CONCLUSIONS

The analysis of FARS and New Mexico data leads to several conclusions about the nature of overturning crashes. They are seen to be a substantial component of the total accident picture, and their typical classification as apparently minor noncollision accidents seriously understates their importance. In those states where they are responsible for more than 20 percent of the annual highway fatalities, they clearly warrant more attention.

A principal finding of the study is that significant differences exist between the characteristics of overturning crashes and those that involve fixed objects. The specific differences between these two classes are as follows: (a) overturning crashes have higher severity, (b) they are more likely to occur on curves or grades, and (c) they are more closely related to adverse weather conditions. Other characteristics that distinguish overturning crashes from fixed-object crashes are their rural locations (also reflected by the dark, unlighted condition and maximum speed), the higher involvement of unfamiliar drivers, vehicles other than passenger cars, road defects, and the lower rate of alcohol involvement. The significant differences in roadway, environment, vehicle, and driver between these two crash classifications is a strong indication that remedial programs directed toward fixed-object crashes and severity reduction will not necessarily have an effect on overturning crashes.

The analyses suggest several things that are of importance to the transportation engineer. The existence of adverse geometrics at crash sites has been shown to be more common at fixed-object crash sites (2), but it appears to be even more prevalent at overturning crash sites. The excessive involvement by unfamiliar drivers suggests the need for improved positive guidance through the application of better delineation and improved warning. The transportation engineer can do little to control the registration and use of vehicles; however, the significantly higher overturning crash experience associated with certain vehicle types suggests that existing design standards for roadways and roadsides may not adequately address the special characteristics of these vehicles. And finally, the unsuccessful maneuvers that some drivers make, which result in overcorrection, may be susceptible to correction through improved shoulder design and maintenance.

The analyses reported in this paper are based primarily on accident record systems. Many crash-related factors that are of interest to the transportation engineer are not adequately or accurately reflected in the computerized record systems. It is therefore risky to draw far-reaching conclusions simply from an analysis of these systems. To counteract this problem, a program is currently under way in New Mexico to collect detailed information concerning the roadway and roadside characteristics at a sample of the overturning crash sites. Results from this study are anticipated in the spring of 1980.

ACKNOWLEDGMENT

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REFERENCES

1. Rollover Accidents. National Highway Traffic Safety Administration, Washington, DC,HS-802-875, Dec. 1977.
2. P.H. Wright and L.S. Robertson. Priorities for Roadside Hazard Modification: A Study of 300 Fatal Roadside Object Crashes. Insurance Institute for Highway Safety, Washington, DC, March 1976.
3. C.P. Brinkman and K. Perchonok. Hazardous Effects of Highway Features and Roadside Objects. Public Roads, Vol. 43, No. 1, June 1979.
4. Motor Vehicle Facts and Figures. Motor Vehicle Manufacturers Assn. of the United States, Washington, DC, 1978.

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Operations and Design Guidelines for Facilities for High-Occupancy Vehicles

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Design guidelines intended to enhance the safety of high-occupancy vehicle (HOV) preferential-treatment projects are proposed. These guidelines reflect the principal findings of a nationwide research program sponsored by the Federal Highway Administration in 1977 that involved the examination of more than 22 HOV projects for safety issues. Virtually every type of HOV technique was investigated, including freeway and arterial separated facilities, concurrent-flow lanes and contraflow lanes, freeway toll-plaza lanes, freeway ramp treatments, and arterial bus-preemption strategies. Cause-and-effect relationships of accident patterns on these projects were investigated and general guidelines formulated. Based on this analysis, HOV treatment-specific recommendations are offered to assist transportation planners and designers in improving the operations and design of HOV facilities with respect to safety.

In the United States, the 1970s were characterized by a proliferation of high-occupancy vehicle (HOV) preferential-treatment projects. Contraflow HOV lanes on arterials and freeways, concurrent-flow arterial freeway lanes, ramp-metering bypasses, separate freeway transitways, toll-plaza priority lanes, downtown transit malls, and signal preemption have all been recently implemented with their own particular design and operational features. The variance in design and operational features even exists among individual applications of the same type of preferential treatment. Without nationally established guidelines, the local project manager has been left to develop project-specific design standards, traffic control devices, and operating strategies. As a result, an extensive experimental base has been established from which local innovations can be analyzed comparatively for safety and operational implications.

In 1977, the Federal Highway Administration (FHWA) initiated such a study to survey existing HOV projects and examine the relationship between project characteristics and accident patterns (1). The research focused on five major areas associated with HOV projects:

1. Examination of accident rates,
2. Analysis of causative factors that influence safety,

Table 1. HOV projects included in FHWA research.

			Treatment					
Project	Location	Type of Road	Separate Facility	Concurrent-Flow Lane	Contraflow Lane	Toll-Plaza Lane	Ramp Treatment	Bus Preemption
Shirley Highway	Washington, DC	Freeway	X					
San Bernardino Freeway	Los Angeles, CA	Freeway	X					
I-95	Miami, FL	Freeway		X				
Banfield Freeway	Portland, OR	Freeway		X				
Moanalua Freeway	Honolulu, HI	Freeway		X				
Santa Monica Freeway	Los Angeles, CA	Freeway		X				
US-101	San Francisco, CA	Freeway		X	X			
I-495	Hudson County, NJ	Freeway			X			
Long Island Expressway	New York, NY	Freeway			X			
San Francisco-Oakland Bay Bridge	CA	Freeway				X		
Santa Monica, Golden State, and Harbor Freeways	Los Angeles, CA	Freeway					X	
I-5	Seattle, WA	Freeway					X	
North Central Expressway	Dallas, TX	Freeway					X	
I-35W	Minneapolis, MN	Freeway					X	
Nicollet Mall	Minneapolis, MN	Arterial	X					
Washington central business district	Washington, DC	Arterial		X				
Elm-Commerce Streets	Dallas, TX	Arterial		X				
US-1-South Dixie Highway	Miami, FL	Arterial		X	X			
Kalanianaole Highway	Honolulu, HI	Arterial		X	X			
Marquette and Second Avenues	Minneapolis, MN	Arterial			X			
Ponce de Leon and Fernandez Juncos Avenues	San Juan, PR	Arterial			X			
NW 7th Avenue	Miami, FL	Arterial		X	X			X

Table 2. Facility accident rates during peak periods by HOV treatments.

Treatment	Peak Period	Number of Projects	Accident Rate (Accidents/MVM)		
			Average[a]	Highest	Lowest
Freeway related					
Separate facility	Morning and evening	3	1.5	2.2	1.1
Concurrent-flow lane	Morning and evening	4	6.7	8.4	4.2
Contraflow lane	Morning or evening	3	3.1	3.3	2.9
Toll-plaza lane	Morning	1	4.7		
Ramp-metering bypass	Morning or evening	1	17.3[b]		
Arterial related					
Concurrent-flow lane					
Median	Morning and evening	3	6.6	10.5	4.6
Curb	Morning and evening	1	6.5		
Contraflow lane					
Median	Morning and evening	3	8.6	12.4	1.3
Curb	Morning and evening	1	9.2		
Signal preemption	Morning and evening	1	4.1		

[a] This figure is calculated by dividing the sum of the accident rates by the number of projects.
[b] This rate refers to accidents per year for 21 ramps.

3. Identification of difficult maneuvers and potential safety problems,
4. Development of recommendations to improve safety, and
5. Review of the legal authority and legal liability issues faced by HOV projects.

In addition, a second research effort (2) was conducted to explore, among other things, the implications or current design and operating practices on effective enforcement of HOV restrictions and regulatory mechanisms.

The research team visited 22 HOV projects on 16 highway facilities. These projects encompass virtually every type of preferential-treatment strategy currently deployed in the United States on both freeways and uncontrolled-access highways. For each HOV project, data on safety, enforcement, operations, and geometrics were collected and analyzed. These data, when coupled with qualitative information, can be used to describe the current experience relating to contemporary design and operating practice on HOV facilities. The projects investigated are summarized in Table 1 (1,2).

ANALYSIS

Accident data from the different projects were compared by using the number of accidents and injuries per million vehicle miles (MVM) and million passenger miles (MPM) as the primary basis of comparison. Tables 2-4 present a summary of the facility and bus accident rates against various types of HOV priority treatments. The facility accident rates (Tables 2 and 3) describe the significance of the effect that various HOV strategies have on a facility's overall safety. The bus accident rates (Table 4) illustrate the relative safety of vehicles traveling in the HOV lane. Absolute comparisons between HOV priority treatments should not be made because local, site-specific factors can contribute significantly to a facility's safety performance. From Tables 2-4, the following general conclusions can be made.

The introduction of an HOV project on the facilities investigated has tended to increase the facility's accident rate. Based on vehicle miles of travel, six projects experienced a statistically significant increase of peak-period facility accident rates subsequent to the

Table 3. Change in accident rates during peak periods from before condition.

		Accident Rate Based on Vehicle Miles		Accident Rate Based on Person Miles	
		No. of Projects That Experienced Change[a]		No. of Projects That Experienced Change[a]	
Treatment	Peak Period	Increase	Decrease	Increase	Decrease
Freeway related					
Separate facility	Morning and evening	1[b]		1[b]	
Concurrent-flow lane	Morning and evening	2[c]	1[b]	2[c]	1[b]
Contraflow lane	Evening	1[b]		1[b]	
Toll plaza lane	Morning	1[b]		1[b]	
Ramp-metering bypass	Morning or evening	1[a]		1[c]	
Arterial related					
Concurrent-flow lane					
Median	Morning and evening	2[d]	1[b]	2[b]	1[b]
Contraflow lane					
Median	Morning and evening	2[d]	1[b]	1[c]	2[b]
Curb	Morning and evening	1[c]		1[c]	
Signal preemption	Morning and evening		1[c]		1[c]
Total significant change		6	1	5	1
Total nonsignificant change		5	3	5	4

[a] Some projects do not have comparative before data.
[b] Not significant.
[c] Level of significance is 95 percent or better.
[d] Evening is significant; morning is not.

Table 4. Bus accident rates during peak periods by HOV treatment.

			Accident Rate (Accidents/MVM)			Change from Before Condition[b]	
Treatment	Peak Period	Number of Projects	Average[a]	Highest	Lowest	Increase	Decrease
Freeway related							
Separate facility	Morning and evening	1	4.4			1[c]	0
Concurrent-flow lane	Morning and evening	3	7.5	18.6	0.0		
Contraflow lane	Morning or evening	3	5.1	8.6	1.7		
Toll-plaza lane	Morning	1	4.8			1[d]	
Ramp-metering bypass	Morning or evening	1	0.0				
Arterial related							
Concurrent-flow lane							
Median	Morning and evening	3	304.5	851.1	8.9		1[c]
Contraflow lane							
Median	Morning and evening	3	323.0	535.7	158.5	1[d]	
Curb	Morning and evening	1	56.4			1[d]	0
Signal preemption	Morning and evening	1	90.9				

[a] This figure is calculated by dividing the sum of the accident rates by the number of projects.
[b] Some projects do not have comparative before data.
[c] Not significant.
[d] Level of significance is 95 percent or better.

initiation of HOV operations, five projects experienced a statistically insignificant increase, one project experienced a statistically significant decrease, and three projects experienced a statistically insignificant decrease. When the accident rates are based on person miles, there was a small improvement in overall performance compared with the data presented above.

For each priority treatment, the average bus accident rates for freeway projects are slightly higher than the corresponding overall average freeway accident rates, in general. In general, the average bus accident rates for arterial street projects are many times higher than the average bus accident rates for freeway projects.

The statistical procedure applied to determine whether a significant change occurred in accident conditions between the various testing stages was standard hypothesis testing that used the normal approximation to the Poisson distribution as a basis. The Poisson constitutes a reasonable measurement of accident occurrence over time because the nature of accident occurrence is essentially random. Approximation of the Poisson distribution by the normal distribution is valid for sufficient sample sizes. The mean of the population is estimated by $\lambda = N/M$ and the standard deviation by $\sigma = \sqrt{\lambda}$ where N = number of accidents and M = millions of vehicle miles. Since a sample of M million vehicle miles was obtained, it is possible to estimate the mean and standard deviation of the sample by $\bar{x} = N/M$ and $\bar{s} = \sqrt{\bar{x}/M}$. Hypothesis testing can be performed by use of either the t-statistic or the z-statistic.

Since HOV projects are designed to increase passenger throughput and minimize passenger travel time, vehicle miles were also converted to passenger miles wherever sufficient data were available. This enables the planner to assess the safety issue in the context of project goals.

Statistical tests are valid only where a sufficient sample size exists. The sample size has to be large enough to ensure that the confidence interval is small enough for realistic analyses and to ensure that the normal distribution is an appropriate approximation to the Poisson. In general, the sample size has to be greater than $(9/\lambda)$.

From the statistical analyses, trends were observed and related to causative factors, geometric deficiencies, and traffic control features of the various subject projects. In this manner, the local innovations developed for projects prior to the establishment of HOV standards could be examined and evaluated from a safety point of view. The recommendations that have been formulated during the course of the research and summarized here are based on the safety and enforcement experience of actual HOV installations of various HOV treatment strategies. The experiences of other HOV projects should enable future HOV installations to operate in a more safe, enforceable, and efficient manner.

SEPARATE HOV FACILITIES ON FREEWAYS

Separate HOV facilities are roadways or lanes that are physically separated from the general freeway lanes. These facilities are designated for exclusive use by specified HOVs, and all other vehicles are prohibited.

The separation can be a barrier wall or a painted buffer area supplemented by cones or other non-fixed-object traffic control devices. Lanes separated by barrier walls are really independent highways that have no interaction with the general lanes, except at the terminal points. Partially separated lanes can have shared medians or shoulders that reduce right-of-way requirements. In this partially separated design, the restricted lanes are accessible (illegally) from the general lanes and this increases the likelihood of violations. The joint-use shoulder can be penetrated by both violators and HOVs.

Analysis

Two separate HOV facility projects were investigated: the Shirley Highway and the San Bernardino Freeway. Shirley Highway contains an 11.5-mile (18.5-km) HOV facility separated from general lanes by concrete median barrier walls. San Bernardino Freeway contains both completely separated and partially separated sections that were treated individually in the analyses. Hence, three design configurations were analyzed for the separate-facility HOV treatment.

The HOV lanes, in all instances, were considerably safer than the general lanes, as demonstrated by the fact that only 2 percent of total facility accidents occurred in the HOV lanes. Moreover, total facility accident rates experienced a statistically significant decrease with the introduction of HOV provisions on the San Bernardino Freeway (sufficient data were unavailable for Shirley Highway).

Recommendations

The research resulted in the identification of certain site-specific safety problems that occurred on the projects studied. The following recommendations are offered in response to these problems.

The ideal terminals to and from separated HOV lanes are exclusive ramps. If this is not possible, the potential exists for a severe accident hazard unless considerable care is exercised at the interface of the HOV lane and the general lane. At the output terminal, it is best to add a lane in order to avoid a left-hand merging condition. At the input terminal, it is best to provide an exclusive concurrent-flow HOV lane upstream of the diverge point, but not of such a distance as to make it attractive to violators as a congestion-avoidance measure.

On the San Bernardino Freeway, a 1-mile (1.6-km) HOV approach lane was provided on the left side of the facility. Violators often used this lane to bypass recurring congestion. A safety problem was created because (a) rear-end accidents resulted from the speed differential between HOVs and violators that enter the lane and (b) violators often became trapped in the lane near the exit and had to stop before being able to merge back into the general traffic lanes. Accident rates more than doubled in this section when the separated HOV lanes were opened. One additional design feature to provide relief for such a condition would be to provide a shoulder for the concurrent-flow HOV lane at the crossover locations to avoid trapping violators.

Totally separated HOV facilities generally require restrictive traffic control devices only at the input terminals to identify the authorized users and times. At outputs it may be necessary to bar wrong-way entry, and this should be accomplished with highly visible gates or barricades, flashing beacons, and NO ENTRY signs. On partially separated sections, HOV lane-use signs should be installed at intervals along the route as a continuous discouragement to violators.

On partially separated HOV lanes, supplemental signing should be provided at inputs to identify the legal exits from the limited-access facility. This should help minimize erratic maneuvers by drivers who need to exit at locations other than the HOV lane terminals. A possible message is RESTRICTED LANE EXITS ONLY AT (location).

On partially separated facilities that have a common shoulder, the shoulder should have distinctive solid white lines on both sides. Double lines are even more forceful. The shoulder should contain chevrons or cross-hatching and word messages to discourage crossing. Flexible tubular markers should be placed at 40-ft (11.9-m) intervals to further discourage crossing.

CONCURRENT FLOW: FREEWAY

Concurrent-flow HOV lane projects on freeways generally involve the designation of the median lanes for use by buses only or by buses and carpools. Access to the restricted lanes is often continuous; that is, there is no physical separation or other barrier between the HOV and general lanes. The lack of physical separation of the HOV from the general lanes permits continuous access and egress, but it is also the cause of several operational and safety problems not experienced in other HOV treatments on freeways.

Concurrent-flow HOV lanes can be created by either reserving an existing lane for HOVs or by constructing new lanes in the median. These two approaches have differing effects on the operation of the facility. The addition of lanes increases capacity but, in order to do so, it often eliminates or reduces median shoulders or refuge areas that could be used by disabled motorists and enforcement operations. Also, the take-a-lane strategy for HOVs will reduce capacity of general traffic and increase the congestion in the general-travel lanes. Public acceptance of the concurrent-flow HOV treatment has been much better when new lanes are added for the HOVs.

Analysis

Four concurrent-flow HOV lane projects were investigated in detail as a part of this research: Moanalua Freeway, Santa Monica Freeway, US-101, and I-95. A general observation was that the implementation of concurrent-flow HOV lanes significantly increased total accident rates for the facility, as evidenced by statistically significant increases in accident rates on all projects except I-95. However, there were no substantial changes in accident types or in the distribution of vehicle types involved in accidents on any of the projects.

High differential speeds between continuously accessible HOV lanes and adjacent general lanes, coupled with merging into and out of the HOV lane, appeared to be the most significant causes of accidents. Weaving across several general lanes to gain access to or leave the HOV lane was a secondary factor. Incidents that blocked any lane, but particularly the HOV lane, were also a significant cause of serious accidents, although it was not possible to quantify the degree of this problem.

Recommendations

Concurrent-flow HOV lanes should be added to a facility rather than taken from existing general use, particularly on heavily congested urban freeways.

The provision of median refuge shoulders is emphatically recommended for this priority treatment. If right-of-way constraints require the compromising of some geometric design standards, the provision of emergency refuge areas in the median should take precedence over such factors as lane width. However, lane width should not be reduced to less than 11 ft (3.3 m).

If the HOV lane is a continuously accessible lane, the lane demarcation between the HOV lane and the general lane should be an extra-wide, broken white line. The Manual on Uniform Traffic Control Devices (MUTCD) now allows a solid line for this purpose (3). However, this can be interpreted as an edge line, and its use for the HOV lane is not recommended except in areas where it is strongly desired to discourage weaving and possibly for bus-only lanes or 24-h HOV lane operations.

The ideal input treatment to a concurrent-flow HOV lane is an added lane on the left. This avoids merging problems because HOVs simply shift into the new lane. If an existing lane must be dropped entirely to create the HOV lane, a right-hand, general-traffic lane should be dropped (preferably at a high-demand exit).

The ideal exit terminal treatment is a continuous lane or, if demand is sufficient, a left-hand exit ramp. If any lane must be dropped at the end of the HOV lane section, it is preferable to drop a right lane at a high-demand exit and have the HOV lane assume general-use status. If the only option is to drop the HOV lane, an extended taper must be provided along with a refuge area for vehicles that have difficulty in merging.

The speed differential between the HOV lane and the general-use lanes provides the travel time savings for HOV traffic but also poses the most severe safety hazard. The resolution of these conflicting goals will require further research to quantify an optimum speed differential that does not adversely affect safety while maintaining the HOV strategy's operational integrity. Metering of general-lane traffic at on-ramps or the use of variable speed control signing on the HOV lane could be used to reduce an excessive speed differential.

Signalization is generally not necessary on concurrent-flow lane treatments. In locations where sight distances are limited, consideration should be given to using either variable message signing or warning beacons to warn motorists of stalled traffic ahead in the HOV lane or other lanes. These could be centrally operated by police officers or by an automated traffic surveillance and control system.

If conventional enforcement techniques are used, the officers should make every effort to minimize disruption to traffic. On-freeway (stationary) monitoring is effective in reducing violations but it can also slow traffic. Weaving across the freeway to apprehend violators is particularly disruptive and should be avoided if possible. Citations should be issued out of the motorists' sight to eliminate gawking. The visibility of issuing citations on the right shoulder has minimal effect since passersby cannot relate the specific violation to the enforcement activity. Legislative action to permit photographic or mail-out citation techniques should also be considered (2).

CONTRAFLOW LANE: FREEWAY

The common practice of installing contraflow HOV lanes is to assign the inside (median) lane in the opposing (off-peak) direction to a special class of vehicles. The contraflow lane is separated from the other travel lanes by flexible tubular markers. If sufficient capacity remains in the off-peak direction, an additional lane can be taken for use as a buffer lane. Thus, the contraflow lane treatment makes use of surplus capacity in the off-peak direction, thereby increasing the vehicle- and person-moving capacity in the peak direction.

Analysis

Three applications of contraflow treatment on freeways were investigated during this research: I-495, Long Island Expressway, and US-101. On all three projects, the accident rates were higher in the off-peak direction than in the peak direction during HOV operations. These differences were statistically significant except on I-495. Only on US-101 were accident data available for both before and after conditions. On this project, the daily accident rate experienced a statistically significant increase with the introduction of the contraflow lane.

The most apparent causative factor related to safety problems on contraflow HOV lanes is the capacity reduction in the off-peak direction. Off-peak decreases in operating speeds and site-specific incidences of congestion resulted in an increased number of rear-end collisions and other congestion-oriented safety problems.

This off-peak safety problem was less prevalent for projects installed on facilities that have superior geometric features. Presumably because of better alignments and fewer geometric constraints, accident rates on US-101 were lower than the comparable accident rates on I-495. Head-on conflicts between the contraflow lane and opposing traffic occurred only on I-495 because of its tight geometrics, although it was not a recurring problem.

Recommendations

Contraflow lanes are generally implemented on existing freeways without substantial modification of the main-line geometrics of the freeway. If possible, contraflow lanes should be implemented on freeways that have high-design standards. Every effort should be made to maximize the safety and quality of the geometric design.

The ideal terminals to and from the contraflow lane are exclusive ramps or toll booth lanes (if the output terminus is to a toll plaza). Where median crossovers are required at the input terminus, a short access lane should be provided upstream of the crossover to allow for deceleration. Terminals should be closed during periods of non-HOV operation.

Where a buffer lane cannot be provided between the contraflow lane and the gereral-use lanes, proper use of the lane should be designated by overhead lane-use control signals displayed over the contraflow lane and the adjacent general-use lane. Spacings should conform to sight distance and MUTCD standards (3).

Where a buffer lane can be provided between the contraflow lane and the general-use lanes, overhead lane-use control signals are not necessary to designate proper lane use if sufficient physical separation and signing is provided.

Signing in the off-peak direction approaching the contraflow section should consist of both advanced-warning and restricted-lane signing along the main line. Messages such as CAUTION--ONCOMING TRAFFIC AHEAD--X FEET (Y KM) and LEFT LANE CLOSED--ONCOMING TRAFFIC, with flashers and merge-right arrows as appropriate, are more positive than the standard MUTCD-restricted lane signing. Blank-out message signs are preferable to specified time periods due to the flexibility in operating hours.

Signing in the off-peak direction at the end of the contraflow section should be the standard MUTCD end-of-HOV-lane sign. A lane-control signal should be placed downstream and all green arrows permanently displayed over each off-peak directional lane.

Signing in the peak direction would depend on the type of terminal treatment. Standard MUTCD signing should be used and emphasis placed on which vehicles may use the contraflow lane.

The demarcation for a contraflow lane should be a double yellow broken line to indicate a reversible lane. Yellow flexible tubular markers should be placed along the lane line. They should be reflectorized and spaced at a maximum distance of 40-ft (11.9-m) intervals. The use of the diamond symbol on the contraflow lane is discouraged, as this implies vehicle classification and not direction.

Use of the contraflow lane should be restricted to experienced and trained operators. In addition to transit operators, operators of other vehicles (charter buses, minibuses, vanpools, taxis, and carpools) could be permitted use of the contraflow lane if special licensing requirements are met. All motorists who use the contraflow lane should be required to use flashers with the vehicle.

Additional restrictions may be desirable on both the contraflow-lane and opposing-lane traffic. Reduction of the speed limit and spatial headways are the most common restrictions.

Quick-reaction incident detection and removal systems should be incorporated into the project. If possible, median cuts should be provided if there is no buffer lane so emergency vehicles can approach in the proper direction; however, these should not be penetrable by general traffic or present a collision hazard themselves. Care must also be taken to minimize pedestrian use of these crossings. Incident management can be greatly enhanced by the provision of freeway surveillance (electronic sensors or television), and warning beacons should be considered as well to alert oncoming traffic of incidents downstream.

Enforcement of contraflow lane use should be directed at the terminals because activity along the main line can be extremely disruptive, if not impossible. Monitoring should be active throughout the project area, especially for violations of the special restrictions suggested above.

Contraflow lanes should not be installed if such action will cause traffic flows in the off-peak direction to deteriorate to levels that induce a significant increase in rear-end accidents.

TOLL-PLAZA LANE: FREEWAY

The establishment of certain toll-plaza lanes for exclusive use by HOVs enables these vehicles to bypass substantial queues and gain access to the toll facility with less delay.

Analysis

On the San Francisco-Oakland Bay Bridge (SFOBB) toll plaza, 3 of the 17 approach lanes are reserved for buses and carpools. The HOV lanes are free flow since carpools pay no toll and bus companies are billed based on scheduled crossings. Further advantage is given to HOVs via a bypass of the ramp-metering station installed to improve flow across the bridge. Thus, the exclusive toll-plaza lanes serve several purposes. They allow HOVs to (a) bypass queues on the approach, (b) move through the toll station with minimal delay, and (c) gain preferential access to the toll facility itself.

Implementation of HOV lanes in the SFOBB toll facility appeared to adversely affect safety on the facility, although this was largely alleviated by the metering system. The most obvious factor that has an effect on safety in the SFOBB toll-plaza area was the congestion pattern that results from the implementation of the HOV lanes. This project had the effect of dividing what was formerly a homogeneous stop-and-move queue, which extended some distance upstream, into two sections separated by HOV lanes in the middle. This resulted in extending the queuing area farther upstream in the two halves of the general roadway lanes and in introducing a speed differential in the center of the facility.

The geometry of the SFOBB was not designed to accommodate the HOV toll-plaza priority treatment. The facility had several problems in this respect:

1. Trucks that enter the facility from the left (Nimitz Freeway) must weave across the lanes to gain access to the right-hand toll-plaza lanes that accommodate trucks;
2. Since HOV lanes are in the center of a 17-lane toll plaza, a large amount of weaving is required;
3. There is a penetrable barrier between the HOV lanes and the general lanes; and
4. There is a rapid narrowing from 17 to 5 lanes in the toll-plaza output section.

These problems do not all result from the HOV priority treatment, but the HOV strategy has, to some extent, compounded the potential hazards.

Recommendations

The following provides a set of recommendations that have been developed in response to the experience of the SFOBB.

The weaving area that provides access to the priority lane should be of sufficient length to minimize conflicts and to permit the distribution of HOVs into the priority lanes well in advance of the queuing area [in order to avoid the unsafe condition of late merges from slower-moving vehicles into the HOV lane where a 15-mph (24-km/h) speed differential exists].

Ideally, the HOV lanes and general lanes should be separated by a physical barrier. Where physical barriers are impossible to implement, some type of lane delineation should be incorporated. Any flexible tubular markers that delineate the HOV lane should be closely spaced to prevent lane-change movements near the toll plaza.

Adequate merging distance should also be provided to the priority lanes where they rejoin the general traffic lanes after passing through the toll booths. HOVs given priority at the toll plaza should be allowed to pass through the toll booths with a minimum amount of delay.

When possible, special refuge areas of shoulders should be provided adjacent to the HOV lanes. Such areas aid both disabled HOVs and enforcement operations.

RAMP TREATMENTS: FREEWAYS

Preferential treatment can also be provided at entry and exit ramps on freeways. There are commonly two types of HOV treatments on ramps:

1. HOV bypass of ramp metering at on-ramps and
2. Exclusive on-ramps or exclusive off-ramps for HOVs.

Analysis

As a part of this research, 21 ramps on the Santa Monica, Golden State, and Harbor Freeways were investigated in detail. All ramps provided ramp-metering bypasses for buses and carpools of two or more persons. Also studied as a part of this research was an exclusive-reversible ramp for buses and carpools that connects the reversible lanes of I-5 with the Seattle central business district (CBD).

The exclusive HOV ramp project in Seattle did not exhibit any accident characteristics that could be directly assigned to the HOV treatment. Indeed, the exclusive use of the ramp probably enhanced the safety of the particular ramp, although comparative data were not available to test this suggestion.

On the Los Angeles area ramp-metering-bypass locations, the installation of HOV provisions increased the number of accidents. These accidents were generally concentrated at or near the interface between the ramp and the surface street. This appears to be directly related to the division of what was formerly a single ramp into two lanes. Because vehicles that enter the ramp from several surface street approaches have to divide into two lanes, some weaving can be expected and accidents can result from the somewhat unpredictable movements associated with entering vehicles. If the metered queue extends back onto the surface street, this safety problem is further compounded. In this event, HOVs trapped in the queue on the surface street may attempt erratic movements to bypass this temporary delay and move directly onto the ramp in the HOV lane.

Recommendations

Ramp-metering-bypass treatment can adversely affect safety. A number of recommendations designed to improve the safety of this HOV strategy are presented below.

Ideally, the HOV lane should be physically separated from the metered lanes, either by being constructed separately (thus having many characteristics of exclusive ramps) or by barriers. This is particularly important at the ramp entry. Shoulders should be provided to enable unintentional violators to pull off the traveled lane.

When separation is not possible, and if the ramp is long and has sufficient storage capacity, the HOV lane should be initiated after the entrance point so there is a single entry lane. This may, at times, delay HOVs, but it would largely eliminate the entry conflicts.

Sufficient distance should be provided for merging on the body of the ramp so that HOVs and general traffic can merge together and assume the same speeds prior to merging on the freeway.

The selection and designation of right or left lanes as the HOV lane is important, particularly at nonseparated ramp-metering-bypass installations. Consideration should be given to access to the ramp, position of signals vis-à-vis the stopped queue, and how the two lanes will merge. Specific guidelines cannot be given because of the diversity of site-specific parameters; however, the most important items to consider are summarized below.

1. The preferred configuration is to have the HOV lane on the left because this allows the slower metered traffic to merge with HOV traffic on the left. This technique provides general traffic with a customary merging situation and eliminates the problem of drivers in the general lane being wary of traffic on both sides (a violation of driver expectancy).
2. If metering signals are pole-mounted, the preferred lane for metering is the left, so that drivers have a better view of the signal. If the right lane is the metered lane, consideration should be given to providing a narrow median with a signal installed both in the median and on the right. Adequate lighting, reflectorization, channelization, and strict application of MUTCD policies are needed to prevent collisions with the median or signal standard during hours of darkness.
3. On curved ramps, the HOV lane should generally be on the outside of the general lane (i.e., the lane having the larger radius). This gives nonstop HOVs a lower degree of curvature but, more importantly, metered-lane traffic has a clearer rear view of the HOV lane and thus the hazard of lane changing is reduced.

Metering rates, queue lengths, and HOV operations should be reviewed on a continual basis to optimize the operation of the ramp and minimize traffic problems.

Although potential safety problems are associated with ramp-metering-bypass installations, exclusive HOV ramps have not been shown to have an adverse impact on safety. Specific recommendations to enhance this position include the following.

Construction of new ramps or conversion of existing ramps is recommended. The addition of ramps generally has a minimal effect, since they do not result in substantially altered traffic patterns. Converted ramps can displace a significant amount of traffic because not all former users can, or will, shift to HOVs. This displacement places a burden on the main-line freeway and ramps at other interchanges. Thus, HOV ramp locations should be carefully selected, and consideration should be given not only to the access needs of the HOVs but also to the resulting adverse impacts.

The intersection with surface streets is of particular concern for HOV ramps. This is especially true if the ramp is reversible. Wrong-way entry can be a problem on these ramps, and traffic controls must be absolutely positive in displaying the proper usage. Changeable message signs, traffic-actuated stop signs, and time-control static signs are generally necessary to identify authorized users and time.

SEPARATE FACILITY: ARTERIAL STREET

Separate facilities on an arterial street system are commonly referred to as transitways because the only type of vehicle that is permitted to travel on such a facility is the transit coach. There are two types of transitways; each serves a distinct objective:

1. A separate facility that serves as a major transit collection-distribution route tends to be located in the CBD in order to provide a high level of transit accessibility in heavily concentrated retail and business districts. Commonly associated with this transitway is some type of pedestrian mall and other aesthetic features. The benefits of this type of transitway are transit accessibility and separation of different classes of vehicles.
2. A separate facility that serves the line-haul portion of transit service tends to connect the CBD with outlying areas. The benefits associated with this type of transitway would be the more-traditional HOV objectives of savings in travel time and increased total person throughput.

The predominant type of arterial-based transitway satisfied the first objective of major transit collection-distribution functions in the CBD. Such transitways exist in Minneapolis, Minnesota (Nicollet Mall); Portland, Oregon (Portland Mall); Chicago, Illinois (Halsted and 63rd Streets); and Philadelphia, Pennsylvania (Chestnut Street) and have been successful in enhancing or reviving downtown vitality.

Analysis

Most arterial transitways have an elaborate pedestrian mall associated with them. Numerous aesthetic features, commercial characteristics, special exhibits, displays, and public entertainment provide visual attractions to the pedestrian.

Access and egress to the separate facility most often occurs only through the facility's terminal points even though the facility will most likely traverse at-grade intersections with cross streets. Access and egress are controlled at the cross-street intersections through both traffic restrictions and possible supportive geometrics such as a low-curvature radius that does not allow for the American Association of State Highway and Transportation Officials' (AASHTO's) 24-ft (7.2-m) minimum turning path for a passenger car. Terminal treatments for a separate facility can vary considerably because the treatments are site specific.

The overall safety experience of arterial-based transitways has been excellent. The general practice of eliminating access and egress to the facility at all intermediate locations greatly enhances safe operation.

The greatest potential safety problem relates to pedestrian conflicts. Pedestrians sometimes unwittingly step into traffic lanes (especially at cross streets) because they become acclimated to a continuous pedestrian mall and become distracted by its attractions.

Recommendations

Specific recommendations that address this and other potential safety problems of arterial-based transitways include the following.

Appropriate pedestrian controls should be instituted. These controls should include highly visible and audible pedestrian signals at locations where cross-street vehicular traffic intersects with the pedestrian walkway.

Cross streets across the transitway should be eliminated whenever possible. When the elimination of cross streets is impossible, the turning movement between the transitway and the cross streets should be restricted. Traffic signals and signs should be standard and easily visible to the motorists. A one-way cross street is preferred to a two-way cross street because of the fewer potential conflicts and traffic operational requirements.

Procedures regarding bus operations on the transitway should include (a) low bus speeds and (b) increased driver awareness and courtesy. A low bus speed should not detract from the bus operations because the prime advantage of the transitway is its accessibility, and that is not affected.

CONCURRENT FLOW: ARTERIAL

Concurrent-flow priority applications on surface streets involve reservation of either the curbside lane or the median lane for HOVs. The different applications have differing operational objectives and requirements. Curbside lanes have historically been installed to provide better transit circulation in the CBD or to improve downtown traffic flow through segregation of buses and automobiles. Median lanes are generally intended to provide HOVs with travel time advantages by bypassing traffic congestion in the general traffic lanes. This type is commonly associated with express bus service that operates in a through or express mode. The concurrent-flow median lane usually operates during the peak period in the peak direction, over a project length of several miles. Carpools may also be permitted to travel in the concurrent-flow median HOV lane.

Analysis

Within the context of this research, four concurrent-flow HOV lane applications on arterial streets were examined, including three median-priority-lane sections and one curbside-priority-lane section. These projects include the Washington, D.C., CBD curbside-concurrent-flow lanes, the US-1-South Dixie Highway median-adjacent concurrent-flow lane, the N.W. 7th Avenue median-adjacent concurrent-flow lane, and the Kalanianaole Highway median-adjacent concurrent-flow lane.

Of the three median-adjacent HOV projects, the N.W. 7th Avenue project experienced a decrease in the total facility accident rate with the introduction of the HOV lane. The primary operational factor that differed between the N.W. 7th Avenue project and other median-adjacent projects was the establishment of the bus-only lane without altering the number of lanes available for general traffic. The other two median-adjacent HOV lane projects (US-1-South Dixie Highway and Kalanianaole Highway) established the HOV lane by taking a lane away from the general traffic, thereby increasing congestion in the remaining lanes. As a result of the congestion, rear-end accidents became more prevalent.

Other safety problems associated with median-adjacent HOV lanes related to left turns from the main line and speed differentials between the HOV lane and general lane. Left turns from a main-line facility that has an HOV lane may create a safety problem due to motorists that stop in the express HOV lane to make the left turn or weave unexpectedly across the HOV lane into a left-turn bay.

A large speed differential between the HOV lane and adjacent general lanes causes slower vehicles to merge into a high-speed HOV lane, or it causes faster vehicles in the HOV lane to decelerate rapidly to merge into the general lane. Either action could result in sideswipe or rear-end accidents.

For curbside HOV applications, buses that use the Washington CBD curb-bus-lanes project experienced parked vehicle (14 percent) and pedestrian (2 percent) accidents in addition to the more common rear-end (27 percent), sideswipe (25 percent), and right-angle (25 percent) accidents. Recommendations useful in alleviating the conditions that contribute to various accident types are listed below.

Recommendations

Taxicabs and other vehicles should be prohibited from stopping in the curb lane to pick up and drop off passengers or to make deliveries. This can be done by posting NO STOPPING OR STANDING regulations and strictly enforcing them.

Parked vehicles should be removed from the curb lane. The technique of putting locked boots on parked vehicles in order to ensure payment of the parking fine has the effect of keeping the parked vehicle in the lane longer.

The potential pedestrian safety problem should be addressed. Several options may be considered:

1. Strict enforcement of jaywalking ordinances,
2. Special visual or audible warning devices installed on the buses,
3. A special yellow stripe of 1-2 ft (0.3-0.6 m) with a warning message painted on the sidewalk adjacent to the curb, and
4. Planting bushes to keep pedestrians away from the curb.

A similar set of recommendations has been compiled for median-adjacent concurrent-flow HOV lanes on arterials.

Left turns should be prohibited at selected locations, if not at all locations. Nonsignalized intersections should be closed by cones, or other implements should be considered to reduce crossing movements across the HOV lane. The operational effect of this recommendation on the cross street or off-line will vary by location.

The speed differential between the HOV lane and general-use lanes should be controlled if necessary and possible. This may be accomplished by using variable-speed-control signing on the HOV lane. Until additional research can be conducted to quantify an optimum speed differential, it is recommended that a 10-mph (16-km/h) maximum speed differential not be exceeded. On each of the concurrent-flow projects studied, the average speed differential did not exceed 10 mph.

Volumes in the HOV lane should be high enough to portray the lane as an operational lane. The higher the volume in the HOV lane, the more keenly alert are motorists to the HOV lane. Increased volumes can be achieved by greater bus use or by permitting carpools to use the HOV lane.

CONTRAFLOW LANE: ARTERIAL STREET

A contraflow HOV lane on an arterial street is commonly a lane in the off-peak direction reserved for HOVs that are traveling in the peak directions. A contraflow HOV lane can incorporate the median lane or the curb lane of a highway facility. The reversible lane is a specialized type of contraflow lane in which the direction of flow for a median lane is always in the peak direction. Left turns are generally permitted from the lane in the off-peak period.

Analysis

The N.W. 7th Avenue reversible-bus-lane section is an example of a reversible lane. The US-1-South Dixie Highway and the Kalanianaole Highway contraflow lanes entailed the dedication of a median-adjacent lane from the off-peak direction for exclusive use by buses. Both the Kalanianaole and US-1-South Dixie Highways are six-lane, divided facilities.

A third type of contraflow operation is exemplified by Ponce de Leon-Fernandez Juncos Avenues. These four- and five-lane, one-way pair arterials contain a contraflow lane along the left-hand curb to provide local bus service along a 13.6-mile (21.9-km) route.

More than 70 percent of the accidents that involve a vehicle from a contraflow lane were associated with a crossing maneuver of some type by the other vehicle involved. These crossing maneuvers may involve (a) a vehicle turning left from the main facility, (b) a vehicle crossing or turning onto the main facility from the side street, and (c) a pedestrian crossing the main facility. The overwhelming causative factor cited by project officials for the occurrence of these contraflow-lane accidents that involve crossing maneuvers is the inability of motorists or pedestrians to recognize a facility's wrong-way operation. Therefore, when performing crossing movements, these individuals may scan for traffic in the direction of the general lane and fail to look for contraflow traffic. These perceptual deficiencies occur because the design of contraflow facilities violates basic driver expectancy based on the following two human factors:

1. The normal symmetrical lane-use distribution, which a driver encounters in nearly all driving experience, is violated by the nonsymmetrical layout that accompanies the contraflow facility and
2. Traffic control devices (signing and marking) used for standard delineation and positive guidance are often superseded by temporary peak-period traffic control measures that define the contraflow lane; however, the motorist or pedestrian may continue to behave in a manner responsive to the permanent traffic control devices.

The omnipresent safety hazard associated with this expectancy phenomenon is dramatically documented on the US-1-South Dixie Highway project. On this project, two contraflow-lane accidents have involved police officers responsible for project enforcement. The officers, while in pursuit of violators of the project's restriction, turned directly into the path of oncoming contraflow-lane buses. The officers, who were very familiar with the operation of the contraflow lane, simply forgot for the moment about the contraflow lane.

There may be an indirect relationship between vehicular volume in the contraflow lane and the accident rate. In other words, the higher the volume, the lower the accident rate. This relationship could result from the fact that motorists are more keenly aware of the contraflow lane due to a higher volume in the contraflow lane. A greater number of vehicles in the contraflow lane provides greater visibility to the motorists of the contraflow-lane operation.

All four contraflow-lane projects experienced bus accident rates that were higher during the early stages than during the later stages of each project. Such accident rate trends may suggest that there is an adjustment period of some duration for the motorists driving the facility to better comprehend the contraflow-lane operation. In other words, driver expectancy may improve with the life of contraflow-lane projects up to a point of optimal driver familiarity.

The contraflow HOV lane treatment is potentially one of the most hazardous priority treatments that can be implemented on an arterial street. On the other hand, it is possible to employ this treatment effectively and safely provided certain precautions are taken.

Recommendations

Specific recommendations that may improve the safety of a contraflow HOV lane on an arterial street include the following.

Left turns should be prohibited at all locations along the contraflow-lane operation. This prohibition should also be considered for the off-peak periods. Any left-turn prohibition should be enforced rigorously. Left-turn prohibitions should be reinforced by physical impediments where possible.

Traffic control devices (signing and pavement markings) should be provided that are highly visible and closely spaced in order to make the motorists more fully aware of any restrictions imposed. The issue of driver expectancy is more pronounced for a median contraflow-lane treatment than for a curb contraflow-lane treatment. In addition, on a median-lane treatment, driver expectancy tends to be greater for a divided facility than for an undivided facility.

The demarcation for a contraflow lane should be a double yellow broken line to indicate a reversible lane. Flexible tubular markers should be placed along the lane line. They should be reflectorized and spaced at a maximum distance of 40-ft (12-m) intervals. The use of the diamond symbol on the contraflow lane is discouraged, as this implies vehicle classification and not direction.

Signing in the off-peak direction approaching the contraflow section should consist of both advanced-warning and restricted-lane signing along the main line. Messages such as CAUTION--ONCOMING TRAFFIC AHEAD--X FEET (Y KM) and LEFT LANE CLOSED—ONCOMING TRAFFIC, with flashers and merge-right arrows as appropriate, are more positive than the standard MUTCD restricted-lane signing. Blank-out message signs are preferable to specified time periods due to the flexibility in operating hours.

Signing in the off-peak direction at the end of the contraflow section should be the standard MUTCD end-of-HOV-lane sign (3). A lane-control signal should be placed downstream with all green arrows permanently displayed over each off-peak directional lane.

Signing in the peak direction would depend on the type of terminal treatment. Standard MUTCD signing should be used with emphasis on which vehicles may use the contraflow lane.

The imposition of additional restrictions on contraflow-lane and opposing-lane traffic may be desirable. Reduction of the speed limit and spatial headways are the most common restrictions. A lower bus headway may make the motorists more aware of the operation of a contraflow lane. A bus headway of 0.5-1 min may be necessary to accomplish this objective. For many express bus operations, it may not be financially feasible to operate with headways of 0.5 min. In view of this and the evidence in support of lower accident rates where HOV lane volumes are higher, consideration may be given to including registered carpools, vanpools, taxis, or other multipassenger vehicles in the HOV lane.

Warning horns or flashing lights could also be used on buses that travel in the contraflow lane. This would improve awareness of the contraflow-lane operation.

Potential provisions that may alleviate, in part, the pedestrian safety problems are as follows:

1. Strict enforcement of jaywalking ordinances,
2. Pedestrian signing and markings that state LOOK BOTH WAYS at designated crosswalks,
3. Special visual or audible warning devices installed on contraflow-lane buses,
4. Special yellow stripe of 1 to 2 ft (0.3 to 0.6 m) with a warning message painted on the sidewalk adjacent to the curb, and
5. For median contraflow projects that have a divided median, application of a combination of fencing and foliage in the median should be provided to obstruct and channel the pedestrian traffic to particular locations equipped with pedestrian signals.

In order to speed up the motorist familiarization process with the operation of a contraflow lane, an intense public education campaign and heavy enforcement of the contraflow-lane restrictions should be undertaken from the onset of the project.

Quick-reaction incident detection and removal systems should be incorporated into the project to minimize the potential for vehicles using oncoming lanes to bypass breakdowns in the contraflow lane.

SUMMARY

This paper has been a summary of an exhaustive nationwide research effort aimed at improving the design and operations of preferential-treatment strategies for HOVs. Potential users of this material are directed to the references for more detailed data and recommendations.

In general, all preferential-treatment strategies can operate in a safe and effective manner. However, since many HOV strategies differ somewhat from normal driver expectancy, considerable effort must be expended during the HOV facility-design phase to ensure safe operation. HOV facility design, traffic operations systems, and enforcement strategies all require careful and comprehensive consideration. Exhaustive attention to operational details as well as to the full range of possible misinterpretations and misuses of the HOV system is esssential.

Certain HOV strategies are inherently more contrary to driver expectations and, hence, pose greater safety problems. Contraflow lanes on arterial streets are an example of potentially unsafe HOV strategy (although for reasons of right-angle collisions rather than the normally feared head-on collisions). Concurrent-flow HOV lanes on freeways are another example.

With proper design, analyses, and attention to details, all forms of exclusive HOV facilities (physically separated HOV systems, contraflow lanes, concurrent-flow lanes, ramp-metering-bypass facilities, exclusive toll-plaza lanes, and bus-priority signalization systems) can be implemented successfully without adversely affecting the safe operation of the transportation facility.

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REFERENCES

1. Beiswenger, Hoch, and Associates, Inc. Safety Evaluation of Priority Techniques for High-Occupancy Vehicles. Federal Highway Administration, FHWA-RD-79-59, Feb. 1979.
2. Beiswenger, Hoch, and Associates, Inc. Enforcement Requirements for High-Occupancy Vehicle Facilities. Federal Highway Administration, FHWA-RD-79-15, Dec. 1978.
3. Manual on Uniform Traffic Control Devices. Federal Highway Administration, 1978.

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