

# SAFETY OF HIGH-OCCUPANCY VEHICLE LANES WITHOUT PHYSICAL SEPARATION

By Thomas F. Golob,<sup>1</sup> Wilfred W. Recker,<sup>2</sup> Member, ASCE,  
and Douglas W. Levine<sup>3</sup>

(Reviewed by the Highway Division)

**ABSTRACT:** This study addresses safety issues associated with the operation of freeway high-occupancy vehicle (HOV) lanes that are not separated by physical barriers from adjacent, general-purpose traffic lanes. Accident frequencies and characteristics obtained from 14 months of operation of an HOV lane in the greater Los Angeles area, together with similar data for 6 years prior to the opening of the lane, are analyzed to evaluate the safety impacts of the lane operation. The analyses rely on comparisons of accident characteristics associated with the HOV lane to those associated with both temporal and spatial control groups. Changes in accident characteristics are also related to existing patterns of freeway congestion. The results of the case study indicate no adverse effect on safety conditions that could logically be attributed to the HOV operation; all of the changes in the patterns of reported accidents can be explained by changes in the location and timing of traffic congestion. Although no overall change in the exposure to accidents was found, there is a significant migration of accident locations due to the combination of relief of congestion in the project area and a corresponding creation of more severe traffic bottlenecks downstream of the project.

## INTRODUCTION

The objective of this study was to evaluate the traffic safety of freeway high-occupancy vehicle (HOV) lanes that are not separated by physical barriers from adjacent, general-purpose traffic lanes. The purpose of the HOV lanes is to offer an incentive to motorists to form carpools, thereby providing some relief for congestion. The research was aimed at determining the causes of any changes in safety conditions due to the operation of such lanes, and identifying possible actions to mitigate any adverse safety impacts.

The study focused on an HOV lane operation in the greater Los Angeles area located on the Riverside Freeway State Route 91 (SR-91). HOV lane operation was introduced on June 10, 1985 ("Route" 1986). The lane is in the eastbound direction only, is located between Central Avenue and the I-605 Freeway, and is operational from 14:00 hr until 19:00 hr on weekdays. The lane was created by using most of the median shoulder, and its minimum width is approximately 11 ft (3.35 m). The lane has two ingress areas and two egress areas.

The principle source for safety data is the TASAS (Traffic Accident Surveillance and Analysis System) data base maintained by the California Department of Transportation (*Manual* 1978). Essentially every accident on the State Highway System reported by a police officer in the field is included

<sup>1</sup>Res. Specialist, Inst. of Transp. Studies, Univ. of California, Irvine, CA 92717.

<sup>2</sup>Prof. of Civ. Engrg., Dir. of Inst. of Transp. Studies, Univ. of California, Irvine, CA.

<sup>3</sup>Grad. Student, Inst. of Transp. Studies, Univ. of California, Irvine, CA.

Note. Discussion open until April 1, 1990. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on August 16, 1988. This paper is part of the *Journal of Transportation Engineering*, Vol. 115, No. 6, November, 1989. ©ASCE, ISSN 0733-947X/89/0006-0591/\$1.00 + \$.15 per page. Paper No. 24069.

in this data base. The period for which data were available at the onset of the study is January 1, 1979, through August 31, 1986. This period includes 14-full months of HOV operation.

In addition, data on roadway characteristics (such as the number of lanes by postmile range) were obtained from the highway records in the TASAS data base and from the published "1985 California State Highway Log, District 7" report ("1985 California" 1986). Data on post-project traffic volumes, occupancy rates, and other project operational parameters were obtained from Caltrans project-monitoring reports. Information on congestion levels was obtained by computerizing diagrams of speed by postmile and time of day provided by the local Caltrans district office for several dates that were representative of daily congestion patterns for the year.

Three distinct, albeit related, analyses were conducted to uncover possible changes in safety associated with the HOV project. The first involved comparisons of accident frequencies. Because of significant, but undocumented, changes in traffic volumes on the facility resulting from the opening of a major new freeway connector during the transition from the pre- to post-project periods, a simple comparison of pre- and post-period frequencies could not be used to assess changes in accident rates. Rather, several comparisons were made of accident frequencies within the project area relative to corresponding frequencies for various control situations that were viewed as similar to those of the project area (excepting the HOV operation). The second part of the analysis focused on the determination of possible changes in the makeup of the accidents comprising the accident frequencies associated both with the project area and with the various control situations. Tests within this analysis were conducted to determine whether or not the HOV operation had altered the tendencies of particular accidents to occur, independently of the total accident counts. Such counts were viewed as potentially influenced by factors that could not be addressed because of the limitations of available data. The third set of analyses is directed at isolating possible congestion effects from those strictly attributable to HOV operation. In the first of these, the locations of various types of accidents are related to spatiotemporal patterns of congestion on the facility; correspondence between the "migration" of accident locations and changing congestion patterns is used to identify likely congestion effects. Secondly, these location effects are adjusted to account for time-of-day interactions of congestion with accident patterns. Finally, changing accident concentrations involving location-timing interactions that could not be explained by congestion effects are analyzed in detail relative to any potential links to the HOV operation.

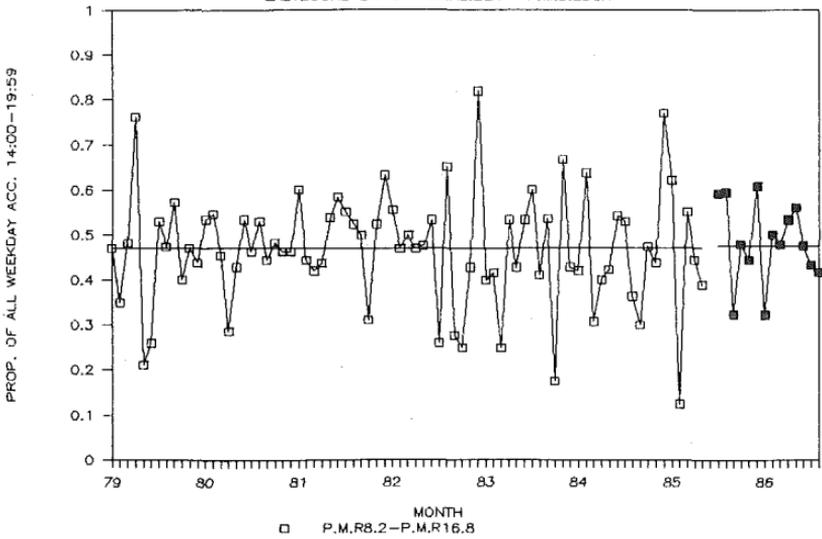
Statistical testing was conducted at the  $P = 0.05$  significance level. The most extensively used statistical tests were the Chi-square test of association between two categorical variables, and the Kolmogorov-Smirnov test of the equivalence of two distributions. In addition, analysis-of-variance ( $F$ -testing) was used when the subject was the categorization using a continuous variable, and the Kendall Tau statistic was used in testing the association between two ordinal variables (or the dichotomous breakdown of an ordinal variable).

## **ACCIDENT FREQUENCIES**

Because accurate traffic volume counts prior to the opening of the HOV lane were unavailable, it was not possible to compute accident rates per

# PROPORTION OF ACCIDENTS IN HOV AREA

EASTBOUND SR-91 P.M.R.8,2LA - P.M.5,850R



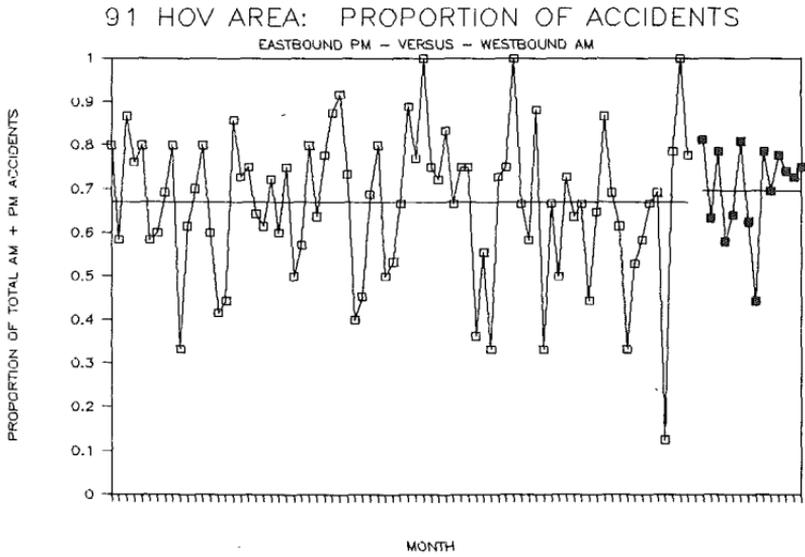
**FIG. 1. Proportion of Total Eastbound SR-91 Accidents in HOV and Downstream Areas in HOV Areas**

vehicle mile of travel before and after implementations of the HOV lane. Thus, analyses of changes in accident frequencies potentially attributable to the HOV operation relied on comparisons to control situations.

As mentioned, the HOV lane on the SR-91 Freeway is unidirectional (eastbound only) and is operated only between 14:00 and 19:00 hr on weekdays. This provides contrasts for controlling for traffic level increases in comparisons of accident rates. One such comparison involved the numbers of raw accidents over time on two sections of eastbound SR-91: The 8.6-mi segment corresponding to the HOV lane location and a 13.4-mi (21.6 km) downstream segment from the end of the HOV lane eastbound to the connector to the SR-57 freeway. This comparison was limited to accidents that occurred on the eastbound highway between 14:00 and 19:59 hr on weekdays (the period 19:01 to 19:59 is selected to capture any safety effects associated with closure of the HOV lane).

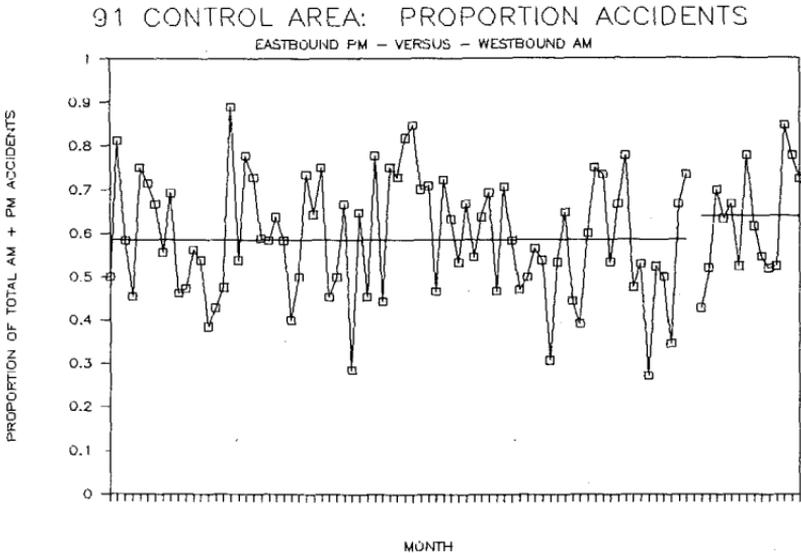
The proportion of total accidents in the project and downstream sections that were located in the HOV section is plotted by month in Fig. 1. The last 14 months correspond to HOV operation in this section, and the month of project initiation (June 1985) is deleted from the plot. The mean proportion in the upstream section prior to the HOV lane (January 1979 through May 1985) was 0.470; during HOV operation it was 0.475. The difference between these mean proportions is not statistically significant.

A second analysis involved the comparison of two accident statistics on a monthly basis, before and after introduction of the HOV lane. The first statistic is the total number of accidents that occurred on weekdays on the eastbound highway between 14:00 and 19:59 hr, denoted by  $E_{pm}$ . The second statistic is the total number of accidents that occurred on weekdays on the same section of the westbound highway between 05:00 and 10:59 hr, de-



**FIG. 2. SR-91 HOV Area: Proportion of Accidents Eastbound P.M. versus Westbound A.M.**

noted by  $W_{am}$ . Beginning in June 1985, the  $E_{pm}$  statistics correspond to HOV operation, but the  $W_{am}$  are not related to HOV operation because the lane is unidirectional. SR-91 is characterized by directional peaking, and this comparison is relative to the extent that peak-interval traffic volume changes over time are similar in the peak eastbound and westbound directions. Shown in



**FIG. 3. SR-91 Downstream Influence Area: Proportion of Accidents Eastbound P.M. versus Westbound A.M.**

Fig. 2 is the ratio of  $E_{pm}$  accidents to the total of the  $E_{pm}$  plus  $W_{am}$  accidents by month for the HOV area. Shown in Fig. 3 is the same ratio for the section of SR-91 downstream from the HOV area (from the end of the HOV lane to the SR-57 connector in Orange County), which is defined to be the influence area for the project. The results reveal no significant accident increases relative to the area of HOV operation: the overall ratio of  $E_{pm}/(E_{pm} + W_{am})$  in the HOV area (Fig. 2) is 0.669 in the pre-HOV period and 0.696 in the post-HOV period; this difference is not statistically significant in a test of proportions. Moreover, the slight shift to more eastbound afternoon accidents for the final 14 months is the same for both the HOV and the influence sections. This is consistent with a greater increase in traffic volume and potential congestion effects in the eastbound direction versus the westbound direction over both the project and downstream areas.

The conclusions from these analyses of total numbers of accidents are: (1) Any effects of the HOV lane operation are too subtle to be identified in aggregate accident frequencies; and (2) changes in accident frequencies before and after project introduction are similar for the area of the HOV lane and the downstream influence area.

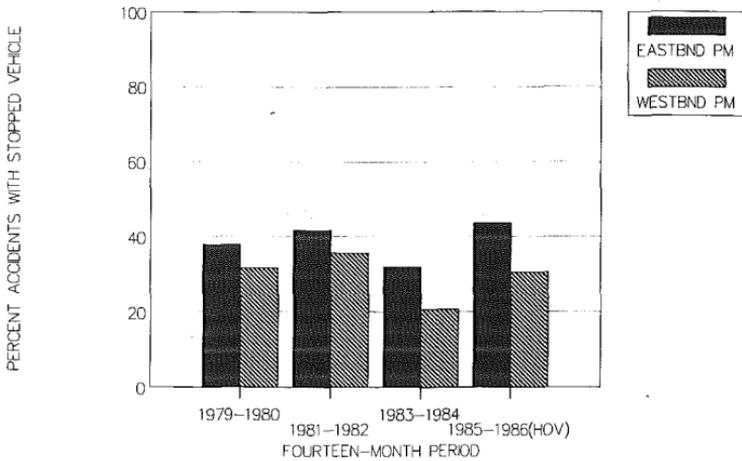
### PATTERNS OF ACCIDENT CHARACTERISTICS

To determine whether operation of the HOV lane on SR-91 has changed patterns of accident characteristics, comparisons were made among the characteristics of multi-vehicle accidents that occurred during the afternoon (14:00–19:59 hr) in the eastbound direction and those that occurred during the morning (5:00 to 10:59 hr) in the westbound direction for each of four 14-month periods: July 1985–August 1986 (HOV operation in the eastbound direction) and nonoverlapping periods corresponding to July to August periods in 1983–84, 1981–82, and 1979–80. The eastbound afternoon 1985–86 statistic corresponds to the operation of the HOV lane. The comparison over time since 1979 facilitates identification of long-term temporal trends that might be independent of influences that are unique to the 1985–86 period.

All characteristics available in the TASAS data were investigated as to differences eastbound P.M. versus westbound A.M. over the four 14-month periods. Two of the tests for differences in accident characteristics represented tests of hypotheses concerning effects of the HOV lane: (1) It was hypothesized that HOV lane operations without physical barrier separations of HOV and mixed-flow lanes would result in an increased incidence of sideswipe collisions; and (2) it was hypothesized that unsafe HOV operation would lead to an increase in the incidence of lane-change accidents.

Both hypotheses were rejected on the basis of all available data. There is only a very slight increase in percentage of sideswipes for the eastbound afternoon interval, 1985–86 versus 1983–84, and no differences or a decrease compared to earlier years. In any case, neither the difference for eastbound afternoon over the four time intervals nor the difference between eastbound afternoon and westbound morning intervals in 1985–86 is statistically significant.

Secondly, there has been only a slight (statistically insignificant) increase for the eastbound P.M. interval in the percentage of multi-vehicle collisions in which at least one vehicle's movement prior to the collision was changing lanes.



**FIG. 4. SR-91: Multiple-Vehicle Accidents with Vehicle Stopped (Weekdays, Mileposts 8.2 to 16.8, Los Angeles County) by Eastbound P.M. versus Westbound A.M.**

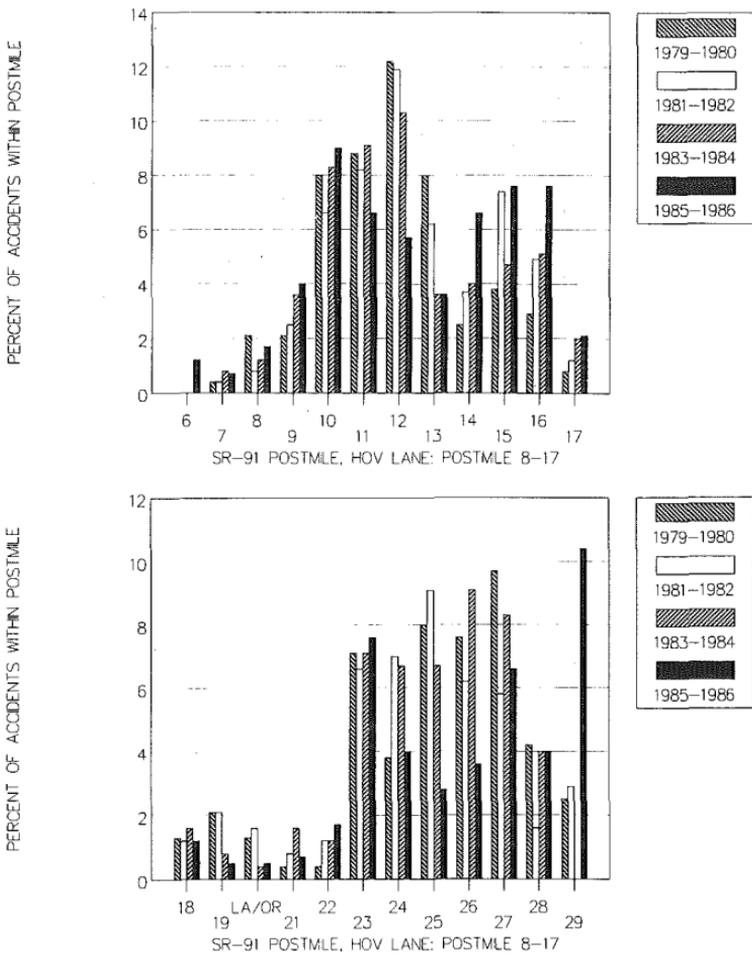
All other accident characteristics that represent direct tests of hypotheses related to the safety of HOV operation were found to be invariant over the 1979-1986 period and in the eastbound afternoon versus westbound morning comparison. However, significant patterns of change were found for two characteristics, and these provide evidence concerning causes of SR-91 accidents. The first of these characteristics was the percentage of multiple-vehicle collisions that involved at least one stopped vehicle. The breakdown for this variable is shown in Fig. 4. The difference between eastbound afternoon and westbound morning is statistically significant for the 1985-86 (HOV) period, but not for previous time periods. This indicates that congestion-related accidents were particularly high during the period of HOV operation, compared to the control westbound morning segment of SR-91.

The second accident characteristic with a significant trend was the percentage of multiple-vehicle collisions that involved a light truck (pickup or van). The pattern of statistically significant differences over time indicates that the variable is not simply a reflection of the proportion of light trucks in the vehicle fleet, as this proportion has not varied over time in a similar pattern. The relatively high proportion of accidents involving light trucks during the 14-month HOV period corresponds to the pattern of stopped-vehicle accidents. The variable is an indicator of congestion effects, reflecting the effect of trucks in reducing sight distances in heavy traffic conditions.

The conclusion from the analysis of accident characteristics is that operation of the HOV lane has not altered the pattern of accident characteristics on SR-91. The only significant changes involved the relative increase in the percentage of accidents involving "stopped" vehicles and those involving light trucks, indicating increased congestion effects.

## ACCIDENT LOCATIONS

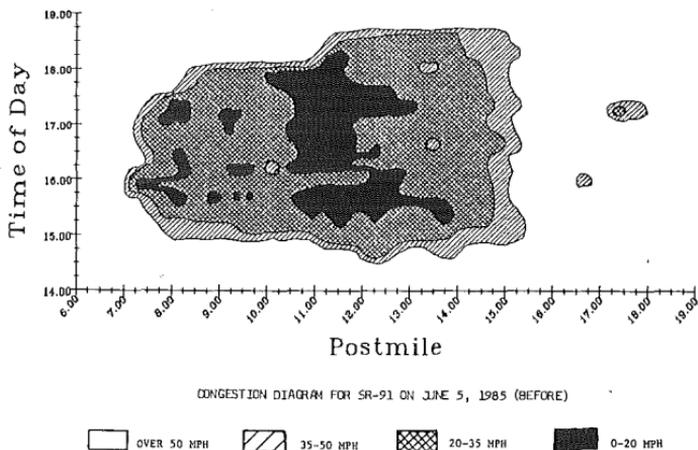
The distribution of accident locations is critical to determining any influence of the operation of the HOV lane. The distribution of weekday after-



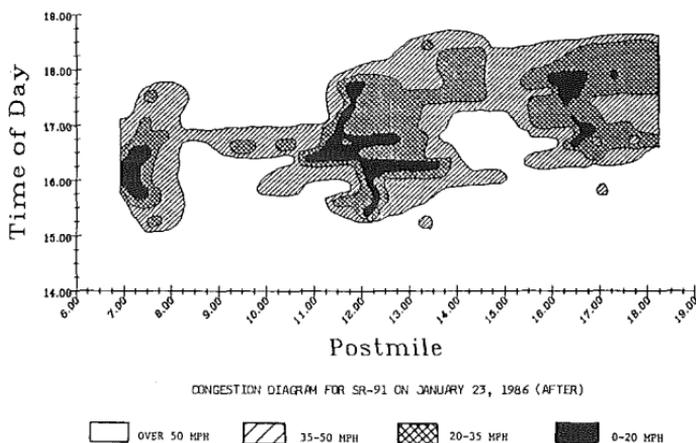
**FIG. 5. SR-91: Weekday Accidents 14:00 to 17:59 hr: Percentage per Mile over 24 mi by 14-Month Period: (a) HOV Lane Postmiles 6-17; (b) HOV Lane Postmiles 18-30**

noon accidents over the length of eastbound SR-91 has changed significantly over time. It is important to investigate accident locations relative to access/egress and buffer locations of the HOV lane and to lane drops and ramps that are potentially related to congestion, such as queue buildups.

The percentage distributions by mile of total weekday accidents from 14:00 to 19:59 hr over the 24-mi (38.6 km) section of SR-91 for each of the four nonoverlapping 14-month periods are graphed in Figs. 5(a) (postmiles 6-17) and 5(b) (postmiles 18-29). Focusing on the spatial distribution for 1985-86 compared to the previous periods, the most outstanding feature in Figs. 5(a-b) is the increase in accidents in the mile represented as postmile 29 in Orange County [Fig. 5(b)]. This mile includes a major overcrossing with on- and off-ramps, and the connector off to another freeway (SR-57) is 0.23 mi (0.37 km) downstream. This could indicate queue buildups from the freeway interchange and sight distance problems at the overpass. This represents



**FIG. 6. Congestion Diagram for SR-91 on June 5, 1985 (Before)**

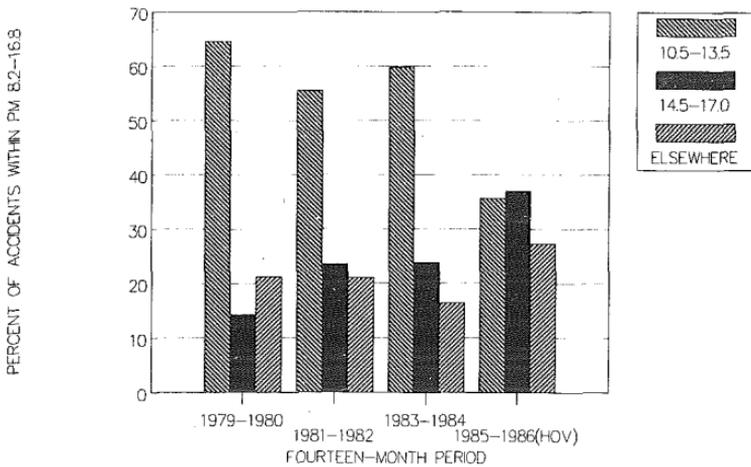


**FIG. 7. Congestion Diagram for SR-91 on January 23, 1986 (After)**

a migration of accident locations to a traffic bottleneck downstream of the project.

There are also differences among the spatial distributions in the area of the HOV lane (postmiles 8.22 to 16.77, Los Angeles County), with a significant shift of locations of accidents in 1985-86 to the miles beginning at postmile 14 to postmile 16, in the general vicinity of the egress of the HOV lane, and away from the postmile ranges beginning at postmile 11 to postmile 12, compared to previous periods. These changes were investigated in more detail by focusing on congestion in the area of the HOV lane.

Congestion diagrams are available for SR-91 in the periods before and after installation of the HOV lane (Figs. 6 and 7). Such diagrams provide information on the speed of travel at each postmile location and time interval on the day on which the data are collected. Data are obtained by driving a fleet of cars along the road and recording speeds at postmile and time of



**FIG. 8. Breakdown of Weekday Accidents (14:00 to 19:15 hr) by Three Locations**

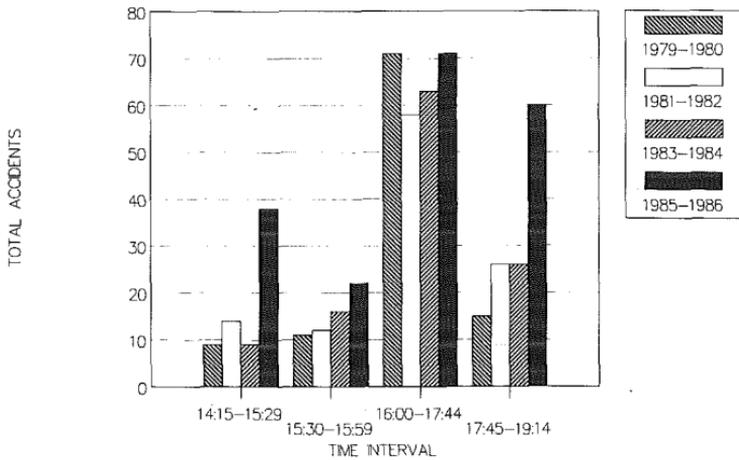
day intervals. This operation was performed on eastbound SR-91 on June 5, 1985 (before the HOV lane) between approximately postmiles 7 and 18 between 14:45 and 19:00 hr. It can be seen from a comparison of Figs. 6 and 7 that the pattern of congestion on SR-91 has changed over time.

Spatial distributions were investigated on a half-mile basis for the 9-mi (14.5 km) area encompassing the present HOV lane for the four 14-month periods. There are new peaks for the 1985-86 period of HOV operation at four half-mile areas beginning at postmiles 10, 14.5, 15.5, and 16.5, while relative concentrations are down in the range of postmiles 10.5 to 13.

The first area of new concentration (postmiles 10.0-10.5) is in the vicinity of a lane drop. Comparing the HOV period to previous periods, there has been an upstream shift in the location of accidents into this area, which encompasses two off-ramps. SR-91 also bridges three major arterials and a rail line in this area. Increasing queue buildups, indicated by the onset of heavy congestion at about postmile 10.5 (Fig. 7), and restricted sight distances account for this upstream shifting of accident locations.

The second area of new concentration (postmiles 14.5-15.0) is again in the vicinity of a lane drop. The area is also immediately preceding an HOV access/egress area; on-ramps may pose potential weaving problems associated with the HOV egress. In the period before implementation of the HOV lane, concentration levels were relatively low in this area during the entire P.M. period, indicating the breakup of queues and resumption of free speed (Fig. 6). However, after implementation of the HOV lane, this decrease in congestion was not generally present (Fig. 7).

The third area of concentration (postmiles 15.5 to 16.0) is in the vicinity of another lane drop. It is in the general area immediately downstream of the HOV egress and is centered approximately 1 mi (1.61 km) from the end of the HOV lane. A comparison of the congestion diagrams of Figs. 6 and 7 shows that there are substantial levels of congestion in the range postmiles 15.5 to 16.0 after implementation of the HOV lane (Fig. 7) that were not present in that range before implementation (Fig. 6). This represents a migration of congestion downstream due to the partial elimination of traffic



**FIG. 9. Eastbound Weekday Accidents by Time Period [Postmiles 8.2 to 16.8 (HOV Area)] by 14-Month Period**

bottlenecks in the project area. Congestion effects with reduced sight distances are expected here and may be affecting merging traffic from the HOV lane. Finally, the fourth and last area of new concentration (postmiles 16.5 to 17.0) is at the end of the HOV lane and roughly coincident with the location of the off-ramp to the I-605 freeway.

The locational distribution of accidents can be simplified by considering three locations: (1) Postmiles 10.5-13.5, the area of the highest levels of congestion immediately before implementation of the HOV lane (Fig. 6); (2) postmiles 14.5-17.0, the area of high congestion after implementation of the lane (Fig. 7), but low congestion before implementation (Fig. 6); and (3) all other locations. The breakdown of accidents according to these three locations (Fig. 8) shows a dramatic shift in accidents from location category 1 to categories 2 and 3, pre-HOV versus post-HOV. This shift is statistically significant, as determined through a Chi-square test. The shift between categories 1 and 2 represents a downstream migration of accidents.

## ACCIDENT TIMING

Further assessment of the role of HOV operations in these new accident locations requires establishing location and time-of-day interactions and investigating accident characteristics. A detailed comparison of temporal distributions on a quarter-hourly basis revealed that systematic shifts in these distributions can be summarized by dividing the overall afternoon/evening interval into four time periods with consistent trends. These periods are: (1) 14:15 to 15:29 hr; (2) 15:30 to 15:59 hr; (3) 16:00 to 17:44 hr; and (4) 17:45 to 19:14 hr. The distribution of accidents over the four time periods is shown for each 14-month time interval for the HOV area (postmiles 8.2 to 16.8) in Fig. 9. The first time period is characterized by a substantial increase in accidents for the 1985-86 period. The second time period is characterized by a relatively steady increase over the four 14-month periods. The total number of accidents during the third time period is relatively constant over

all 14-month periods. Finally, for the fourth time period (17:45 to 19:14 hr), there is an increase between 1979–80 and 1981–82, no increase between 1981–82 and 1983–84, and a substantial increase from 1983–84 to 1985–86. Thus, the 14-month HOV period is characterized by substantial increases in accidents during the intervals before 15:30 hr and after 17:44 hr, but no increases at other times.

### LOCATION-TIMING INTERACTIONS

In analyzing the spatial distribution of accidents for each of the four time periods, it was determined that the second time period exhibited no HOV-related effects. The remaining three periods (14:15–15:29, 16:00–17:44, and 17:45–19:14) were found to exhibit different spatial distributions of accidents. Moreover, two of the time periods (16:00–17:44 and 17:45–19:14 hr) were found to have spatial distributions that were different for the 1985–86 period, compared to previous periods, while the period 14:15–15:29 hr was found to be the same in 1985–86 as in prior years.

The first time period exhibited an increase in the number of accidents in the area of the HOV lane, 1985–86 versus prior years (Fig. 9), but no increase in the number of accidents in the influence area. The spatial distribution of these accidents over 1-mi categories in the area of the HOV lane is statistically indistinguishable for 1985–86 and for previous years, as determined using a Kolmogorov-Smirnov test.

There are too few accidents during the second time period to support the study of spatial distributions. However, the third time period (16:00–17:44 hr) exhibited essentially no increase in accidents in the HOV area, pre-HOV to post-HOV, but a substantial increase in accidents downstream of the HOV lane. The accident locations have shifted for both the HOV and control areas, even though the total number of accidents is essentially constant for the HOV area. The percentage distribution of accidents by half-mile over the HOV area is shown in Fig. 10. There are new peaks in the HOV period at the

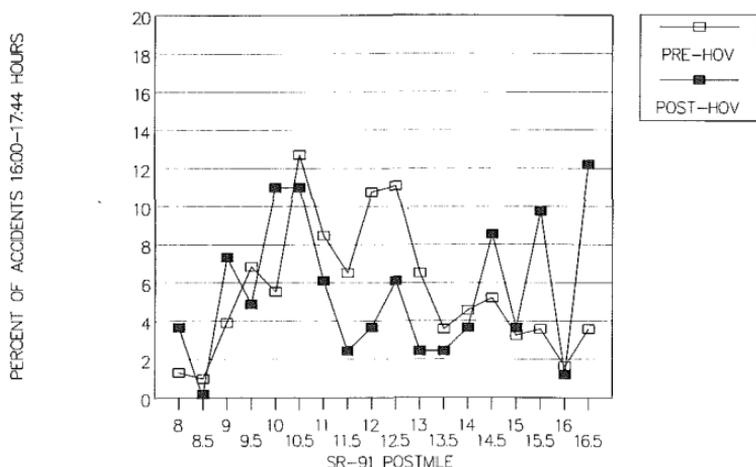
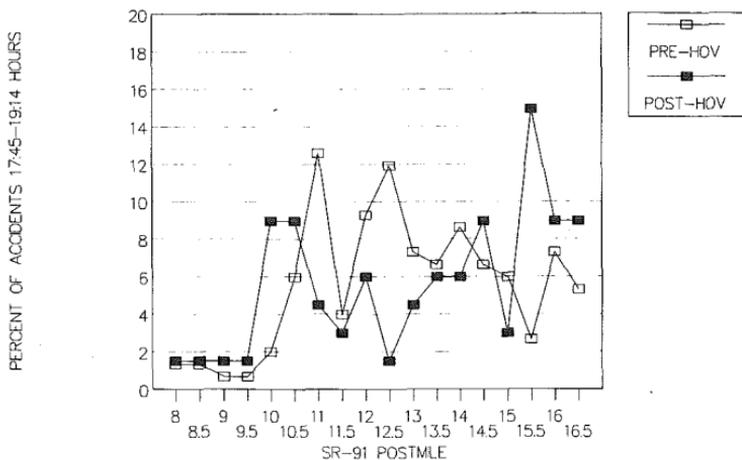


FIG. 10. SR-91: Eastbound Accidents, Weekdays 16:00 to 17:44 hr, by Postmile, Pre-HOV versus Post-HOV Period



**FIG. 11. SR-91: Eastbound Accidents, Weekdays 17:45 to 19:14 hr by Postmile, Pre-HOV versus Post-HOV Period**

half-miles beginning at postmiles 10.0, 14.5, 15.5, and 16.5, and the HOV period shows lower relative concentrations over the postmile range 11.0 to 14.0.

The concentrations between postmiles 14.5 and 16.5, which are in the general vicinity of the egress and end locations of the HOV lane, indicate a merging problem during congested conditions (when the disparity in speed between vehicles in the HOV lane and those in the general use lanes is greatest). However, there is no absolute increase in the number of accidents occurring during this time interval in the area encompassing the HOV lane, despite the added capacity (and presumed additional volumes) provided by the HOV lane. This indicates that this potential problem is counterbalanced either by improved safety resulting from the additional capacity provided by the HOV lane or by more intense congestion in the general use lanes with the associated lower speeds.

The fourth time period (17:45–19:14 hr) exhibited increased numbers of

**TABLE 1. Location and Time-of-Day Interactions**

Time period (weekdays only) (1)	HOV Lane Area (Postmiles 8–17)		Influence Area (Postmiles 17–29)	
	Total accidents 1985–86 versus prior years (2)	Spatial distribution of accidents 1985–86 versus prior years (3)	Total accidents 1985–86 versus prior years (4)	Spatial distribution of accidents 1985–86 versus prior years (5)
14:15–15:29	Increase	Same	Same	Shifted
15:30–15:59	Slight increase	(Insufficient sample size)	Slight increase	(Insufficient sample size)
16:00–17:44	Same	Shifted	Increase	Shifted
17:45–19:14	Increase	Shifted	Increase	Shifted

accidents, 1985–86 versus prior years, in both the HOV and control areas. For both areas, there was a significant shift in accident locations. The pre-HOV and post-HOV spatial distributions for the HOV section are compared in Fig. 11. Some of the 1985–86 areas of concentration are similar to those for accidents in the 16:00 to 17:44 hr period (Fig. 10), but there is even a greater migration of accidents downstream (to postmiles 15.5 to 17.0), a phenomenon consistent with the changes in congestion patterns. The two distributions are statistically different from one another, and are each statistically different from a uniform distribution, as determined by Kolmogorov-Smirnov tests.

The location and time-of-day interactions are summarized in Table 1. The concentrations of increased accidents in specific locations at specific times represent SR-91 problem areas.

### CAUSAL FACTORS IN CHANGING ACCIDENT CONCENTRATIONS

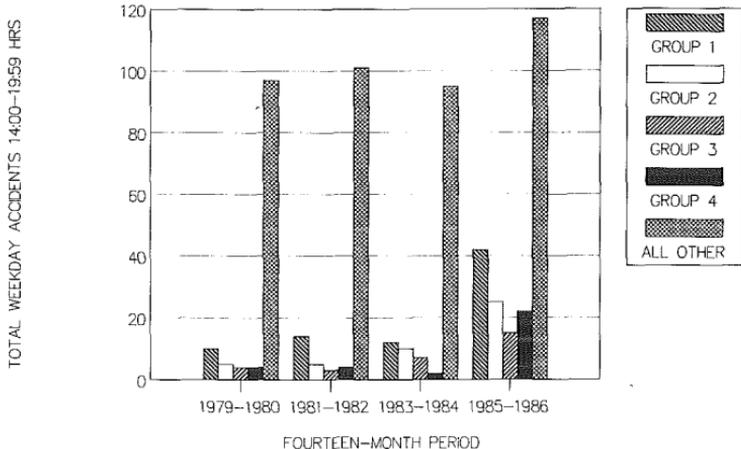
To help determine any causal factors involved in the shifts of accident locations noted, four combinations of time-of-day and locations were analyzed that account for almost all of the increase in total weekday accidents on eastbound SR-91 between 14:00 and 19:59 hr for the 14 months July 1985 through August 1986 compared to previous 14-month periods. The four concentration groups are the following.

1. 14:15–15:29/all locations: postmiles 8 to 17 Los Angeles (9 miles or 4.5 km).
2. 16:00–17:44/postmiles 14.5 to 15, 15.5 to 16, and 16.5 to 17 (1.5 miles or 2.4 km).
3. 17:00–19:14/postmiles 10 to 11.5 (1.5 miles or 2.4 km).
4. 17:45–19:14/postmiles 15.5 to 17 (1.5 miles or 2.4 km).

The four groups accounted for a 235% increase in accidents for the 14-month period July 1985–August 1986 over July 1983–August 1984 (Fig. 12). The increase from 95 to 117 accidents for all other time interval and location combinations (23%) from 1983–84 to 1985–86 is within the range expected from traffic volume increases. Consequently, the four groups of accident concentrations can be a key to understanding changes in the traffic safety situation on SR-91. (There is no relationship between the time-location dimensions and whether or not an accident involves injuries.)

The percentage of total accidents in each 14-month period accounted for by each of the four concentration groups is graphed in Fig. 13. There are statistically significant differences in the relative concentrations of accidents in groups 2 and 3 between 1981–82 and 1983–84, indicating that factors contributing to these concentrations have been on the rise since 1981–82. However, the increases in the relative concentrations of accidents in groups 1 and 4 are solely between 1983–84 and 1985–86.

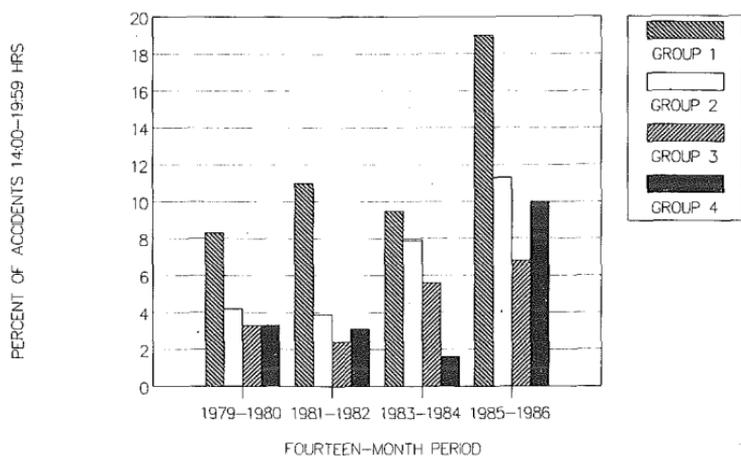
Comparisons were made of the characteristics of the accidents among the groups for the 1985–86 period. Accidents related to the HOV lane would be expected to be located in the left portions of the roadway, but there were no significant differences among the groups on the basis of location of the primary collision. Alternatively, it was found that group 4 accidents are more likely than accidents of other groups to be rear-end collisions ( $P = 0.04$ ),



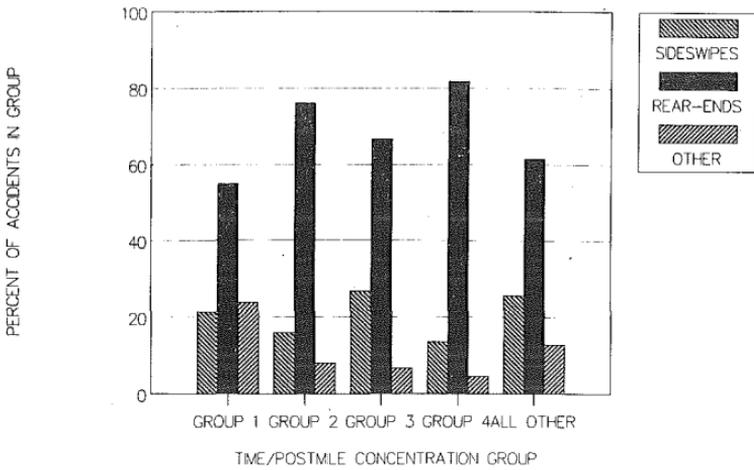
**FIG. 12. SR-91: Total Eastbound Accidents, 14:00 to 19:59 hr (Postmiles 8 to 17) by 14-Month Period by Time/Postmile Concentration Groups**

as shown in Fig. 14, indicating congestion-related causes. However, the greatest differences among the groups are in terms of the movements of the first two vehicles prior to collision, as shown in Fig. 15: a higher proportion of the vehicles involved in group 2 and group 4 accidents were stopping or slowing, while a higher proportion of vehicles involved in group 3 accidents were changing lanes. No other accident characteristics were significantly different among the groups.

Indications of causality for the increased concentrations of accidents in each of the time-location groups were uncovered by investigating the changes in congestion patterns over time (Figs. 6 and 7) and by analyzing the changes over time in the characteristics of the accidents in each group. For group 1 accidents, three characteristics were found to vary systematically over time,



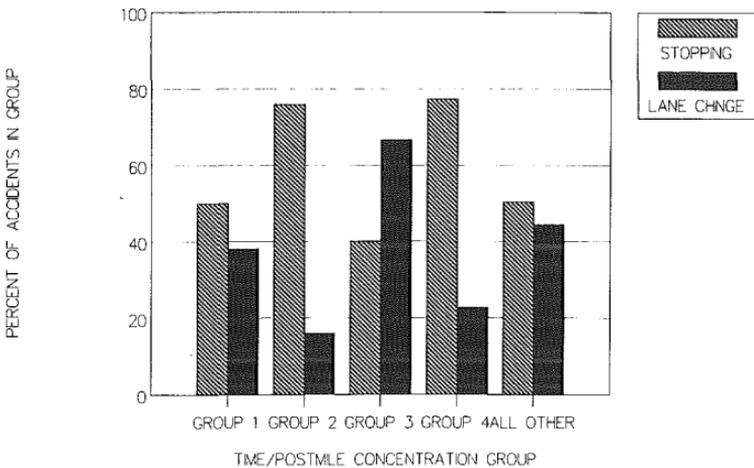
**FIG. 13. SR-91: Percentage of All Weekday Accidents, 14:00 to 19:59 hr (Postmiles 8 to 17) by 14-Month Period by Time/Postmile Concentration Groups**



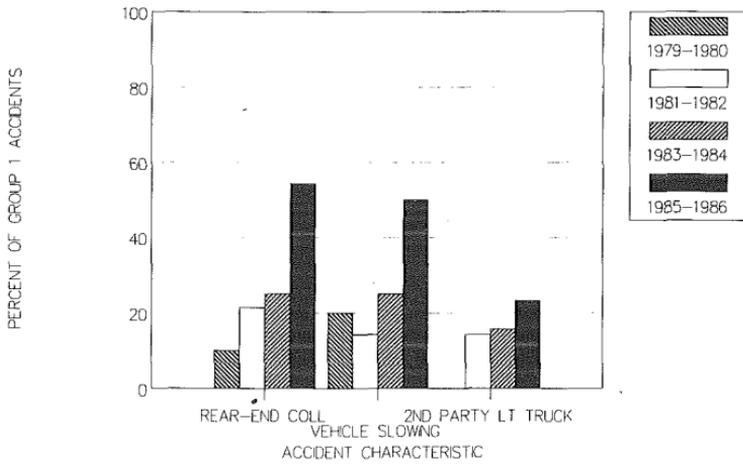
**FIG. 14. SR-91: Collision Types by Time/Postmile Concentration Groups (July 1985 to August 1986)**

as shown in Fig. 16. The percentage of all collisions that are rear-end collisions increased significantly over time. Second, the percentage of all collisions that involved at least one of the first two vehicles slowing or stopping also increased significantly, as did the percentage of collisions involving a light truck (pickup or van) as the second vehicle. The accelerating increase over time in these three characteristics indicates increasing congestion levels between 14:15 and 15:29 hr as a cause of this increased accident concentration, although this is not apparent from comparisons of the congestion diagrams of Figs. 6 and 7. There is no indication, based on the location of these accidents, that the HOV lane is a primary contributor to this effect.

For the second concentration group (16:00–17:44 hr, postmiles 14.5–15, 15.5–16, and 16.5–17), five characteristics were found to be systematically



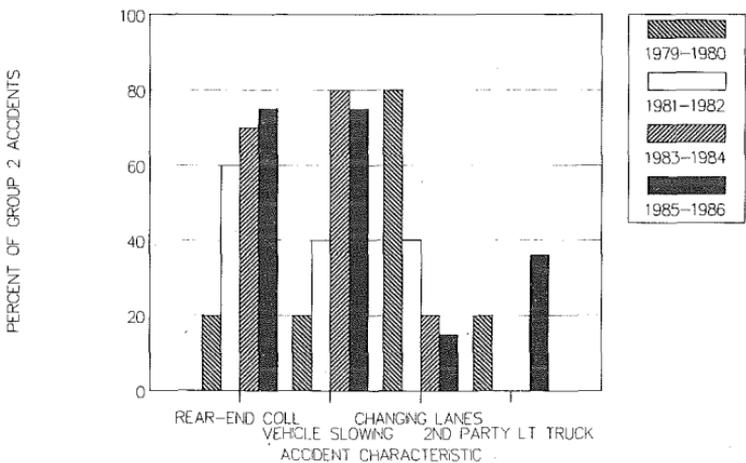
**FIG. 15. SR-91: Movements Preceding Collision by Time/Postmile Concentration Groups (July 1985 to August 1986)**



**FIG. 16. SR-91: Accident Characteristics for Time/Postmile Concentration Group 1 (14:15 to 15:29 hr, Postmiles 8 to 17) by 14-Month Period**

changing over time, as shown in Fig. 17: percentage of rear-end collisions, percentage of collisions with a primary vehicle slowing or stopping, percentage of collisions with a vehicle changing lanes, and percentage of collisions with a light truck as the second party. With the exception of the last characteristic, there has been little change in these characteristics between 1983-84 and the HOV period 1985-86. Increasing congestion is indicated, as in the case of group 1 accidents.

For the third concentration group, only one characteristic varies systematically over time, and that is the percentage of collisions that involves at least one of the first two primary vehicles involved in a lane-changing maneuver: such accidents are relatively more common in the HOV period. This increase in accident concentration is largely due to increased weaving, pos-



**FIG. 17. SR-91: Accident Characteristics for Time/Postmile Concentration Group 2 (16:00 to 17:44 hr, Postmiles 14.5, 15.5, and 16.5) by 14-Month Period**

sibly caused by the lane drops associated with two off-ramps to major arterials. This increased concentration of accidents is apparently unrelated to the HOV lane.

As shown in Fig. 7, the postmile range 15.5 to 17 is subject to heavy congestion for much of the time between 15:45 and 19:14 hr, and such congestion was not generally present in the pre-project period (Fig. 6).

Concentration group 4 accidents in the 1985-86 period are congestion-related, with about 82% of them being rear-ends and 77% involving slowing or stopping maneuvers. It can be concluded that concentration group 4 accidents are due to traffic bottlenecks at the end of the HOV lane and downstream of the project.

## **SUMMARY AND CONCLUSIONS**

It is concluded that the HOV lane operation on SR-91 has had no adverse effect on safety conditions on that route. There is no overall change in the exposure to accidents, but there is a significant migration of accident locations. This is due to the relief of congestion in areas of lane drops in the project area, and the creation of more severe traffic bottlenecks downstream of the project. Patterns of traffic congestion on SR-91 have changed due to the additional roadway capacity provided by the HOV lane. The worst traffic congestion eastbound during the afternoon peak period has moved downstream to the end of the HOV lane and beyond the project. Accident concentrations have been similarly relocated; this migration of accidents is consistent with effects found in case studies of added mixed-flow lanes (Levine et al. 1988). All of the changes in the patterns of reported accidents on SR-91 can be attributed to changes in the location and timing of traffic congestion.

While the HOV lane on SR-91 has not degraded safety, it has also not alleviated conditions. Due to traffic bottlenecks at the end of the HOV lane and downstream of the project, there has been a migration of accidents, but no reduction in their apparent rate, based on comparisons to control groups.

## **ACKNOWLEDGMENTS**

The research reported herein was supported in part by grants from the AAA Foundation for Traffic Safety, the Orange County Transportation Commission, the California Department of Transportation, the Los Angeles County Transportation Commission, and the Southern California Association of Governments. Their support is gratefully acknowledged. The views expressed in this report are those of the writers and do not necessarily reflect the views of the sponsoring agencies.

## **APPENDIX. REFERENCES**

- "1985 California state highway log, district 7." (1986). California Dept. of Transp., Sacramento, Calif.
- Levine, D. W., Golob, T. F., and Recker, W. W. (1988). "Accident migration associated with lane-addition projects on urban freeways." *Traffic Engrg. and Control*, 29(12), 624-629.
- Manual of traffic accident surveillance and analysis system.* (1978). California Dept. of Transp., Office of Traffic Engrg., Sacramento, Calif.
- "Route 91 Artesia freeway: Operational report based on 18 months of commuter lane use." (1986). California Dept. of Transp., District 7, Dec. 8, Los Angeles, Calif.