Operational and Safety Experience with Freeway HOV Facilities in California

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Highlights of a technical investigation conducted to evaluate various designs of HOV lanes currently in use on freeways in California are presented. Operational efficiency and safety were the measures of effectiveness examined. None of the currently operating facilities was found to contain severe operational or accident problems. All three of the broad design types identified in the state and studied were found to be operating relatively smoothly. Although statistically reliable conclusions could not be made, it did appear that certain designs were better than others. The physically separated facility appears to be the safest type because interaction of HOV lane vehicles and mixed flow vehicles is virtually eliminated. Of the facilities that were not physically separated (which were the primary focus of the study), the wide buffer (full lane width) facility was clearly superior to the contiguous types. The study was unable to differentiate between the various contiguous designs, which were categorized by whether they restrict intermediate access or not.

In this paper, the major findings of a 14-month study aimed at investigating the operational and safety experience of HOV facilities on freeways in California are abstracted. The full report is available from the Institute of Transportation Studies (University of California, Berkeley) on request (*1*). The objectives of the study, which was sponsored by the California Department of Transportation (Caltrans), were to evaluate HOV lane effectiveness in terms of both safety and operational efficiency and to recommend the most appropriate design for specific circumstances.

Although similar facilities nationwide were surveyed in the study, only the pertinent results from an analysis of California facilities are presented in this study. In 1986, there were about 73 directional miles of freeway HOV facilities of various designs operating in California, all in the Los Angeles and San Francisco areas. However, most of these facilities have only been in operation for a short time. It was evident that the available operational data and accident experience were not adequate to provide reliable conclusions on the relative benefits of the various designs under specific operating conditions. Certain conclusions have been drawn, however, on the basis of data obtained in the study, together with the experience and opinions of the project investigators. It is believed that the information presented will be of interest.

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BACKGROUND

In recent years, growth of suburbanization and commuter travel in metropolitan areas has continued to increase at a steady rate, while both the economic and environmental costs of providing highway facilities have been increasing at an even faster rate. There is little chance that enough freeway capacity can be constructed to satisfy traffic demands. Recent emphasis has therefore been on making the existing transportation corridors more efficient in terms of passenger-carrying capacity.

One of the strategies used is high-occupancy vehicle lanes (HOVL). This general term covers transitways, busways, carpool lanes, and so on. Essentially, an HOVL is a facility designated for use by a specific class of vehicles, giving them a time advantage over mixed-flow traffic. Caltrans has been engaged in developing HOV facilities since the early 1970s, and the state is considered a U.S. leader in their use. There are 73 directional miles of freeway HOV lanes in California alone as of 1986, compared to 190 directional miles in seven other states.

Currently, many different designs are being used for freeway main-line HOV lanes. In particular, these designs differ from one another in regard to their separation from mixed flow lanes. The HOVL may be broadly categorized into three design types (Figures 1–4):

- physically separated facilities (8 mi total),
- buffer-separated facilities (13-ft-wide buffers; 11 mi total); and
- essentially contiguous facilities with various types of separation, striping, and access control.

There are 54 mi of this last type of design, with separations varying from a normal lane line to a 2-ft-wide buffer. Striping ranges from broken white stripe through broad (8-in.-wide) solid white stripes to double yellow lines (barrier striping). The double yellow lines are intended to restrict access between the HOV and mixed flow lanes to specified areas only. Table 1 presents a summary of existing freeway HOV facilities in California, including their design characteristics.

As more jurisdictions adopted the HOV concept, the state realized that an evaluation of the design characteristics of existing facilities was necessary. The state also decided that it might be desirable to determine the most effective designs in terms of both operational efficiency and safety, thereby resolving some of the design issues currently being debated within the state. The primary concern was the design of facilities that

FIGURE 1 Physically separated HOVL. Barrier is visible at left center, with westbound HOVL immediately to the right and the eastbound HOVL at far right.

FIGURE 2 HOVL separated from regular lanes by a wide, traversable buffer (center).

FIGURE 3 HOVL separated by double yellow stripe indicating restricted access (stripe visible starting at bottom left).

are not physically separated. The major design issues addressed are as follows:

- Where an HOV lane cannot be physically separated, should it be separated with a traversable buffer or should it be contiguous with the mixed flow lanes?
- Should the HOV facility be operative full time or part time?

FIGURE 4 HOVL with unrestricted access. In this case, the HOVL is marked by signage.

- If the facility is operative part time, how should the lane be used during the nonoperative hours?
- How should the facility start and end?
- How should any intermediate access be provided?
- What provisions for enforcement should be included in the design?

PROCEDURE AND ACCIDENT ANALYSIS

The main portion of the general investigative process was an attempt to relate operational and accident data. The intent was to determine measures of effectiveness of each major design type and then to compare them under identical operating conditions. The comparison was carried out via a matrix. The operating characteristics considered were speed differentials and HOV lane utilization. It was hypothesized that entries in each cell of the matrix belonged to one design, and these entries were treated as a sampling from that design. The cells with identical operating characteristics were then compared to determine whether differences in accident rates were statistically significant.

Two types of accident data were used in the analysis. First, inferences were made about HOV lanes by using accident data from entire freeways. Second, the relative safety levels of different HOV lanes were determined more directly by using data from HOV lane-related accidents.

Peak Freeway Accident Rates

Accident data were obtained and rates calculated for six of the eight HOV facilities currently operating on freeways in California (Table 1). The remaining two facilities were only put into operation very recently. Of the six, Ala 80 (the approach to the Bay Bridge) was considered too unique to be fairly compared with the others. Thus five facilities (LA 10, LA 91, Ora 55, Mrn 101, and SF 280) were put to critical analysis.

The source of the accident data was the state's Traffic Accident Surveillance and Analysis System (TASAS). Accident reporting levels in this system can vary among different areas. Although it is generally accepted that less than half of

TABLE 1 FREEWAY HOV FACILITIES IN CALIFORNIA AS OF 1986

FACILITY(1)	INBOUND MILES	INBOUND OPER HRS	OUTBOUND MILES	OUTBOUND OPER HRS	HOVL/dir	Mix Ln/dir	Type (2)	Sep. (3)	Spd Dif(4)	HOVL Vol (5)	HOV Def	Acc/mvm	% Viol(6)	REMARKS
1a LA I-10 BUSWAY	4.0 WB	24 HR	4.0 EB	24 HR	1	4	C	P	varies from section to sect.	b	3+		highly variable : 5 - 30 %	facility has 3 different designs
1b LA I-10	6.1 WB	24 HR	5.3 EB	24 HR	1	4	C	B		c	3+	0.90		
1c LA I-10	0.7 WB	24 HR	2.5 EB	24 HR	1	4	C	L		c	3+	0.90		
2 LA RTE 91	no facility		8.6 EB	2-7p	1	4	C	L		c	2+	1.05		
3 MRN US 101	3.7 SB	6-9a	3.7 NB	4-7p	1	3	C	L		a	3+	1.06		hrs changed in 1987 to 6:30-8:30am 4:30-7:00pm
4 ORA RTE 55	10.9 SB	24 HR	11.9 NB	24 HR	1	3	C	L		c	2+	1.27		
5 SF I-280	1.9 SB	24 HR	no facility		1	3	C	L		a	3+	0.5		
6 ALA I-80 SFOBB	0.6 WB	6-9a	no facility		3	16	C	L		b	3+			
	WB	3-9p	no facility		3	16	C	L		a	3+	7.72		
7 MRN US 101	no facility		3.0 NB	4-7p	1	3	C	L		–	3+	–		new facility north of San Rafael hrs changed in 1987 to 4:30-7:00pm
8 SCL US 101	2.8 NB	5-9a	3.3 SB	5-9a	1	3	C	L		b	2+	.90		inbound considered towards S.F.
	NB	3-7p	SB	3-7p	1	3	C	L		c	2+	.90		
TOTAL	30.7		42.3											

1. Information is for 1986 conditions
2. Types of HOVL: R=Reversible; C=Concurrent; F=Contra-Flow
3. The separation is between the HOV lanes and mixed flow lanes. forms: P=Physical; B=Buffer; L=Normal Lane Line
4. This is the estimated difference in speeds between HOV and mixed flow vehicles during the peak hour. Categories: 1 = 0-10; 2 = 10-20; 3 = >20 (mph).
5. HOVL Utilization -- 3 groups:a = <500; b = 500-1000; c = >1000 veh.
6. These are approximations and are the % of all vehicles in HOVL that are violators

TABLE 2 MATRIX OF DESIGN TYPES BY OPERATING CONDITIONS

SPEED DIFFERENTIAL	I. < 10 MPH						II. 10-20 MPH						III. > 20 MPH					
HOVL UTILIZATION (PK HR)	LOW (<500)			HIGH (>1000)			LOW (<500)			HIGH (>1000)			LOW (<500)			HIGH (>1000)		
S E P A R A T I O N	SEC	ACC !	INJ !	SEC	ACC	INJ	SEC	ACC	INJ	SEC	ACC	INJ	SEC	ACC	INJ	SEC	ACC	INJ
A) CONTIGUOUS UNRESTRICTED ACCESS	101S-2 101N-1 280S-1 280S-2	1.23 2.50 0.66 1.38	0.50 0.06 0.19 0.57	10E-6 10W.4 55N-1 55S-1 55S-6 55N-6	2.32 0.93 3.19 0.36 1.00 1.14	0.91 0.55 1.67 0.18 0.29 0.29	101S-1 101N-2 101N-3	0.52 5.36 7.13	0.19 1.57 0.41				10E-1 10E-2	1.85 5.53	0.98 1.82			
	* AVG = 1.44 ** SD = 0.67			AVG = 1.49 SD = 0.96			AVG = 4.34 SD = 2.79						AVG = 3.69 SD = 1.84					
B) CONTIGUOUS RESTRICTED ACCESS				55S-2 55S-5 91E-1 91E-5	1.08 2.08 1.08 2.22	0.39 0.25 0.36 1.03				55N-3 55N-5 55S-4 91E-4	4.45 1.44 3.92 1.62	0.75 0.21 0.78 0.45				55N-2 55N-4 55S-3 91E-2 91E-3	8.18 3.48 3.3 2.97 2.3	2.37 1.14 0.27 1.15 0.56
				AVG = 1.62 SD = 0.54						AVG = 2.86 SD = 1.34						AVG = 4.05 SD = 2.11		
C) BUFFER				10E-5 10W-1	2.49 0.49	0.91 0.16				10E-4 10W-2 10W-3	1.42 1.45 1.75	0.52 0.51 0.20				10E-3	1.37	0.36
				AVG = 1.49 SD = 1.00						AVG = 1.54 SD = 0.15						AVG = 1.37 SD = 0		

* AVG = AVERAGE OF TOTAL PEAK PERIOD ACCIDENT RATES
** SD = STANDARD DEVIATION OF SAME
! ACC = PEAK PERIOD TOTAL ACCIDENT RATE
! INJ = PEAK PERIOD INJURY RATE

accidents involving property damage only (PDO) are reported, as many as 90 percent of accidents involving injury are reported. Thus an analysis based on the rate of injury accidents would appear to provide a more accurate perspective of safety conditions than one based on PDO. However, to obtain a reasonable sample size and uniformity in coding, rates were calculated for total accidents (PDOs, injuries, and fatalities) and then separate rates were calculated for injuries. The injury rates were used in cross checking abnormalities or extremities that might become apparent in rates for various facilities.

The physically separated HOV facility was excluded from detailed analysis. The only existing case is a 4-mi section of the San Bernardino Freeway "Busway." This section, which operates 24 hr/day with a 4,000 ADT rate (two-way), had just five recorded accidents in a 4-year period (1983–1986), including one fatal accident.

Each HOV facility was divided into study sections primarily on the basis of differences in design and secondarily on the basis of estimated differences in operating conditions. All the study sections were then grouped by various peak period operating conditions and typical designs. Table 2 is a matrix of the groupings. Three basic designs were used:

- full buffer,
- contiguous (no separation) with unrestricted access and without differentiation as to type of line separation, and

• contiguous with sections of barrier stripe buffer.

The operating conditions were in terms of speed differential and HOVL use. There are 18 possible combinations, or "cells." Unfortunately, there were many cells with no examples, and some with just one or two.

The primary points indicated by the matrix are that when there is no significant speed differential (less than 10 mph), the peak period accident rates were about 1.5 per mvm, regardless of design type. When speed differentials increase, the contiguous design accident rates went up, but the buffer design accident rates stayed the same. Two conclusions may be drawn. The first is that when speed differential is low or nonexistent, the HOV lane design characteristics do not really matter. The second is that the buffer-separated design is likely to be superior to other types, even under varied operating conditions. Consideration of this latter conclusion, however, should include the fact that the buffer-separated facility is used on only one freeway. It is also worth noting that no left shoulder is available in the contiguous designs studied, and thus the total space for evasive action in case of sudden moves is less than on the buffer design. A section of contiguous design with a full left shoulder is currently in operation but has not been active long enough for evaluation.

Figure 5 is a plot of individual study sections against ADT and peak period accident rates. The plot indicates no correlation between the variables: increasing ADT appears to have no impact on peak period accident rates. However, the results generally reflect the same conditions indicated by the matrix. The buffer design sections had low rates and variability in comparison to the other design types. The total peak period

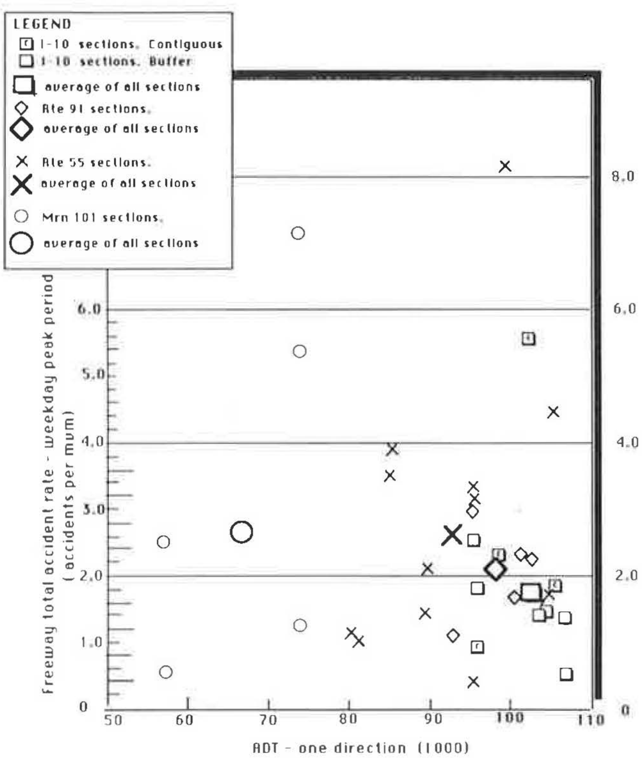

FIGURE 5 Summary of recorded weekday peak period total accident rates for various study sections.

accident rate for all I-10 sections, as indicated in the figure, was 1.77 per mvm. If the contiguous sections were not included, then the rate for only the buffer sections would be 1.58 per mvm.

Figure 6 is a plot for weekday peak period injury accidents. The rates are naturally much lower, but the same general pattern is indicated. The injury rate for Ora 55 is 0.63 per mvm. The injury rate for the buffer sections of I-10 alone is 0.52 per mvm. The rate given in the figure for all of I-10 is 0.69 per mvm.

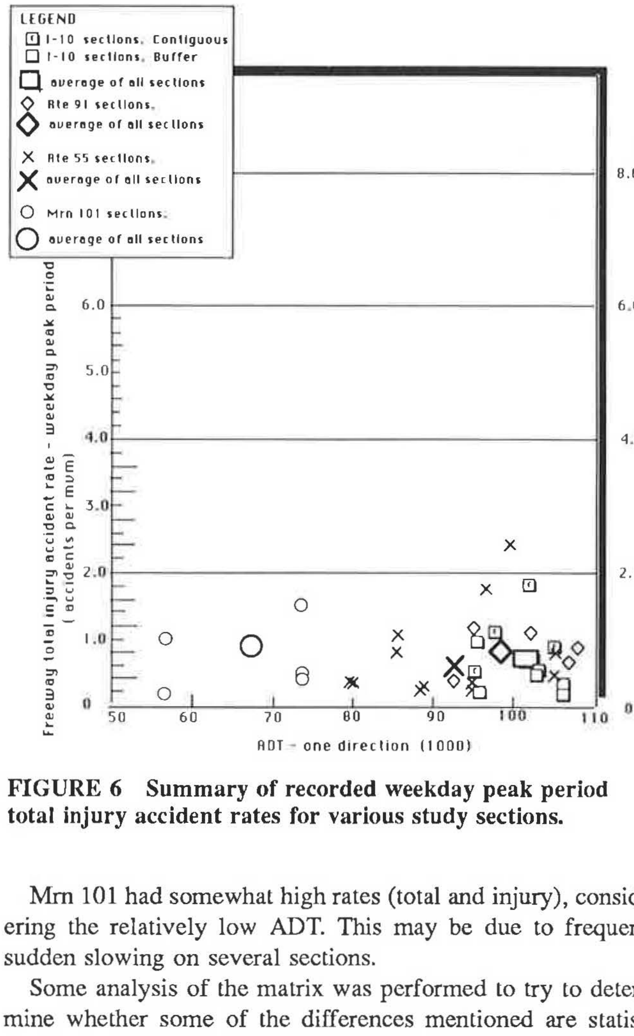

FIGURE 6 Summary of recorded weekday peak period total injury accident rates for various study sections.

Mrn 101 had somewhat high rates (total and injury), considering the relatively low ADT. This may be due to frequent sudden slowing on several sections.

Some analysis of the matrix was performed to try to determine whether some of the differences mentioned are statistically significant. An analysis of variance was performed as an attempt to compare the mean rates computed for entries within each cell. Because the main concern is the type of design, the tests of significance conducted were directed at groups of cells that are comparable vertically instead of horizontally. Vertically comparable cells are two or more cells with exactly the same operating characteristics but different designs.

Five cells were determined to be comparable. For low speed differential (less than 10 mph) and high HOV lane utilization, all three design types have entries that are comparable. Also, for medium speed differential (10–20 mph) and high HOV lane utilization, the buffer and the restricted designs are comparable. At the 5-percent level, the differences in mean accident rates between various designs are not statistically significant for either total accident or injury rates.

Next, all cells for each type of design were lumped together, and the test was applied between various designs. Analysis of variance indicates that the differences in means between various designs were again not significant for either total accident rates or injury rates. These results are interesting for two reasons. First, on the basis of available data, one result confirms an earlier opinion, that contiguous HOV lanes were basically the same in safety and effectiveness irrespective of limitations placed or not placed on intermediate access. Second, the results (on the basis of available data) could not indicate conclusively that a wide buffer–separated facility is superior to the contiguous types.

Off-Peak Period Freeway Accident Rates

One of the design issues considered in this study is how the facility should be used during off-peak periods. There is considerable pressure to use the lanes during off-peaks for mixed flow traffic. For barrier- or buffer-separated designs, this type of use would be difficult operationally, although it is easy for contiguous designs. In both cases, signing is even more complicated.

At locations where HOV facilities operate 24 hr/day, there is usually no significant speed differential and no significant congestion in any of the lanes during off-peak periods. However, from a safety viewpoint there is still a question about what type of operation will provide the best level of safety. Caltrans has already gathered a large amount of data indicating that, for a given ADT, the greater the number of lanes (and thus the lower the densities), the lower the accident rate.

In this study, the related data are limited in this regard. Figure 7 is a plot of off-peak accident rates related to 24-hr ADT for the various study sites. Mrn 101, LA 91, and LA 10 all have average accident rates of roughly 0.75 per mvm. During off-peak periods, each of these freeways has four mixed lanes and, in the case of LA 10, one HOVL (with approximately 4,000 ADT). ADT per mixed lane varies from about 17,000 (Mrn 101) to 24,000 (LA 91 and LA 10).

Ora 55 has an average off-peak accident rate of slightly over 1.0 per mvm. This section has three mixed lanes plus an HOVL (with 10,000 ADT). The mixed lanes averaged about 27,000 ADT per lane. If the HOVL were opened to mixed traffic during off-peak periods, the average would be about 23,000 per lane, with a likelihood of reduced accident rates.

HOV Lane–Related Accidents

For each of the study locations, all accident reports were examined for varying periods, and any accident that appeared to involve HOVL operation or design was read and summarized. In a few cases, certain individual accidents that were not considered to have any bearing on HOV design or operation were not selected.

The predominant type of accident was multivehicle and involved or was caused by a vehicle entering or exiting the HOVL. The movement could be voluntary, involuntary, legal, or illegal. It is possible that other accidents noted as "rearenders" in the HOVL or lane 1 (the lane next to the HOVL) could have actually been caused by vehicles entering or exiting the HOVL, causing a queue that ultimately caused the rearender.

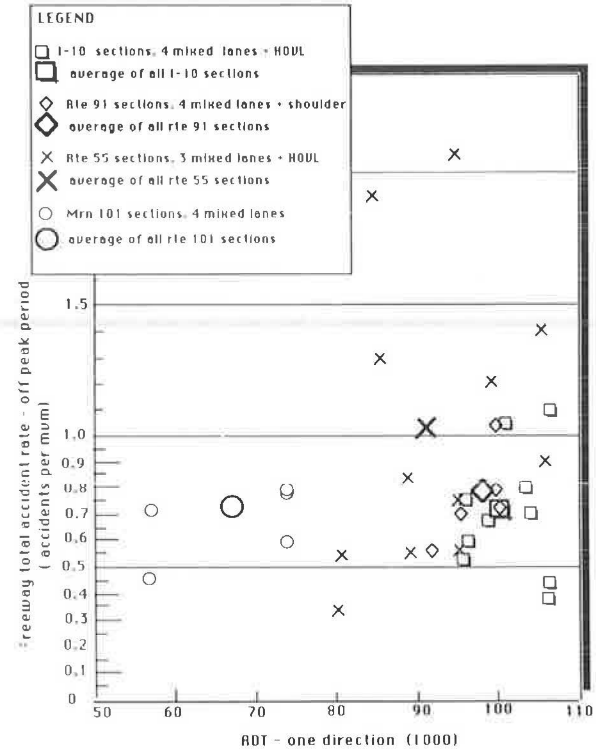

FIGURE 7 Summary of recorded off-peak total accident rates for various study sections.

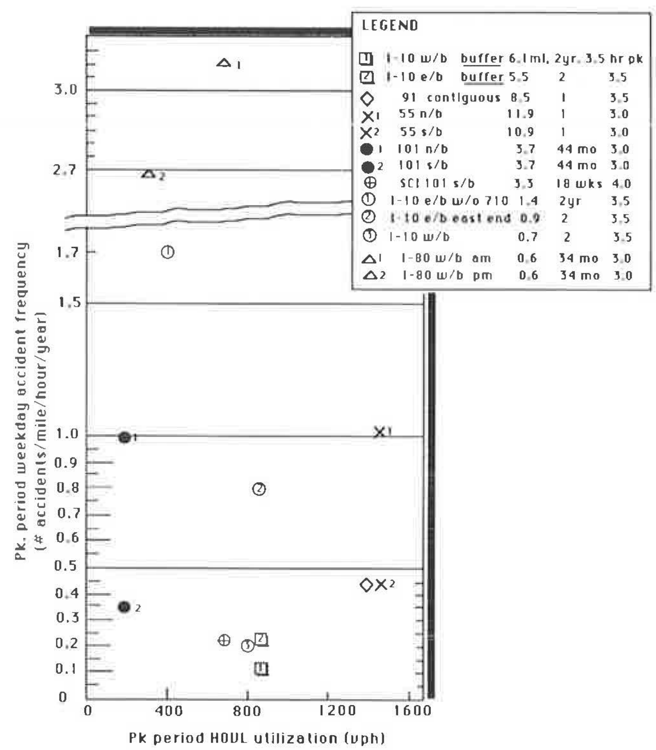

FIGURE 8 Summary of recorded HOVL-related accidents involving vehicles entering or exiting the HOVL.

Figure 8 plots the peak period accident frequency involving vehicles entering or exiting the HOVL at different locations against the peak period HOVL utilization. One rather surprising result is that the utilization of the HOVL does not appear to have a direct relationship to accident frequency. It had been hypothesized that increased usage of the lane would cause more exposure to accidents. Apparently, when the lane is crowded, drivers are less likely to make a sudden move into it, whereas if the lane is moderately used, sudden maneuvers are more likely to be attempted.

A significant point is that, again, the full buffer design has lower accident frequencies than the contiguous designs do. The peak period average of the I-10 buffer sections is about 0.17 accidents/mi/hr/yr, compared to about 0.75 for contiguous sections (excluding I-80, a special case). In aggregate terms, this means that in a 5-mi buffer section (one direction) for a 3-hr peak (typical), about 2.5 accidents per year are likely to occur. For a similar contiguous design there are likely to be about 11 accidents per year—a 440-percent increase. In both instances, most of the accidents would be of the property damage–only (PDO) type.

SUMMARY

Results from the investigation of California facilities for various issues are described next. As noted, experience and accident sample size was very limited, and the remarks made should be considered in this context.

Separation

The physically separated design virtually eliminates interaction of HOVL and mixed flow vehicles except at designated access points. This design generally provides optimum operation, even if it does not provide maximum HOVL utilization. Where it is feasible, this is the preferable design

The accident analysis indicated that the 13-ft buffer section on I-10 had significantly fewer accidents involving entry and exit maneuvers than sections without buffers. The data indicate, for example, that for a 3-hr peak period a 5-mi one-way section with a 13-ft buffer could expect 2.5 multivehicle accidents per year involving vehicles entering or exiting the facility. Sections without buffers could expect, on average, about 11 accidents per year. In both cases, most of the accidents would be PDO accidents.

The accident analysis could not differentiate between the various nonbuffer designs. A nonbuffer design with a full left shoulder may have different accident characteristics. However, the one example—SCl 101 (Santa Clara County, south of San Francisco)—has not been in operation long enough to allow any conclusions.

On Ora 55 and LA 91 the separation includes barrier striping (a marking for no crossing) with yellow stripes 1 ft apart on Ora 55 and 2 ft apart on LA 91. On both routes, intermediate access between the start and end points of the HOV lane was desired at points where the highway passed crossing freeways and relatively high-volume ramps. In terms of location of entry or exit to the HOVL, by far the highest-rate (per mile) locations used were the designated entry and exit locations. This is because these locations were carefully selected in terms of demand for access (and were revised for Ora 55) and presumably because most people try to obey the law.

However, significant numbers of drivers cross the barrier stripe, and because the length of the nondesignated sections is much greater than the length of the designated intermediate access locations, probably as many vehicles enter or exit across the barrier stripe as at the designated locations. The impacts of this, as noted, cannot be quantified. However, it is the opinion of the project investigators that these crossings are beneficial, given the assumption that all the crossings are going to be made somewhere. The belief is that these nondesignated crossings reduce the concentration and give drivers more opportunity to select gaps because the geometry at designated access locations is not different from that at the nondesignated locations.

HOVL Utilization and Speeds

Peak hour usage of the various facilities varied from about 200–300 vehicles to 1,600–1,700 vehicles. On a single-lane HOV facility of substantial length (no passing), some slowing can occur at flow rates of 1,300 vehicles per hour (vph). Indications are that capacity is probably about 1,800 passenger automobiles per hour. There were instances of stoppages at flow rates of 1,500 to 1,700 vph, probably caused by merging or diverging movements downstream of the stoppage.

No clear trends for HOV speed were detected. In some cases, speeds remained high (>50 mph), even with slow speeds in the mixed flow lanes. In other cases, with apparently the same circumstances, HOV speed was less.

When there is no significant speed differential between HOV and mixed flow vehicles (i.e., differential of <10 mph), there are no apparent operational problems related to the HOV facility. A moderate speed differential (10–20 mph) appears to cause as many operational problems as a high differential (>20 mph). The high differential usually indicates severe congestion in the mixed flow lanes, whereas the moderate differential usually indicates that the mixed flow lanes are operating at very high flows and are subject to frequent shock waves and sudden queues. This may result in more frequent and sudden changes involving the HOVL.

The utilization of an HOVL does not appear to have a direct relationship to the rate of HOVL-related accidents involving vehicles suddenly entering or exiting the lane. This somewhat surprising condition may result from the discouraging effect that a crowded HOVL has on these movements, whereas more of these maneuvers may be attempted on a moderately used facility.

Part-Time Use

There are indications that for contiguous HOVL designs, opening HOV lanes to mixed flow traffic during off-peak periods (including weekends) might reduce accident rates through the lowering of average lane density. Off-peak use of the HOVL as a shoulder may also be considered. However, in 1986, the LA 91 part-time shoulder facility did have several accidents during shoulder use in which drivers said that they thought the shoulder was a lane. This is still an unresolved issue, and appropriate signing and striping needs to be determined before part-time use can be considered a viable strategy.

Start and End Treatments

It was not possible to relate the relatively small number of HOVL-related accidents to these specific design issues. In general, however, whenever the lane ended in a free-flow area, there were rarely any definable safety problems, whether the end of the HOVL was a merge or continuous. The eastbound merge at the end of the LA 10 facility did have a number of merging accidents and rear end accidents that were caused by merges. The merge endings on LA 91 and Ora 55 had fewer problems. The Mrn 101 facility ended as a mixed flow lane. The northbound direction, which had several accidents near the end, was a special case because a mixed flow queue often started right at the end of the HOVL. There were not enough data from which to draw any conclusions about capacity impacts of the end treatments.

The only facility that did not start as a new lane was on the I-80 approach to the San Francisco–Oakland Bay Bridge. Although the data did not indicate that this was a safety problem, visual observation indicated that many vehicles went past the starting point. This often disrupted HOVL operation when the vehicles exited, especially when there was a high speed differential, and reduced capacity of the HOVL.

Enforcement

None of the facilities except LA 91 had specific enforcement areas set up. Some had been constructed for Ora 55, but they were considered inadequate by the California Highway Patrol and are not used. In most cases, however, because of a lack of enforcement areas and left shoulders, the normal procedure is to escort a violator to the right shoulder.

Experience in other states indicated that violations in physically separated facilities are very low (less than 10 percent). In California, occupancy violations varied greatly at the different facilities (from 5 to 30 percent). It is difficult to relate this variance to design because it appears that violations are just as much a function of public acceptance as of enforcement effort. The violation percentage (as opposed to the actual number) is also affected by the utilization of the HOVL. For instance, if there are 1,000 legal carpools, the violation percentage will almost always be less than at a location where there are 400 legal carpools.

General

It is interesting (although not directly related to the study objectives) that at all locations where a.m. and p.m. data are available, freeway accident rates and HOVL-related accident frequencies are always less in the morning than in the afternoon. An explanation for this is that the early a.m. traffic stream is more homogeneous, consisting primarily of commuters, and presumably the drivers are more rested and alert. From this it might be assumed that installation of an HOV facility that is operative during the morning peak, even of an undesirable design, will cause fewer problems than an installation that operates in the afternoon.

ACKNOWLEDGMENTS

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