STATE OF CALIFORNIA DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT DOCUMENTATION PAGE

TR0003 (REV. 10/98)

1. REPORT NUMBER	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
CA09-0968		ISSN 1055-1425

4. TITLE AND SUBTITLE A Comparative Safety Study of Limited versus Continuous Access High Occupancy Vehicle (HOV) Facilities	5. REPORT DATE March 2009 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Kitae Jang, David R. Ragland, Ching-Yao Chan	8. PERFORMING ORGANIZATION REPORT NO. UCB-ITS-PRR-2009-22
9. PERFORMING ORGANIZATION NAME AND ADDRESS Institute of Transportation Studies University of California, Berkeley Berkeley, CA 94720	10. WORK UNIT NUMBER 193 11. CONTRACT OR GRANT NUMBER 65A0208
12. SPONSORING AGENCY AND ADDRESS California Department of Transportation Division of Research and Innovation, MS-83 1227 O Street Sacramento CA 95814	13. TYPE OF REPORT AND PERIOD COVERED Final Report October 2005 to March 2009 14. SPONSORING AGENCY CODE

15. SUPPLEMENTAL NOTES

16. ABSTRACT

The report summarizes the findings from comparative studies of safety performance between two different types of High Occupancy Vehicle (HOV) facilities in California - continuous access versus limited access. The findings show that HOV facilities with limited access offer no safety advantages over those with continuous access, whether measured by percentage of collisions, collisions per mile, collisions per VMT, or collision severity. As part of the present research, the authors investigated the relationship between HOV design features and safety performance of HOV facilities. One key design feature is shoulder/total width. The findings indicate that maintaining adequate shoulder and total width is essential, and a quantitative estimate for the relationship between shoulder and total width versus safety performance of HOV lanes is provided. Additionally, findings from investigating other influential factors on safety performance of HOV facilities, including design features of ingress/egress section in limited access HOV facilities, congestion, High Collision Concentration Locations and etc., were also documented. While further research is needed, results to date suggest that improvements in HOV facility performance can be achieved by improved HOV facility design.

17. KEY WORDS	18. DISTRIBUTION STATEMENT	
High Occupancy Vehicle (HOV) Lanes, Managed Lanes, Limited Access, Continuous Access, Design Features, Shoulder/Total Width, Safety, Traffic Collisions	No restrictions	
19. SECURITY CLASSIFICATION (of this report) None	20. NUMBER OF PAGES 73	21. PRICE

DISCLAIMER STATEMENT

CALIFORNIA PATH PROGRAM
INSTITUTE OF TRANSPORTATION STUDIES
UNIVERSITY OF CALIFORNIA, BERKELEY

A Comparative Safety Study of Limited versus Continuous Access High Occupancy Vehicle (HOV) Facilities

Kitae Jang, David R. Ragland, Ching-Yao Chan

California PATH Research Report
UCB-ITS-PRR-2009-22

This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation, and the United States Department of Transportation, Federal Highway Administration.

Final Report for Task Order 6601

March 2009

ISSN 1055-1425

CALIFORNIA PARTNERS FOR ADVANCED TRANSIT AND HIGHWAYS

A Comparative Safety Study of Limited versus Continuous Access High Occupancy Vehicle (HOV) Facilities

Task Order 6601

March 10, 2009

Prepared for:

California Department of Transportation

Prepared by

Kitae Jang, MS, UC Berkeley Traffic Safety Center (TSC)
David R. Ragland, PhD, MPH, UC Berkeley Traffic Safety Center (TSC)
Ching-Yao Chan, PhD, Partners for Advanced Transit and Highways (PATH)

UC Berkeley Traffic Safety Center (TSC)
Institute of Transportation Studies
University of California, Berkeley, CA 94720
Tel: 510/642-0655
Fax: 510/643-9922
and
Partners for Advanced Transit and Highways (PATH)
Institute of Transportation Studies
University of California, Berkeley
Tel: 510/665-3406
Fax: 510/665-3537

A Comparative Safety Study of Limited versus Continuous Access High Occupancy Vehicle (HOV) Facilities

ACKNOWLEDGMENTS

The University of California Traffic Safety Center (TSC) and Partners for Advanced Transit and Highways (PATH) appreciate and acknowledge the contributions of the Department's Advisory Committee for this research project:

Jason Osman
District Traffic Safety Engineer (District 12)
Chief, Office of Traffic Studies

Jerry Champa
HQ Division of Traffic Operations
Traffic Operations Liaison Engineer (Districts 7 & 12)

Janice Benton
HQ Division of Traffic Operations
Chief, Office of Traffic Safety

Monica Kress
HQ Division of Traffic Operations
Chief, Office of System Management Operations

Fred Yazdan
HQ Division of Research & Innovation
Contract Manager

GLOSSARY OF ACRONYMS AND TERMS

PDO Collision: Property Damage Only collision

HOV Lane: High Occupancy Vehicle lane

HOT Lane: High Occupancy Toll lane

GP Lanes: General Purpose (GP) lanes

Left Lane: General Purpose (GP) lane closest to HOV lane

Ingress/Egress Area: A section of HOV lane open for exiting and entering HOVs

Shoulder: Area between median and traveling lanes. There are two shoulder areas on both sides of the freeway. Since HOV lanes in California are generally on the median, the present report indicates median (i.e., inner or left) shoulder.

Buffer: Pavement markings separating the HOV and GP lanes, which exist only in limited access HOV facilities.

Total Width: Consists of three parts: 1) shoulder width, 2) HOV lane width, and 3) buffer width.

HCCL: High Collision Concentration Location

VMT: Vehicle Miles Traveled

VHT: Vehicle Hours Traveled

CRP: Continuous Risk Profile, a method for estimating continuous risks along a roadway.[1]

Continuous Access HOV Lane: Drivers may move in and out of the HOV lane at any point.

Limited Access HOV Lane: Drivers may enter and exit the HOV lane only at ingress/egress areas.

---

[1] Chung, K. and Ragland, D. R., Method for generating continuous risk profile for highway collisions, Proceedings of 86th Transportation Research Board Annual Meeting, 2007.

A Comparative Safety Study of Limited versus Continuous Access High Occupancy Vehicle (HOV) Facilities

ABSTRACT

The report summarizes the findings from comparative studies of safety performance between two different types of High Occupancy Vehicle (HOV) facilities in California – continuous access versus limited access. The findings show that HOV facilities with limited access offer no safety advantages over those with continuous access, whether measured by percentage of collisions, collisions per mile, collisions per VMT, or collision severity. As part of the present research, the authors investigated the relationship between HOV design features and safety performance of HOV facilities. One key design feature is shoulder/total width. The findings indicate that maintaining adequate shoulder and total width is essential, and a quantitative estimate for the relationship between shoulder and total width versus safety performance of HOV lanes is provided. Additionally, findings from investigating other influential factors on safety performance of HOV facilities, including design features of ingress/egress section in limited access HOV facilities, congestion, High Collision Concentration Locations and etc., were also documented. While further research is needed, results to date suggest that improvements in HOV facility performance can be achieved by improved HOV facility design.

Keywords: High Occupancy Vehicle (HOV) Lanes, Managed Lanes, Limited Access, Continuous Access, Design Features, Shoulder/Total Width, Safety, Traffic Collisions

A Comparative Safety Study of Limited versus Continuous Access High Occupancy Vehicle (HOV) Facilities

EXECUTIVE SUMMARY

SYNOPSIS

Limited access HOV facilities were designed to separate higher speed traffic in HOV lanes from lower speed traffic in adjacent lanes in order to reduce the risk of collisions caused by vehicles weaving between lanes of traffic traveling at different speeds. Using data from California freeways, limited access HOV and left lanes were compared with those of continuous access HOV facilities to evaluate the safety of each, and to determine which characteristics could improve performance in either type of facility. Based on these results, limited access HOV facilities do not appear to provide increased safety, whether measured by percentage of collisions, collisions per mile, collisions per VMT, or collision severity—the pattern actually seems to suggest the opposite. From a strictly safety viewpoint, this suggests that constructing limited access facilities would not achieve the goal of increasing freeway safety. However, the study recommends design features that could maximize the safety of limited access facilities, such as maintaining adequate total and shoulder width, adequate length of access segments, and adequate distance between access areas and on/off ramps. While further research is needed to expand understanding of safety performance of HOV facilities, results to date suggest that improvements in HOV facility performance can be achieved through refinements in freeway design.

BACKGROUND

Two configurations for HOV lanes—limited and continuous—are prevalent in California. **Limited access HOV lanes (predominant in Southern California)**, have specified locations for ingress and egress HOV maneuvers, and are separated from other freeway lanes by buffer zones demarcated by pavement markings or physical barriers. Such separation is intended to facilitate smooth and safe operation of traffic flows, typically at relatively high speeds, within HOV lanes. Concerns about limited access lanes include possible impacts on traffic maneuvers due to: (i) vehicle lane-changing concentrated near ingress/egress locations, and (ii) extensive vehicle lane-changing between freeway ramps and HOV access points within a fixed and often relatively short distance. **Continuous access HOV lanes (predominant in Northern California)** do not include a buffer zone, allow vehicles to enter and exit at any location, and are in operation only during peak hours (generally, Monday–Friday, 5–9AM, 3–7PM).

One of the objectives of the California Department of Transportation (Caltrans) is continuous evaluation and improvement of safety and operational efficiency in all facilities. A large number of HOV facilities have been implemented on California freeways as one of the major demand management strategies to counteract continuously increasing congestion in metropolitan areas. HOV facilities are an evolving part of freeway infrastructure and induce significant complexity for driving tasks. Unlike continuous access HOV facilities, limited access HOV facilities have demarcation between HOV and GP lanes, and allow HOVs to enter and exit only within limited

sections of HOV lanes. Geometric features associated with limited access HOV facilities often create weaving movements both upstream and downstream of ingress/egress areas, and also encourage concentrated and consecutive lane changes across lanes in the vicinity of ingress/egress sections. Such traffic movements can conflict with existing traffic flow and cause high-risk situations. Therefore, there are strong incentives to (i) investigate the safety performance of the two major types of HOV facilities in California, and (ii) enhance the level of understanding about the characteristics influencing safety performance in both types of HOV facilities.

A research project at the University of California, Berkeley was funded by Caltrans to compare traffic collision patterns between limited access and continuous access HOV lanes and, if any, investigate the attributes accounting for such differences. While some facilities utilize an actual barrier between HOV and adjacent lanes, the current study focuses only on facilities that are buffer-separated, meaning that the separation is indicated solely by pavement markings.

DATA SOURCES

Data for the study was collected from the following sources:

Collisions

- Traffic Accidents Surveillance and Analysis System (TASAS), 1999–2003 collisions in traveling lanes: TASAS is a collision database which records information associated with each collision that occurs within the California state freeway system.

Traffic Data

- Freeway Performance Measurement System (PeMS), (https://pems.eecs.berkeley.edu/): PeMS is a tool that processes and analyzes traffic data collected by loop detectors and tags.

Geometric Features

- Highway Performance Monitoring System (HPMS): This is a federally mandated inventory system and planning tool, designed to assess the nation's highway system.
- California Department of Transportation Document Retrieval System (DRS): DRS is a document database which enables users to search for, view, and print documents including built plans and survey files by using a browser on the California DOT intranet.
- California Department of Transportation Photolog (http://video.dot.ca.gov/photolog/): This is a series of photos recorded in accordance with post mile in the California state freeway system.

- Aerial Photos: Google Earth (http://earth.google.com/): Google Earth is a virtual globe program which maps the earth via the superimposition of images obtained from satellite imagery, aerial photography, and GIS 3D globe.

HOV Facilities

- California Department of Transportation HOV reports, which contain information regarding HOV lanes on the California state freeway system.
- California Department of Transportation HOV inventory (2005), which is an inventory of HOV facilities within the California state freeway system.

METHODS

The safety performance of both the HOV lane itself and adjacent left lane are likely to be affected by the type of access (limited versus continuous). For HOV and left lanes, a general analysis was conducted of HOV facilities constructed before 1999 (to provide sufficient collision data) and consisting of over 60 percent of all California HOV lanes. All collisions (fatal, injury, and PDO) that occurred within traveling lanes between 1999 and 2003 were included in the analysis. Since continuous access HOV lanes are in operation only during peak hours (generally, Monday–Friday, 5–9 a.m., 3–7 p.m.), the comparison was limited to those hours. More detailed analyses were then conducted on a subset of eight sites (four continuous access and four limited access).

The following analyses were conducted for HOV and left lanes:

- Percentage of total collisions for HOV and left lanes compared with all freeway lanes (62 sites, analysis replicated for 8 sites)
- Number of total collisions per mile per hour (62 sites, analysis replicated for 8 sites)
- Number of fatal and injury collisions per mile per hour (62 sites, analysis replicated for 8 sites)
- Number of fatal and injury collisions per VMT (8 sites)
- Impact on congestion (8 sites)

The following analyses focused on HOV lanes:

- Shoulder width (13 sites)
- Total width (shoulder plus lane plus buffer) (13 sites)
- Spatial analysis (4 sites)
- Type of collision analysis (8 sites)

A Comparative Safety Study of Limited versus Continuous Access High Occupancy Vehicle (HOV) Facilities

RESULTS FOR HOV LANES

Compared with continuous access HOV lanes, we observed the following characteristics for limited access HOV lanes:

- Higher percentage of total collisions across all freeway lanes
- Higher number of total collisions per mile per hour
- Higher number of fatal and injury collisions per mile per hour
- Higher number of total collisions per VMT
- Higher number of fatal and injury collisions per VMT

These differences were statistically significant ($p<0.05$).

Additional Findings for HOV Lanes:

- The difference in safety performance was apparently not due to differences in congestion.
- Shoulder width was a very strong predictor of safety performance in both limited and continuous access HOV lanes. However, differences in shoulder width between continuous and limited access facilities did not account for the differences in safety performance between the two HOV configurations.
- A spatial analysis of collisions along the length of the freeway suggested a difference in patterns of clustering collisions between the two types of facilities.
- An analysis of collision types indicated a higher proportion of rear-end collisions, and a lower proportion of side-swipe collisions in limited access facilities.

In sum, the safety performance of HOV lanes was <u>lower</u> in limited access HOV facilities compared with continuous access facilities. The spatial and collision analyses are consistent with the interpretation that vehicles in limited access HOV lanes have less room to maneuver in the event of bottlenecks within the lane.

RESULTS FOR LEFT LANES

Compared with continuous access left lanes, we observed the following characteristics for limited access left lanes:

- Higher percentage of total collisions across all freeway lanes
- Higher number of total collisions per mile per hour
- Lower number of fatal and injury collisions per mile per hour
- Higher number of total collisions per VMT
- Lower number of fatal and injury collisions per VMT (Statistically insignificant)

These differences—except those for the fatal and injury collisions per VMT—were statistically significant ($p<0.05$). In sum, the results for left lanes are mixed. Generally, limited access left lanes experience lower levels of safety performance for total collisions, but slightly better performance when analysis is limited to fatal and injury collisions.

RESULTS FOR HOV AND LEFT LANES COMBINED

Compared with continuous access HOV and left lanes combined, we observed the following characteristics for limited access HOV and left lanes combined:

- Higher percentage of the total collisions across all freeway lanes
- Higher number of total collisions per mile per hour
- Higher number of fatal and injury collisions per mile per hour (statistically insignificant)
- Higher number of total collisions per VMT
- Higher number of fatal and injury collisions per VMT

These differences—except those for the fatal and injury collisions per mile per hour—were statistically significant ($p<0.05$). In sum, most of these measurements indicate a lower overall (HOV and left lanes combined) level of safety performance for limited access facilities compared with continuous access facilities.

CONCLUSIONS

Our results suggest that, compared with continuous access HOV facilities, limited access HOV facilities do not appear to provide increased safety, whether measured by percentage of collisions, collisions per mile, collisions per VMT, or collision severity—the pattern actually seems to suggest the opposite. Potential differences in traffic volume, number of lanes, shoulder width, lane width, or total width (shoulder plus HOV lane plus buffer) did not appear to account for these findings. Strictly from a safety viewpoint, this suggests that construction of limited access facilities to achieve a safety objective is not warranted.

However, our study recommends design features that could maximize the safety of limited access facilities. One of these features is shoulder/total width. Our findings suggest that maintaining adequate shoulder and total width is essential, and we provide a quantitative estimate for the relationship between shoulder and total width versus safety performance of HOV lanes. Unfortunately, we do not currently have sufficient data to analyze the tradeoff between shoulder width and buffer width. This would be a fairly straightforward extension of our study and could be conducted by including additional sites in our analysis.

Another potential safety enhancing feature is to optimize the length of the access section and its location in relation to on/off ramps. Based on our analysis of collision rates near

access points in limited ingress and egress HOV facilities, it appears that collision rates are higher in short access sections. We hypothesize that short access sections create queues in the HOV lane and increase the incidence of rear-end collisions (our findings showed increased rates of rear-end collisions in limited access facilities) and intensify weaving. Our findings also suggest that locating access areas in close proximity to on/off ramps should be avoided, since it may lead to intense weaving and hot spots for collisions across freeway lanes. Additional analyses would be required to develop a quantitative estimate for the optimal access segment length and distance of access segments from on-off-ramps.

In general, our study demonstrates that HOV design features can have an impact on safety performance. While further research is needed, results to date suggest that improvements in HOV facility performance can be achieved by improved HOV lane design.

TABLE OF CONTENTS

ACKNOWLEDGMENTS ii

GLOSSARY OF ACRONYMS AND TERMS iii

EXECUTIVE SUMMARY iv

TABLE OF CONTENTS xi

1. DEFINITIONS AND BACKGROUND 1

2. PREVIOUS STUDIES 2

3. STUDY OBJECTIVE 4

4. DATA SOURCES 5

5. COMPARISON OF HOV COLLISION STATISTICS IN STATEWIDE ANALYSIS 7

6. COMPARISON OF HOV COLLISION STATISTICS IN DETAILED STUDY ROUTES 9

6.1. Comparison of HOV Collisions in Detailed Study Sites (8 Study Routes) 9

6.2. Comparison of HOV Collisions accounting for traffic volume (8 Study Routes) 10

7. DETAILED HOV COLLISION ANALYSIS 12

7.1. Shoulder Width Analysis (13 study routes) 12

7.2. Total (shoulder + HOV lane + buffer) width analysis (13 study routes) 13

7.3. Congestion Analysis (8 study routes) 14

7.4. High Collision Concentration Location (HCCL) Analysis (8 study routes) 15

7.5. Spatial Collision Analysis (4 study routes) 15

7.6. Ingress/Egress Area Analysis (8 study routes) 16

7.7. Collision Type Analysis (8 study routes) 17

8. CONCLUSION AND IMPLICATIONS 18

9. FURTHER RESEARCH 20

9.1. Investigation of safety performance of HOV lanes at micro level 20

9.2. investigation of role of shoulder and buffer widTH 20

9.3. Design criteria for limited access openings and evaluation of effectiveness of HOV flyovers 20

9.4. Application to High Occupancy Toll (HOT) Facilities 21

9.5. Drivers' Behavior in HOV/HOT Facilities 21

ATTACHMENTS 22

TABLE OF FIGURES

Attachment A Diagram of Continuous and Limited Access HOV Configurations 22

Attachment B Location of HOV Facilities and Collection of Collision Data for HOV and Left Lanes 23

Attachment C A Comparison of Collision Distribution in HOV and Left Lanes (Statewide Analysis) 24

Attachment D A Comparison of Collisions Per Mile Per Hour in HOV and Left Lanes (Statewide Analysis) 25

Attachment E A Comparison of Fatal and non-fatal injury Collisions Per Mile Per Hour in HOV and Left Lanes (Statwide Analysis) 26

Attachment F Detailed Study Routes for HOV Collision Analysis 27

Attachment G A Comparison of Collision Distribution in HOV and Left Lanes (8 Study Routes) 28

Attachment H A Comparison of Collisions Per Mile Per Hour In HOV and Left Lanes (8 Study Routes) 29

Attachment I A Comparison of Fatal and non-fatal injury Collisions Per Mile Per Hour In HOV and Left Lanes (8 Study Routes) 30

Attachment J Collision Rate (Collisions Per VMT) (8 Study Routes) 31

Attachment K Fatal and non-fatal injury Collision Rate (Collisions Per VMT) (8 Study Routes) 32

Attachment L Statistical tests (Statewide and 8 Study Routes) 33

Attachment M Detailed Study Routes for HOV Collision Analysis (8 Study Routes) ...37

Attachment N Relationship Between Shoulder Width and Collisions Per Mile Per Hour 38

Attachment O Relationship Between Total Width and Collisions Per Mile Per Hour 39

Attachment P The Relationship Between HOV Lane Occupancy and Collisions/Million VMT in Study Sites 41

Attachment Q Continuous Risk Profiles (CRPs) in HOV and Left Lanes (8 Study Routes) 42

Attachment R Cross-Sectional Distribution of Collisions Near Ingress/Egress Areas (Interstate 210 Eastbound, Los Angeles County) 43

Attachment S Cross-Sectional Distribution of Collisions Near Ingress/Egress Areas (Interstate 5 Northbound, Orange County) 44

Attachment T Relationship Between Collisions Per Mile and Distance to Nearest Entrance/Exit Ramp in Limited Access HOV Facilities 45

Attachment U Types of Collisions in HOV Lanes Per Facility 46

A Comparative Safety Study of Limited versus Continuous Access High Occupancy Vehicle (HOV) Facilities

1. DEFINITIONS AND BACKGROUND

High Occupancy Vehicle (HOV) lanes have been implemented on crowded urban freeways to mitigate continuously growing traffic congestion and to improve overall mobility within metropolitan freeway systems. HOV lanes are designed to enable vehicles carrying more passengers to bypass the congested General Purpose (GP) lanes, while encouraging the use of carpools and public transportation to move more people per lane with a fewer vehicles. In California, HOV lanes were first introduced in the San Francisco Bay area as early as 1962 and near Los Angeles in 1971. In the 1990s, HOV lanes were increasingly implemented in congested freeway segments in Southern and Northern California metropolitan regions. As of 2005, HOV lanes comprised 1,305 (directional) lane-miles of freeway, with 895 lane-miles located in Southern California, 410 in Northern California, and 950 additional lane-miles of HOV lanes proposed.

Since their inception, two configurations for HOV lanes—limited and continuous—have emerged in California (Attachment A). **Limited access HOV lanes** have specified locations for ingress and egress maneuvers, and are separated from other freeway lanes by buffer zones,[2] demarcated by pavement markings or physical barriers. Such separation is intended to facilitate smooth and safe operation of traffic flows, typically at relatively high speeds. However, safety concerns include potential impacts on traffic maneuvers due to: (i) vehicle lane-changing concentrated near ingress/egress locations, and (ii) extensive vehicle lane-changing between freeway ramps and HOV access points within a fixed and often relatively short distance. **Continuous access HOV lanes** do not include a buffer zone, and allow vehicles to enter and exit at any location.

Predominant in Southern California, limited access HOV lanes are in operation 24 hours a day, seven days a week, while continuous access HOV lanes, which are predominant in Northern California, are in operation only during peak hours (generally, Monday–Friday, 5–9 a.m., 3–7 p.m.).[3]

The differences between HOV configuration and operation throughout the state largely reflect different freeway commute patterns at the initial stage of HOV lane implementation. In areas in which periods of congestion last for many hours of the day, full-time HOV operation with limited access has been favored. In areas in which commute patterns consist of short peak periods and clear directional flows, continuous access HOV operation during peak commute hours has been preferred.

[2] Some facilities utilize an actual barrier between HOV and adjacent lanes. The current study focuses only on facilities that are buffer-separated, meaning that the separation is indicated solely by pavement markings. The buffer can vary in width.
[3] Operation hours vary across routes depending on their specific commute and congestion patterns.

2. PREVIOUS STUDIES

Previous studies regarding the safety performance of HOV facilities have focused mainly on comparing collision patterns before and after implementation of HOV facilities, and identifying factors influencing collision occurrence. The studies have been based on data from a limited number of study routes and consequently the results have been relatively inconclusive due to data limitations in both quantity and quality. Moreover, there has been lack of research comparing the safety performance of different types of HOV facilities.

One recent research study conducted a before and after comparison of buffer-separated limited access HOV facilities in two corridors in Dallas, Texas. The before and after comparison of corridor crash rates showed a substantial increase in injury crash rates after installation of the buffer-separated HOV lanes. The study also suggested several factors that might have contributed to the increased crash risk: speed differential between HOV and general purpose lanes, reduced width of general purpose lanes, loss of the inside shoulder, and difficulty for vehicles in the HOV lane to find gaps in traffic when entering the general purpose lanes.[4]

Another study also compared the frequency and characteristics of collisions before and after installation of an HOV lane without physical separation (i.e., buffer-separated) by converting the inner shoulder area to an HOV lane on State Route 91 in Los Angeles, California. The study concluded that installation of HOV lanes did not have an adverse effect on the safety performance of the corridor and that the changes in crash characteristics were due to the changes in spatial and temporal attributes of traffic congestion.[5]

An additional study documented findings based on analysis of how HOV facility operation affects the safety of selected California freeways. The study suggested that the collision patterns showed no systematic differences in the lane locations of collisions or other influential factors, but were characterized by the location of traffic congestion. Localized traffic congestion results in the clustered collisions, HCCLs, during peak hours with and without HOV lanes. [6]

The study, funded by FHWA, conducted a before and after comparison for four different types of HOV facilities: 0–2 foot buffer, 3–8 foot buffer, 8 foot buffer with 6 inch raised barrier, and 13 foot (full) buffer. The latter two designs did not appear to increase overall collision rates, while the first design appeared to increase the collision rates when compared with the pre-HOV collision rates. The results of the study for the second design

---

[4] Cooner, S. A. and Ranft, S. E., Safety evaluation of buffer-separated High-Occupancy Vehicle lanes in Texas, *Transportation Research Record*, No. 1959, 2006

[5] Golob, T. F., Recker, W. W. and Levine, D.W., Safety of High-Occupancy Vehicle lanes without physical separation, Journal of Transportation Engineering, Vol. 115, No. 6, 1989

[6] Sullivan, E.C. and Devadoss, N., High-Occupancy Vehicle facility safety in California, *Transportation Research Record*, No. 1394, 1993

type were inconclusive.[7] Since more than 70% of HOV facilities implemented in California are based on the former two designs, however, the safety performance of HOV facilities currently in place in California cannot be explained based on the results of this study.

Unlike the previously described studies, another study compared three specific types of HOV facilities in California: physically separated facilities, buffer-separated facilities (full lane width), and contiguous facilities. In the study, the term “contiguous facility” referred to continuous access as well as limited access facilities in which the buffer width was narrower than full lane width (13 ft). The study found that separated facilities were superior to contiguous facilities.[8] During the past two decades since the study was conducted, however, continuous and limited access HOV facilities, which were categorized as a single group in the study, become the two predominant types of HOV configurations in California. The findings of that study are not applicable to the questions addressed in our study.

Hockaday et al. investigated collision patterns in three different types of HOV facilities; contiguous, buffer-separated and barrier separated. For this investigation, the authors used TASAS collision data from 1989 to 1991 and concluded that HOV facilities did not show any significant and systematic differences when compared with non-HOV facilities with comparable features.[9] However, this study did not specifically compare collision statistics between different types of HOV facilities, but instead compared overall collision statistics between HOV and non-HOV facilities.

The findings of previous studies are not directly applicable to the questions addressed in our study. The present study compares collision patterns occurring in continuous access HOV facilities with those of limited access facilities (of various buffer widths), which represent the two major types of HOV facilities in California.

[7] Case, R. B.. The safety of concurrent-lane HOV projects, Hampton roads planning district commission, Chesapeake, Virginia, 1995

[8] Newman, L., Nuworsoo, C. and May, A. D., Operational and safety experience with freeway HOV facilities in California, *Transportation Research Record*, No. 1173, 1988.

[9] Hockaday, S., Sullivan, E., Devadoss, N., Daly, J. and Chatziiouanou, A., *High-Occupancy Vehicle Lane Safety.* Submitted to the State of California Department of Transportation by California Polytechnic State University. Contract Number 51P278, TR 92-107. September 1992.

3. STUDY OBJECTIVE

One of the objectives of the California Department of Transportation (Caltrans) is continuous evaluation and improvement of all facilities. Therefore, there are strong incentives to (i) investigate the safety performance of the two major types of HOV facilities in California, and (ii) enhance the level of understanding about the factors influencing safety performance in both types of HOV facilities. A research project at the University of California, Berkeley was funded by Caltrans to compare traffic collision patterns between limited access HOV lanes (predominant in Southern California) and continuous access HOV lanes (predominant in Northern California) and, if any, investigate the attributes accounting for such differences.

4. DATA SOURCES

Comparison of safety performance between the two different types of HOV facilities involved multi-dimensional issues including geometric features, demand for each facility, inherent collision features, and other factors. Diverse data sources were utilized to maximize accuracy in comparison and explanation of differences in collision patterns between the two different HOV configurations.

Collisions

- Traffic Accidents Surveillance and Analysis System (TASAS), 1999–2003 collisions on traveling lanes: a collision database which records information associated with each collision that occurs within the California state freeway system.[10]

Traffic Data

- Freeway Performance Measurement System (PeMS), (https://pems.eecs.berkeley.edu/): a tool that processes and analyzes traffic data collected by loop detectors and tags.

Geometric Features

- Highway Performance Monitoring System (HPMS): a federally mandated inventory system and planning tool, designed to assess the nation's highway system.[11]
- California Department of Transportation document Retrieval System (DRS): a document database which enables users to search for, view, and print documents including built plans and survey files by using a browser on the California DOT intranet.
- California Department of Transportation Photolog (http://video.dot.ca.gov/photolog/): a series of photos recorded in accordance with postmile in California state freeway system.
- Aerial Photos: Google Earth (http://earth.google.com/): a virtual globe program which maps the earth via the superimposition of images obtained from satellite imagery, aerial photography, and GIS 3D globe.

[10] California Department of Transportation, California DOT traffic manual Ch. 3. Accident and roadway records, 2004.
[11] California Department of Transportation Division of Transportation System Information, Highway Performance Monitoring System (HPMS) instruction for updates, 2007.

HOV Facilities

- California Department of Transportation HOV reports: these reports contain information regarding HOV lanes in the California state freeway system.[12,13]
- California Department of Transportation HOV inventory (2005): an inventory of HOV facilities within the California state freeway system.

[12] California Department of Transportation, District 4, Office of Highway Operations, Bay Area HOV lanes, 1999-2005.
[13] California Department of Transportation, District 7, HOV annual report, 2005 and 2006.

5. COMPARISON OF HOV COLLISION STATISTICS IN STATEWIDE ANALYSIS

A statewide/general analysis was conducted using a large sample of HOV lanes constructed before 1999 to allow sufficient time to observe collisions after implementation. A total of 824 HOV lane-miles were examined, including 279 lane-miles of continuous access, and 545 lane-miles of limited access HOV lanes. The selected routes covered more than 60 percent of all existing HOV facilities as of 2005 (Attachment B). All collisions (fatal, injury, and PDO) that occurred within traveling lanes between 1999 and 2003 were included in the analysis. Since continuous access HOV lanes are in operation only during peak hours (generally, Monday–Friday, 5–9 a.m., 3–7 p.m.), the comparison was limited to those hours.

In the TASAS database, collisions are recorded by lane (i.e., HOV, left, interior, and right) and location along the freeway. Thus, we were able to calculate the distribution of collisions across lanes and as a function of lane miles. Collisions per mile per hour were averaged by weighting operational hours and lane miles of the routes.

We observed the following characteristics in **limited access** HOV facilities compared with continuous access facilities:

- Limited access facilities experienced a higher percentage of total collisions in the combined HOV and left lanes (43% for limited, versus 33% for continuous) (i.e., differences in collision distribution across the freeway). The same pattern was observed separately in HOV lanes (9% for limited, versus 5% for continuous) and left lanes (34% for limited, versus 28% for continuous) (Attachment C).
- Limited access facilities experienced a higher number of collisions per mile per hour in the combined HOV and left lanes (3.6 collisions for limited, versus 2.9 for continuous). The same pattern was observed separately in HOV lanes (0.8 for limited, versus 0.4 for continuous) and left lanes (2.8 for limited, versus 2.5 for continuous) (Attachment D).
- Limited access facilities experienced a higher number of fatal and injury collisions per mile per hour in HOV and left lanes combined (0.88 collisions for limited, versus 0.86 for continuous). The same pattern was observed for the HOV lane separately (0.25 collisions for limited, versus 0.13 collisions for continuous), but the opposite pattern was observed in left lanes (0.63 for limited, versus 0.73 for continuous) (Attachment E).

For the comparison between distributions of collisions across lanes and collisions per mile per hour, a test statistic for each case was derived (Attachment U). All the differences except for the disparity in injury collision rates in combined HOV and left lanes were statistically significant ($p<0.05$). In other words, only the difference in injury collision rates in combined HOV and left lanes was *not* statistically significant.

Compared with HOV lanes in continuous access facilities, HOV lanes in limited access facilities experienced (i) a higher percentage of collisions compared with other lanes, (ii) a higher number of total collisions per mile per hour, and (iii) a higher number of fatal and injury collisions per mile per hour. Each of these differences was substantial and statistically significant.

The pattern for left lanes was different than the pattern for HOV lanes. Compared with left lanes in continuous access facilities, HOV lanes in limited access facilities experienced (i) a higher percentage of collisions compared with other lanes, and (ii) a higher number of collisions per mile per hour, but, (iii) a *lower* number of fatal and injury collisions per mile per hour. The differences were statistically significant.

The HOV lanes in this study appeared to have greater safety performance than left lanes in all comparisons of collision statistics. Compared with other traveling lanes, however, such advantageous safety performance could also be observed in any type of lane adjacent to the median, either HOV or non-HOV lane. This could be due to the interaction level between the lanes. Traffic in the median lane interacts with traffic on the right side only, while traffic in other lanes interacts with traffic on both sides. For further interpretation, HOV lanes need to be compared with non-HOV median lanes. However, the present study is limited to the comparison of HOV and left lanes, and further comparisons are outside the scope.

There are two general categories of explanations for the apparent superiority in safety performance of HOV lanes, and to some degree, left lanes, in continuous versus limited access facilities: (i) differences in traffic volume, traffic congestion, or design features not integral to the continuous versus limited access facilities, or (ii) features inherent in continuous versus limited access design. Some of these potential explanations are addressed in the following sections.

6. COMPARISON OF HOV COLLISION STATISTICS IN DETAILED STUDY ROUTES

6.1. COMPARISON OF HOV COLLISIONS IN DETAILED STUDY SITES (8 STUDY ROUTES)

To understand the geometric factors and other components that may impact the distribution of collisions across lanes, a detailed analysis was carried out with a subset of HOV facilities recommended by the Caltrans Advisory Group: four facilities with limited access and four with continuous access HOV lanes (Attachment F). Fatal, injury, and PDO collisions were included in the analysis. The average number of lanes in both continuous and limited access HOV facilities in the analysis was similar (i.e., 4–4.5 lanes). Therefore, the number of lanes did not account for the difference between continuous and limited access HOV facilities. To begin this detailed investigation, we first replicated the analysis described in the previous section.

Since this was a subset of the sites included in the previous statewide analysis, the HOV lanes were all constructed before 1999. For the eight sites, a total of 91.6 HOV lane-miles were examined, including 40.7 lane-miles of continuous access, and 50.9 lane-miles of limited access HOV lanes (Attachment F). As with the statewide/general analyses, all collisions (fatal, injury, and PDO) that occurred within traveling lanes between 1999 and 2003 were included in the analysis and the comparison was limited to peak hours (generally, Monday–Friday, 5–9 a.m., 3–7 p.m.). Regarding the statewide/general analyses, we calculated the distribution of collisions across lanes. Collisions per mile per hour were calculated by dividing the number of collisions by operational hours and lane miles of the routes.

We observed the following characteristics in **limited access** HOV facilities compared with continuous access facilities:

- Limited access facilities experienced a higher percentage of total collisions in the combined HOV and left lanes (49% for limited, versus 29% for continuous) (i.e., differences in collision distribution across the freeway). The same pattern was observed separately in HOV lanes (10% for limited, versus 4% for continuous) and left lanes (39% for limited, versus 25% for continuous) (Attachment G).
- Limited access facilities experienced a higher number of collisions per mile per hour in the combined HOV and left lanes (4.0 for limited, versus 2.7 for continuous). The same pattern was observed separately in HOV lanes (0.8 for limited, versus 0.4 for continuous) and left lanes (3.2 for limited, versus 2.3 for continuous) (Attachment H).

- Limited access facilities experienced a higher number of fatal and injury collisions per mile per hour in the combined HOV and left lanes (0.92 for limited, versus 0.80 for continuous). There was a higher number of fatal and injury collisions per mile per hour in the HOV lane (0.29 for limited, versus 0.10 for continuous), but the opposite pattern in left lanes (0.63 for limited, versus 0.70 for continuous). (Attachment I).

The same statistical tests were conducted as for the previous analyses. All the differences except for the difference in injury collision rates in left lanes were statistically significant ($p<0.05$). In other words, only the difference in injury collision rates in left lanes was *not* statistically significant.

Collision patterns observed in the eight study routes are generally consistent with those observed in the statewide/general collision comparison, suggesting that the set of eight study routes is representative of the larger set used for the statewide collision comparison.

6.2. COMPARISON OF HOV COLLISIONS ACCOUNTING FOR TRAFFIC VOLUME (8 STUDY ROUTES)

Traffic volumes were fairly similar, on average, for both the continuous and limited access HOV facilities, suggesting that differences in traffic volume did not account for the different collision patterns. However, to further clarify the possible influence of traffic volumes on the distribution of collisions across lanes, we controlled for traffic volumes by calculating collision rates (collisions per million vehicle miles traveled). The same set of eight routes used in the previous section for which data from PeMS was available was selected. Using data from PeMS, we were able to calculate collisions per million vehicle miles traveled (rate) by dividing collisions per mile per hour by traffic volume across various types of lanes. Four of the HOV facilities were limited access and four were continuous access. For the eight sites, a total of 91.6 HOV lane-miles were examined, including 40.7 lane-miles of continuous access, and 50.9 lane-miles of limited access HOV lanes (Attachment F). As in the previous analyses, fatal, injury, and PDO collisions were included in this analysis.

We observed the following characteristics in **limited access** HOV facilities compared with continuous access facilities:

- Limited access facilities experienced a higher rate of collisions in the combined HOV and left lanes (4.49 for limited, versus 3.12 for continuous). The same pattern was observed separately in HOV lanes (1.43 for limited, versus 0.59 for continuous) and left lanes (3.06 for limited, versus 2.53 for continuous) (Attachment J).

- Limited access facilities experienced a higher number of fatal and injury collisions per million VMT in the HOV lane (1.10 for limited, versus 0.92 for continuous), but the opposite pattern in left lanes (0.49 for limited, versus 0.16 for continuous). The number of fatal and injury collisions per million VMT was higher for HOV and left lanes combined (Attachment K).

A test statistic derived in the previous section was extended for use in the collision rate comparison (Attachment L). Differences in collision rates and fatal and injury collision rates were statistically significant at the 95 percent level of confidence.

With traffic volume controlled for, it is notable that observed collision rates were much lower for HOV lanes than for the adjacent lanes. This is true for both limited and continuous access facilities, and is consistent with the finding that the percentage of collisions and number per mile per hour is also lower in the HOV lanes. Although this finding is very interesting, and should be explored further, it is outside the scope of the current study.

The results controlling for traffic volume—the results for rates—were generally consistent with the results above for the number of collisions per mile per hour. The rate differences between continuous and limited access HOV facilities did *not* appear to be accounted for by higher traffic volumes in limited access HOV facilities. HOV lanes in limited access facilities appear to be associated with an increased number of collisions compared with HOV lanes in continuous access facilities. For left lanes, the mixed pattern was observed. These patterns are explored further in the next section.

7. DETAILED HOV COLLISION ANALYSIS

7.1. SHOULDER WIDTH ANALYSIS (13 STUDY ROUTES)

The primary purpose of the shoulder is to accommodate stopped or disabled vehicles so that they do not disrupt traffic flow in traveling lanes, and to manage water accumulation on the roadway by installation of drainage facilities. The shoulder also provides drivers with lateral clearance where they can avoid direct contact with other vehicles, recover from error, and resume normal driving in order to increase safety performance of freeways.[14,15] Because in California HOV lanes are usually located next to the inner shoulder, we were able to analyze the influence of shoulder width on the safety performance of HOV lanes to determine whether shoulder width accounts for differences between limited and continuous access facilities.

For this analysis we used 13 sites, which are a subset of HOV facilities recommended by the Caltrans Advisory Group; nine facilities with limited access and four with continuous access HOV lanes (Attachment M). A total of 184 HOV lane-miles were examined, including 50 lane-miles of continuous access, and 134 lane-miles of limited access HOV lanes. All collisions (fatal, injury, and PDO) occurring within traveling lanes between 1999 and 2003 were included in the analysis, and the comparison was limited to peak hours (generally, Monday–Friday, 5–9 a.m., 3–7 p.m.). Collisions per mile per hour were calculated by dividing the number of collisions by operational hours and lane miles of the routes.

Shoulder widths varied greatly in segments within these two sets of facilities, with a minimum width of about 2 feet, and a maximum width of about 12.2 feet. The variation in shoulder width in the data collected from our study sites made it possible for us to analyze the impact of shoulder width on collision patterns.

An initial comparison of the 13 sites showed that average shoulder width was about the same for both limited and continuous access facility sites. This suggests that shoulder width was not a factor in the differences in collision patterns found between the two HOV configurations. We then investigated the relationship between the average shoulder widths of *individual* freeway segments with collision rates from those segments. In this analysis, narrower shoulder width was associated with a higher number of collisions per mile per hour, regardless of whether the HOV facility was limited or continuous access (Attachment N). As shoulder width increased from 2 to 12.2 feet, the number of collisions per hour per mile decreased sharply.

[14] Hauer, E., Shoulder width, shoulder paving and safety, *Unpublished*, 2000

[15] Gross, F. and Jovanis, P.P., Estimation of the safety effectiveness of lane and shoulder width: case-control approach, *Journal of Transportation Engineering, Vol. 133, Issue 6*, 2007

These findings indicate that shoulder width did not account for the differences in collision patterns between the two types of HOV facilities. Consistent with previous findings, however, shoulder width appears to be an important safety performance factor. This was true in both continuous and limited access HOV facilities. This outcome should be studied further to determine whether this is true for other Caltrans HOV facilities, and to identify the mechanisms.

7.2. TOTAL (SHOULDER + HOV LANE + BUFFER) WIDTH ANALYSIS (13 STUDY ROUTES)

Total width is the lateral space or degree of freedom allocated to drivers in the HOV lane. The present analysis focuses on the safety performance of HOV facilities in accordance with the consumption of spatial resources. Total width consists of three different components: 1) shoulder, 2) HOV lane, and 3) buffer.[16] Among these three components, shoulder widths observed in the study sites varied from 2 to 12.2 feet (i.e., a range of 10.2 feet), lane width varied only between 11.5 and 13 feet (i.e., a range of about 1.5 feet), while buffer width varied between 0 and 5.2 feet (i.e., a range of 5.2 feet). Continuous access facilities, of course, have no buffer between HOV and left lane. Most of the variation in total width was contributed by variation in shoulder width, followed by buffer width. For this analysis we used the same 13 sites studied in the previous analyses, and the outcome was collisions per hour per mile. As with the previous analysis, this analysis was limited to HOV lanes.

A scatter plot of collisions per mile per hour relative to total width was constructed. A trend line for each type of HOV facility was estimated, based on the scatter plot, to determine the variation of collisions per mile per hour with respect to total width. Narrower total width (shoulder plus lane plus buffer) was associated with a higher number of collisions per mile per hour in both types of HOV configurations (Attachment O). The scatter plot appeared to yield different curves showing the relationship between total width and collisions/mile/hour, with the curve for limited access facilities shifted to the right. For any given total width, the number of collisions per mile per hour was higher in limited access HOV lanes than in continuous access HOV lanes. Additionally, the vertical discrepancy between the trend lines of continuous and limited access HOV lanes could be interpreted as the potential safety benefit of continuous access with respect to limited access, while holding all other influential factors constant.

This analysis does not establish the separate influence of each component of total width in the study. Additional sites would need to be studied to evaluate the individual influence of shoulder, lane, and buffer widths in a statistically meaningful manner, and to determine the optimal balance between shoulder and buffer width.

[16] Since continuous access HOV facilities do not have buffer zones, and observed lane width variations were small, only two of the components, shoulder and HOV lane width, are included in total width.

7.3. CONGESTION ANALYSIS (8 STUDY ROUTES)

It has been suggested that congestion affects occurrence of collisions in HOV lanes. The HOV lane is intended to be less congested than the GP lanes so that vehicles meeting the criteria for use of HOV lanes can save travel time by bypassing congested GP lanes. Due to high HOV demand or traffic operational issues, however, HOV lanes often become congested.[17,18] In the congestion analysis, the relationship between HOV lane congestion and HOV collisions was studied.

There are various congestion measurements based on either density or speed. Density directly measures the degree of crowdedness on the freeway as the unit of vehicles per unit distance, while measurements based on speed quantify the degree of congestion relative to a specific freely flowing traffic condition. Speed measurement is advantageous in terms of measuring delay with respect to freely flowing travel time. Caltrans produces the Highway Congestion Monitoring Program (HICOMP) annual data compilation which measures congestion occurring on urban freeways in California based on speed data or estimates. The compilation only provides regional congestion levels and the data collecting method varies across routes and districts.[19] Moreover, variations inherent in the range of freely flowing traffic conditions cannot be measured using speed measurements. Due to such data issues in HICOMP, it is more feasible to use congestion data from loop detectors.

From the perspective of traffic safety, density can more accurately reflect risk by measuring the number of vehicles in the vicinity, which may be related to the probability of conflicts between vehicles. For this reason, density was adopted to represent congestion in the analysis. Occupancy data, *dimensionless measure of density*, from inductive loop detectors were analyzed to measure the density of traffic flow.[20,21]

By displaying a scatter plot of HOV lane occupancy versus HOV collisions per mile per hour, no significant relationship was observed (Attachment P). The graph shows that higher collision rates are not always associated with higher levels of congestion and vice versa. Therefore, we conclude that congestion itself does not account for the difference in collision rates between limited and continuous access HOV facilities.

---

[17] Chen, C., Kwon, J. and Varaiya, P., An empirical assessment of traffic operations, *Proceedings of International Symposium on Transportation and Traffic Theory*, 2005.
[18] Federal Highway Administration (FHWA), Safe, Accountable, Flexible, Efficient Transportation Equity Ace: A legacy for Users (SAFETEA-LU), 2005 (accessed 02. 03. 08) (http://www.fhwa.dot.gov/safetealu/legis.htm)
[19] California Department of Transportation, 2006 State Highway Congestion Monitoring Program Annual Data Compilation, 2007.
[20] Cassidy, M. J. and Coifman, B., Relation among average speed, flow, and density and analogous relation between density and occupancy, *Transportation Research Record*, No. 1591, 1997.
[21] 3. Hall, F. L., The relationship between occupancy and density. *Transportation Forum*, Vol. 3-3, 1986.

7.4. HIGH COLLISION CONCENTRATION LOCATION (HCCL) ANALYSIS (8 STUDY ROUTES)

Continuous Risk Profile (CRP) is a method that can directly generate a variation of risk measurement interpretable as the number of collisions or collisions per unit distance along a freeway segment.[22] In the high collision concentration location (HCCL) analysis, CRPs were constructed along the HOV and left lanes of eight detailed study sites to examine the concentration of collisions in the vicinity of the ingress/egress areas. The eight sites were the same as those analyzed previously in this report. Four of the HOV facilities were limited access and four were continuous access. For the eight sites, a total of 91.6 HOV lane-miles were examined, including 40.7 lane-miles of continuous access, and 50.9 lane-miles of limited access HOV lanes (Attachment F). Fatal, injury, and PDO collisions were included in the analysis, and we calculated the number of collisions/mile/hour.

For the eight routes examined, two exemplary routes are displayed (Attachment Q). The peaks in the profile represent HCCLs for which collisions per mile exceed 90 percent of collisions per mile along the route. The pattern of HCCLs is different for continuous and limited access facilities. In continuous access facilities, each of the peaks accompanies peaks in adjacent lanes. This implies that the factors causing collision concentration appear to have an equivalent influence on HOV and left lanes, and possibly on all lanes. In contrast, in limited access HOV facilities, some of the peaks are observed only in the HOV lanes. This distinguishable pattern for limited access and continuous access HOV facilities was observable in all of the study routes.

7.5. SPATIAL COLLISION ANALYSIS (4 STUDY ROUTES)

As an example of a potentially more detailed analysis, the cross-sectional distribution patterns of collision frequencies were analyzed along four freeway routes with limited access HOV lanes. The number of collisions within each 0.05 mile segment on the freeway was counted and the segment was classified into one of five categorical groups and shaded in accordance with its recorded collision frequencies. Darker shading represents higher collision frequencies while lighter shading represents lower collision frequencies. The plots constructed in this way facilitated visual observation of collision concentrations along the freeway and across lanes in conjunction with the locations of other freeway facilities including on- and off- ramps and HOV flyovers.[23]

[22] Chung, K. and Ragland, D. R., Method for generating continuous risk profile for highway collisions, Proceedings *of 86th Transportation Research Board Annual Meeting*, 2007.

[23] HOV flyover is also called HOV direct connector. An HOV flyover is a structure providing uninterrupted access between freeways that enables HOV vehicles to move directly from the HOV lane of one freeway to the HOV lane of the second freeway, without leaving the commuter lane to exit one freeway only to merge back across the next freeway into its HOV lane.
(http://carpoolconnect.com/glossary/show/HOV%20Direct%20Connector%20Ramp)

In this figure, three sections of freeway in the near ingress/egress area are displayed: two with ingress/egress areas only (Attachment R) and one with ingress/egress area and HOV flyover (Attachment S). The following patterns were observed:

- The freeway sections where merging and diverging HOV maneuvers were expected were associated with HCCLs, particularly when these areas were closely located to on- and off-ramp areas (Attachment R).
- Some HCCLs in GP lanes did not overlap HOV access areas but were located close to HOV access areas. Although these sections do not reside within HOV access areas, they appear to be associated with anticipated HOV maneuvers (Attachment R).
- The freeway section in the vicinity of an HOV access area where HOV maneuvers directly travel through HOV flyovers have lower collision concentrations (Attachment S).

The analysis provided potential explanations of the causes of HCCLs associated with HOV ingress/egress areas. More detailed investigation is required in order to understand the influences of traffic movement induced by HOV facilities.

7.6. INGRESS/EGRESS AREA ANALYSIS (8 STUDY ROUTES)

The above analysis suggests that collision patterns in limited access HOV facilities may be related to ingress/egress sections. There are two principle factors related to ingress/egress sections. The first factor is the distance to the ingress/egress area from the nearest on- and off-ramps. An ingress/egress area a short distance from either an on- or off-ramp forces intensive weaving on the part of drivers attempting to enter the freeway and then enter the HOV lane, or those attempting to exit the HOV lane and then the freeway itself. The second factor is the length of the section. A shorter ingress/egress section forces more weaving within a smaller length of freeway, potentially increasing the probability of collisions. In addition, shorter ingress/egress sections might create bottlenecks in either the HOV or left lane as drivers attempt either to exit or enter the HOV lane. In field visits to HOV facilities we have observed and video-recorded both of these phenomena, but we have not yet assessed them quantitatively.

To address the first factor, collisions per mile per hour at 24 limited ingress and egress sections along four limited access HOV routes were plotted relative to their distance from nearby on- or off-ramps (Attachment T). From these plots, there was no clear systematic relationship between distance from the nearby on- or off-ramps and collisions. This may be because the plot does not systematically control for other factors.

However, three locations showed significantly higher numbers of collisions per mile per hour than the average collisions per mile per hour in limited access HOV lanes. These three ingress/egress segments were all within 0.3 mile of the nearest on- or off- ramp. However, the three segments also had short access lengths (0.25 mile) and high traffic volume in the HOV lane during peak hours (1000–1200 vehicles per hour versus 700–800 vehicles per hour on average).

The data from the 24 sites in this eight-route analysis were not sufficient to separate the impact of distance from the nearest on/off ramp, length of access segment, and volume. These are critical components related to the design of limited access HOV facilities and further research is recommended to determine how these separate factors operate individually and/or together to impact safety performance. Sufficient additional sites are available for this analysis.

7.7. COLLISION TYPE ANALYSIS (8 STUDY ROUTES)

An analysis of collision types was conducted to determine the different collision patterns of limited versus continuous access facilities. For this analysis, the set of eight study routes was used, and all collisions were included. Rear-end and sideswipe collisions together comprised just over 90 percent of all collisions in both limited and continuous access HOV lanes. Limited access HOV lanes experienced more rear-end and side-swipe collisions in absolute numbers. However, the major difference was in the distribution of rear-end versus side-swipe collisions in limited versus continuous access facilities. (Attachment U). In continuous access HOV lanes, 66 percent of collisions were rear-end, and 26 percent were side-swipe collisions. In limited access HOV lanes, 75 percent were rear-end, and 17 percent were side-swipe collisions.

The difference in type of collision pattern observed in limited versus continuous access HOV lanes could be explained by traffic movements inherent to continuous and limited access HOV facilities. Compared with HOVs traveling in limited access HOV lanes, HOVs traveling in continuous access HOV lanes were more likely to be exposed to continuous interaction with traffic in adjacent lanes, and thus there was a greater occurrence of side-swipe collisions versus rear-end collisions. Meanwhile, HOVs in limited access HOV lanes are prohibited from changing lanes except in ingress/egress areas, and tended to have more interaction with vehicles in the back or front than those in adjacent lanes and thus experienced a greater number of rear-end collisions.

8. CONCLUSION AND IMPLICATIONS

HOV lanes have been used for decades to improve freeway capacity. Two different HOV configurations have been widely implemented in the state of California over the past several decades, and are defined as follows:

- **Continuous access**, in which HOV lanes are demarcated only by signage and pavement markings. This configuration is predominant in Northern California, and operates only during peak hours (generally, Monday–Friday, 5–9 a.m., 3–7 p.m.).
- **Limited access**, in which pavement buffers separate HOV lanes. This configuration is predominant in Southern California, and is in operation 24 hours a day, seven days a week.

Limited access HOV facilities, where signage and pavement markings are designed to separate higher speed traffic in HOV lanes from lower speed traffic in adjacent lanes, are designed to reduce the risk of collisions caused by vehicles traveling in different lanes at different speeds. Using collision data, traffic data, and infrastructure data from California freeways, limited access HOV and left lanes were compared with those of continuous access HOV facilities to evaluate the safety of each, and to determine which characteristics could improve performance in either type of facility.

Our results suggest that, compared with continuous access HOV facilities, limited access HOV facilities do not appear to provide increased safety, whether measured by percentage of collisions, collisions per mile, collisions per VMT, or collision severity—the pattern actually seems to suggest the opposite. Potential differences in traffic volume, speed differential, number of lanes, shoulder width, lane width, and total width (shoulder plus lane plus buffer) did not appear to account for these findings. Strictly from a safety viewpoint, this suggests that construction of limited access facilities to achieve a safety objective is not warranted.

However, our study recommends design factors that could maximize the safety of limited access facilities. One of these factors is shoulder/buffer width. Our findings suggest that maintaining adequate shoulder and buffer width is essential, and we provide a quantitative estimate for the optimal shoulder width. Unfortunately, we do not currently have sufficient data to analyze the tradeoff between shoulder width and buffer width. This would be a fairly straightforward extension of our study and could be conducted by including additional sites in our analysis.

Another potential safety enhancing feature is the length of the access section and its location in relation to on/off ramps. Based on our analysis of collision rates near access points in limited ingress and egress HOV facilities, it appears that collision rates are higher in short access sections. We hypothesize that short access areas creates queues in the HOV lane and increase the incidence of rear-end collisions (we found increased rates of rear-end collisions in limited access facilities) and intensify weaving. Our findings also suggest that locating access areas in close proximity to on/off ramps should be avoided. This may lead to intense weaving and hot spots for collisions across freeway lanes. Additional analyses would be required to develop a quantitative estimate for the optimal access segment length and distance of access segments from on- off-ramps.

In general, our study demonstrates that HOV design factors can have an impact on safety performance. While further research is needed, results to date suggest that improvements in HOV facility performance can be achieved by improved HOV lane design.

9. FURTHER RESEARCH

9.1. INVESTIGATION OF SAFETY PERFORMANCE OF HOV LANES AT MICRO LEVEL

For the present study, influential factors on the safety performance of HOV facilities were identified and quantified at the macro level (i.e. corridor level). However, in order to maximize safety performance, these findings should be expanded to a more accurate microscopic level of quantification. Based on the refined quantifications, the current HOV implementation guidelines can be improved by the following:

- Quantify the influence of various design features on safety performance
- Propose new design criteria for constructing new HOV lanes (improving the current design criteria)
- Conduct a before/after HOV lane retrofit study

9.2. INVESTIGATION OF ROLE OF SHOULDER AND BUFFER WIDTH

Our findings suggest that wider shoulders and buffers are associated with increased safety performance. However, data are not sufficient to determine the relative contribution of shoulder and buffer width. This information is crucial when it is necessary to design facilities for locations with limited space. With additional study sites it would be possible to:

- Quantify the influence of shoulder and buffer width separately in detail
- Quantify the relative contribution of shoulder and buffer width
- Quantify the relative importance of the Weave Lane to the operation of the buffer-separated HOV lane, including an analysis to see if it would be more beneficial to reduce shoulder widths to provide for the Weave Lane.

9.3. DESIGN CRITERIA FOR LIMITED ACCESS OPENINGS AND EVALUATION OF EFFECTIVENESS OF HOV FLYOVERS

Our findings indicate that there are higher collision concentrations at locations where HOV maneuvers conflict with freeway ramp traffic. Additionally, such conflicts substantially limit freeway capacity, leading to excessive delays and congestion in general purpose lanes. Therefore, it is necessary to properly locate the access openings so that operational and safety disadvantages can be minimized.

- Determine optimal locations of access areas with respect to ramps
- Evaluate length of access areas

As a countermeasure to mitigate such conflicts, HOV flyovers are constructed to enable HOV lanes to directly connect between major interchanges. For greater efficiency, the effectiveness of HOV flyovers needs to be evaluated.

- Evaluate the effectiveness of HOV flyovers in terms of safety and operation

9.4. APPLICATION TO HIGH OCCUPANCY TOLL (HOT) FACILITIES

Recently, High Occupancy Toll (HOT) facilities have emerged as an alternative means to control the level of utilization of HOV lanes that are often under- or overused. Some HOV facilities in the California State Highway System have been selected for conversion to HOT facilities. The design features of HOT facilities are similar to those of limited access HOV facilities. Therefore, applicability of HOV facility design criteria needs to be investigated and further developed to accommodate the HOT facility adaptation.

- Study applicability of HOV design criteria for HOT facilities
- Further develop design criteria and adapt some of the features into HOT facilities

9.5. DRIVERS' BEHAVIOR IN HOV/HOT FACILITIES

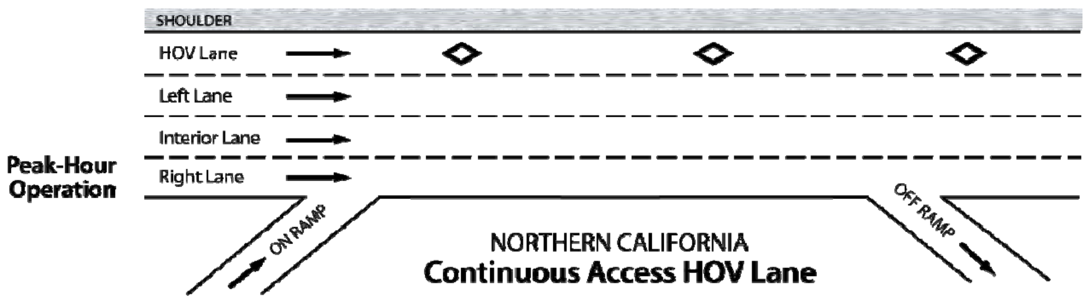
A substantial proportion of collisions are caused by drivers' behavior, not by other environmental factors. Previous research suggested that operational features inherent to HOV/HOT configurations induce unique driver behaviors including increased lane changes, smoothing effects, and synchronized speed drops on HOV facilities (inducing degradation of HOV facility, SAFETEA-LU). In-depth understanding of drivers' behavior might enable us to identify the causes of HOV collisions and operational issues related to HOV facilities, leading to mitigation strategies for improving operation and safety of HOV facilities.

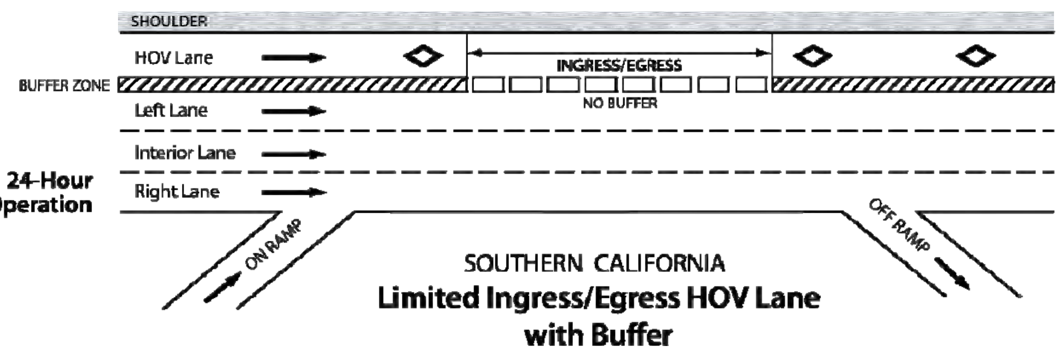
- Study drivers' behavior in relation to HOV facilities
- Develop mitigation strategies for HOV operation and HOV safety

ATTACHMENTS

Attachment A
Diagram of Continuous and Limited Access HOV Configurations

There are two configurations for HOV facilities in California. Drivers may move in and out of the **continuous access** HOV lane at any point; drivers may enter or exit the **limited access** HOV lane only at ingress/egress areas.





Attachment B
Location of HOV Facilities and Collection of Collision Data for HOV and Left Lanes

Collision Data
TASAS, 1999–2003, Weekdays (Mon.–Fri.)
Traveling Lanes Only (HOV, Left, Interior, and Right Lanes)
HOV Operation Hours (Peak Hours, 5–9 a.m. & 3–7 pm.)
Continuous Ingress/Egress: HOV report and Inventory
Limited Ingress/Egress: 5–9 a.m. & 3–7 p.m.

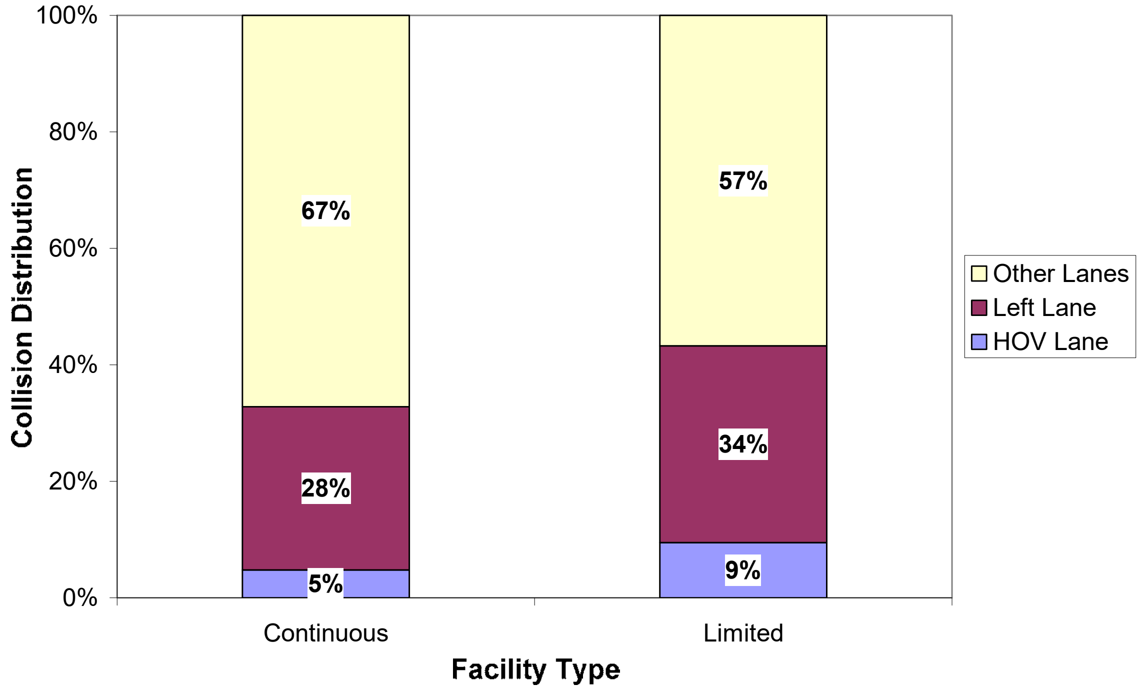
HOV Location Data
HOV lanes constructed before 1999
HOV lanes existing before 1999 were identified to allow comparable analysis
Routes with unique HOV operation were excluded (HOT, Bus-Only, Elevated, etc.)
HOV Reports (D4 & D7), HOV Inventory (as of 2005), Google Earth Aerial Photo

Study Site Summary (Comparison)

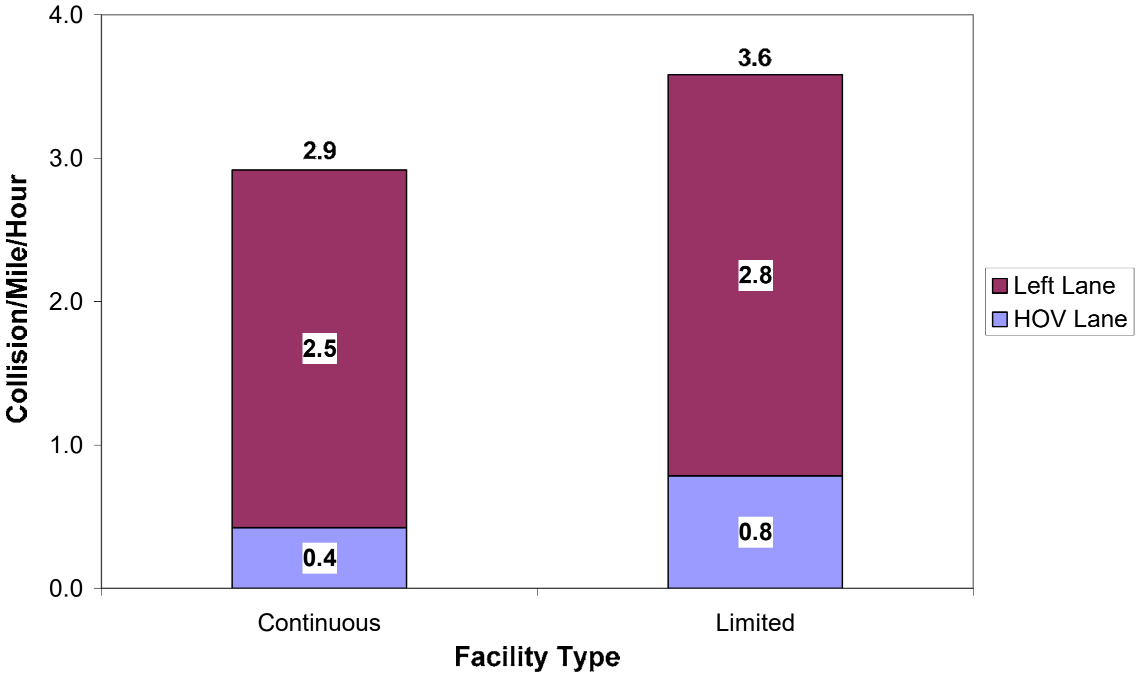
Facility Type	District	Number of Route Segments	Lane-Miles
Continuous	3	2	25
	4	22	254
Limited	7	24	311
	8	4	55
	12	10	179
Total Study Routes		62	824
		Total (Entire HOV system)	1305

- Lane-mile calculation is based on HOV inventory as of June, 2005

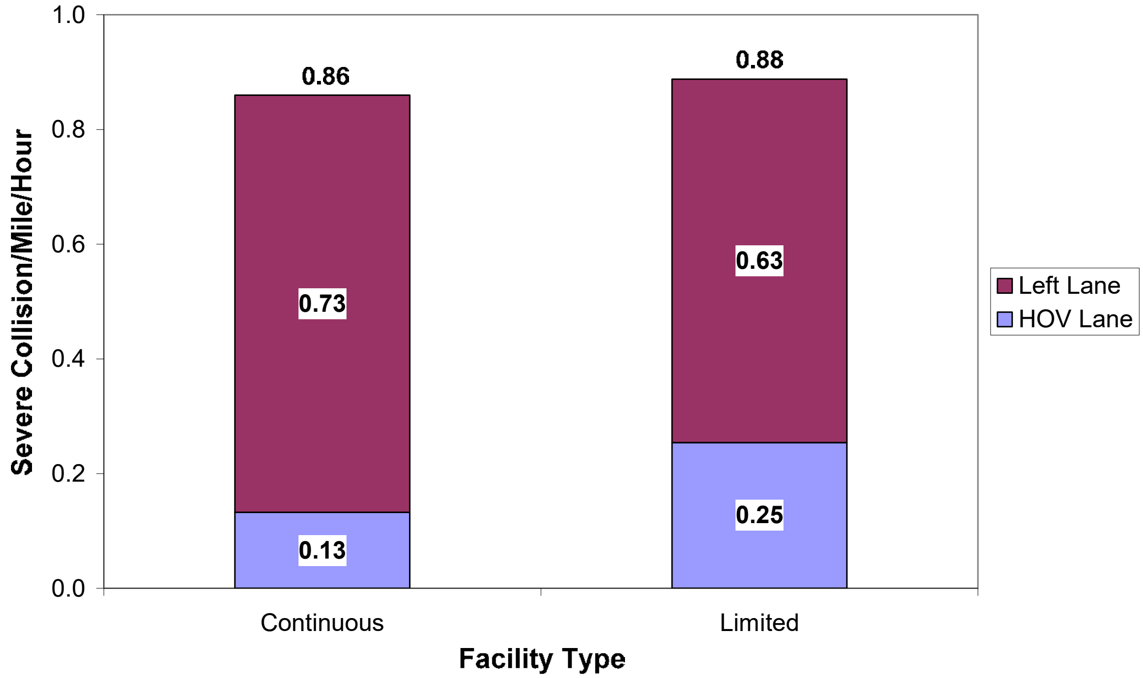
Attachment C
A Comparison of Total Collision Distribution in HOV and Left Lanes
(Statewide Analysis)



Attachment D
A Comparison of Total Collisions Per Mile Per Hour in HOV and Left Lanes
(Statewide Analysis)



Attachment E
A Comparison of Fatal and injury Collisions Per Mile Per Hour
in HOV and Left Lanes (Statewide Analysis)



Attachment F
Detailed Study Routes for HOV Collision Analysis

Site Selection
List of HOV facilities provided by Caltrans Advisory Group

Collision Data
TASAS, 1999–2003, Weekdays (Mon. – Fri.)
Traveling Lanes Only
HOV operation hours (See table below)

Study Routes Included in Detailed Analysis

Facility Type	County	Freeway	Postmile		Length	Operation Hr.
			Start PM	End PM		
Continuous	Contra Costa	I-80 E	0.0	10.0	10.0	Monday~Friday, 5~10 AM, 3~7 PM
	Contra Costa	I-80 W	0.0	9.8	9.8	Monday~Friday, 5~10 AM, 3~7 PM
	Alameda	I-880 N	13.5	20.9	7.4	Monday~Friday, 5~9 AM, 3~7 PM
	Santa Clara	SR-101 S	26.4	39.9	13.5	Monday~Friday, 5~9 AM, 3~7 PM
Limited	Los Angeles	I-105 E	1.2	16.9	15.7	24 hours
	Los Angeles	I-105 W	2.6	16.8	14.3	24 hours
	Los Angeles	I-210 E	24.8	36.4	11.6	24 hours
	Los Angeles	I-405 S	12.9	22.2	9.3	24 hours

Further analysis was conducted by incorporating traffic data in the calculation of collision rates based on vehicle-miles. The study sites for this analysis were selected from the list of study sites from the previous section, based on the loop detector coverage and condition.

Data Description
Peak hour traffic volume data in one-month period (June 2003) were downloaded from Performance Measurement System (PeMS).
Data only reported as "good" by PeMS were selected for traffic volume estimation by comparing with detector health data.

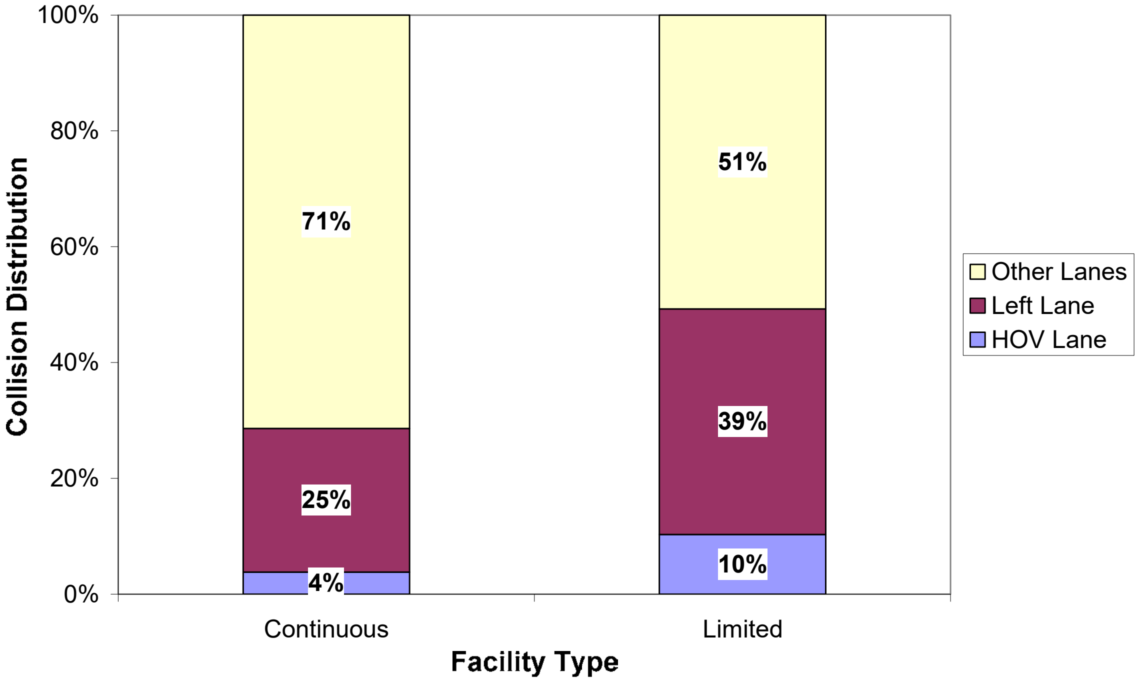
Collision rates were calculated based on the following equation:

$$Collision\ rate = \frac{Number\ of\ Collisions \times 10^6}{Total\ Peak\ Hour\ Traffic\ Volume(5\,Yr.) \times Lane \cdot Mile}$$

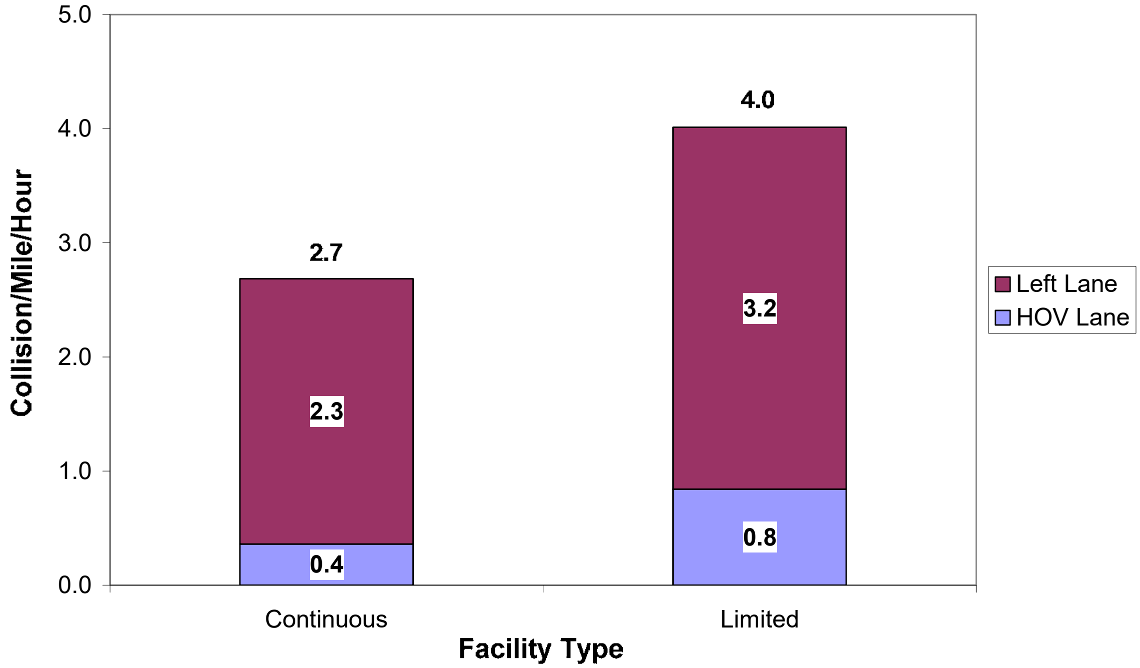
Collision rates in continuous access HOV lanes were lower than those in limited access HOV lanes. Meanwhile, collision rates in the left lane were slightly higher in continuous access HOV lanes.

Attachment G
A Comparison of Total Collision Distribution In HOV and Left Lanes
(8 Study Routes)

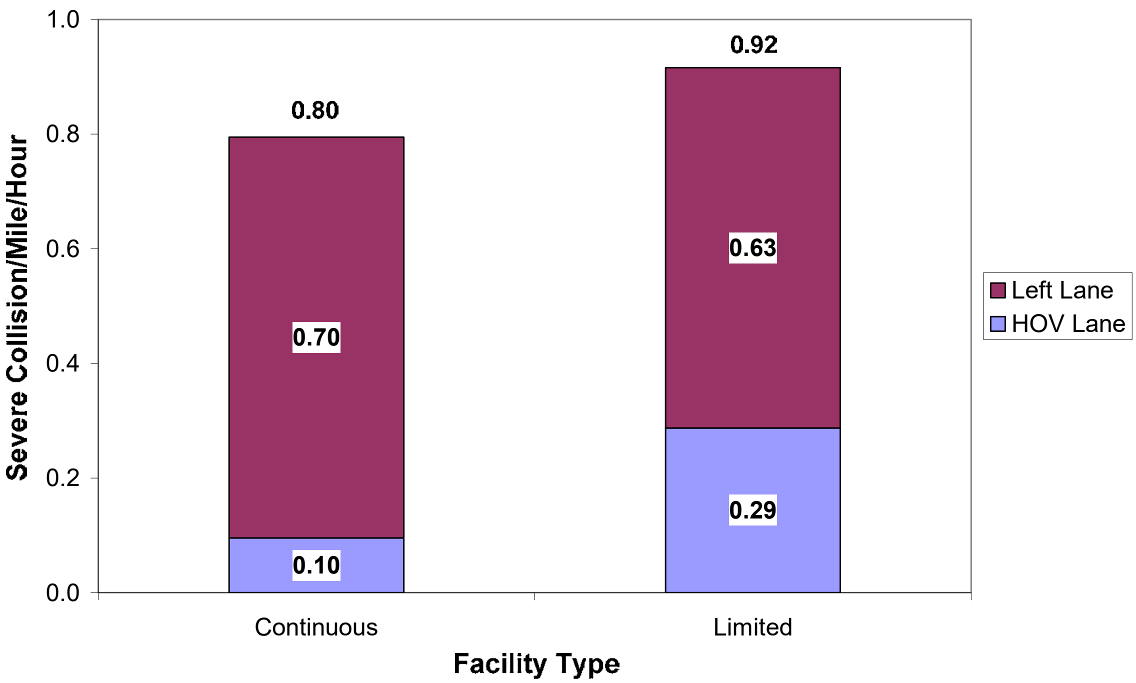
Four of the eight study routes were continuous HOV facilities and four were limited access facilities. Our subset of eight routes closely replicates findings of the collision distribution (See Attachment C).



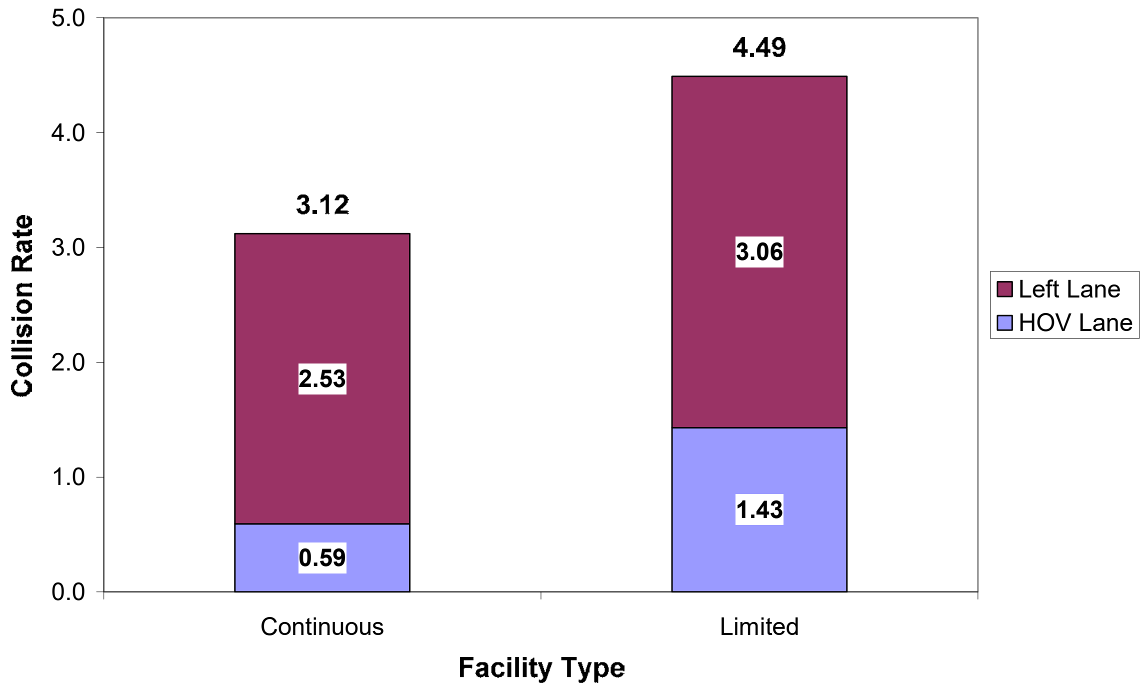
Attachment H
A Comparison of Total Collisions Per Mile Per Hour In HOV and Left Lanes
(8 Study Routes)



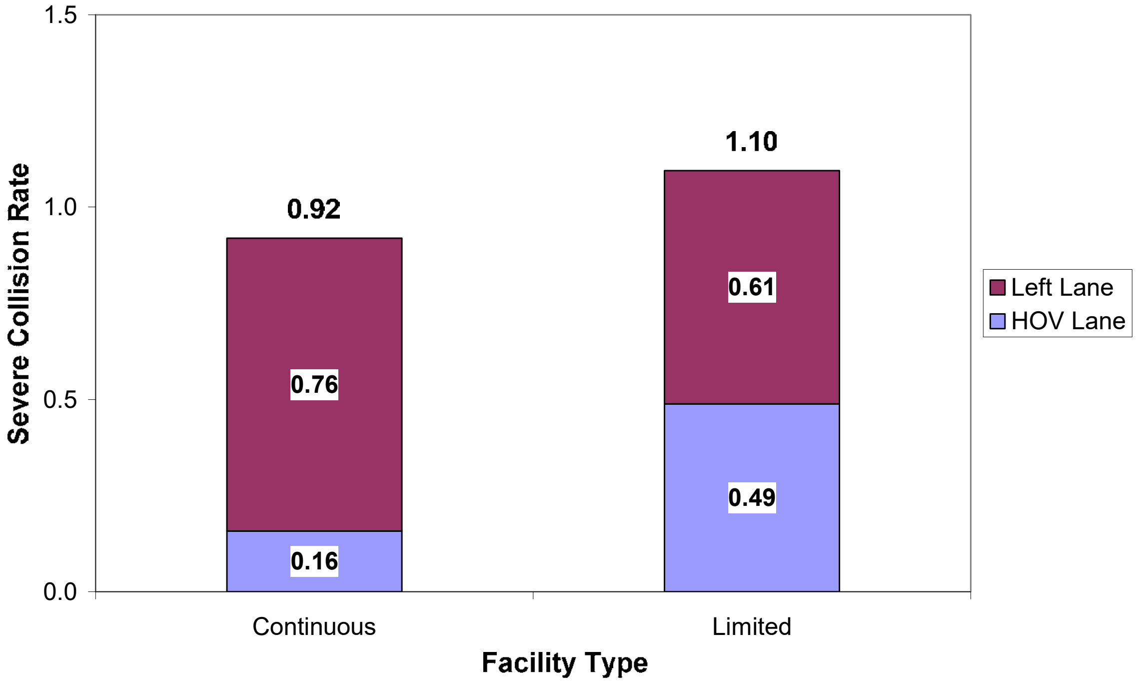
Attachment I
A Comparison of Fatal and injury Collisions Per Mile Per Hour In HOV and Left Lanes (8 Study Routes)



Attachment J
Total Collision Rate (Collisions Per VMT) (8 Study Routes)



Attachment K
Fatal and injury Collision Rate (Collisions Per VMT) (8 Study Routes)



Attachment L
Statistical tests (Statewide and 8 Study Routes)

1. Statistical test for the differences between collision distributions

Methodology

Let C_C and C_L denote the numbers of collisions observed in a specific lane in two independent sets of C and L Bernoulli trials (i.e. total collisions across lanes), respectively. In the analysis, all collisions that occurred in continuous and limited access HOV facilities are considered to be C and L, where p_C and p_L represent the true collision distribution associated with each set of trials (i.e. total collisions across lanes). Let $p_e = \frac{C_C + C_L}{C + L}$ and define

$$z = \frac{\frac{C_C}{C} + \frac{C_L}{L}}{\sqrt{\frac{p_e(1-p_e)}{C} + \frac{p_e(1-p_e)}{L}}} \sim \mathrm{N}(0,1)$$

A test at • significance level against one-sided alternative;

$H_0 : p_C = p_L$ versus $H_A: p_C < p_L$

The hypothesis H_0 is rejected at the • level of significance level if $Z \geq z_{1-\bullet}$, where $\bullet(z_\bullet) = \bullet$. (*Larsen and Marx*, 2006)

Application

Since the number of days during the study period did not change, average operation hours per day and total lane mile in each HOV facility were estimated.

Statewide

	Continuous access HOV	Limited access HOV
HOV collisions (total)	885	3424
Left collisions (total)	5218	12198
Total collisions (total)	18593	36105

Both differences reject the null $H_0 : p_C = p_L$ at 5% significance level. (i.e. the differences are statistically significant at 5% significance level)

Eight Study Routes

	Continuous access HOV	Limited access HOV
HOV collisions (total)	124	343
Left collisions (total)	804	1291
Total collisions (total)	3248	3317

Both differences reject the null $H_0 : p_C = p_L$ at 5% significance level. (i.e. the differences are statistically significant at 5% significance level).

2. Statistical test for the differences between collisions per mile per hour

Methodology

Suppose that the collisions that occurred in continuous and limited access HOV facilities follow two different Poisson processes. In the analysis, these two Poisson processes were observed for fixed mile-hours s_C and s_L. Let C_C and C_L represent the number of collisions observed in continuous and limited access HOV facilities, respectively.

C_C ~ POISSON ($\bullet_C$)
C_L ~ POISSON ($\bullet_L$)

Where, $\bullet_i = s_i \cdot \bullet_i$ (i=C, L)

A test at $\bullet$ significance level against one-sided alternative;
$H_0 : \bullet_C = \bullet_L$ versus $H_A: \bullet_C < \bullet_L$

The approximated normal test statistic mentioned above can be generalized to the unequal mile-hour case. Under $H_0 : \bullet_C = \bullet_L$ we have, approximately,

$$Z = \frac{s_C \cdot C_L - s_L \cdot C_C}{\left[s_L \cdot s_C \cdot (C_C + C_L)\right]^{1/2}} \sim N(0,1)$$

The hypothesis H_0 is rejected at the $\bullet$ level of significance level if $Z \geq z_{1-\bullet}$, where $\bullet(z_\bullet) = \bullet$. (*Sichel*, 1973 and *Shiue and Bain*, 1982)

Application

Average operation hours per day and total lane mile in each HOV facility were estimated.

Statewide

	Continuous access HOV	Limited access HOV
Length (mile)	279	545
Hour (hr)	7.5	8
HOV collisions (total)	885	3424
Left collisions (total)	5218	12198
HOV collisions (fatal and non-fatal injury)	277	1109
Left collisions (fatal and non-fatal injury)	1522	2761

All four differences reject the null $H_0 : \bullet_C = \bullet_L$ at 5% significance level. (i.e. the differences are statistically significant at 5% significance level)

Eight Study Routes

	Continuous access HOV	Limited access HOV
Length (mile)	40.7	50.9
Hour (hr)	8.5	8
HOV collisions (total)	124	343
Left collisions (total)	804	1291
HOV collisions (fatal and non-fatal injury)	33	117
Left collisions (fatal and non-fatal injury)	242	256

All four differences reject the null $H_0 : \bullet_C = \bullet_L$ at 5% significance level. (i.e. the differences are statistically significant at 5% significance level)

3. Statistical test for the differences between collisions per million VMT

Methodology

A methodology similar to that used for the comparison of collisions per mile per hour is applicable to collisions per million VMT. Suppose that collisions that occurred in continuous and limited access HOV facilities follow two different Poisson processes. In the analysis, these two Poisson processes were observed for fixed mile-hours s_C and s_L. In the analysis, we additionally consider the different numbers of vehicles in continuous and limited access HOV facilities, n_C and n_L vehicles per hour. Therefore, we can conduct the same statistical test by weighting s_C and s_L by the amount of n_C and n_L, respectively. Let C_C and C_L be the number of collisions observed in continuous and limited access HOV facilities.

$C_C \sim$ POISSON ($\bullet_C$)
$C_L \sim$ POISSON ($\bullet_L$)

Where, $\bullet_i = n_i \bullet s_i \bullet \bullet_i$ (i=C, L)

A test at $\bullet$ significance level against one-sided alternative;
$H_0 : \bullet_C = \bullet_L$ versus $H_A: \bullet_C < \bullet_L$

The approximated normal test statistic mentioned above can be generalized to the unequal mile-hour case. Under $H_0 : \bullet_C = \bullet_L$ we have, approximately,

$$Z = \frac{n_C \cdot s_C \cdot C_L - n_L \cdot s_L \cdot C_C}{\left[n_C \cdot s_L \cdot n_L \cdot s_C \cdot \left(C_C + C_L\right)\right]^{1/2}} \sim N(0,1)$$

The hypothesis H_0 is rejected at the $\bullet$ level of significance level if $Z \geq z_{1-\bullet}$, where $\bullet(z_\bullet) = \bullet$. (*Sichel*, 1973 and *Shiue and Bain*, 1982)

Application

Eight Study Routes

	Continuous access HOV	Limited access HOV
Length (mile)	40.7	50.9
Hour (hr)	8.5	8
Vehicles Per Hour (HOV lane)	3950	3610
Vehicles Per Hour (Left lane)	5980	6350
HOV collisions (total)	124	343
Left collisions (total)	804	1291
HOV collisions (fatal and non-fatal injury)	33	117
Left collisions (fatal and non-fatal injury)	242	256

All four differences reject the null $H_0 : \bullet_C = \bullet_L$ at 5% significance level. (i.e. the differences are statistically significant at 5% significance level)

Attachment M
Detailed Study Routes for HOV Collision Analysis (13 Study Routes)

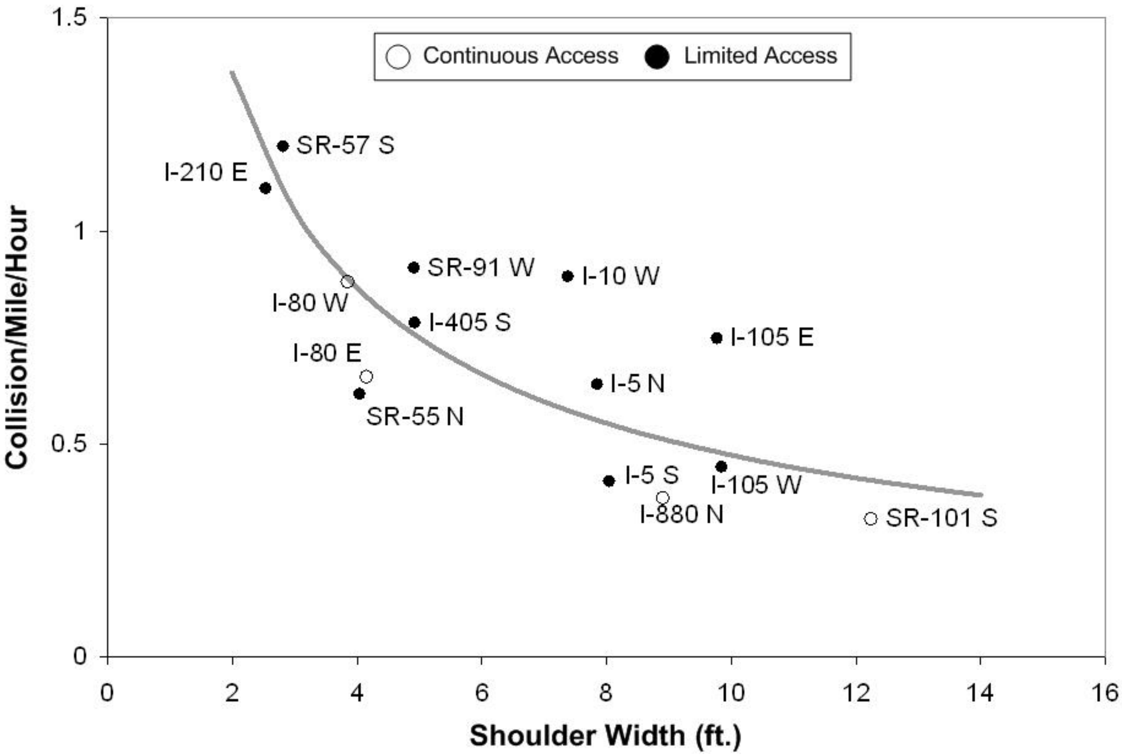
Site Selection
List of HOV facilities provided by Caltrans Advisory Group

Collision Data
TASAS, 1999–2003, Weekdays (Mon.–Fri.)
Traveling Lanes Only
HOV Operation Hours (See table below)

Facility Type	District	County	Freeway	Direction	Postmile		Length	Operation Hr.
					Start PM	End PM		
Continuous	D4	ALA/CC	I-80	E	ALA 3.373	ALA 8.036	15.029	Monday~Friday, 5~10 AM, 3~7 PM
					CC 0.000	CC10.043		
		ALA/CC	I-80	W	ALA 3.8	ALA 8.036	13.87	Monday~Friday, 5~10 AM, 3~7 PM
					CC 0.000	CC 9.76		
		ALA	I-880	N	13.51	20.876	7.366	Monday~Friday, 5~9 AM, 3~7 PM
		SCL	SR-101	S	R 26.4	39.92	13.886	Monday~Friday, 5~9 AM, 3~7 PM
Limited	D7	LA	SR-91	W	R 19.434	R 6.85	12.584	24 hours
		LA	I-105	E	R 1.164	R 16.864	15.7	24 hours
		LA	I-105	W	R 2.556	R 16.847	14.291	24 hours
		LA	I-210	E	R 24.784	R 36.407	11.932	24 hours
		LA	I-405	S	12.925	26.298	13.373	24 hours
	D12	ORA	SR-55	N	7	R 17.825	10.927	24 hours
		ORA	I-5	N	7	29	22	24 hours
		ORA	I-5	S	7	29	22	24 hours
		ORA	SR-57	S	11.083	R 22.551	11.468	24 hours

Attachment N
Relationship Between Shoulder Width and Collisions Per Mile Per Hour

Facilities with wider shoulder width generally experienced fewer collisions per mile, regardless of whether the facility was a limited or continuous access facility, based on an analysis of 13 study routes.



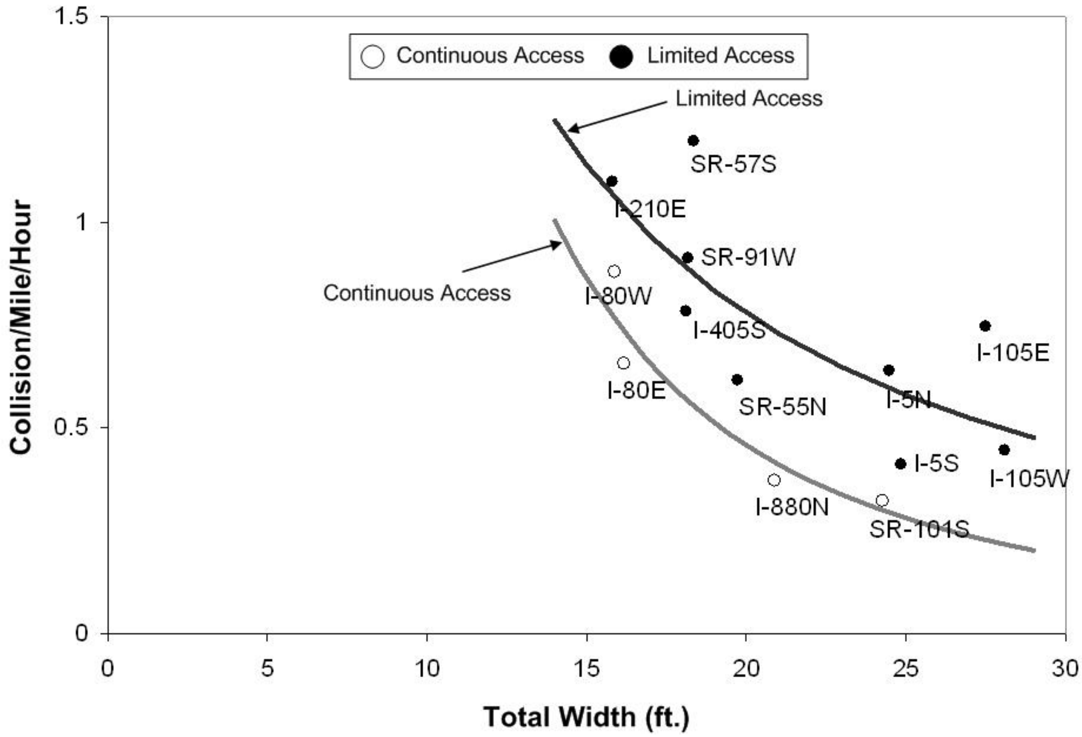
Attachment O
Relationship Between Total Width and Collisions Per Mile Per Hour

Facilities with wider total width generally experienced fewer collisions per mile, and collisions/mile/hour were higher in limited access HOV lanes than continuous access facilities in our analysis of 13 study routes.

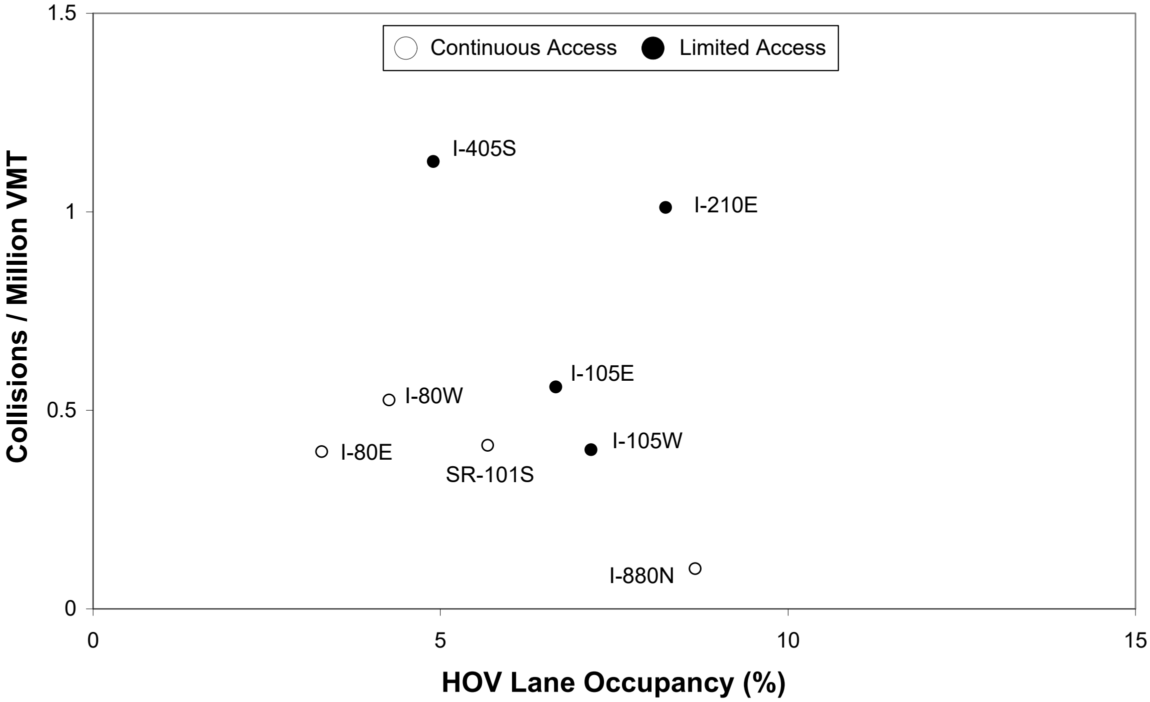
Total width = Shoulder width + lane width + buffer width.
The light gray line was constructed by using the data from four routes with continuous access and the black line was based on the data from nine routes with limited access (see figure on following page).

Data Description
Shoulder and lane widths were extracted from Highway Performance Monitoring System (HPMS).
Lane widths were estimated by averaging total width across all traveling lanes divided by number of lanes.
Buffer widths were based on Caltrans Digital Photolog were provided by Caltrans Engineers. The accuracy is fully dependent on the quality of images.

Shoulder width takes the largest portion of variation in total width.
Maximum difference in lane width across all detailed study corridors is 1.5 ft.
Maximum difference in buffer width across all detailed study corridors is 5.2 ft.
Maximum difference in shoulder width across all detailed study corridors is 12.2 ft.
Collisions/mile/hour in continuous access HOV lanes is lower than that in limited access HOV lanes.
A wide total width provides better safety performance in both continuous and limited access HOV lanes.
Total width = Shoulder width + lane width + buffer width.
The light gray line is constructed by using the data from four routes with continuous access and the black line is based on the data from nine routes with limited access.


Continuous Access
Limited Access
Limited Access
Continuous Access
SR-57S
I-210E
SR-91W
I-80W
I-405S
I-105E
I-80E
SR-55N
I-5N
I-5S
I-105W
I-880N
SR-101S
Collision/Mile/Hour
Total Width (ft.)
1.5
1
0.5
0
0
5
10
15
20
25
30

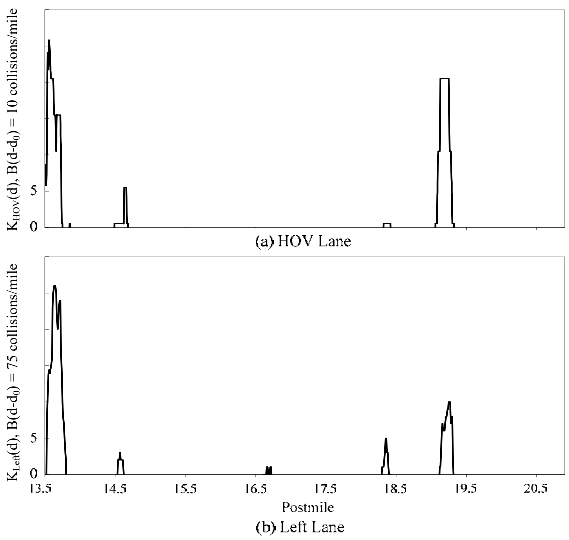
Attachment P
The Relationship Between HOV Lane Occupancy and Collisions/Million VMT in Study Sites



Attachment Q
Continuous Risk Profiles (CRPs) in HOV and Left Lanes (8 Study Routes)

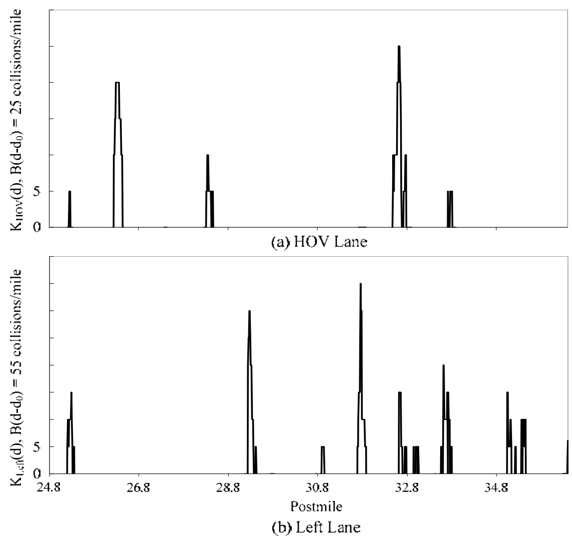
A route for each type of HOV facility was selected for presentation. (Interstate 880, Northbound and Interstate I-210, Eastbound)

I-880N



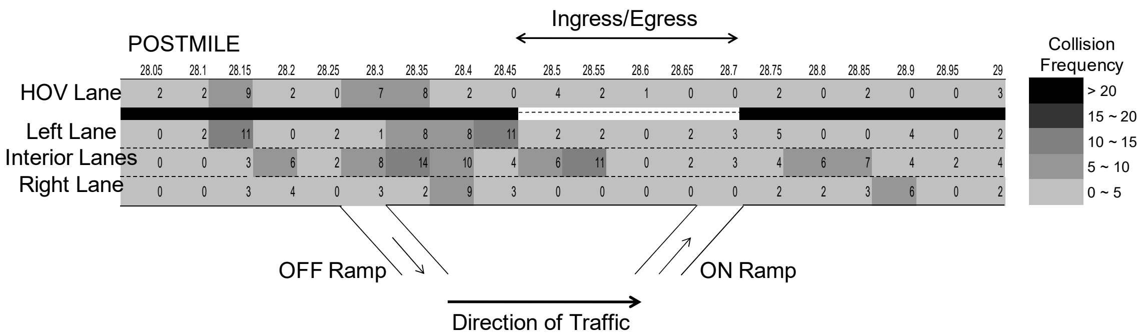
Continuous Access

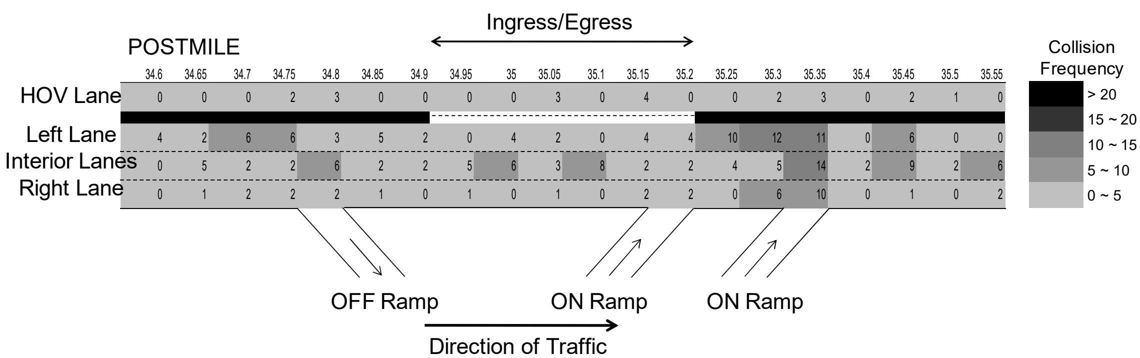
I-210E



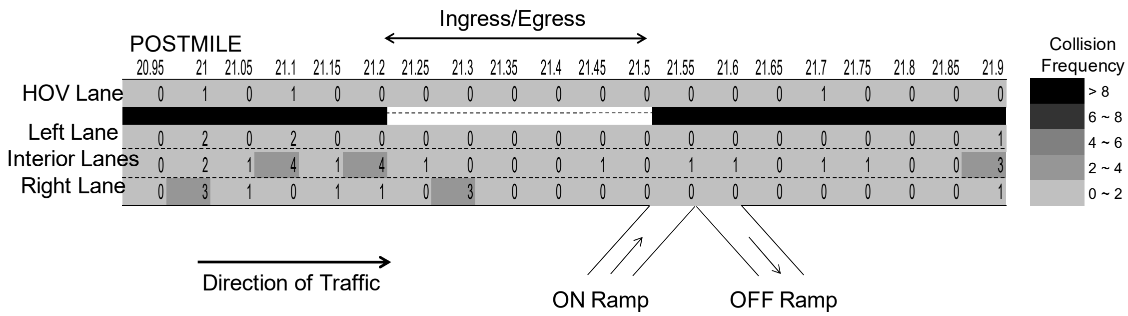
Limited Access

Attachment R
Cross-Sectional Distribution of Collisions Near Ingress/Egress Areas
(Interstate 210 Eastbound, Los Angeles County)

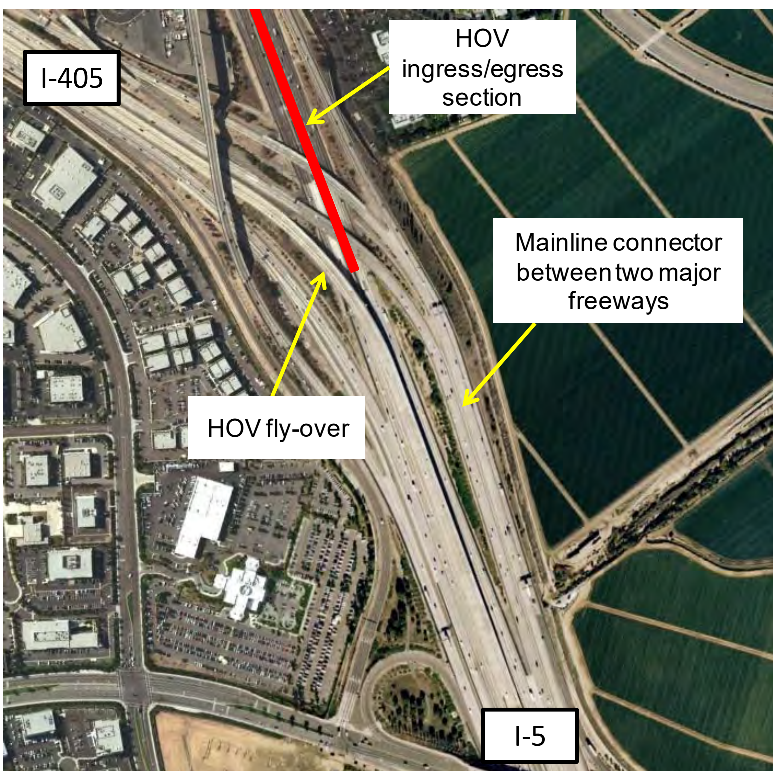




Attachment S
Cross-Sectional Distribution of Collisions Near Ingress/Egress Areas (Interstate 5 Northbound, Orange County)

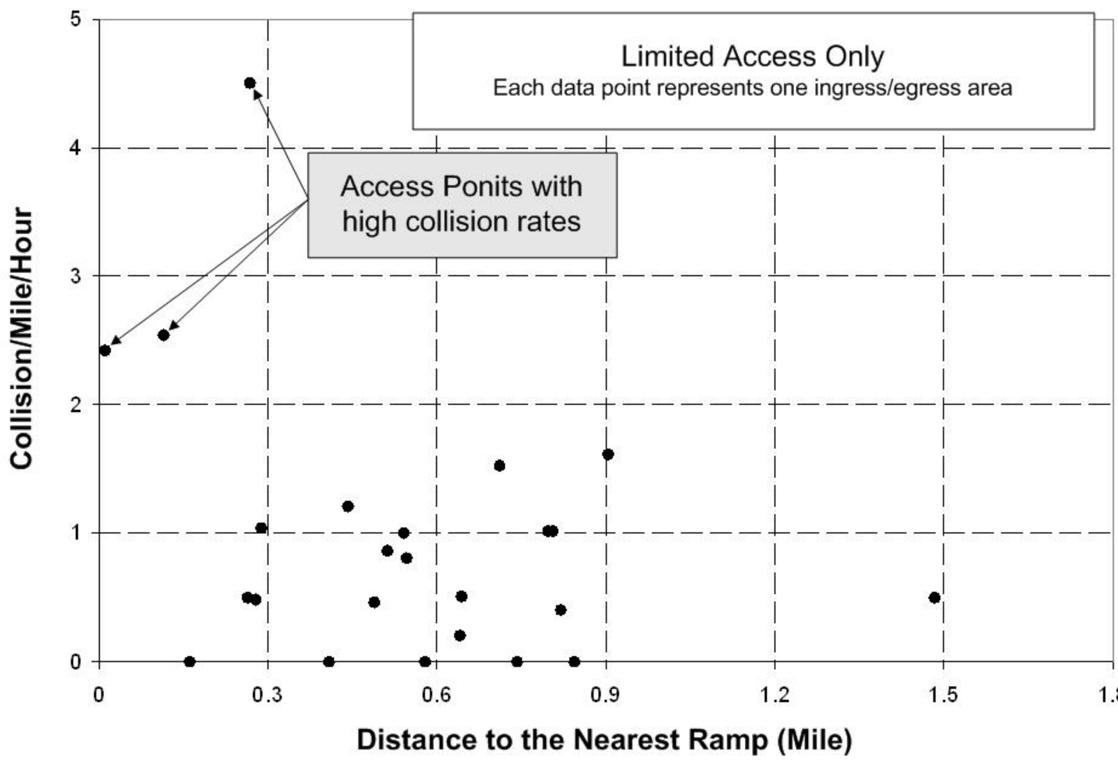


An HOV flyover is located approximately 0.2 mile upstream from the right most segment of the graph. The HOV direct connector carries a large proportion of HOV traffic volume from I-5 northbound to I-405 northbound resulting in a relatively small number of HOVs being expected to use the ingress/egress area displayed in the graph. The aerial photo covers the area in the vicinity of HOV flyover, which is displayed in the graph above.

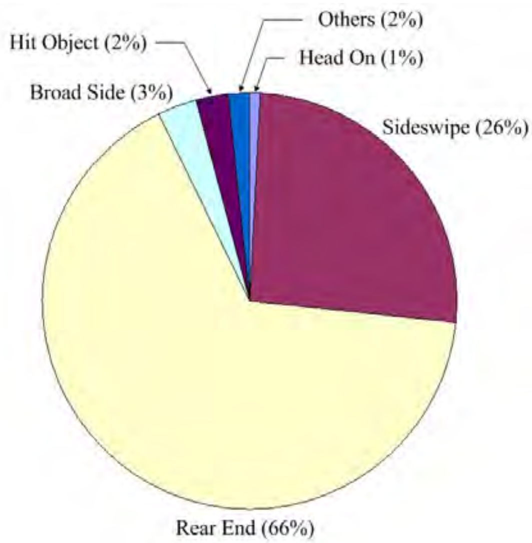


Attachment T
Relationship Between Collisions Per Mile and Distance to Nearest Entrance/Exit Ramp in Limited Access HOV Facilities

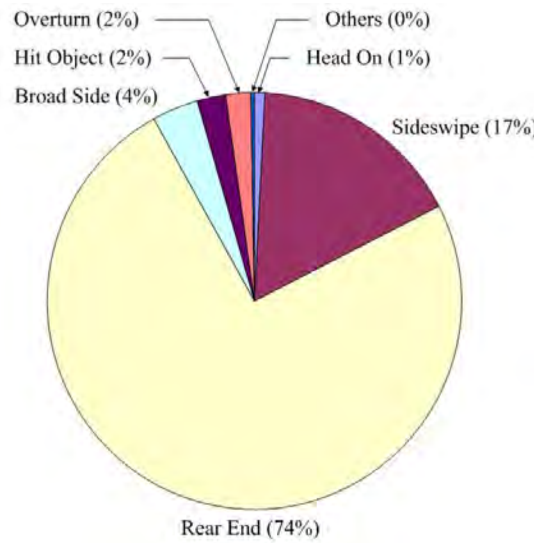
Three common features which may cause higher collision rates in ingress/egress areas were identified by investigating three HCCLs and are as follows: high peak hour HOV volume, 1000–1200 vph (compared to an average of 700–800 vph in general), short access distance of a quarter mile, which is the minimum access length, and location within 0.3 mile of ramps.



Attachment U
Types of Total Collisions in HOV Lanes Per Facility



(a) Continuous access



(b) Limited access