High-Occupancy Vehicle Facility Safety in California

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The findings of a study on how high-occupancy vehicle (HOV) facility operation affects the safety of selected California freeways are documented. The principal conclusion supported by the findings is that the accident rates on freeways with HOV facilities are sensitive to variations in traffic congestion in much the same manner that accident rates are influenced by congestion on non-HOV facilities. Careful investigation of the patterns of accident characteristics revealed no systematic differences in the lane locations of accidents or other factors that could be attributed directly to the presence of the HOV facilities. Freeways with and without HOV facilities appear to be characterized by the presence of locations where peak-period accidents are clustered, typically because of localized congestion conditions.

California has led the country in efforts to use freeway high-occupancy vehicle (HOV) lanes as tools to increase passenger-mile capacities by encouraging travelers to shift from single-occupant vehicles to carpools, vanpools, and public transit. California Department of Transportation (Caltrans) districts in major urban areas continue to advance programs to integrate HOV facilities into new freeway construction and reconstruction projects.

Despite their popularity among transportation professionals, HOV facilities invite controversy on several fronts. One such area of controversy is the question of HOV safety, especially where HOV lanes and mixed-flow lanes operate as a common facility. This situation provides opportunities for traffic conflicts between the rapidly moving HOV lane and stop-and-go traffic using adjacent mixed-flow lanes. At locations where vehicles begin and end HOV operation, conflicts may also arise from vehicle lane changes in the presence of significant speed differentials between lanes.

It is also true that when drivers are confronted by obviously difficult conditions, they may exercise so much extra care that the overall facility operation may actually be safer. Because of these opposing factors, the only valid way to conclude whether freeways with HOV lanes have special safety problems compared with fully mixed-flow facilities is to measure the traffic safety performance of these facilities in the field.

This study is not the first to attempt to quantify the traffic safety consequences of HOV facilities, but it is the most comprehensive investigation undertaken to date. The purpose of the study is to conduct a detailed analysis of the traffic safety impacts of a number of HOV facilities on California freeways. This will provide quantitative evidence to show if some or all of the selected HOV freeway sections differ in accident experience from control sections on similar non-HOV freeways.

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PREVIOUS RESEARCH

The majority of previous research on HOV implementation focused on "effectiveness," usually defined as a measure of how many people are transported through the facility. Safety was often mentioned as a concern, but only occasionally was it specifically studied. Betts et al. and others have indicated that traffic conditions on HOV facilities present a higher potential for accidents involving injuries (*1*).

Several studies conducted in California and Texas deal with the safety of implementing a concurrent-flow HOV lane. The results are varied, but appear to follow a general pattern: accidents increase in the first months of operation, presumably due to driver unfamiliarity with the system. After a period of several months, accident rates tend to stabilize at either pre-project or slightly higher levels (*2–7*).

Accident rates were evaluated before and after installation of HOV facilities with and without physical separation. Where the HOV lane was separated from the mixed-traffic lanes, no upward surge in accident rates was discernable (*4*). In several southern California studies of before and after accident rates, increased congestion was named as the major factor contributing to the increase in accident rates after HOV implementation (*5–7*).

Conclusions on the use of data for analysis vary. Some studies conclude that aggregate data (such as annual accidents per million vehicle-miles) should not be used to evaluate safety impacts (*8*). Instead, data stratified according to time of day, type of accident, and other operational characteristics should be used to provide insight into the safety effects of an HOV lane addition. In one study the data were stratified for analysis (*5,9*), and in a parallel investigation the corresponding aggregate data were used (*10*). Very different results were obtained from the two types of analysis. Measures of safety used in accident analysis are a complex topic of continuing research.

STUDY APPROACH

The group of HOV facilities considered in this study vary considerably in design. However all are located in the freeway median and have one of three basic designs:

- Contiguous HOV lanes with unconstrained access along their entire lengths,
- Buffer-separated HOV lanes with controlled ingress and egress at the ends and at numerous intermediate locations via lane changes from adjacent mixed-flow lanes, and

- Barrier-separated HOV lanes with controlled ingress and egress, typically using special ramps at each end and at a limited number of intermediate locations.

The safety impacts of particular freeway sections representative of each of these designs were studied using three interrelated but distinct approaches:

- Statistical analysis of computerized accident records from the Caltrans Traffic Accident Surveillance and Analysis System (TASAS): Accident frequencies and characteristics for the HOV freeway sections during their hours of operation were compared with the same operating periods for non-HOV freeway sections (control sections).
- Examination of selected original accident reports: California Highway Patrol (CHP) personnel provided field reports containing additional detail on the characteristics of certain accidents at locations where accidents tend to occur (or "hot spots"), which provided insights not attainable from the computerized data records alone.
- Visual analysis of HOV and control facility operations: Driver behavior was studied in relation to the traffic conditions observed. The visual analysis was performed using videotapes of peak-period traffic operations at selected locations along both the HOV and control facilities.

The comparisons made between the HOV and control sections generally focused on the heaviest travel directions. It should be noted that the sections vary considerably in their imbalance of directional peak-period volumes.

CHARACTERISTICS OF SELECTED FREEWAYS

HOV sections and control sections were selected on the basis of their similar traffic and geometric characteristics. Some of the selected HOV facilities operate at all times, others during limited hours, outside of which the HOV lanes either revert to mixed-flow use or are closed to traffic.

It should be emphasized that this study addressed cross-sectional comparisons (HOV sections against control non-HOV sections) instead of before and after comparisons relative to HOV facility implementation. Although imperfect, the cross-sectional approach was chosen to avoid the influence of changes in traffic volumes and other underlying conditions over time. Resources did not permit both cross-sectional and before and after comparisons to be combined in the study.

The identities and basic characteristics of the HOV facilities and control sections considered in the study are presented in Table 1.

DATA SOURCES

A variety of data types from Caltrans and CHP were needed to carry out the statistical analysis. The following are data types used in the analysis:

- TASAS accident data,
- Traffic counts,
- Speed data,
- MODCOMP data,
- Vehicle occupancy counts, and
- Video data.

TABLE 1 Characteristics of Selected Study Sections

HOV SECTIONS								
Section	Highway	County	Post-miles	Year Opened	Number of Directional Lanes		Section Type	Operating Hours
					Mixed	HOV		
LA 10	I-10	Los Angeles	LA 101 1.57 - LA 10 29.19	1973	4	1	Barrier and Buffer	24 hr./ 7 days
MRN 101	U.S. 101	Marin	MRN 2.00-17.80	1974	3	1	Conti-guous	6:30-8:30 A.M. SB [1] and 4:30-7:00 P.M. NB [1]
ORA 405	I-405	Orange	ORA 0.23-24.18	1989	4	1	Buffer	24 hr./ 7 days
SCL 101	U.S. 101	Santa Clara	SCL 38.3-SM 1.87	1986	3	1	Conti-guous	5-9 A.M. [1] 3-7 P.M. [1]
SD 15	I-15	San Diego	SD 11.10-M19.47	1988	3	2	Barrier	6-9 A.M. SB [2] 3-6:30 P.M. NB [2]

1 HOV lanes used as mixed flow lanes during other periods
2 Reversible HOV lanes closed during other periods.

ANALYSIS RESULTS

Because of the magnitude of the study and the large quantity of information produced, it is possible to provide only a sample of the results obtained.

The results that follow are associated with two HOV facilities (SCL 101 and MRN 101) in the San Francisco Bay Area in northern California and three HOV facilities (LA 10, ORA 405 and SD 15) in southern California. Results for the SCL 101 section are discussed in greater detail; the results for other HOV sections are discussed briefly. The results presented for the southern California HOV facilities generally reinforce the conclusions reached in northern California. For the complete findings of the study, the reader is referred to the final report (*11*).

SCL 101 HOV Versus SM 101 and CC 80 Control Sections

Comparison of Accident Rates

The time period from January 1, 1989, to September 30, 1990, was selected to make accident comparisons between SCL 101, the HOV facility, and two control sections (SM 101 and CC 80). The number of accidents in TASAS remaining after the elimination of those occurring under atypical conditions (bad weather, bad road conditions, during maintenance activities, etc.) are presented in Table 2.

The larger number of accidents on SCL 101 compared with SM 101 and CC 80 may be due in part to differences in scale and traffic volumes, or other variations in exposure, such as more lanes or a longer section. Unfortunately SCL 101 was one of two study sections for which traffic count coverage was not available for the time periods considered. Consequently, in this case, only geometric features of the sections were used to standardize the accident counts. The accident rates given in Table 3 are standardized on a lane-mile basis.

Northbound (NB) U.S. 101 and westbound (WB) CC 80 serve commuter traffic bound for San Francisco in the morning peak-period hours, whereas southbound (SB) U.S. 101 and eastbound (EB) CC 80 serve the heavy out-bound evening commute.

Generally, morning and evening peak-period accident rates on a lane-mile basis are higher on the SCL 101 HOV facility than on the two control sections. However accident rates are similar during the midday and night hours. The similarity in off-peak rates suggests that there is no obvious design flaw that causes SCL 101 to be uniformly more dangerous than the control sections. Whether the peak-period differences may be attributed directly to the HOV lane operation requires further investigation at the disaggregate level.

Spatial Distribution of Accidents

Accidents tend to be concentrated at a few locations along any freeway. Density traces were developed to identify these "hot-spots." Each density trace shows the number of accidents within 0.05 mi of the indicated postmile locations. Figures 1 and 2 show density traces for accidents on SCL 101 in the heaviest directions for the morning and evening peak periods.

Figure 1 shows two large accident clusters for the morning peak period northbound. They are in the weaving sections between the Trimble Road on-ramp and Montague Expressway off-ramp (Postmile 40.93) and within the Stierlin Road interchange (Postmile 48.60).

Figure 2, for the evening peak period southbound, shows the largest accident clusters at Postmiles 40.68, 41.10, and 50.35. These are also located within major interchanges.

The corresponding congestion diagrams in Figures 3 and 4 show that the four major accident clusters, Postmiles 40.93 and 48.60 northbound and Postmiles 40.68 and 41.10 southbound, coincide with locations of localized congestion. The largest northbound clusters and many of the smaller accident clusters coincide with the congested transition section before the beginning of the higher capacity section containing the NB HOV lane. The congestion is caused largely by the bottleneck directly downstream of the Trimble Road on-ramp. Similarly, many of the southbound accident clusters coincide with the localized congestion that occurs upstream of a far right lane drop at the end of the SB study section. Based on the observations and discussions with Caltrans officials, it was learned that congestion occurs on a recurring basis, especially during peak periods.

In general most accident clusters occur close to on- or off-ramps and in locations of recurrent congestion. These accidents may be related to merging and weaving of traffic, especially at times of congestion. From the limited available

TABLE 2 Total Number of Accidents (SCL 101 and Control Sections)

SECTION	DIR	TIME OF DAY				TOTAL
		A.M.	P.M.	MIDDAY	NIGHT	
SCL 101 - HOV	NB	201	257	82	71	611
	SB	99	352	74	74	599
SM 101 - CONTROL	NB	54	138	95	78	365
	SB	71	147	72	80	370
CC 80 - CONTROL	EB	12	119	39	52	222
	WB	74	32	33	22	161

Note: A.M. = 5:00 a.m. - 9:00 a.m.;
P.M. = 3:00 p.m. - 7:00 p.m.;
MIDDAY = 9:01 a.m. - 2:59 p.m.;
NIGHT = 7:01 p.m. - 4:59 a.m.

TABLE 3 Accident Rates (Total Accidents/Lane-Mile)

SECTION	DIR	TIME OF DAY			
		A.M.	P.M.	MIDDAY	NIGHT
SCL 101 - HOV	NB	3.39	4.34	1.38	1.20
	SB	1.64	5.84	1.23	1.23
SM 101 - CONTROL	NB	0.96	2.44	1.68	1.38
	SB	1.26	2.60	1.28	1.42
CC 80 - CONTROL	EB	0.41	4.09	1.34	1.79
	WB	2.54	1.10	1.13	0.76

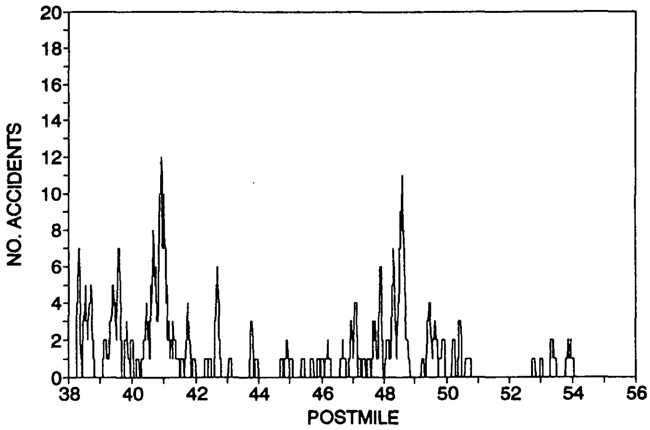

FIGURE 1 Morning accident frequency and locations for SCL 101-NB.

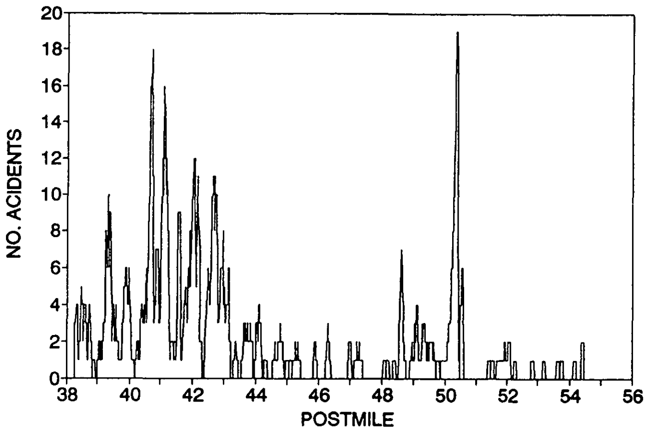

FIGURE 2 Evening accident frequency and locations for SCL 101-SB.

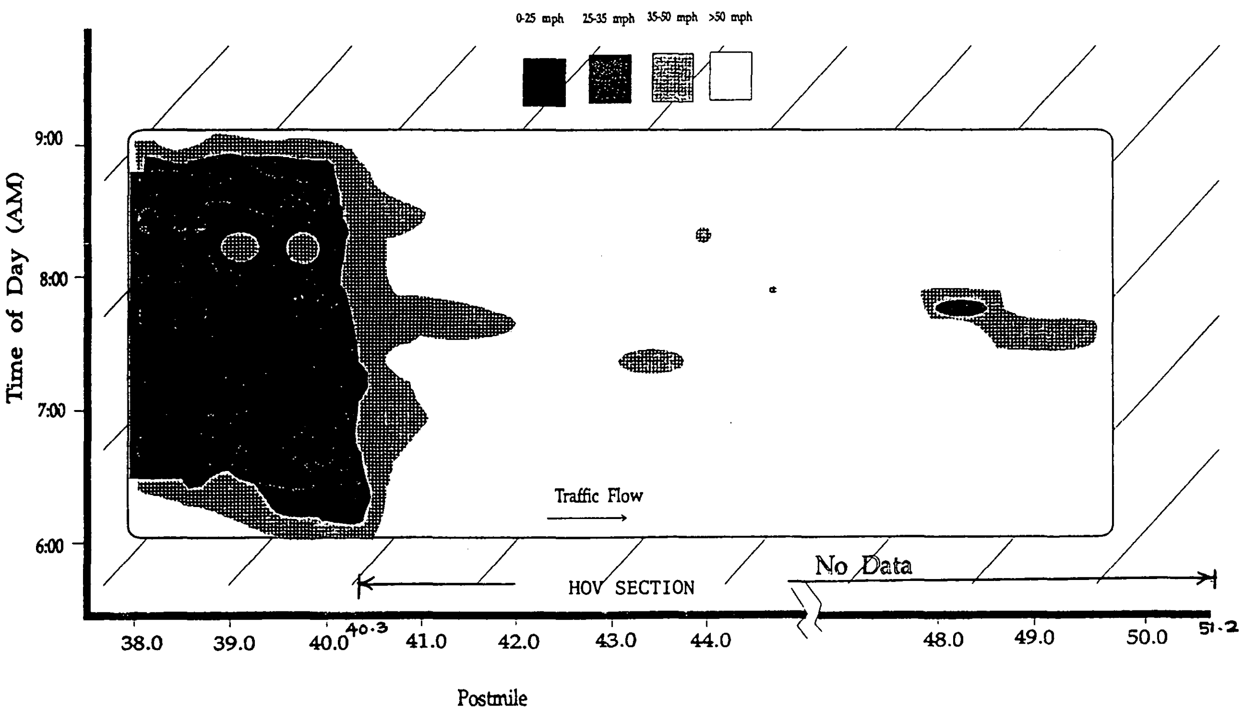

FIGURE 3 Morning congestion diagram for SCL 101-NB.

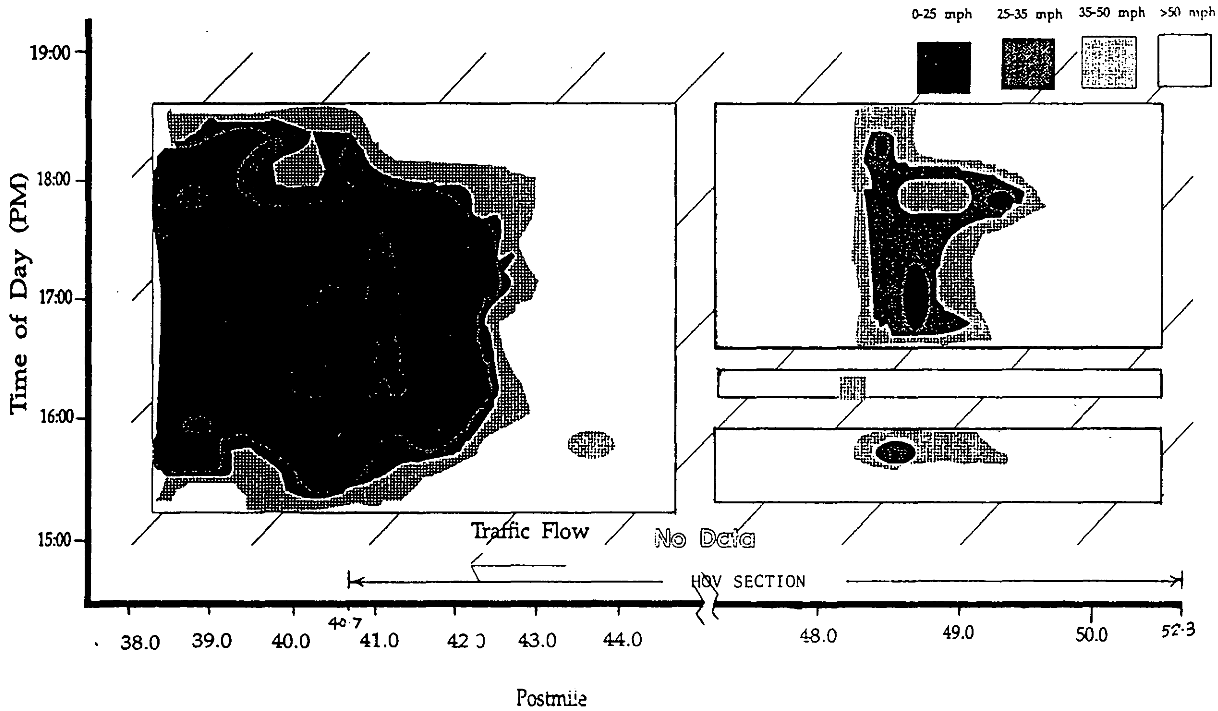

FIGURE 4 Evening congestion diagram for SCL 101-SB.

data, it was not possible to identify whether these weaving maneuvers are a result of drivers trying to use HOV lanes. The disaggregate analysis of the accidents with respect to this issue is discussed later.

Accidents Resulting in Fatalities or Injuries

Separate tabulations and density traces were developed for accidents resulting in fatalities or injuries to investigate whether their patterns might be different from those of total accidents, of which the majority involve property damage only. The accident rates and density traces for accidents resulting in fatalities or injuries generally reflect the patterns observed for total accidents. As in the case of total accidents, accidents involving fatalities or injuries coincide with the congested regions and occur close to the major on- and off-ramps.

Interaction Between Accidents and Speed

Numerous studies have identified a strong relationship between accidents and congestion because congestion tends to increase conflicts and driver frustration and often creates conflicts where high-speed vehicles do not have sufficient distance to stop.

On the basis of the expected times and locations of different speeds under recurrent conditions, the accidents in the peak-period direction were grouped to obtain the numbers of accidents by speed category. Each group of accidents was normalized by dividing by the lane-mile-hours associated with the speed range. The analysis shows somewhat higher accident rates for lower speeds. Although the relationship is not as strong as had been anticipated, the result does support the expected finding of a positive correlation between accident rates and increased congestion.

Types of Collisions

Major collision types are classified in TASAS data.

For the present analysis Figures 5 and 6 show comparisons of collision type on a percentage basis for the morning and evening peak-period directions. By far, the most frequent type of collision for all three sections is the rear-end collision.

One might hypothesize that any peculiar influence of HOV operations on accidents might be manifested in a shift in the relative proportions of rear-end and sideswipe accidents. The distribution of accidents by collision type is similar for all three study sections. The distributions for the other HOV study sections and their control sections also proved similar. Clearly, the hypothesis that the operation of HOV lanes during congested periods encourages particular accident types is not supported by these findings.

Accident Lane Location

Accident data were analyzed on the basis of the lane location of the accident. The collision location is coded in the TASAS data as follows:

- A. Beyond median or stripe—left;
- B. Beyond shoulder, driver's left;
- C. Left shoulder area;
- D. Left lane;

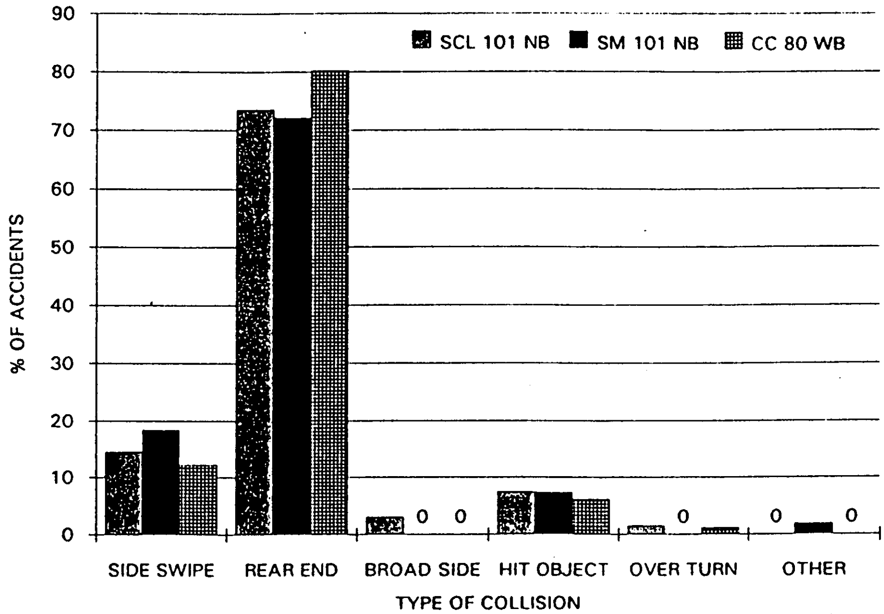

FIGURE 5 Morning collision type comparison.

- E. Interior lanes;
- F. Right lane;
- G. Right shoulder area;
- H. Beyond shoulder, driver's right;
- I. Gore area;
- <. Not stated; and
- –. Does not apply.

It should be noted that a value of accident location is coded for each vehicle involved, so the total number of accident locations exceeds the total number of accidents.

The categories listed above were grouped for analytical purposes. Categories A and B were combined as the Beyond Left Shoulder (BL) category, and were combined with Category C: Left Shoulder (LS). When the left lane operates as an HOV lane, the adjacent interior lane acts as the left lane for mixed-flow traffic, much as the left lane on control sections. Therefore to keep comparisons consistent between study sections and controls, Categories D: Left Lane (LL) and E: Interior Lanes (IL) were also combined. Category F was considered separately as Right Lane (RL), and Categories G, H, and I were combined as Right of Right Lane (RRL). The remaining categories were combined in a category labelled "Other."

The accident location summaries for SCL 101 are shown in Figures 7 and 8. In both figures, the highest accident per-

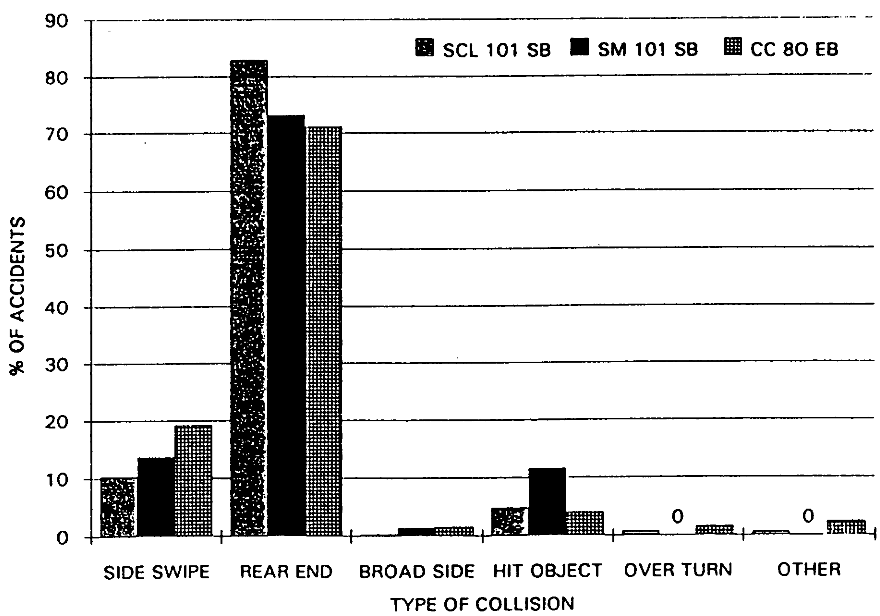

FIGURE 6 Evening collision type comparison.

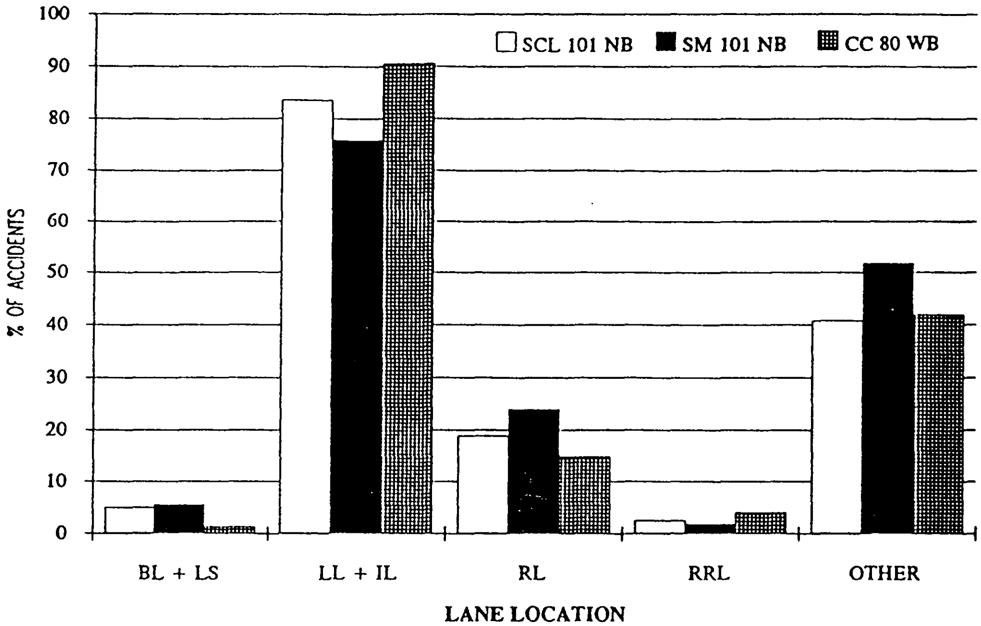

FIGURE 7 Comparison of morning accident lane location.

centages occurred in the left and interior lanes. If the HOV lane were an inherent contributing factor to accidents on SCL 101, one would expect to find consistently higher percentages in the LL + IL category compared with the control sections. Although the LL + IL percentage is higher for the evening peak period, no such effect is evident in the morning. Similar results were found for the other HOV study sections.

In conclusion, the comparison does not support the hypothesis that accident location is consistently different in the presence of HOV lanes.

Movement Preceding Collision

The categories for the analysis discussed in this paper are indicated in the TASAS data. As with lane locations, each observation corresponds to an involved vehicle. The percentages of vehicles in each classification for peak-period accidents in the study sections are shown in Figures 9 and 10.

It may be hypothesized that contiguous HOV lanes might lead to an increase in the number of accidents that occur when drivers are slowing or stopping or changing lanes. From the

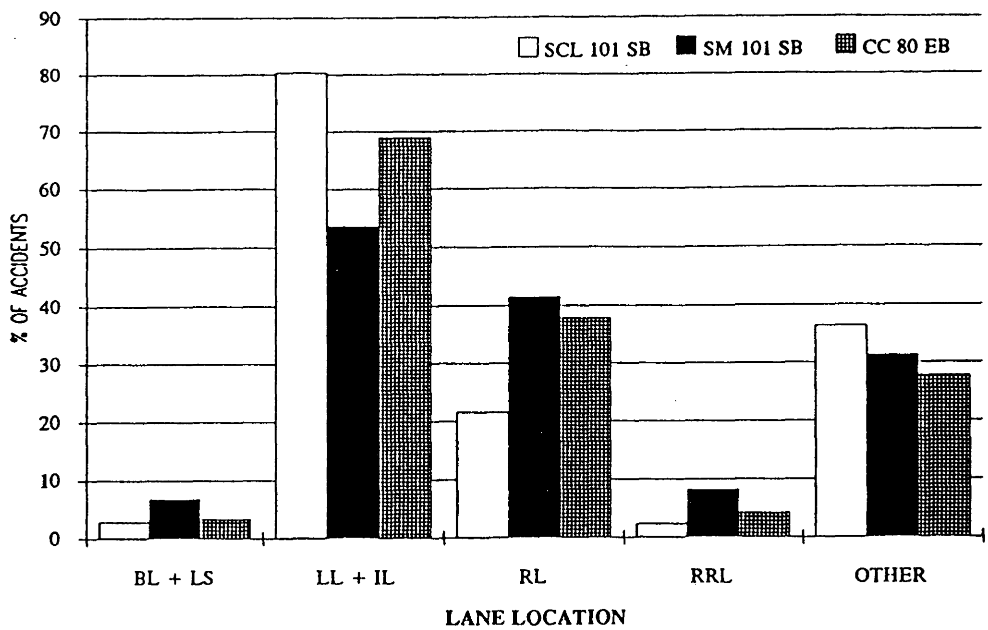

FIGURE 8 Comparison of evening accident lane location.

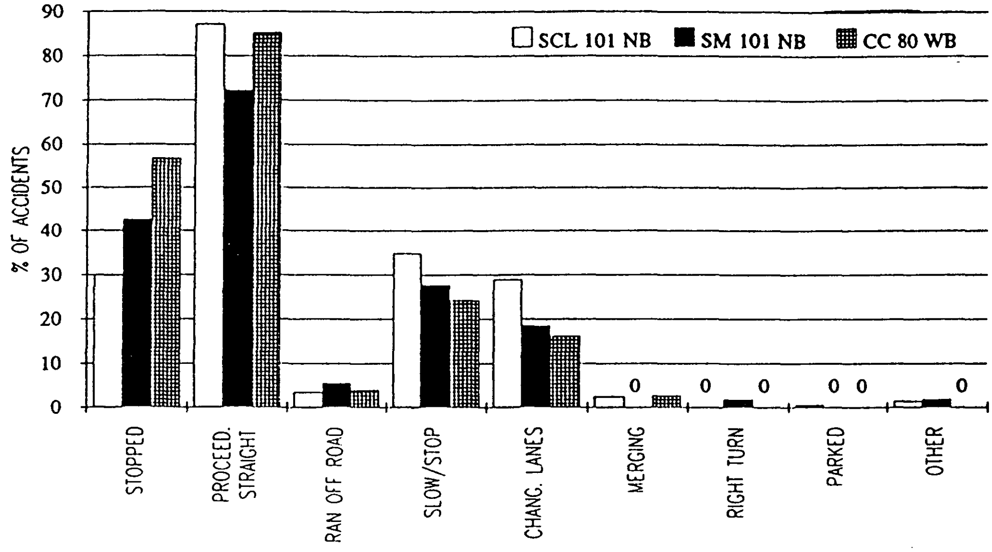

FIGURE 9 Comparison of movement preceding collision, morning.

present findings, the percentage of slowing or stopping accidents on SCL 101-NB is generally the same or less than on the control sections. However the percentage of accidents that occur when drivers change lanes on SCL 101 is always higher than on control sections, although the difference may be regarded as insignificant for the evening peak period.

It may be noted that accident percentages are higher in the "proceeding straight" category on SCL 101 in peak-period hours, possibly because of the influence of congestion during peak-period hours. However except possibly for the "change lanes" category, there is no clear pattern of difference that might be attributable to the presence of HOV lanes.

Results of the Review of CHP Individual Accident Reports

To further investigate accident characteristics at the "hot spots," the original written accident reports were reviewed. This investigation revealed congestion and resulting sudden slowdowns as the main causes of accidents. Of the accidents examined, the lane next to the HOV lane had the majority of accidents.

Most accidents at the hot spots were coded as rear-end accidents, indicating the contribution of speed differentials. Nearly all of the remaining accidents, coded as sideswipe

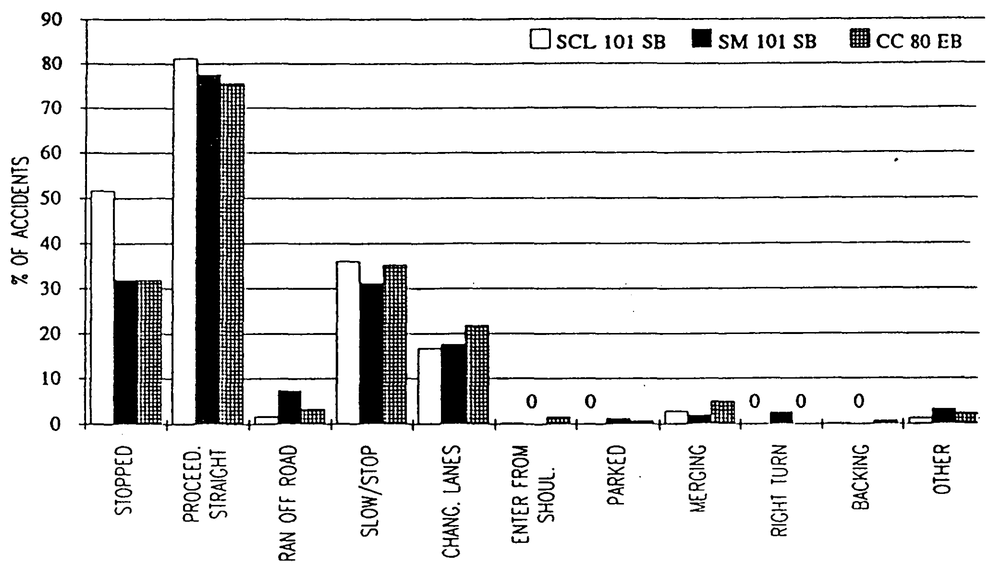

FIGURE 10 Comparison of movement preceding collision, evening.

accidents, appeared from the narratives and collision diagrams to be the results of driver efforts to avoid rear-end collisions. In some cases, drivers attempting to avoid rear-end collisions in the leftmost mixed-flow lane caused a side-swipe or rear-end accident in adjacent lanes. All accidents in the reports for SCL 101 belonged to one of these two categories. Congestion is clearly the major contributing cause of these accidents.

Video Data Analysis

The video data analysis was conducted to determine whether operational conditions on a per-lane basis in the mixed-flow lanes (densities, speeds, lane changes, etc.) are affected by the presence of an adjacent HOV lane, relative to the control sections.

Traffic parameters were manually extracted from the video recordings. These parameters, in combination with visual interpretation of vehicle motions in the field and video tapes, yielded better understanding of the possible causes of traffic accidents.

Data extracted from the video tapes were useful in understanding congestion patterns and how operating conditions varied among different sections. The video data were useful, for example, in revealing unusually high variations in values of flow and density between adjacent lanes in the vicinity of documented accident hot spots. These conditions, which appear unrelated to the HOV lane, clearly make drivers in the left mixed-flow lane especially vulnerable to becoming involved in accidents due to downstream congestion. The causes and consequences of these extreme lane-flow differentials warrant further study.

Summary of the Analyses

Accident rates on SCL 101 are systematically higher than on SM 101 and CC 80 during morning and evening peak-period hours, and are similar during the midday and night hours. It appears that any differences or similarities in accident rates between the SCL 101 HOV facility and the two control sections are largely a result of the differences in their congestion patterns and not of anything inherent in the geometric or operational characteristics of the HOV lanes themselves. The sole exception is that the proportions of accidents following lane change maneuvers are always greater in the presence of the contiguous HOV lane, although this effect is not characterized by amounts that can be considered significant.

MRN 101 HOV Versus CC 80 Control Section

The Marin 101 (MRN 101) HOV facility is unique in its operational and geometric character in that the HOV lane is contiguous and is in operation during the morning peak period (6:30–8:30 a.m.) only in the SB direction toward San Francisco and in the evening peak period (4:30–7:00 p.m.) only in the NB direction away from San Francisco. The facility consists of two HOV lane subsections in each direction separated by a 4- to 5-mi mixed-flow section. CC 80, on the other side of San Francisco Bay, was used as the control section because of its similar flow characteristics.

Analyses of accident rates based on lane-miles, vehicle-miles, and person-miles were compared. Accidents for lane-miles, vehicle-miles, and person-miles were consistently less than on CC 80 during the morning peak period, but higher for the evening peak period in the NB direction. The higher accident rates are associated with accident clusters at a few locations, especially in the gap between the HOV sections, which can generally be associated with localized congestion problems. Disaggregate analysis showed no noteworthy differences due to the presence of HOV lanes even during the evening peak period.

LA 10 HOV Versus LA 210 Control Section

An analysis was performed of accidents along the LA 10 barrier-separated HOV facility (El Monte Busway), parallel mixed-flow lanes, and terminal transition sections on I-10 and U.S. 101, in comparison with the LA 210 (Foothill Freeway) control section. Accident rates for lane-miles, vehicle-miles, and person-miles were calculated. It was found that accident rates on LA 10 are slightly higher than on the LA 210 control section. This may be attributed to the relatively heavy congestion on LA 10.

From the disaggregate analysis it was found that there is no evidence that the patterns of accidents recorded on LA 10 in the presence of the HOV facility is systematically different than on LA 210. Because the LA 10 HOV lanes are barrier-separated and operate as an isolated highway, except at transition sections, these findings are not particularly surprising.

ORA 405 HOV Versus LA 405 Control Section

Another analysis was performed of accident characteristics along the Orange County (ORA 405) buffer-separated HOV facility as compared with the LA 405 control section. The analysis for ORA 405 covered only 1 year because the HOV facility opened in May 1990. The LA 405 control section is of special interest because the standard median shoulders on that facility were reconstructed for use as mixed-flow lanes.

The accident rates for lane-miles, vehicle-miles, and person-miles are generally lower on ORA 405 than on the LA 405 control section, except for the morning peak period in the SB direction. However, fatal and injury accident rates are generally equal during most time periods.

From the disaggregate analysis it was found that there are no systematic differences between the ORA 405 HOV facility and the control sections during both the morning and evening peak periods.

Further investigations of the original accident reports revealed no evidence that the HOV facility specifically contributes to the incidence of accidents.

SD 15 HOV Versus LA 210 Control Sections

The reversible HOV facility north of San Diego on Interstate 15 is unique in several respects. It is a two-lane, barrier-separated facility that operates in the SB direction toward San Diego between 6:00 and 9:00 a.m. and in the NB direction between 3:00 and 6:30 p.m. The HOV facility is closed during off-peak hours and weekends.

The analysis revealed that accident rates on SD 15 in all time periods for corresponding directions are lower than on the LA 210 control section.

Further disaggregate analysis with respect to types of collisions and movements preceding collisions suggests that there are no systematic differences in the presence of the HOV facility. However, the analysis did reveal that accidents located on the left shoulder and beyond are proportionally higher on SD 15 than on LA 210. If time had permitted, it would have been interesting to investigate this issue further. However the number of accidents of this type is so small that any possible effect would be of minor consequence.

CONCLUSIONS AND RECOMMENDATIONS

An extensive study was performed of accident rates and accident characteristics on several California HOV facilities, in comparison with a group of selected control sections. The assembled evidence suggests that there are no inherent operational features of HOV facilities that per se appear to affect either the frequency or the nature of accidents to a significant degree. As reported in previous studies of this type, the influence of congestion on accident rates and locations clearly overwhelms any other operational factors.

It may be concluded that the addition of an HOV lane may lead to more accidents, to fewer accidents, or be neutral with respect to accidents depending on how the additional capacity fits within the overall urban network. This implies the need to examine the short-term and long-term congestion mitigation and migration aspects of proposed capacity enhancement projects and their staging, whether or not they include HOV facilities.

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