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Publication Date
2008-04-01

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UCB-ITS-TSC-2008-3

April 2008

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WORD COUNT: 3,649 (BODY TEXT)

NUMBER OF FIGURES: 8

NUMBER OF TABLES: 4

ABSTRACT
This paper describes comparisons of traffic safety during the morning and afternoon peak hours in extended stretches of eight High Occupancy Vehicle (HOV) lanes with two different types of access – four corridors with continuous access and the others with limited access. Traffic collision patterns in two different types of HOV lanes were investigated by evaluating 1) the differences in collision distribution, severity, types of collisions and per lane traffic utilization, 2) spatial distribution of collision concentrations by using Continuous Risk Profile (CRP) approach, and 3) collision rates in the vicinity of access points in HOV lanes with limited access. In the paper, the authors conducted detailed analysis on collision data occurred during peak hours in relation to geometry and traffic features. Based on the findings from the assessment on eight routes, the limited access HOV lanes appear to offer no safety advantages over the continuous access HOV lanes. Such difference is due to more frequent and sporadic distribution of collision concentration in limited access HOV lanes.

INTRODUCTION
In an effort to enhance the understanding of the effect of different types of High Occupancy Vehicle (HOV) access on safety, this study analyzed collisions that occurred along HOV lanes and adjacent lanes from eight California freeway corridors, ranging from 7.4 miles to 15.7 miles in length. Traffic collision data from the eight corridors were obtained from the Traffic Accident Surveillance and Analysis System (TASAS), a collision database maintained by California Department of Transportation (Caltrans).

The eight corridors consist of two different types of HOV facilities: one with continuous access and the other with limited. HOV lanes with continuous access allow vehicles to enter or exit the lane at any point from the adjacent lane on the highway. In contrast, vehicles can access the limited HOV facilities only through the dedicated ingress/egress sections. Beside the differences in geometric configurations, there is one other major difference in the operation of these facilities. The HOV lanes with continuous access typically operate only during the morning and afternoon peak hours –generally from 5 to 9 AM and 3 to 7 PM. On the other hand, the high-occupancy policy is enforced 24 hours a day for the limited access HOV facilities.

The work reported in this paper included several components. First, the relationship between collision concentration locations at HOV lanes and their proximity to nearby on- and off-ramps were studied. A technical approach called the Continuous Risk Profile (CRP) method is used in this study [1]. Second, a comparison of collision analysis performed for the selected highways is presented. Certain discrepancies in safety performance were found between the two HOV types in terms of collision distribution, and type and severity of collisions. Descriptions of the technical approaches, the data sources, and the findings are given in the following sections.

PREVIOUS STUDIES
The Texas Transportation Institute performed a detailed analysis of the safety issues associated with HOV lanes, focusing particularly on buffer-separated concurrent flow HOV lanes [2]. A

study of traffic collision data and collision reports from the Dallas area examined pre- and post-installation collision characteristics in chosen corridors. Increased collision rates were observed. Although unable to identify a single cause for the increased collision rates in and around HOV lanes, the research team suggested that the increase in collisions could be the result of: a) the loss of the inside shoulder, b) the reduction in widths of general purpose lanes, c) the speed differential between HOV and general purpose lanes, and d) vehicles weaving from lane to lane to gain access or exit the HOV. Based on the findings of the collision data analysis, guidance was developed in selecting advantageous corridor characteristics when considering HOV lane implementation and roadway cross sections.

In a study conducted in the Salt Lake City area, HOV lanes were determined not to be inherently unsafe based on collision data analysis [3]. The study did, however, recommend stricter enforcement, construction of direct-on ramps and off-ramps and installation of prominent signs to increase public awareness.

A study [4] conducted in early 90's compared freeway sections with and without HOV lanes in California and found higher collision rates during peak periods in freeway sections containing HOV lanes. Furthermore, the peak-hour collision rates of the HOV lanes were higher than the non-HOV lanes. However, when HOV lanes were open to regular traffic during non-HOV hours (that is, the designated HOV lanes were open to all types of traffic), collision rates in these sections were, lower than in freeway sections without HOV lanes. The discrepancies appeared to occur during the heaviest traffic periods.

Another study [5] analyzed collision frequencies and characteristics from a California highway with continuous HOV lane access. The analysis concluded that there was no change in safety on that route with the addition of HOV lanes. However, they did observe that collision locations migrated due to the relief of congestion in areas of lane drops and the creation of more severe traffic bottlenecks downstream.

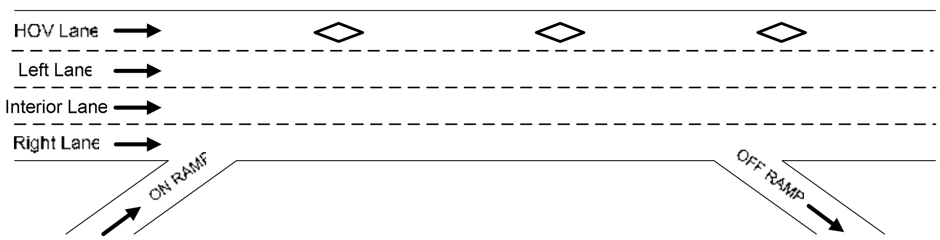
In the following section, we will report the work conducted in this study and the findings based on the analysis of historical collision data in California.

STUDY SITES AND DATA DESCRIPTION

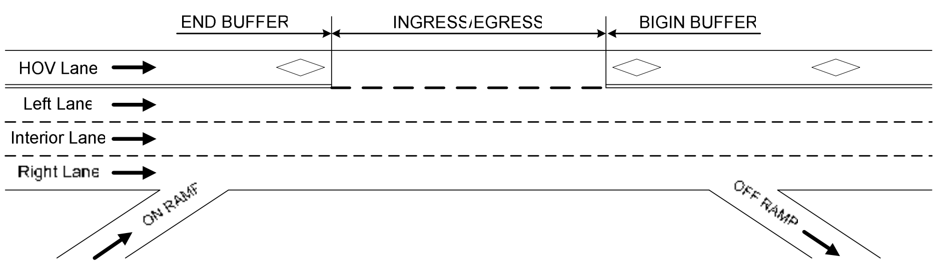
A total of eight freeway corridors with HOV facilities, listed in Table 1, were included in this current study. These corridors include four HOV facilities with continuous access, depicted in Figure 1(a) and four with limited access shown in Figure 1(b). Collision data from 1999 through 2003 were used to investigate the patterns of collision occurrence. Note that the length of the corridor segments is expressed in miles, to be consistent with the post mile numbers contained within the TASAS database and easier for references. The exact corridor segments were suggested by regional transportation engineers for the comparison of collisions on different types of HOV facilities.

TABLE 1 List of Freeway Corridors Included in Data Analysis

Facility Type	County	Freeway	Postmile		Length
			Start PM	End PM	
Continuous	Contra Costa	I-80 E	0.0	10.0	10.0
	Contra Costa	I-80 W	0.0	9.8	9.8
	Alameda	I-880 N	13.5	20.9	7.4
	Santa Clara	SR-101 S	26.4	39.9	13.5
Limited	Los Angeles	I-105 E	1.2	16.9	15.7
	Los Angeles	I-105 W	2.6	16.8	14.3
	Los Angeles	I-210 E	24.8	36.4	11.6
	Los Angeles	I-405 S	12.9	22.2	9.3



a) Continuous Access



b) Limited Access

Figure 1 HOV facility types and lane designation for freeways with HOV Lane.

Figure 2 shows how TASAS defines different traveling lanes on a freeway corridor with multiple lanes. Typically, the HOV lane, either single or multiple, is located on the inside portion of the freeway. The lane adjacent to the HOV lane is referred to as the left lane. The outermost right traveling lane is referred to as the right lane, and lanes between the left and right lanes are referred as interior lane(s). TASAS also defines a number of areas outside of traveling lanes; in this paper, these areas are aggregated as *others*. The percentage of collisions that occurred in these *other* areas ranged between 11% and 20 % of total collisions. However, since our primary objective is to compare collision that occurred in traveling lanes during the peak hours, the ones that occurred in these *other* areas were excluded from our analyses.

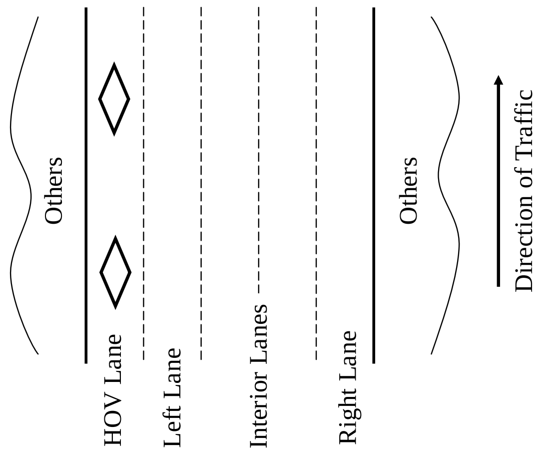
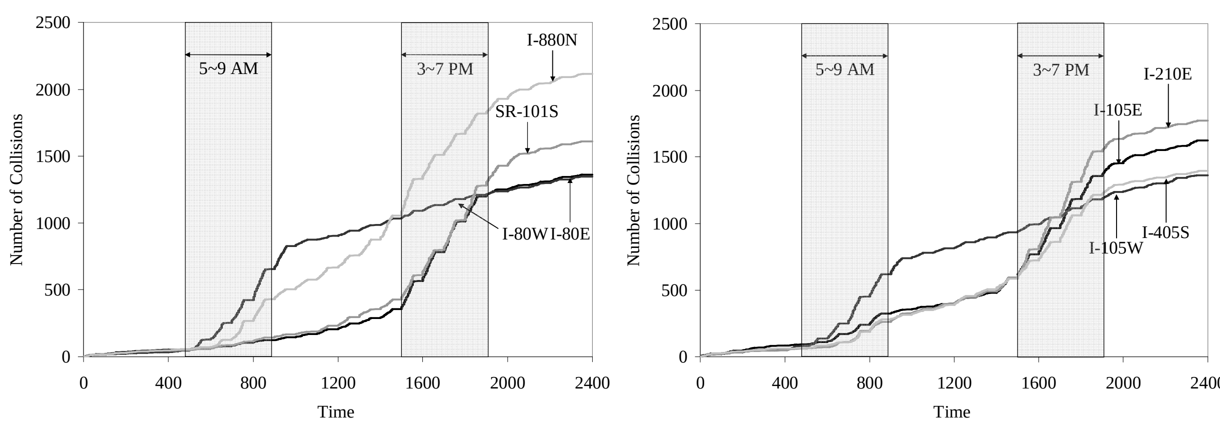


Figure 2 Description of collision locations in TASAS.

Since the HOV facility with continuous access operates only during the peak hours, only the collisions that occurred within these hours were used in this study to allow fair comparison between the two types of HOV facilities. Figure 3 shows the cumulative number of collisions at various hours of the day with two charts for the corridors with continuous-access and limited-access HOV respectively. The collisions occurring in the peak hours represent 55 to 68 percent of the total number of collisions during the 24-hour period along the traveling lanes, as illustrated in Table 2.

TABLE 2 Time-Series Collision Distribution during Peak hours (5~9 AM and 3~7 PM)

Facility Type	Continuous				Limited			
Route	I-80E	I-80W	SR-101S	I-880N	I-105E	I-105W	I-210E	I-405S
Percent	68%	60%	61%	55%	62%	60%	66%	62%



a) Continuous Access b) Limited Access

Figure 3 Time-Series collisions distribution.

SUMMARY OF COLLISION ANALYSIS

The collision data from all eight study corridors were analyzed and compared. The results are tabulated in Table 3, with the numbers of collisions per mile given for the two HOV types. It can be seen that on average the collisions/mile of HOV and left lanes in continuous access is lower than those in limited access.

TABLE 3 Summary of Collision Statistics in HOV and Left lanes, 1999~2003

		Continuous Access				Limited Access			
		I-80E	I-80W	SR-101S	I-880N	I-105E	I-105W	I-201E	I-405S
Collisions/Mile	HOV	3.1	4.8	1.8	3.0	6.1	3.7	9.4	9.1
	Left	21.4	20.9	12.1	30.1	22.1	18.5	27.7	31.1
Injury & Fatal collision (%)	HOV	11 (35%)	15 (32%)	4 (13%)	3 (18%)	28 (34%)	34 (42%)	22 (26%)	33 (40%)
	Left	61 (28%)	61 (30%)	81 (24%)	39 (36%)	65 (20%)	64 (22%)	59 (20%)	68 (22%)
PDO collision (%)	HOV	20 (65%)	32 (68%)	18 (88%)	21 (82%)	81 (66%)	51 (58%)	31 (74%)	63 (60%)
	Left	154 (72%)	143 (70%)	141 (76%)	124 (64%)	257 (80%)	225 (78%)	205 (80%)	279 (78%)

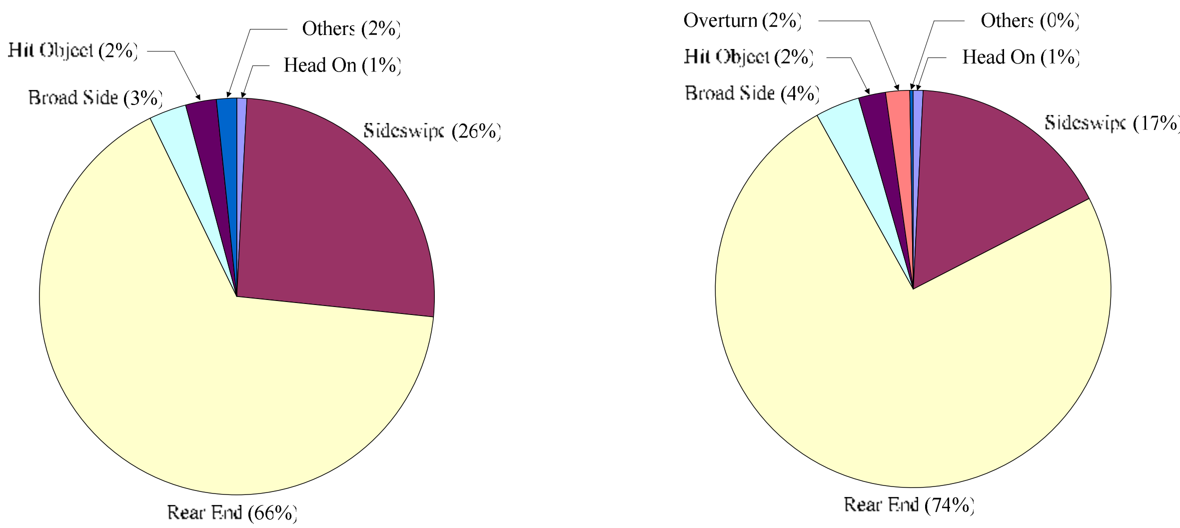
For severity analysis, collisions were categorized into two groups: injury and fatality collisions and Property Damage Only (PDO) collisions. Injury and fatality collisions involved at least one injury or fatality, while property-damage-only collisions had no injury or fatality involved. In HOV lanes, proportion of injury and fatal collisions in limited access is higher than that in continuous access while slightly higher proportion of injury and fatal collision in continuous access was observed in the left lanes.

TABLE 4 Peak Hour Traffic Volumes and Collision Distributions (5~9 AM and 3~7 PM)

	Routes	Traffic Peak Hour Volume (Vehicles / 8Hour)				Collision			
		All lanes	HOV + Left Lanes	HOV lane	Left lane	All lanes	HOV + Left Lanes	HOV lane	Left lane
Continuous	I-80E	33600 (100%)	17360 (52%)	6000 (18%)	11360 (34%)	795 (100%)	246 (31%)	31 (4%)	215 (27%)
	I-80W	38880 (100%)	19920 (51%)	7040 (18%)	12880 (33%)	661 (100%)	251 (38%)	47 (7%)	204 (31%)
	SR-101S	37120 (100%)	16800 (45%)	6080 (16%)	10720 (29%)	776 (100%)	187 (24%)	24 (3%)	163 (21%)
	I-880N	42960 (100%)	25360 (59%)	12480 (29%)	12880 (30%)	1016 (100%)	244 (24%)	22 (2%)	222 (22%)
Limited	I-105E	52480 (100%)	23120 (44%)	8400 (16%)	14720 (28%)	903 (100%)	443 (49%)	96 (11%)	347 (38%)
	I-105W	43920 (100%)	18560 (42%)	7120 (16%)	11440 (26%)	678 (100%)	317 (47%)	53 (8%)	264 (39%)
	I-210E	54720 (100%)	18960 (35%)	7120 (13%)	11840 (22%)	981 (100%)	431 (44%)	109 (11%)	322 (33%)
	I-405S	50560 (100%)	18240 (36%)	6240 (12%)	12000 (24%)	938 (100%)	443 (47%)	85 (9%)	358 (38%)

Table 4 shows the distribution of collisions and traffic volume on the eight corridors. Column three shows the amount of traffic observed at each of the corridors during the peak hours and column four and five shows amount of traffic observed at the HOV and left lanes. The remaining columns show the total number of collisions observed at each of the corridors and their distribution at HOV and left lane. Note that ratio between the collision and traffic volume distribution at HOV lanes are less than 1 indicating that less collisions are concentration on HOV lanes compared to the concentration of traffic volume in terms of percentage. However, when similar comparison is made after combing the traffic volume and collisions at the HOV and left lanes together, it shows that while the ratio remains less than 1 for the HOV lanes with continuous access and the one with limited access exceed 1. This implies an over-representation of collisions in the HOV and left lanes for the limited access type.

Recall that HOV lane with continuous access allows vehicles to enter or exit anywhere along the HOV lane while the one with limited access allows such lane-change maneuvers only at the designated locations that are normally set up before and after junctions or ramps with other highways. As a result, there can be a concentration of lane-change maneuvers in these ingress/egress sections. Since traffic in the HOV lane is typically moving at a higher speed, the lane-change maneuvers under heavy traffic conditions impose challenging situations and can potentially lead to collisions.



a) Continuous Access b) Limited Access

Figure 4 Type of collisions in HOV lane.

Figure 4 shows a comparison of collision types in the HOV lanes between continuous and limited access HOV lanes. More than 90% of collisions occurred in HOV lanes were reported as rear-end or sideswipes in both continuous and limited HOV lanes. However, a higher percentage of sideswipes was observed in continuous access HOV lanes.

CRASH CONCENTRATION IDENTIFICATION

Using the continuous risk profile [1], the collision concentration locations were identified to determine; (i) if there exist concentrations of collisions in the vicinity of limited ingress and egress sections; (ii) if there exist concentrations of collisions in HOV lanes with continuous access; and (iii) the relationships between collision concentration locations with respect to freeway ramps. A brief description of the CRP method is given next, which is followed by a summary of the findings.

Continuous Risk Profile

The continuous risk profile can be constructed first by cumulatively plotting collisions, A(d), with respect to distance, d. Then by rescaling it by a reference risk, $B(d - d_0)$, determined by the user, one can visually identify extended segment of the freeways with higher collision rates (see Figure-5). Similar rescaling techniques have been used in studying the propagation of kinematic waves [6]. The rescaled cumulative collision count curve amplifies the changes in the slope of the curve and makes it easier to observe how risk changes continuously with respect to the distance (i.e., number of collisions observed at a given postmile). In this example, the average collision count per unit distance observed over a 10-year period was used as the rescaling factor. The plot for the I-880 freeway segment in the year 2003 is shown in Figure 5. The positive slope in the figure indicates that the risk in the corresponding segment is higher than $B(d - d_0)$ and negative slope indicates lower risk: Such plot can enable the reader to instantly identify extended section of freeway segments with high collision counts.

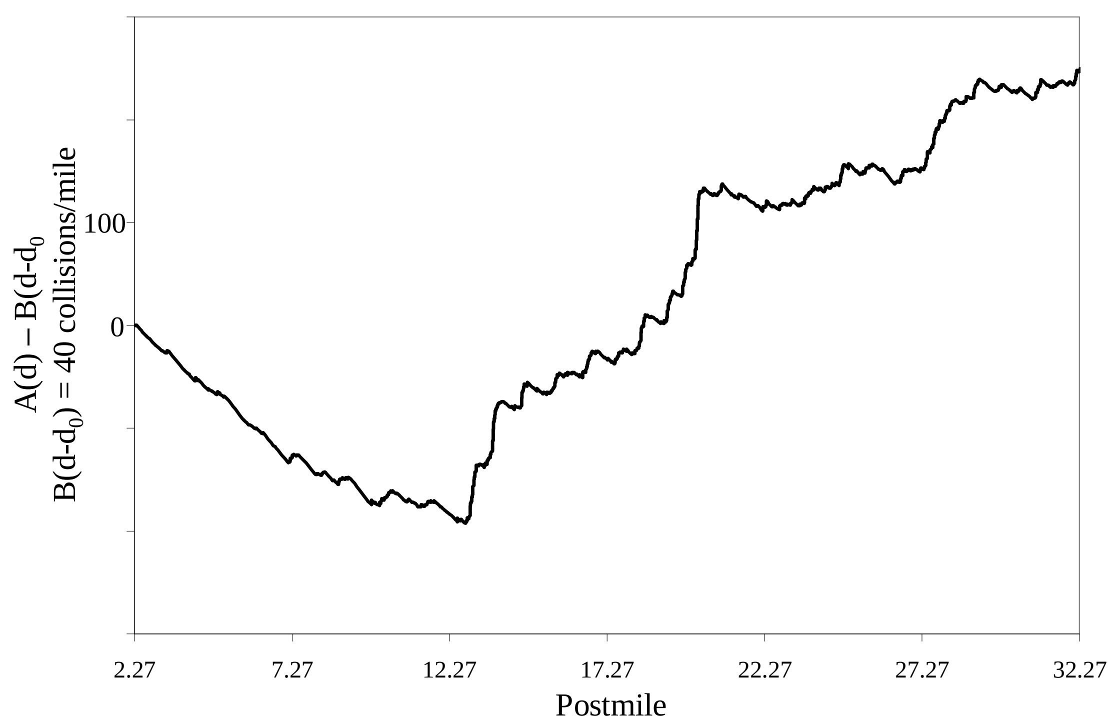


Figure 5 Rescaled cumulative collision count curve (I-880 Northbound, Alameda County, California, 2003).

Some of the fluctuations shown in rescaled cumulative collision counts (see Figure 5) are due to statistical variations and these variations can be pre-filtered [7] by using a moving average as shown in equation (1).

$$M(d) = \frac{\sum_{i=-\min(L/l,(d-d_0)/l)}^{\min(L/l,(d_{end}-d)/l)} f(d + i \times l)}{\min(L/l,(d_{end}-d)/l) + \min(L/l,(d-d_0)/l) + 1} \quad (1)$$

For

$$d = d_0 + k \times l \text{ and } k = 1,2,\ldots\frac{d_{end} - d_0}{l}$$

Where

$f(d) = k(d) - B(d - d_0)$

d_0 = beginning postmile

d_{end} = ending postmile

$D_{start} < D_{end}$

l = increment

2L = size of the moving average

k, $\frac{L}{l}$ and $\frac{d_{end} - d_0}{l}$ are integers

Since we are only interested in high collision concentration locations, we can then apply equation (2) below to identify the positive portion of the rescaled smoothed cumulative curve:

$$K(d) = Max\left(\frac{M(d+l) - M(d)}{l}, 0\right) \quad (2)$$

Note that in equation (2), K(d) will not only identify high risk locations, but also show the excess risk that the segment has compared to the base risk, B. This will allow us to determine where the risk started to increase and decrease as well as locations of the localized peaks in risk. Examples of such plots are presented next.

Findings from CRP Analysis

CRP were constructed along HOV and left lanes for all the study sites to examine the concentration of collisions in the vicinity of the designated access. Figure 6 provides one such illustration for highway I-210E. Figure 6 (a) shows the locations of designated HOV access locations, on and off ramps. The horizontal axis in Figure 6 (c) also applies to figures 6 (a) and (b) and shows the increase in distance (in miles) in the direction of vehicles traveling. 90% percentile was used as a reference risk and the excess collision rate is shown on the vertical axis. Figure 7 (a) shows the similar plot for Highway I-880N. Since there are no designated access locations in I-880N, Figure 7 (a) only shows the locations of on and off ramps, but no access areas.

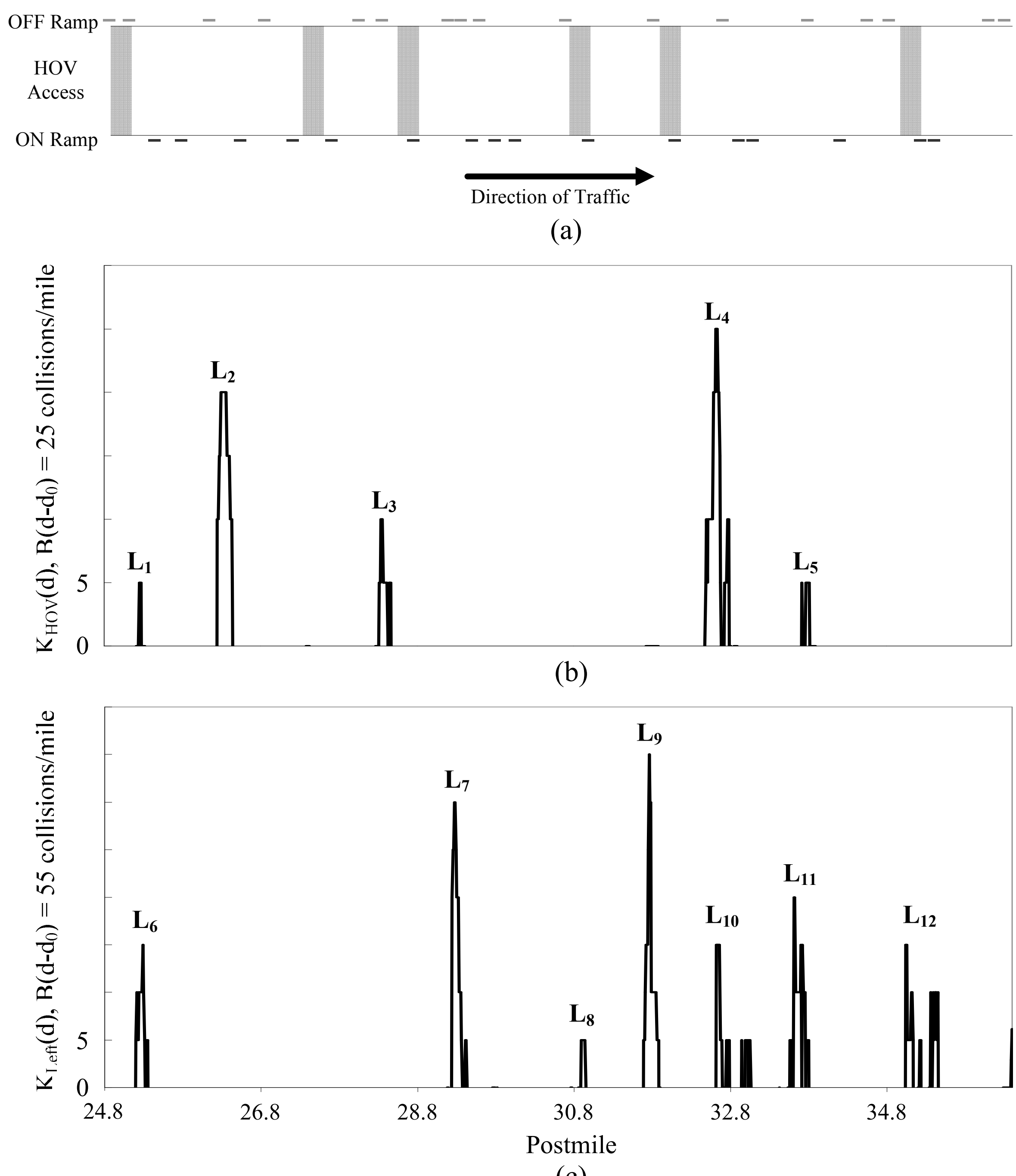


Figure 6 Continuous Risk Profile Plot (I-210E); (a) On- and off-ramps and HOV Access Locations, (b) CRP plot for HOV lane, and (c) CRP plot for Left lane

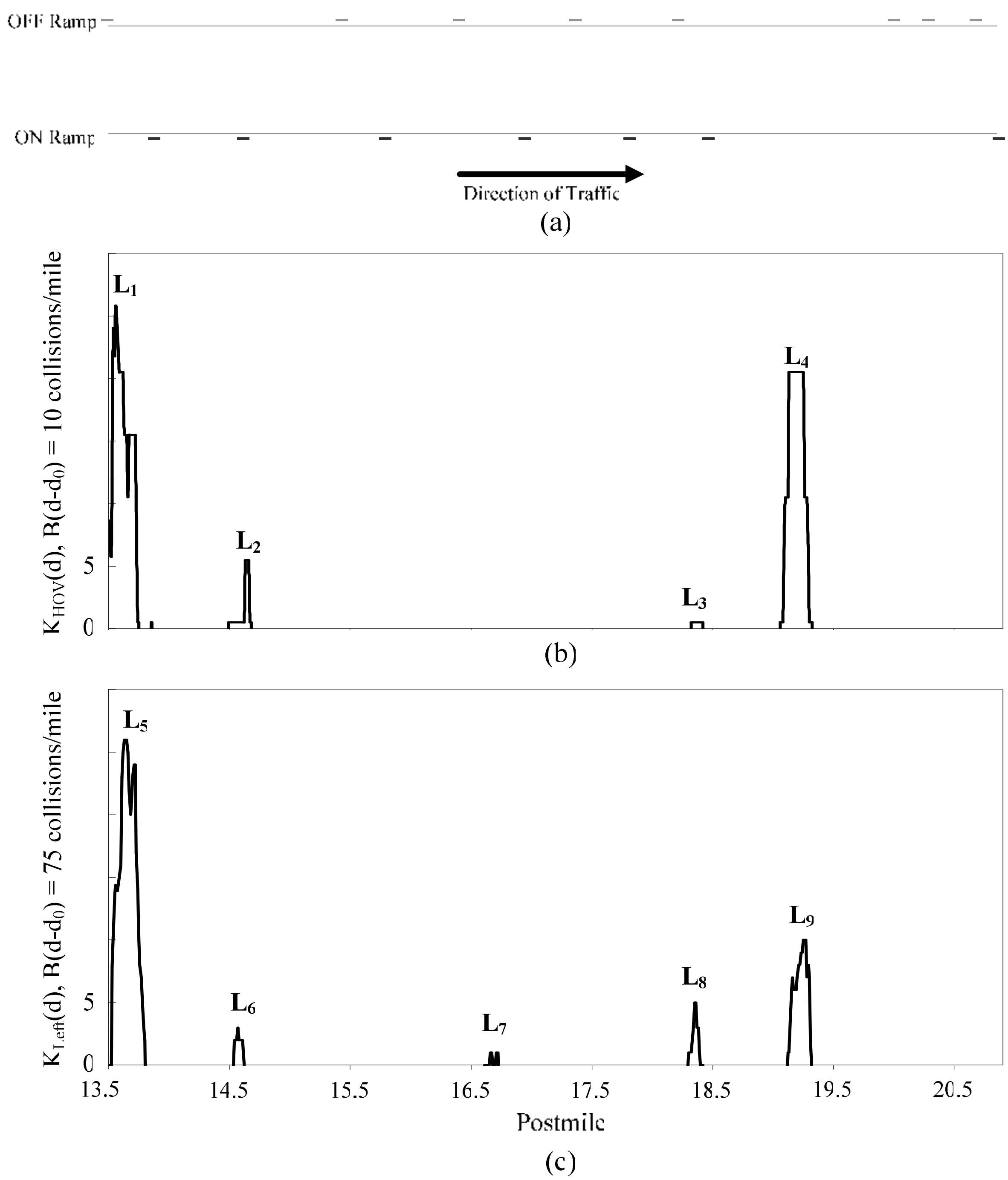


Figure 7 Continuous Risk Profile Plot (I-880N); (a) On- and off-ramps, (b) CRP plot for HOV lane, and (c) CRP plot for Left lane

The peaks labeled as L_1 to L_{12} in figures 6 (b) and (c) show the concentration of collisions, exceeding 90% percentile for each HOV and left lane within the corridor. Together with Figure 6 (a) they reveal important findings. Note that only two peaks out of the five, L_2 and L_3, shown (b) are located in proximity to the designated access areas. The other three peaks were found at locations where HOV lane is separated by buffers from the adjacent general purpose lanes where lane change is prohibited.

Some of the peaks in HOV lane, (See L_2 and L_3 in Figure 6 (b)) and the left lane (See L_7, L_8 and L_{12}) did not accompany similar peaks in the adjacent facility. However, other peaks, L_4 and L_5 (See (a)) were located very close to peaks in the left lane, L_{10} and L_{11} (See (b)) at the same post-mile, indicating that the same factor causing the concentration of collision influenced both facilities. It appears that the buffer whose function is to provide less interrupted flows at the HOV lanes also mitigates the effect of causative factors for high collision rates at the HOV lane on its adjacent lanes and vice versa.

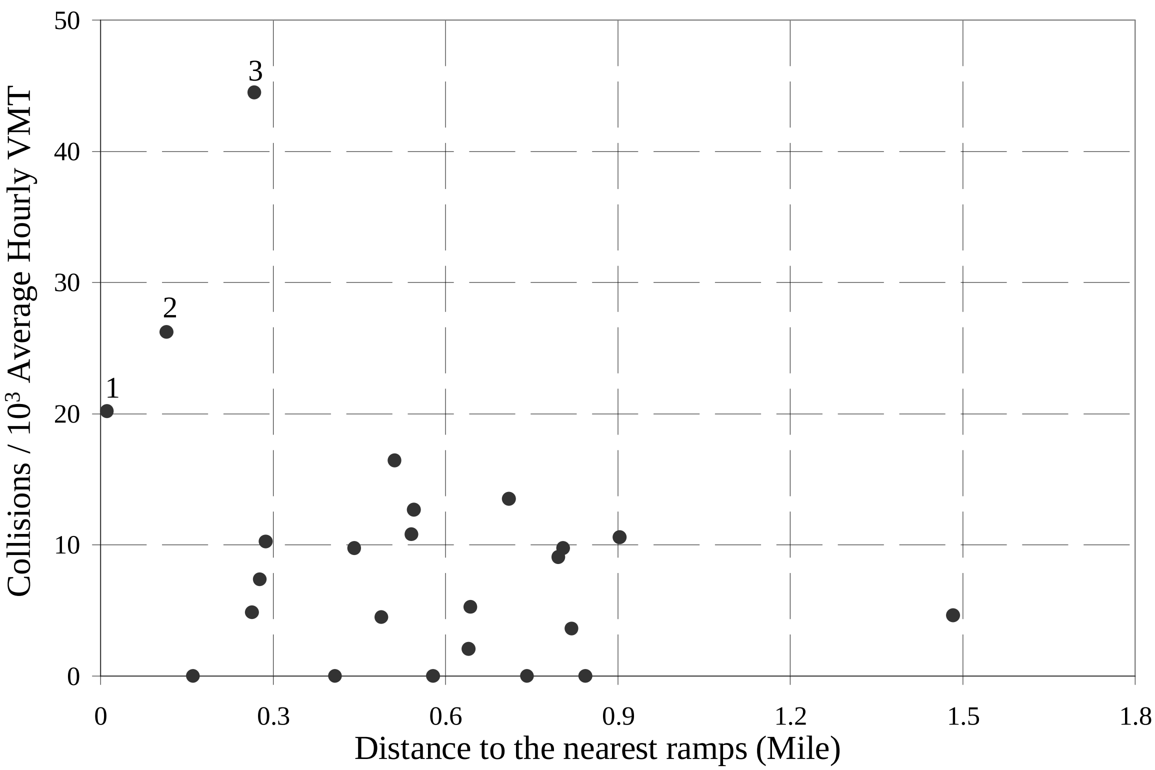


Figure 8 Relationship between collision/10^3 Average Hourly VMT and distance to the nearest ramps.

On the other hand, when the CRP patterns in the continuous access corridors are examined, they reveal very distinct characteristics. For example, each of the peaks in HOV lanes with continuous access (see Figure 7 (b) and (c)) accompany peaks in the adjacent lanes. This implies that the factors causing collision concentration appear to have more equivalent influence on the HOV and left lanes, and possibly on all lanes, for the highway corridors with continuous-access HOV lanes. The distinguishable patterns for limited-access and continuous access are also observable in all other six corridors that were evaluated by the CRP method. (Note that the scales of the y-axis are different in each figure to allow better assessment of relative heights of peaks.)

The collisions rates (in collisions per thousand average hourly vehicle-miles) at twenty four limited ingress and egress sections of the four routes are plotted with respect to their distance to nearby on or off ramps and they are shown in Figure 8. The average collision rates for all the access points shown in the figure was 9.4 while the average collision rates for all HOV lanes (from the four corridors with limited access) was 7.3. Excluding the three locations denoted by numbers 1, 2 and 3, the collisions rates remained below 16.4 collisions per thousand average hourly vehicle-miles and 7.3 collisions per thousand average hourly vehicle-miles, on average. The common features observed from the three sections (see data labeled 1, 2 and 3 in Figure 7) were (i) high peak hour HOV volume, 1500 vph (compared to average of 700~1000 vph in general), (ii) short access distance of 0.25 miles which is the minimum access length and (iii) within 0.3 miles of ramps.

CONCLUSION

In this paper, the historical data from eight freeway corridors over a five-year period were used to illustrate the various collision patterns on different lanes on the freeway. The analysis was conducted to explore the potential effects of the HOV lane configurations. The study includes a selective set of freeway corridors with differences in HOV operation and layout. The HOV facilities with continuous access permit vehicles from the adjacent lanes to enter or exit anywhere along the HOV lane and are in operation only during the morning and afternoon peak hours – generally 5 to 9 AM and 3 to 7 PM. Alternatively, the HOV facilities with limited ingress and egress access only allow vehicles to make the lane change at the designated access points and are in operation 24 hours a day.

Our findings were based on differences in various statistics such as collision distribution by lane, types of collisions, ratio of collision distribution to traffic volume and spatial patterns in collision occurrences. The present study shows limited access HOV facilities appear to offer no safety advantages. In fact, at least in the corridors examined, compared to continuous access HOV lanes, limited access HOV lanes have a higher proportion of collisions across lanes of the freeway, a higher number of collisions per mile, a higher ratio of collision distribution to traffic volume distribution and are of greater severity. These differences are not induced by the weaving traffic movements in the vicinity of ingress/egress areas in limited access HOV lanes.

Continuous risk profiles (CRP) were constructed for the HOV and the left lanes to study the concentration of collisions. The CRP for the limited HOV lanes showed concentrations of collisions near some of the access points as well as at locations where entering or exiting the facility is prohibited. The high concentration of collisions in the buffer separated limited access

HOV lanes were not always accompanied by concentrations of collisions at the adjacent lanes while the concentrations of collisions in the HOV lanes with continuous access were.
The access points (see data labeled 1, 2, and 3 in Figure 8) with much higher collision rates had higher HOV peak hour traffic volume,1500 vph (compared to average of 700~1000 vph in general). These access points had a short access distance of 0.25 miles, which is the minimum access length, and were located within 0.3 miles of ramps.

In order to better understand the relationship between HOV configurations and collision concentrations, the current study should be expanded to further investigate and quantify the causality of such safety differences in continuous and limited HOV lanes. Differences in the speed differential due to the different level of congestion on general purpose lanes across the study corridors or geometric design related to HOV lanes such as shoulder width, lane width and buffer configuration may also have a significant effect on the collision occurrence and distribution. Furthermore, in-depth site investigation of collision concentration locations is necessary to confirm the causes and identify associated countermeasures. These remain topics of future study.

ACKNOWLEDGEMENTS
The authors are indebted to the support provided by our research partners from the California Department of Transportation, who provided their assistance in the use of Traffic Collision Surveillance and Analysis System (TASAS). This work was performed as part of a project (PATH Task Order 6601) sponsored by the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation and Housing Agency, Department of Transportation. The contents of this paper reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California.

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