2.83
819514	MF	59.839	4839	4776	-1%	38.96	37.14	-5%	0.91
809036	MF	60.439	4769	4415	-7%	38.34	31.69	-17%	5.22
816194	MF	61.139	4666	4895	5%	57.88	55.78	-4%	3.31
809117	MF	61.839	4667	4222	-10%	59.93	62.53	4%	6.67
810280	MF	64.102	5320	5233	-2%	62.10	63.39	2%	1.20

Table 4-2. Summary of validation targets and results

Criteria and Measures	Acceptability Targets	Validation Results
Hourly flows: simulated versus observed		
Individual link flows		
Within 100 veh, for flow <700 veh	>85% of all cases	100% of 0 cases
Within 15%, for 700 veh < flow <2700 veh	>85% of all cases	100% of 13 cases
Within 400 veh, for flow >2700 veh	>85% of all cases	92% of 13 cases
Total link flows-within 5%	All accepting links	1.8%
GEH statistics-individual link flow (GEH<5)	>85% of all cases	88% of 26 cases
GEH statistics-total link flows (GEH<4)	All accepting links	2.5
Visual audits		
Individual link speeds		
Visually acceptable speed-flow relationship	To analyst's satisfaction	Satisfied
Bottlenecks		
Visually acceptable queuing	To analyst's satisfaction	Satisfied

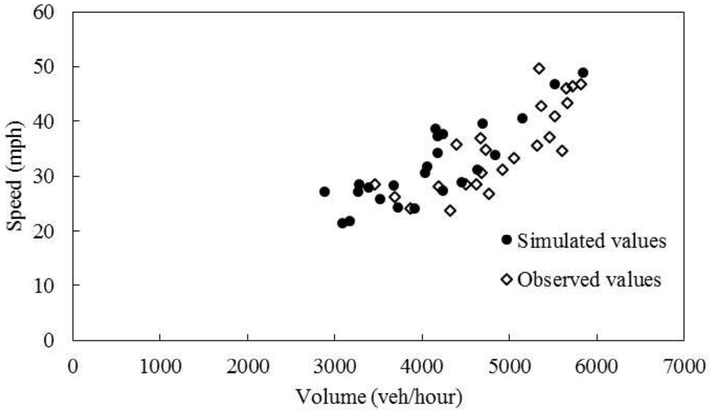


Figure 4-3. Validation of fundamental traffic flow relationships from simulation

After the simulation network with the existing limited access design had been calibrated and validated, we also coded another simulation network of SR-210 E but with the continuous access design by removing all the buffers along the freeway section. In PARAMICS, this was implemented by having the HOV lane and the MF lanes share the same link. The HOV lane was set as a special lane which only allows HOVs to enter. We then applied the same model parameters from the simulation network with the limited access design to the simulation network with the continuous access design in order to conduct a fair performance comparison between the two designs. In addition, a third simulation network of SR-210 E with the partially limited access design was also coded and evaluated in the same manner. The details are provided in the next section.

4.4. Partially Limited Access Design Performance Evaluation

4.4.1. Operational Performance of Partially Limited Access HOV Facility

We applied the partially limited access design methodology described above to design the partially limited access HOV lane for SR-210 E, as shown in Figure 4-4. The buffer lengths vary from 1,600 ft to 2,400 ft, depending on the number of MF lanes immediately upstream of the off-ramps. Since two out of the eight pairs of on-ramp/off-ramp have the interspacing distance shorter than 4,000 ft (4,000 = 800x3 + 800x2), no buffer is placed in those areas.

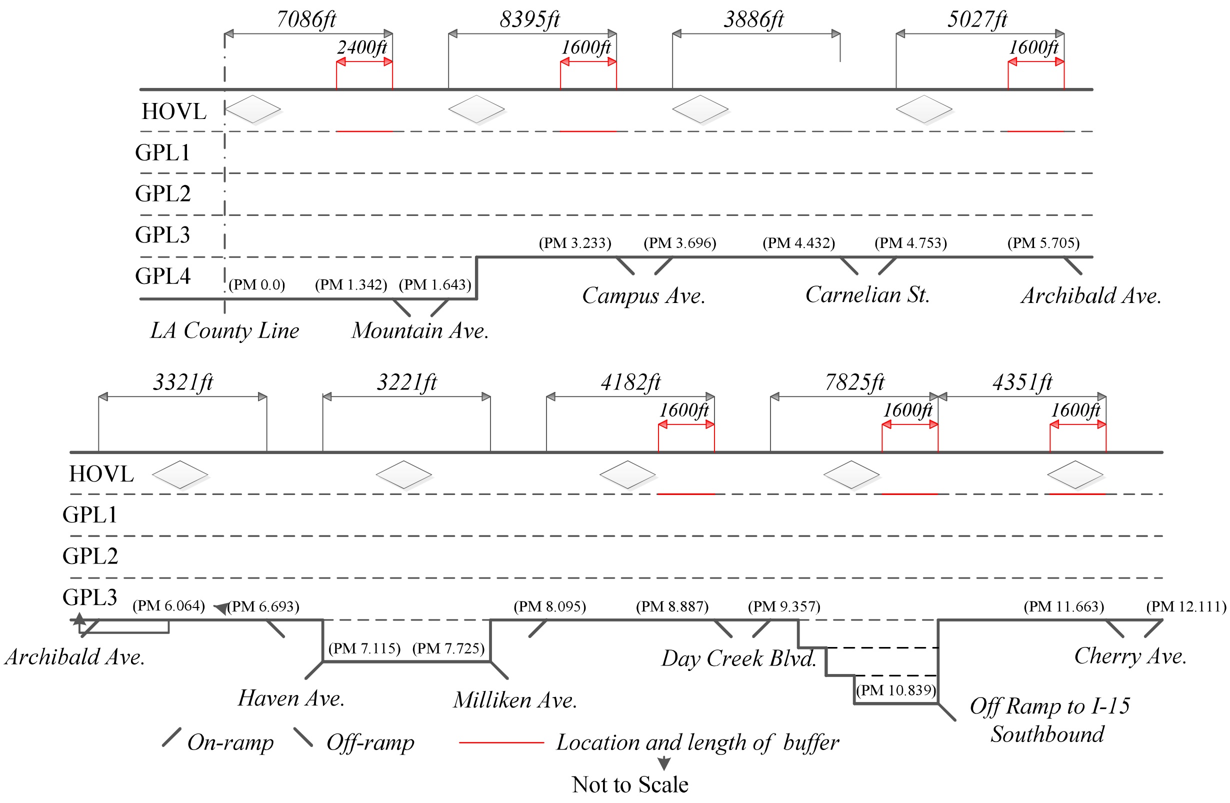
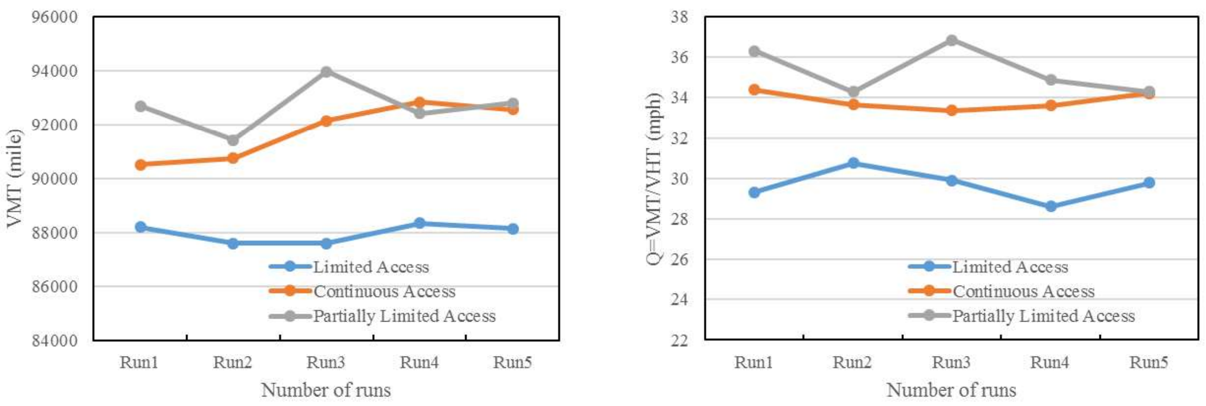


Figure 4-4. Geometric diagram of SR-210 E with partially limited access HOV lane

Based on the calibrated simulated network (with limited access control), we coded two additional simulation networks, one with continuous access control and the other with partially limited access control. Five simulation runs with different seed numbers were made using each simulation network. Then, operational performances of the three HOV access controls were analyzed, including vehicle miles travel (VMT), vehicle hours traveled (VHT), and average travel speed (Q = VMT/VHT), as shown in Figure 4-5. According to this figure, the limited access control consistently has the lowest VMT and Q across all five simulation runs. The continuous access control has a significantly better performance in terms of both VMT and Q while the partially limited access control has the best performance in all but one case.



(a) VMT for different simulation runs **(b) Q for different simulation runs**

Figure 4-5. Operational performance of different HOV access designs from multiple simulation runs

Table 4-3 summarizes the average operational performances of the three HOV access controls. It shows that the partially limited access control increases the throughput (represented by VMT) and decreases the delay (represented by VHT) of the freeway as compared with the limited access and continuous access controls. As a result, the average travel speed (represented by Q) of the freeway with partially limited access HOV facility is 21% and 6% higher than that of the freeway with limited access and continuous access HOV facility, respectively. Note that these results are specific to the study site of SR-210 E under the traffic condition simulated in this study.

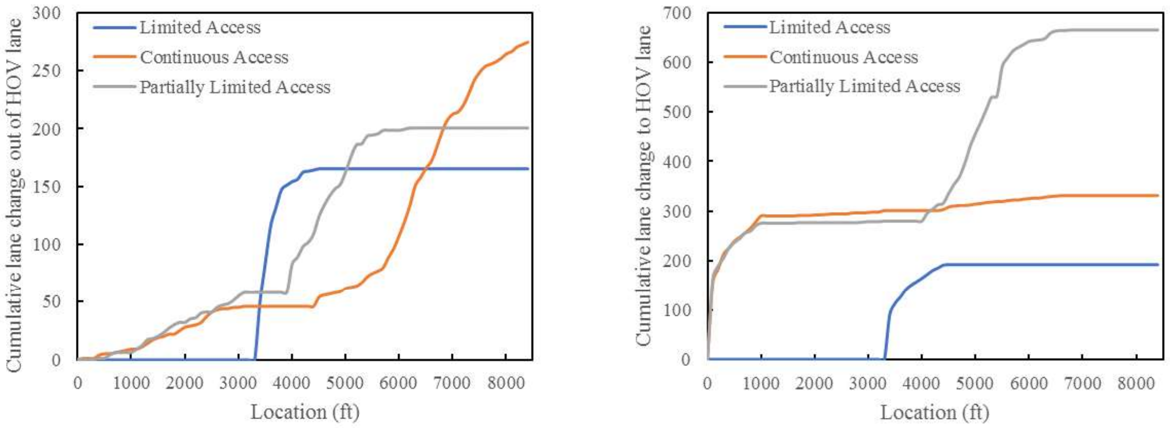
Table 4-3. Comparison of operational performance among different HOV access designs

Performance indicators	Limited access	Continuous access	Partially limited access
VMT (mile)	87,985	91,775 (4%)	94,745 (8%)
VHT (hour)	2,968	2,711 (-9%)	2,638 (-11%)
Q=VMT/VHT (mph)	29.6	33.8 (14%)	35.9 (21%)

Note: The percent values in parentheses are in comparison with the limited access control.

4.4.2. Lane Change Behaviors on Partially Limited Access HOV Facility

Lane change behaviors on the three different HOV facilities were also analyzed between the on-ramp from Mountain Ave and the off-ramp to Campus Ave. Using the simulation network, we recorded the lane-changing position of each vehicle from the HOV lane to the adjacent MF lane, and vice versa. The cumulative counts of lane changes for the three HOV access types were then calculated, and plotted in Figure 4-6.



(a) Out of HOV lane **(b) In to HOV lane**

Figure 4-6. Cumulative lane changes between HOV lane and the adjacent MF lane

As can be seen in Figure 4-6(a), in the case of limited access, the lane changes are highly concentrated over the short ingress/egress area (Location 3,300-4,100 ft). In the case of continuous access, lane changes are spread out. Some of them occur much in advance (before Location 3,000 ft), while others may delay significantly (after Location 6,000 ft). The lane changes close to the exit ramp can disrupt the mainline flow. On the other hand, the partially limited access addresses the drawbacks of the other two access types. It allows lane changes over a longer distance, thus avoiding intensive lane changes at a specific location. This eliminates those lane changes too close to the exit ramp. For the cumulative number of lane changes into HOV lane in Figure 4-6(b), the partially limited access shows the largest number of lane changes from the adjacent MF lane into the HOV lane, leading to the highest HOV lane utilization. On the other hand, buffers placed upstream of off-ramps in the partially limited access HOV facility can help spread the spatial distribution of lane changes and reduce the last-minute lane changes, as compared with the other two access controls. This may result in a better operational performance.

4.4.3. Sensitivity Analysis of Buffer Length

Sensitivity analysis is conducted for the proposed partially limited access design methodology to quantify the impact of buffer length l_{min}. The value of l_{min} ranges from 50 ft to 1,000 ft. The operational performances are calculated based on the simulation results, as shown in Table 4-4.

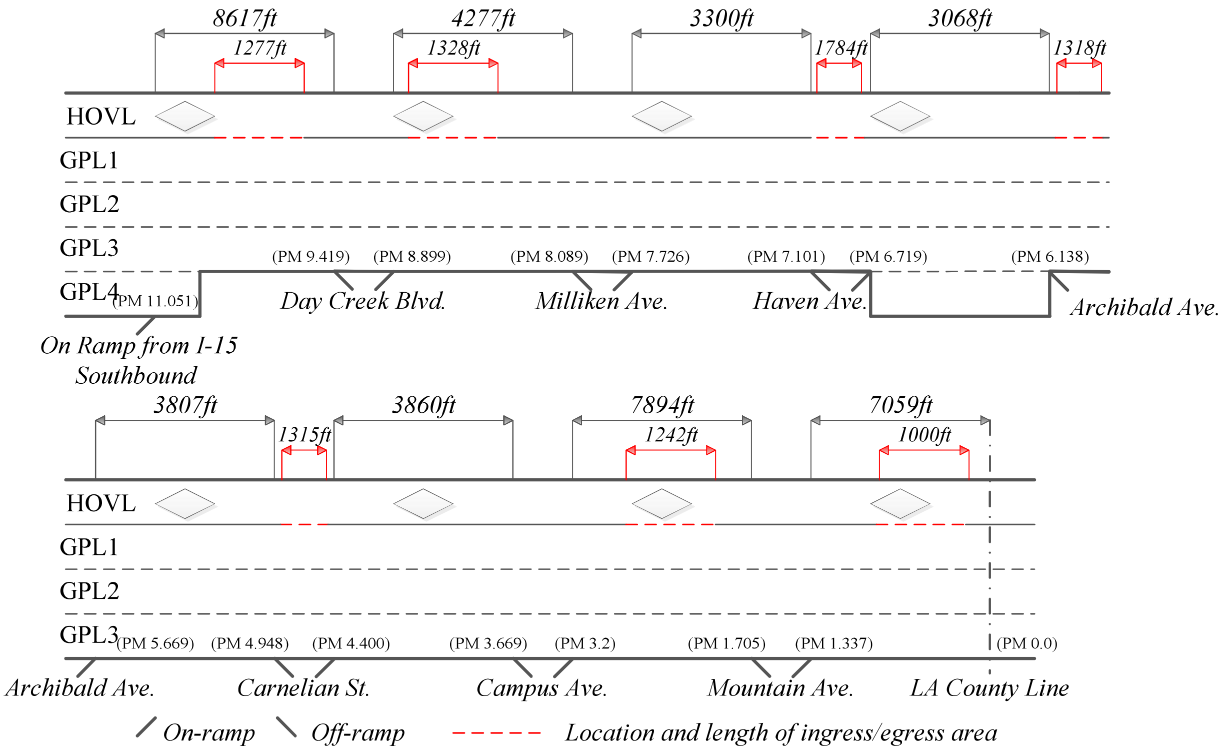
Table 4-4. Operational performance of partially limited HOV access with different l_{min}

Performance indicators	l_{min}= 50 ft	l_{min}= 200 ft	l_{min}= 400 ft	l_{min}= 600 ft	l_{min}= 800 ft	l_{min}= 1,000 ft
VMT (mile)	80,011	86,333	90,951	93,759	94,745	90,447
VHT (hour)	3,799	3,038	2,722	2,555	2,638	2,841
Q=VMT/VHT	21.1	28.4	33.4	36.7	35.9	31.8

As can be seen in Table 4-4, for the partially limited access control, the average travel speed increases with moderate value of l_{min} and later decreases with large l_{min}. The results of l_{min}=600 ft show the best operational performance in terms of average travel speed (Q = 36.7 mph). When l_{min} is greater than 600 ft, HOV vehicles need to get out HOV lane early before off-ramps, resulting in low HOV lane utilization. When l_{min} is less than 600 ft, the compound effect due to HOV cross weave and capacity drop at off-ramps may lead to serious congestion on MF lanes.

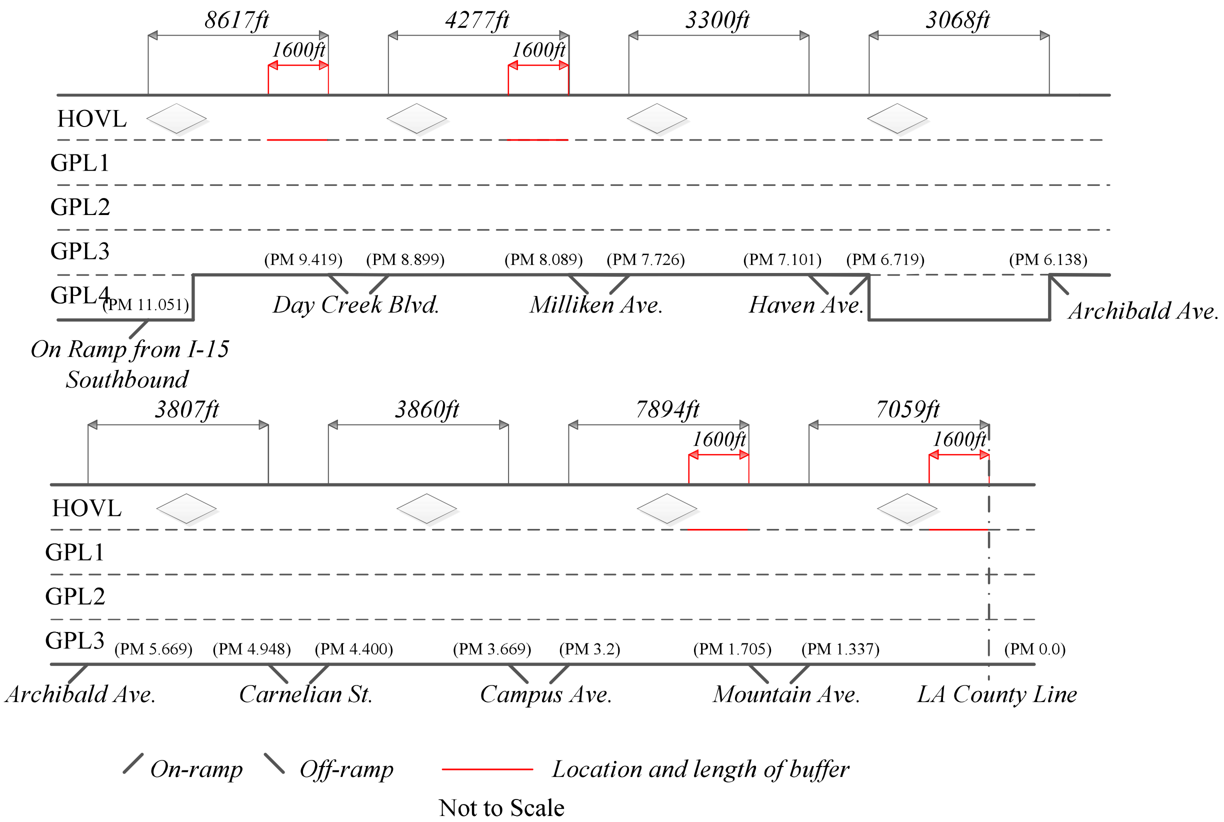
4.5. Application of the Design Methodology

We also applied the design methodology to the westbound of the same section of SR-210 used in this study, as shown in Figure 4-7. Based on the promising evaluation results in simulation presented above, further evaluation of the performance of the partially limited access design in real-world settings is warranted.



Not to Scale

(a) With the existing limited access control



(b) With the proposed partially limited access control

Figure 4-7. Geometric diagram of SR-210 W

5. Conclusions

Managed lanes, including HOV lanes, are an integral part of California's freeway systems. Traditionally, HOV lanes have been designed with either limited access or continuous access control. Over the last several years, the performance of limited access and continuous access HOV facilities in terms of safety, mobility, environment, enforcement, etc. have been extensively compared through empirical and simulation studies. The findings from these previous studies imply that the two existing designs have both advantages and disadvantages.

In this research, the research team developed a new design of HOV access control that combines the advantages of the two existing designs. In the new design, called *partially limited access*, continuous access is generally provided along the majority of HOV facilities in order to achieve higher travel speed while buffers are strategically placed on selected freeway segments (e.g., recurrent bottlenecks, ramp areas) to mitigate the impact of weaving maneuvers, thus accommodating higher throughput, on those segments. We also evaluated the operational performance of the partially limited access control in traffic microsimulation environment.

In the development of the new HOV access control design, the HOV cross-weave effect upstream of off-ramps was first analyzed. Then, a method for determining the location and length of buffers in the partially limited access control was developed and applied to the study site on SR-210 E in Southern California. Next, the operational performance of the new design was compared with the performance of limited access and continuous access designs in a well-calibrated traffic microsimulation network of SR-210 E. Finally, a sensitivity analysis of the operational performance of the partially limited access design with respect to buffer length was also conducted.

The results revealed that HOV cross-weave flow had tangible effect on the capacity of MF lanes upstream of off-ramps. Three influential factors, i.e., HOV cross-weave flow, number of MF lanes, and length of buffer were analyzed. It was found that placing a buffer (with appropriate length) before an off-ramp could reduce the HOV cross-weave effect, keeping the capacity of MF lanes at a high level.

The methodology for designing partially limited access control for HOV facilities was developed based on the following criteria: (1) to reduce HOV cross-weave effect; (2) to improve HOV lane utilization; and (3) not to violate existing HOV design guidelines. In general, a freeway segment can be divided into four portions: (1) between off-ramp and on-ramp, (2) downstream of on-ramp, (3) basic segment, and (4) upstream of off-ramp. For partially limited access HOV lanes, buffers should be placed upstream of off-ramps as long as the buffer length could satisfy other requirements of the existing HOV design guidelines.

The traffic microsimulation results for the case study of SR-210 E showed that the partially limited access control increased the throughput and decreased the delay of the freeway as compared with the limited access and continuous access controls. As a result, the overall network efficiency of the freeway with partially limited access HOV facility was 21% and 6% higher than that of the freeway with limited access and continuous access HOV facility, respectively. For the sensitivity analysis of buffer length, buffers designed with a weaving distance per lane change of 600 ft had the best operational performance in terms of average travel speed.

It should be noted that these results and findings are based mostly on simulation, and an evaluation of the operational performance of a freeway with partially limited access HOV facility in real world is warranted in the future. As part of the future work, other types of performance, such as safety and environmental sustainability, of the partially limited access design should also be evaluated in comparison with the two existing designs. Also, the weaving distance per lane change should be further investigated with the consideration of many site-specific factors, such as level of service and number of MF lanes.

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Appendix A:

Bottleneck Analysis of Selected Freeway Sections

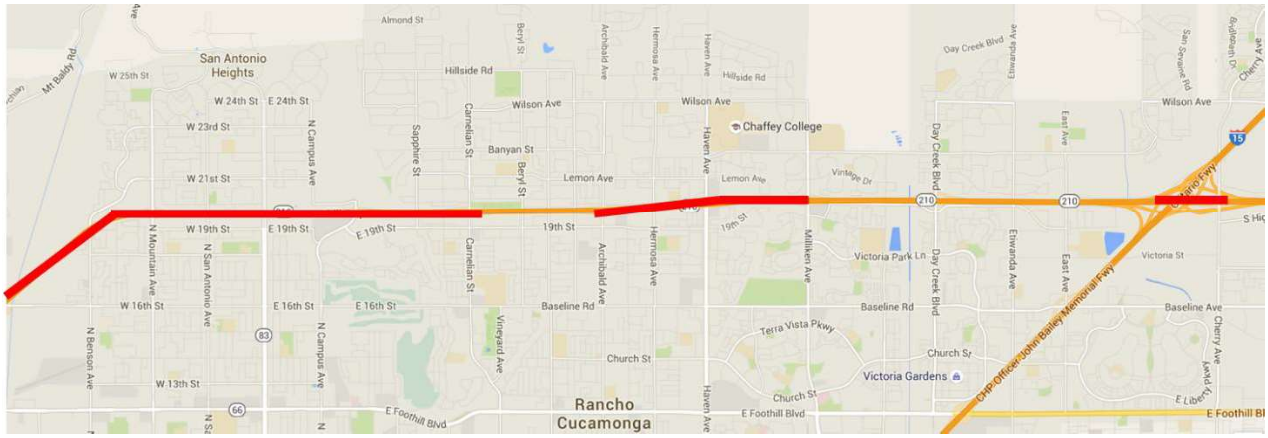
SR- 210 E between LA County Line and I-15 (Abs PM: 52.53-64.59)

Mainline

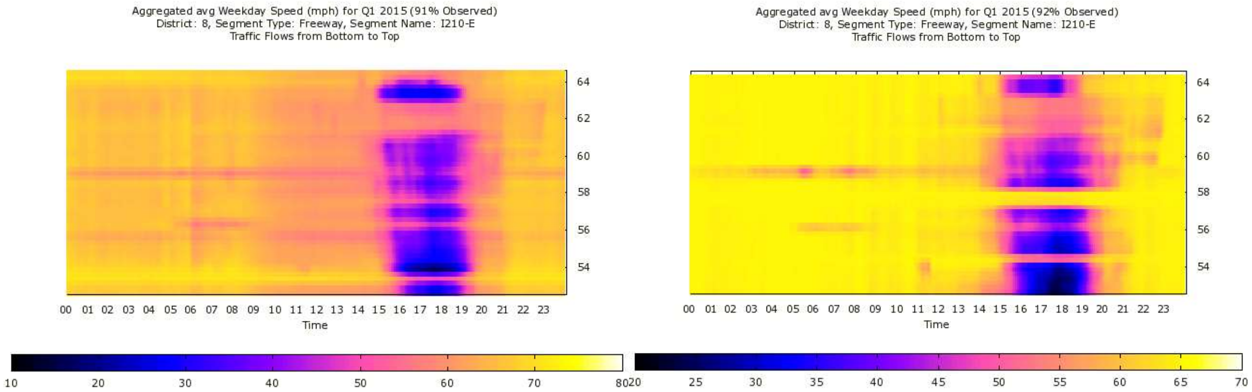
ID	Abs PM	Name	Lane Type	Time	Speed	Day of Week
1	52.54 - 52.94	From .1 E/O CO LINE to .5 E/O COUNTY LINE	Mainline	17:45	26 - 27	Weekday
2	53.84 - 57.14	From MOUNTAIN AVE WB ON to E/B CARNELIAN	Mainline	17:45	15 - 31	Weekday
3	58.14 - 61.14	From ARCHIBALD to .75 E/O MILLIKEN	Mainline	17:45	33 - 41	Weekday
4	63.56 - 64.10	From .5 E/O CHERRY IDS to CHERRY AVE	Mainline	17:45	28 - 41	Weekday

HOV

ID	Abs PM	Name	Lane Type	Time	Speed	Day of Week
1	52.54 - 57.14	From .1 E/O CO LINE to E/B CARNELIAN	HOV	17:45	22 - 36	Weekday
2	58.44 - 61.14	From E/B ARCHIBALD ONR to .75 M E/O MILLIKEN	HOV	17:45	33 - 43	Weekday
3	64.10	CHERRY AVE EB @ 210	HOV	17:45	35	Weekday



(a) Location of Bottlenecks



(b) Speed contour map for Mainline, weekdays

(c) Speed contour map for HOV, weekdays

Figure A-1. Bottleneck and speed contour map of SR-210 E between LA County Line and I-15

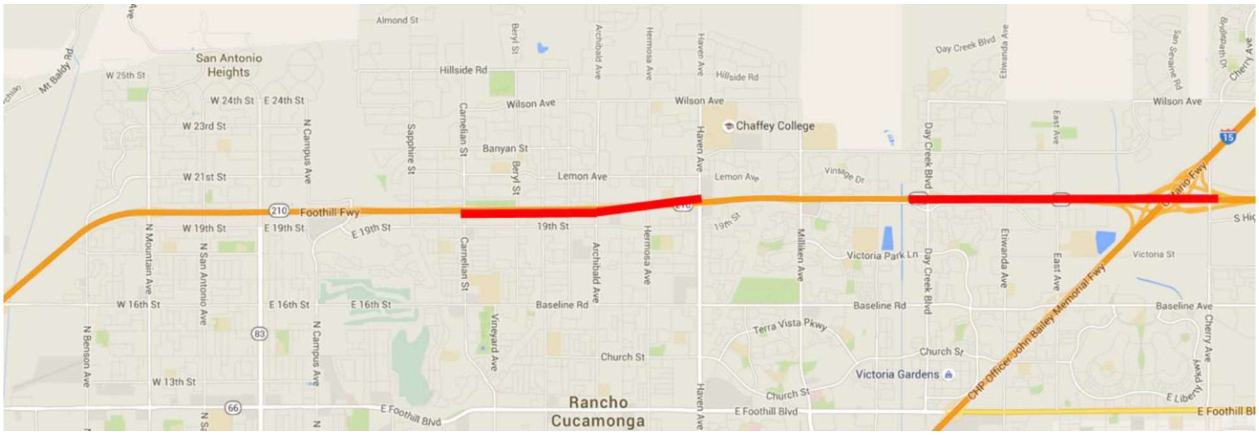
SR-210 W between LA County Line and I-15 (Abs PM: 64.73 – 53.84)

Mainline

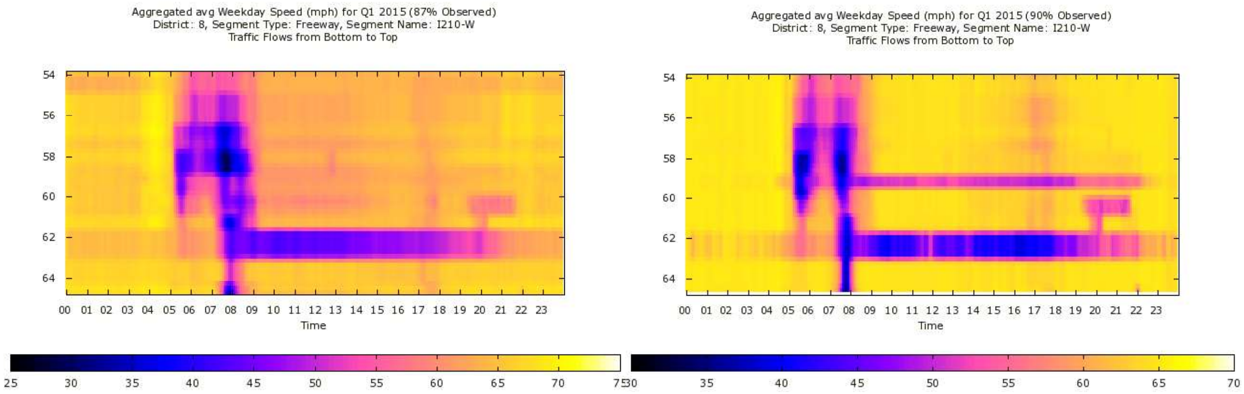
ID	Abs PM	Name	Lane Type	Time	Speed	Day of Week
1	64.73 - 64.38	From 210 W/B 15 IC IDS to .25 E/O 210/15 IC	Mainline	8:00	33 - 36	Weekday
2	61.84 - 61.24	From DAY CREEK EB ON (OS) to DAY CREEK WB ON	Mainline	8:00	36 - 42	Weekday
3	58.44 - 56.94	From E/B ARCHIBALD ONR to W/B CARNELIAN	Mainline	7:45	29 - 35	Weekday

HOV

ID	Abs PM	Name	Lane Type	Time	Speed	Day of Week
1	64.59 - 61.24	From 210@CHERRY WB to DAY CREEK WB ON	HOV	8:00	34 - 40	Weekday
2	59.24 - 56.94	From HAVEN EB ON to W/B CARNELIAN	HOV	5:30 & 7:40	35 - 41	Weekday
4	61.84	DAY CREEK EB ON (OS)	HOV	10:00 – 20:00	35	Weekend



(a) Location of Bottlenecks



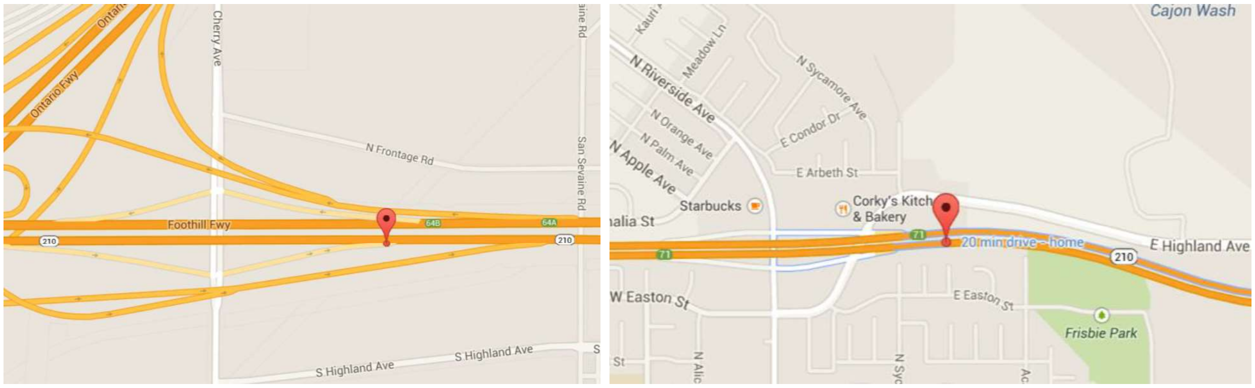
(b) Speed contour map for Mainline, weekdays

(c) Speed contour map for HOV, weekdays

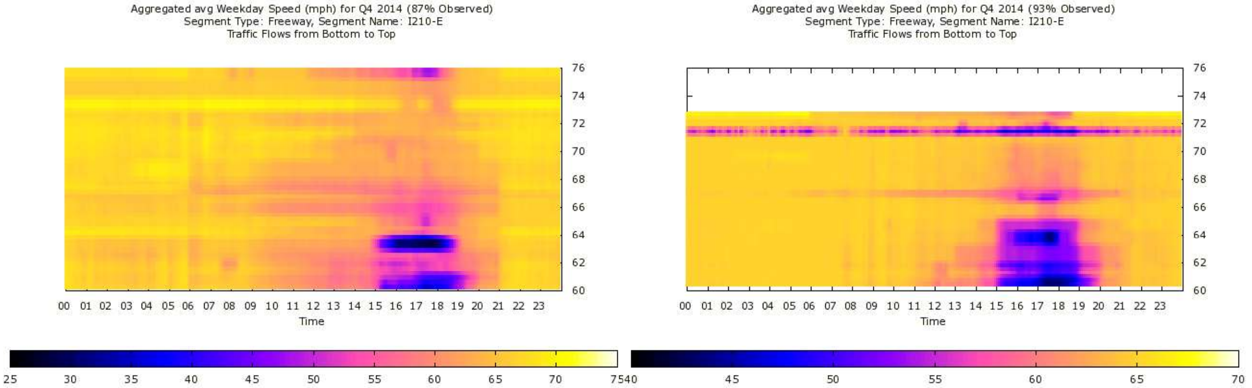
Figure A-2. Bottleneck and speed contour map of SR-210 W between LA County Line and I-15

SR-210 E between I-15 and I-215 (Abs PM: 64.21-72.93)

ID	Abs PM	Name	Lane Type	Time	Speed	Day of Week
1	64.587	CHERRY WB 210 (OS)	Mainline	17:30	46	Weekday
2	71.319	210@RIVERSIDE EB/ON	HOV	15:30	45	Weekday
				15:55	41	Weekend



(a) Location of Bottleneck 1 (b) Location of Bottleneck 2



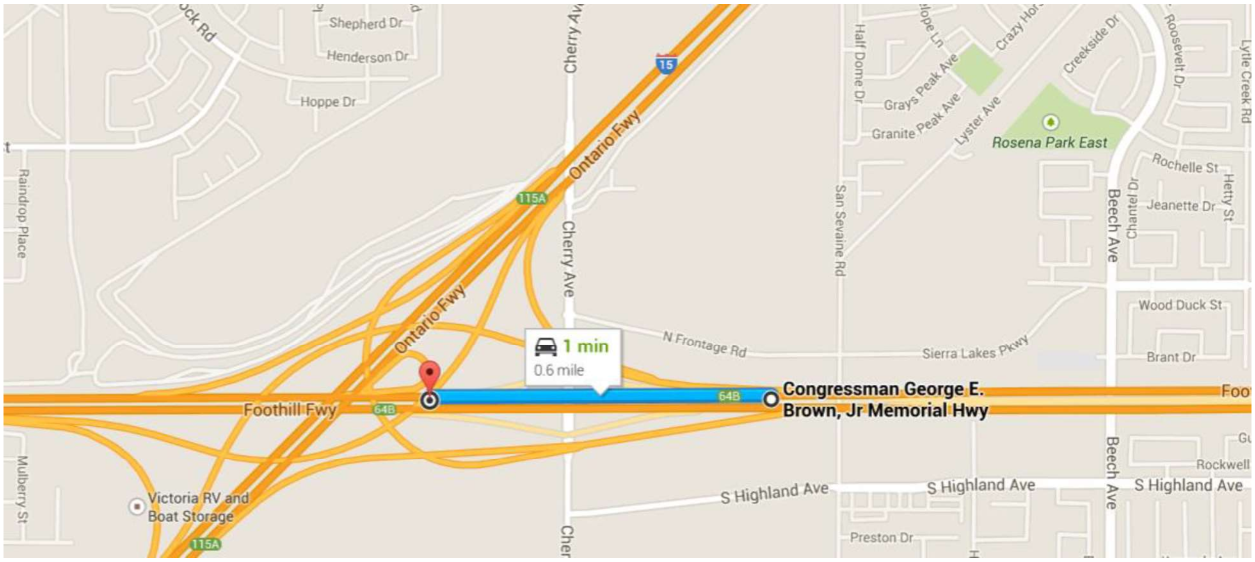
(c) Speed contour map for Mainline, weekdays (d) Speed contour map for HOV, weekdays

Figure A-3. Bottleneck and speed contour map of SR-210 E between I-15 and I-215

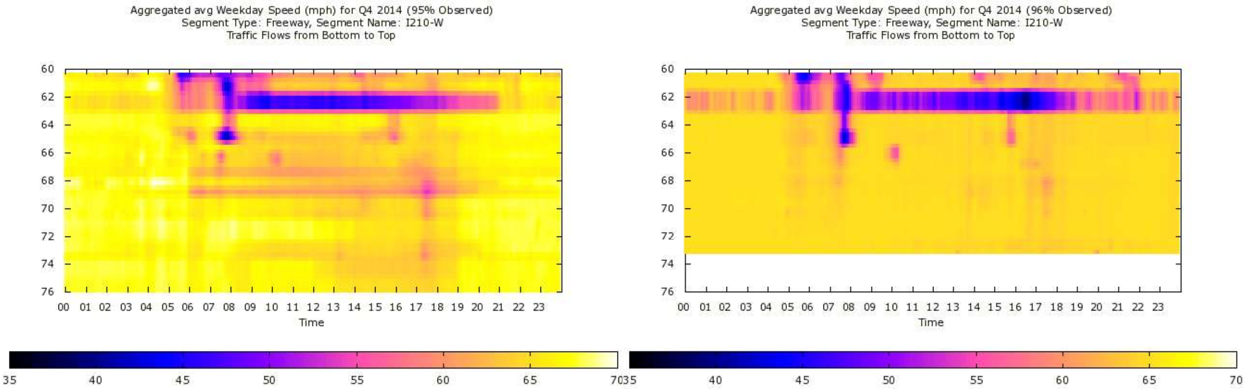
Note that in Figure A-3(c) and Figure A-3(d) we show the speed contour map within 60-76 postmile range, and the actual postmile range for the selected section (SR-210 E between I-15 and I-215) is 64.21-72.93. Therefore, the upstream bottleneck between 60 and 64 is not listed in the table.

SR-210 W between I-15 and I-215 (Abs PM: 73.95-64.10)

ID	Abs PM	Name	Lane Type	Time	Speed	Day of Week
1	64.73	210 W/B 15 IC IDS	Mainline	7:50	40	Weekday
			Mainline	17:50	48	Weekend
	64.587	210@CHERRY WB	Mainline	7:50	43	Weekday
			HOV	7:45	41	Weekday
	64.379	.25 E/O 210/15 IC	Mainline	7:50	41	Weekday
	64.102	CHERRY EB ON (OS)	HOV	7:45	48	Weekday



(a) Location of Bottleneck 1

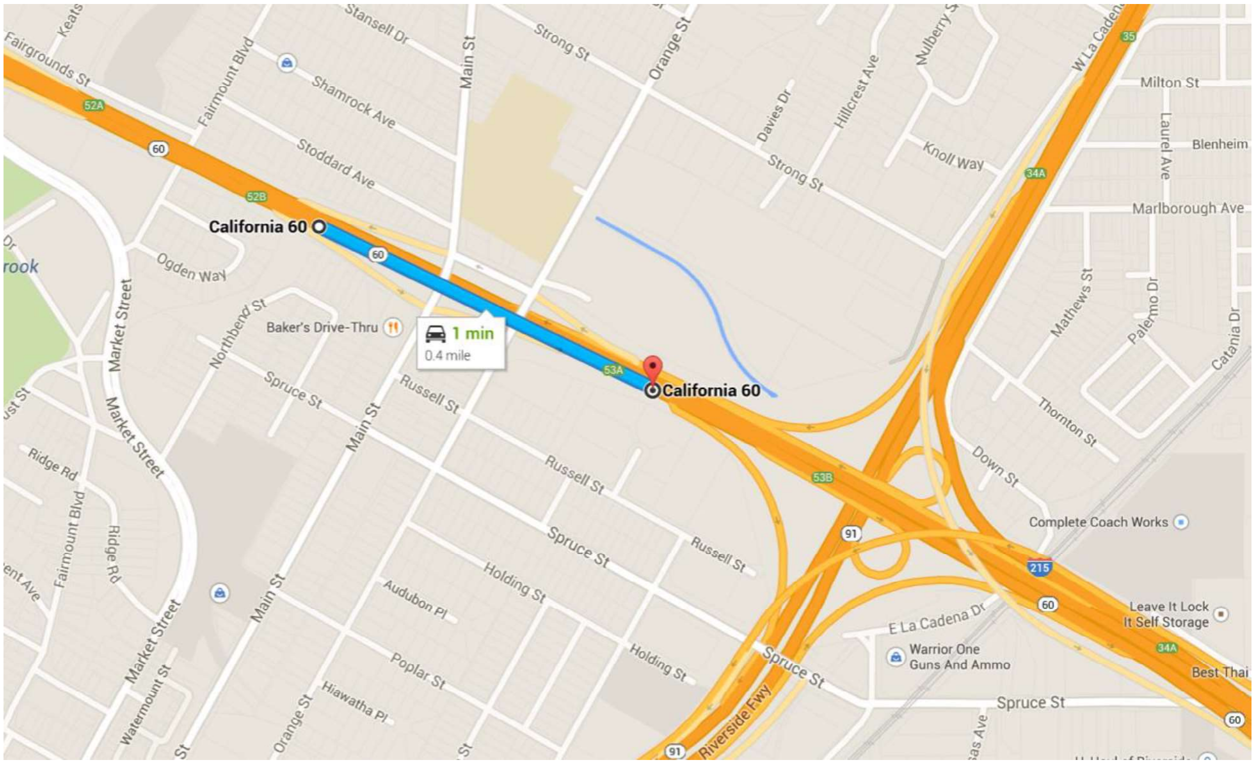


(b) Speed contour map for Mainline, weekdays (c) Speed contour map for HOV, weekdays

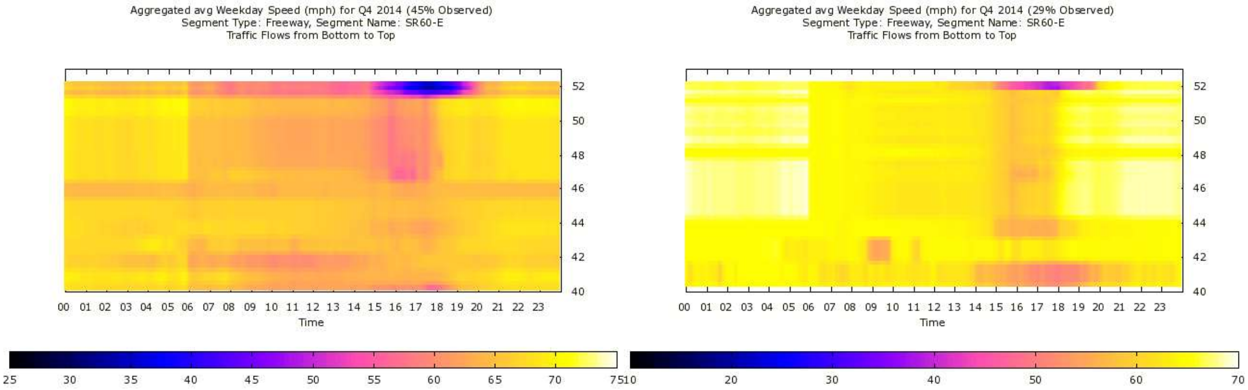
Figure A-4. Bottleneck and speed contour map of SR-210 W between I-15 and I-215

SR-60 E between I-15 and I-215 (Abs PM: 41.87 - 52.26)

ID	Abs PM	Name	Lane Type	Time	Speed	Day of Week
1	51.88	W/O Main Street	Mainline	17:40	41	Weekday
	52.095	MAIN ST	Mainline	17:40	25	Weekday
			HOV	18.00	19	Weekday
	52.256	W/O 60/91/215 IC	Mainline	17:40	45	Weekday



(a) Location of Bottleneck 1

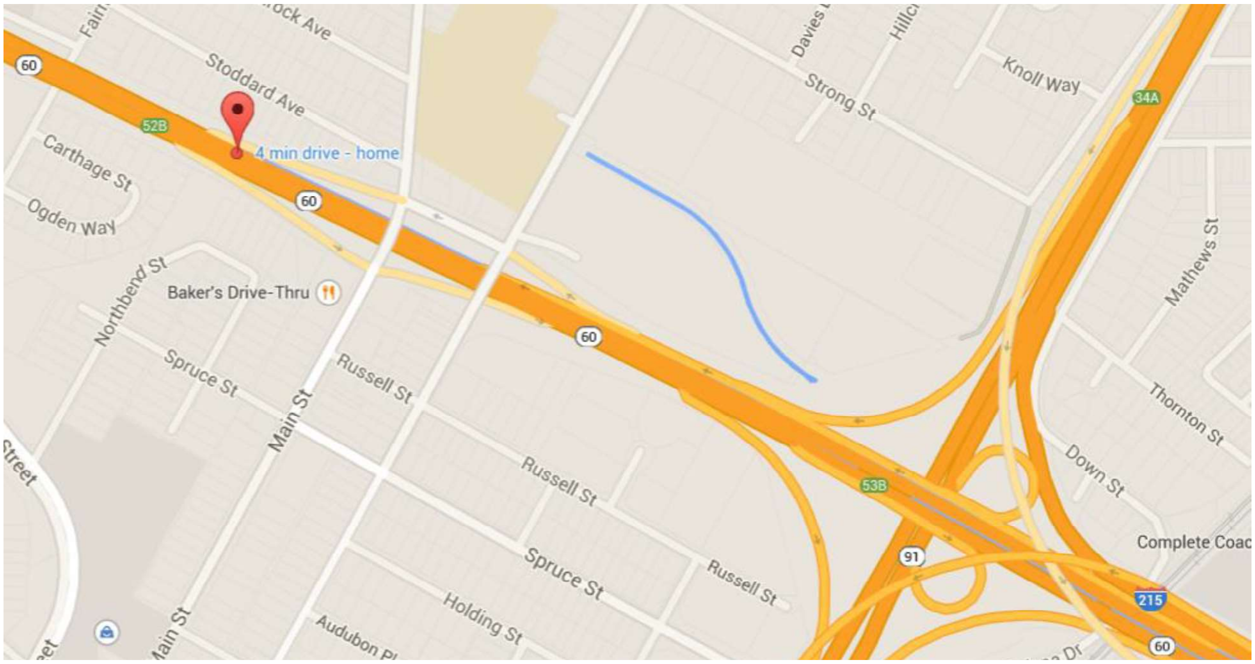


(b) Speed contour map for Mainline, weekdays (c) Speed contour map for HOV, weekdays

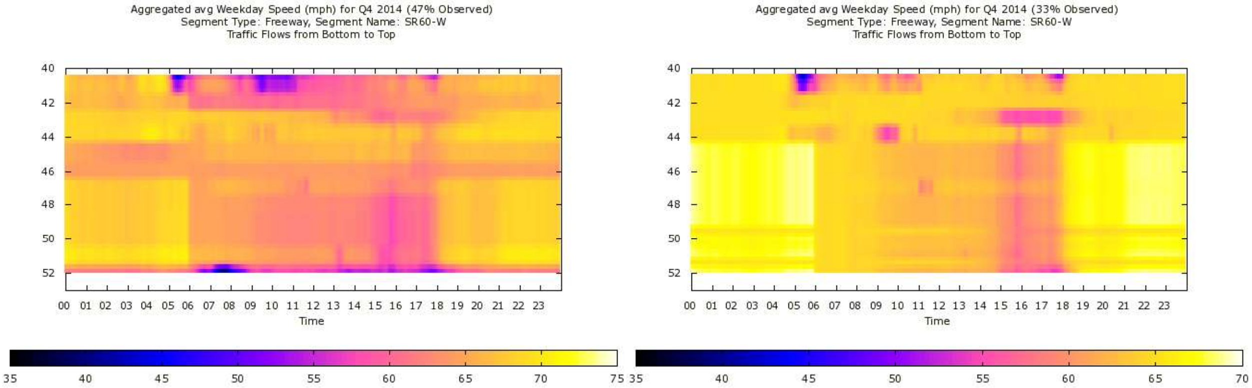
Figure A-5. Bottleneck and speed contour map of SR-60 E between I-15 and I-215

SR-60 W between I-15 and I-215 (Abs PM: 51.88 - 41.87)

ID	Abs PM	Name	Lane Type	Time	Speed	Day of Week
1	51.88	W/O Main Street	Mainline	7:40	40	Weekday
			Mainline	18:30	41	Weekend



(a) Location of Bottleneck 1

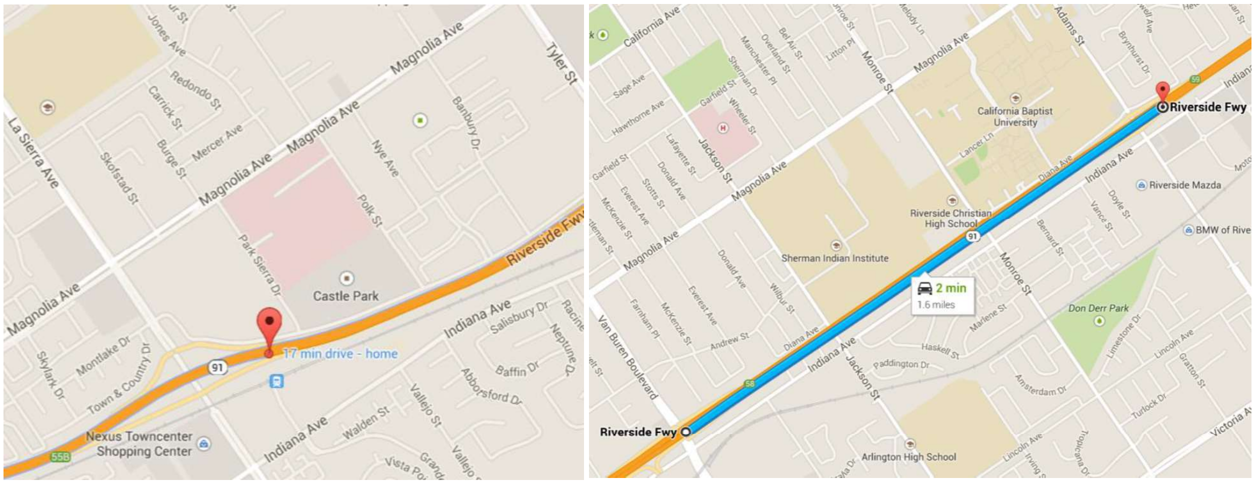


(b) Speed contour map for Mainline, weekdays (c) Speed contour map for HOV, weekdays

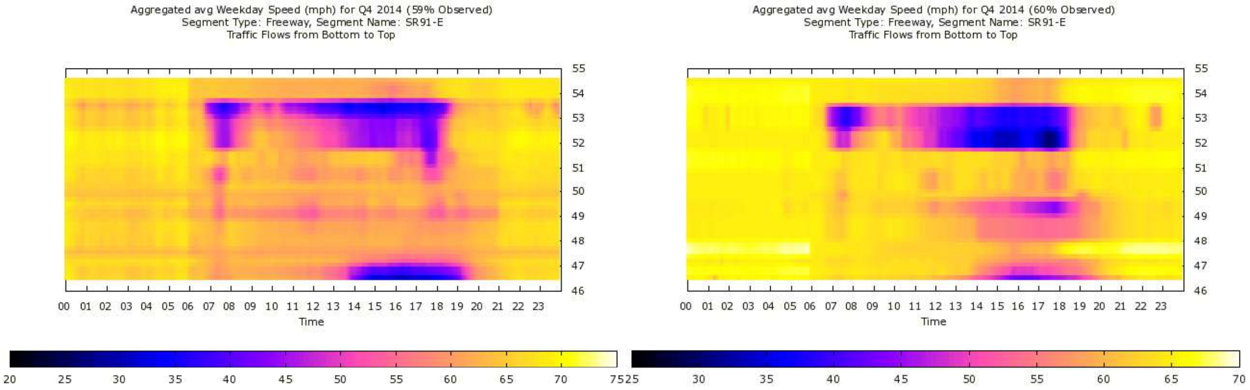
Figure A-6. Bottleneck and speed contour map of SR-60 W between I-15 and I-215

SR-91 E between Pierce St and Adams St (Abs PM: 48.07-53.06)

ID	Abs PM	Name	Lane Type	Time	Speed	Day of Week
1	49.509	LA SIERRA	HOV	18:10	40	Weekday
				16:55	38	Weekend
2	51.44	VAN BUREN	Mainline	17:40	44	Weekday
	52.058	.11 E/O JACKSON	Mainline	17:30	40	Weekday
		600' E/O JACKSON	HOV	17:30	30	Weekday
				17:30	38	Weekend
	52.9	ADAMS	Mainline	17:30	40	Weekday
	53.057	ADAMS	Mainline	15:25	34	Weekday
				17:10	43	Weekend
			HOV	15:45	37	Weekday
				16:10	44	Weekend



(a) Location of Bottleneck 1 (b) Location of Bottleneck 2

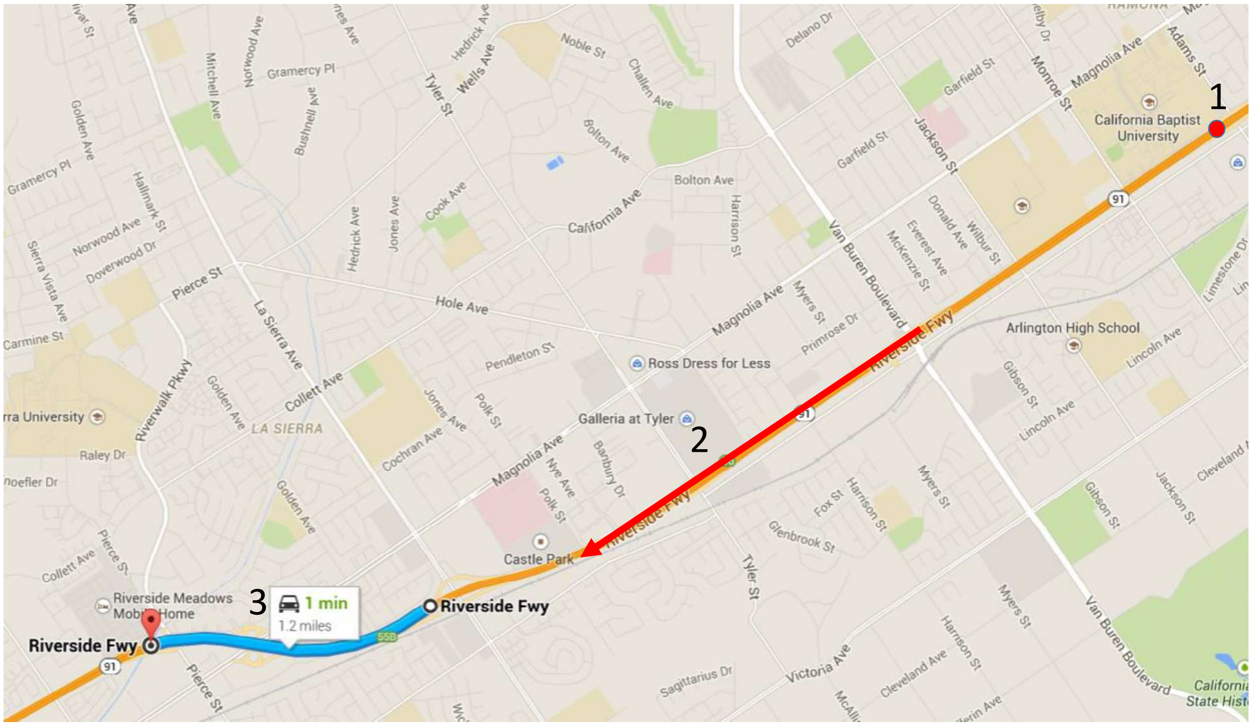


(c) Speed contour map for Mainline, weekdays (d) Speed contour map for HOV, weekdays

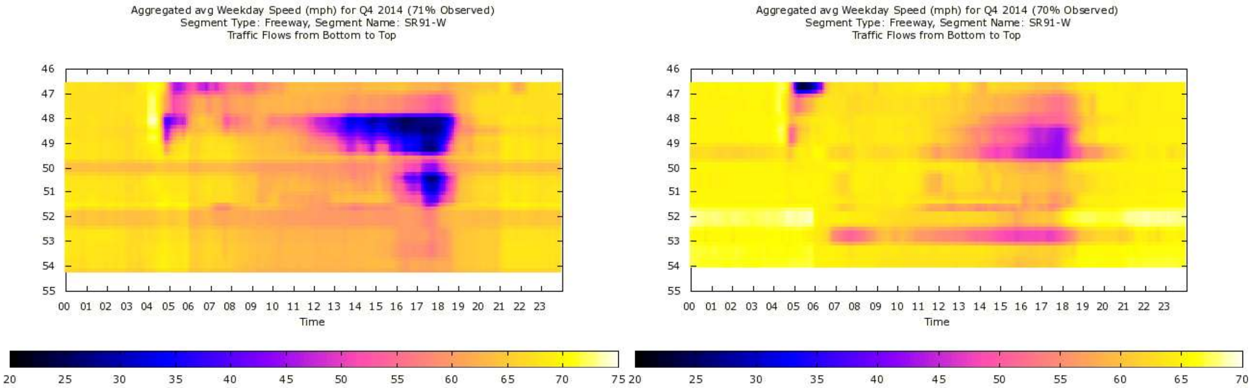
Figure A-7. Bottleneck and speed contour map of SR-91 E between Pierce St and Adams St

SR-91 W between Pierce Street and Adams St (Abs PM: 53.14-48.15)

ID	Abs PM	Name	Lane Type	Time	Speed	Day of Week
1	52.995	ADAMS	HOV	17:35	36	Weekday
				16:20	41	Weekend
2	51.526	VAN BUREN	Mainline	17:35	49	Weekday
	51.407	VAN BUREN	Mainline	17:40	38	Weekday
	50.626	TYLER	Mainline	17:45	30	Weekday
	50.337	TYLER	Mainline	17:45	26	Weekday
	49.93	M .5 W/O TYLER ST	Mainline	17:45	44	Weekday
3	49.31	LA SIERRA	Mainline	17:45	26	Weekday
			HOV	17:45	38	Weekday
				16:55	35	Weekend
	48.649	MAGNOLIA	Mainline	17:45	29	Weekday
				16:30	40	Weekend
			HOV	17:45	42	Weekday
				17:00	41	Weekend
	48.482	MAGNOLIA	Mainline	17:45	25	Weekday
				16:30	32	Weekend
			HOV	17:45	43	Weekday
				17:00	40	Weekend
	48.154	PIERCE	Mainline	17:45	27	Weekday
				16:30	27	Weekend
			HOV	17:40	46	Weekday
				16:30	39	Weekend



(a) Location of Bottleneck 1, 2 and 3



(b) Speed contour map for Mainline, weekdays

(c) Speed contour map for HOV, weekdays

Figure A-8. Bottleneck and speed contour map of SR-91 W between Pierce St and Adams St