Evaluation of High-Occupancy-Vehicle Lanes in Phoenix, Arizona

MARK J. POPPE, DAVID J. P. HOOK, AND KEN M. HOWELL

High-occupancy-vehicle (HOV) lanes were first introduced into the Phoenix metropolitan area freeway system with the opening of I-10 west of I-17. The system now contains approximately 27 mi (43 km) of freeway with HOV priority lanes. The system will include approximately 40 mi (64 km) of freeway with HOV lanes by the year 2000. A study was undertaken to field evaluate the operation of HOV lanes in the Phoenix metropolitan area to examine the use of HOV lanes, priority-lane violation rates, and the overall effectiveness of HOV lanes in the Phoenix metropolitan area. The results showed that HOV lanes become very effective in periods of high congestion on the adjacent freeway lanes. It appears that freeways with HOV lanes have much higher automobile occupancy than do freeways without HOV lanes. One possible cause of this increase in occupancy is a shift from single-occupancy vehicles to higher-occupancy modes of travel along HOV facilities. Although the Phoenix area HOV system may not, in large part, be effective by some of the more traditional measures of effectiveness, the system has been successful in encouraging higher vehicle occupancies and improving HOV travel.

High-occupancy-vehicle (HOV) lanes were first introduced into the Phoenix metropolitan area freeway system with the opening of I-10 west of I-17. The system now contains approximately 27 mi (43 km) of freeway with HOV priority lanes as shown in Figure 1. Additional HOV lanes are planned along with new freeway construction and existing freeway reconstruction. The entire system will include approximately 40 mi (64 km) of freeway with HOV lanes by the year 2000. All current and planned HOV lanes in the metropolitan Phoenix area are designed as concurrent-flow lanes on the median side, with a painted stripe or buffer zone separating them from the general traffic lanes. Initially, priority-lane usage was restricted to vehicles with three or more occupants. This was soon reduced to two occupants to increase HOV lane utilization. The HOV lanes are also open for use by single-passenger motorcycles. The air quality impact of freeway HOV lanes was modeled for consideration in the Maricopa Association of Governments Transportation Planning Office air quality plans, but no formal assessment of the performance of existing HOV lanes was conducted as verification to input parameters to the model.

This study provides the first opportunity to field evaluate the operation of HOV lanes in the Phoenix metropolitan area. This report examines utilization of HOV lanes, priority-lane violation rates, and the overall effectiveness of HOV lanes in the Phoenix metropolitan area.

STUDY DESIGN AND DATA COLLECTION PROCEDURES

This research was part of a larger study that examined vehicle occupancy and vehicle classification in the metropolitan Phoenix area. Automobile occupancy data were collected by observers stationed on overpasses or at roadside at 16 locations for freeways with HOV lanes and at an additional 18 locations for freeways without HOV lanes. A total of 18 arterial locations were also counted. Collectors counted automobile occupancy for an average of 15 min/hr for each lane. Commercial vehicles were not included in the calculation of automobile occupancy.

Automobile occupancy was evaluated in terms of three factors: area type, time of day, and roadway functional classification, as described below. To see the change in vehicle occupancy by these factors, an experimental design approach was undertaken. This is a fixed-effects 3 by 3 by 4 factorial design, as shown in Figure 2. To find the differences in vehicle occupancy based on these parameters, six locations per cell were randomly selected to predict the response in vehicle occupancies. Only four samples were drawn for suburban freeways with HOV lanes because there were few available facilities. Using the FHWA *Guide for Estimating Urban Vehicle Classification and Occupancy* (*1*), 44 locations would be needed to obtain a 0.02 tolerance with 95 percent confidence for metropolitan-wide statistics.

Area Type

Area type as used in this study is defined by density, where density is total population plus 2 times total employment divided by gross area. The core area is where density is greater than 10,000/mi^2 (3,600/km^2). Urban densities are 5,000 to 10,000/mi^2 (1,800 to 3,600/km^2) and suburban $\leq$ 5,000/mi^2 (1,800/km^2). The area types for the Phoenix metropolitan area are also shown in Figure 1.

Time of Day

Data were collected for 13 hourly periods from 6:00 a.m. to 7:00 p.m., which allowed the study team to form time periods into any logical combination necessary.

Functional Classification

Data were collected for three classifications:

1. Freeways with priority lanes (HOV);
2. Freeways without priority lanes (non-HOV); and
3. Arterial streets.

This paper will focus on freeways with priority HOV lanes.

Lee Engineering, Inc., 3240 E. Camelback, Suite 180, Phoenix, Ariz. 85018.

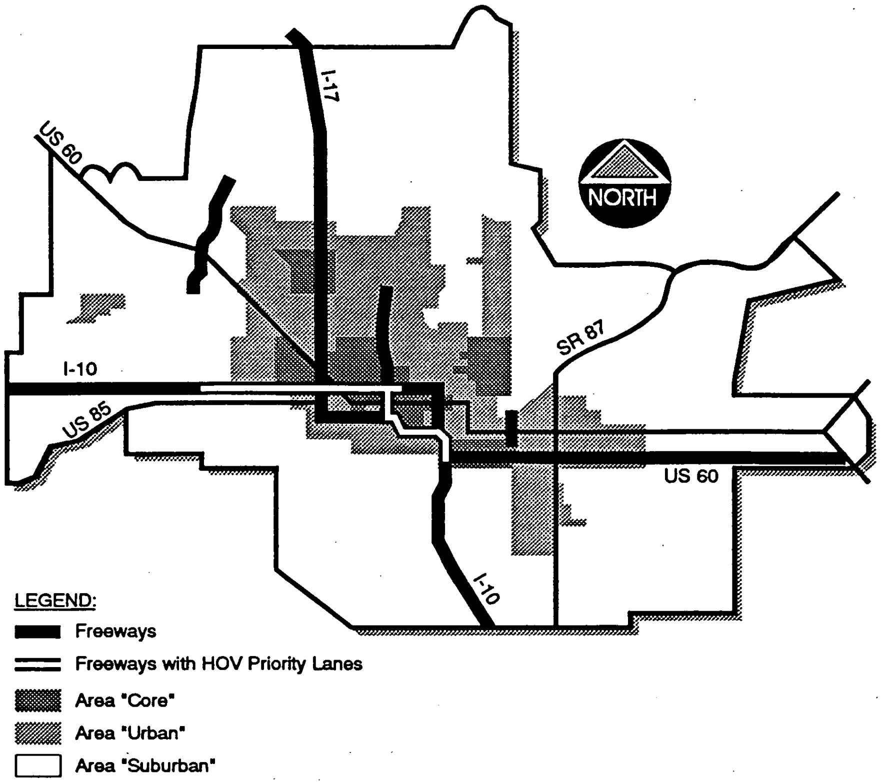

FIGURE 1 Phoenix metropolitan area.

UTILIZATION OF HOV LANES

Volume of Traffic on HOV Lanes

To determine how extensively priority lanes are utilized, a tabulation of the average volume by time of day was prepared for each freeway with an HOV lane. The sampled data were factored to present an approximate total hourly volume by lane. The volume of traffic on priority lanes is substantially less than that on the nonpriority lanes. The highest volume counted on a priority lane occurs on I-10 at 39th Avenue in the eastbound (peak) direction between 5:00 and 6:00 p.m. Assuming a lane capacity of 2,200 vehicles per hour, the 975 vehicles per hour sampled at this location represents a ratio of volume to capacity (*V/C*) of approximately 0.44. At this *V/C* ratio, there is very little speed loss caused by congestion on the HOV facility. On the basis of subsequent travel time runs, all priority lanes in the Phoenix area operate at uncongested speeds, even during peak times. A statistical test was performed to determine if the volume on priority lanes is a function of either area type or time of day. Table 1 is the analysis of variance for the total number of vehicles on the priority lane. AREA is the area type (urban, suburban, core) and HTIME is the hour in which the sample was taken. The analysis indicates that there is a significant difference in the number of vehicles on priority lanes associated with area type and time of day. The AREA*HTIME interaction is also significant at the $P = 0.02$ level. The AREA*HTIME interaction is best explained by examining the plot shown in Figure 3.

The plot shows that HOV lane volumes peak sharply from 4:00 to 6:00 p.m. in both the urban and core areas. Conversely, suburban HOV lane volumes stay relatively constant throughout the day. The lower volumes also indicate light demand for HOV lane usage in the suburban area.

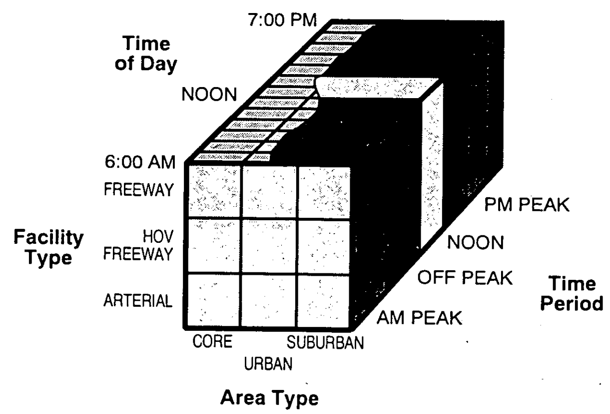

FIGURE 2 Experimental design used in study.

HOVs in Nonpriority Lanes

Sometimes HOVs will not utilize the priority lanes. There are several reasons why this may occur. It is possible that the trip length is so short that it is not worth shifting over to the inside priority lane. When the facility is not congested, there may not be a time savings in doing so. Also, HOVs must usually enter and

TABLE 1 Analysis of Variance for Total Vehicles on Priority Lanes

Source	DF	Type III SS	Mean Square	F Value	Pr>F
AREA	2	906235.12	453117.56	20.53	0.0001
HTIME	12	1788675.94	149056.33	6.75	0.0001
AREA*HTIME	24	921133.81	38380.58	1.74	0.0233
ERROR	169	3729489.50	22067.99		
TOTAL	207	7837145.19			

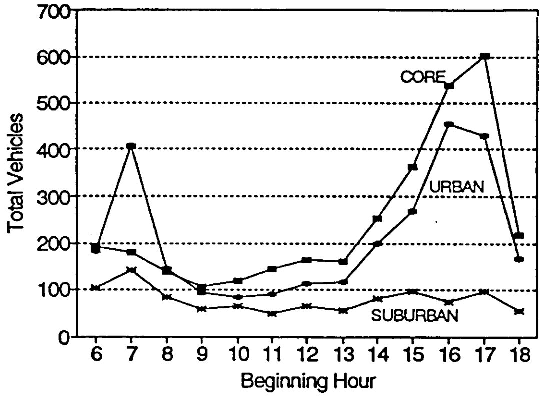

FIGURE 3 Average volume on priority lanes by time of day and area type.

exit the freeway from right-side ramps, requiring them to travel in the nonpriority lanes before reaching the HOV lanes and after leaving the HOV lanes.

The lowest percentage of HOVs in nonpriority lanes occurs in the 6:00 to 7:00 a.m. and 7:00 to 8:00 a.m. periods. This percentage steadily increases until 2:00 p.m., when it starts to decrease. From 2:00 to 6:00 p.m. the freeways are more congested and there are more work trips, which tend to be made in single-passenger vehicles, on the roadways. In the 6:00 to 7:00 p.m. period, the percentage of non-priority-lane vehicles that are HOVs increases considerably. During this period there are a large number of nonwork trips with higher occupancies.

A statistical analysis was performed on these data to determine if the percent of HOVs is affected by either area or time of day. The analysis of variance shown in Table 2 indicates that both area type and time of day have an effect on the percentage of HOVs in nonpriority lanes. Table 3 shows the percentage of HOVs on

TABLE 2 Analysis of Variance of HOVs in Nonpriority Lanes

Source	DF	Type III SS	Mean Square	F Value	Pr>F
AREA	2	1323.07	661.54	22.31	0.0001
HTIME	12	3157.96	263.16	8.88	0.0001
AREA*HTIME	24	511.11	21.30	0.72	0.8283
ERROR	169	5010.78	29.65		
TOTAL	207	9885.84			

TABLE 3 Percent of Total Facility HOVs on Priority Lanes

Time of Day	% of HOV Veh. in HOV Lane
6:00 - 7:00 AM	27
7:00 - 8:00 AM	29
8:00 - 9:00 AM	22
9:00 - 10:00 AM	14
10:00 - 11:00 AM	14
11:00 - 12:00 AM	13
12:00 - 1:00 PM	15
1:00 - 2:00 PM	14
2:00 - 3:00 PM	20
3:00 - 4:00 PM	24
4:00 - 5:00 PM	29
5:00 - 6:00 PM	32
6:00 - 7:00 PM	17

TABLE 4 Automobile Occupancies of Priority and Nonpriority Lanes: Freeways with Priority Lanes

Time of Day	Priority Lane	Non-Priority Lanes
6:00 - 7:00 AM	2.10	1.18
7:00 - 8:00 AM	2.10	1.15
8:00 - 9:00 AM	2.18	1.19
9:00 - 10:00 AM	2.23	1.28
10:00 - 11:00 AM	2.26	1.31
11:00 - 12:00 AM	2.18	1.31
12:00 - 1:00 PM	2.19	1.31
1:00 - 2:00 PM	2.11	1.32
2:00 - 3:00 PM	2.17	1.28
3:00 - 4:00 PM	2.15	1.28
4:00 - 5:00 PM	2.18	1.27
5:00 - 6:00 PM	2.17	1.25
6:00 - 7:00 PM	2.30	1.38

the priority lane. If all HOVs on the facility utilized the HOV lane this value would be 100 percent. It is interesting to note that the highest percentage occurs in the p.m. peak, when 32 percent of the HOVs are on priority lanes systemwide. This value reaches nearly 70 percent for heavily congested locations.

Occupancies of Priority and Nonpriority Lanes

Because each vehicle in the priority lane should have at least two occupants, the average automobile occupancy of priority lanes should be greater than 2.0. The tabulation of automobile occupancies for priority and nonpriority lanes is given in Table 4. On some links in the system the average occupancy of a priority lane is less than 2.0 because of violations of the HOV system. Automobile occupancy is calculated as the average occupancy of those vehicles classified as private automobiles. It does not include the other classifications, such as motorcycles, vans, buses, or taxis.

The lowest automobile occupancy for both priority and nonpriority lanes occurs during the a.m. peak. Areawide, priority lanes have an automobile occupancy of 2.10 persons per vehicle during the 6:00 to 8:00 a.m. period. The areawide automobile occupancy for nonpriority lanes during the 7:00 to 8:00 a.m. period is 1.15 persons per vehicle. The highest areawide automobile occupancy occurs during the 6:00 to 7:00 p.m. period, with 2.30 and 1.38 persons for priority and nonpriority lanes, respectively. The average 13-hr occupancy for priority and nonpriority lanes is 2.18 and 1.27 persons, respectively.

The mean automobile occupancy for priority and nonpriority lanes is shown in Figure 4. The plot indicates that occupancies for the priority lanes mimic those for the nonpriority lanes, with the exception of the 11:00 a.m. to 2:00 p.m. period, when the priority-lane occupancy dips slightly although the non-priority-lane occupancy remains relatively constant.

PRIORITY-LANE VIOLATIONS

To determine violation rates, tabulations were developed showing the percentage of one-person automobiles in priority lanes. The overall violation rate is approximately 6 percent.

An analysis of variance was performed to test whether violation rates were different based on area type or time of day. Only AREA has a significant effect ($P < 0.001$) on the violation rate of priority lanes. This means that time of day has no significant effect on violation rates. A Duncan's test was performed on these means as a function of area type; the results are shown in Table 5.

The violation rate in the core area is approximately twice as high as that in the urban and suburban areas. There may be any number of reasons for this phenomenon. Part of this may be because traffic volumes tend to be higher in the core area. The nonpriority lanes may be congested to the point where there is a significant travel time advantage in moving to the priority lane, and violators may be willing to accept the risk of being cited to gain this travel time advantage. The travel time advantage may not be as great in the less congested urban and suburban area types. Another possible explanation may be that drivers are taking advantage of exclusive HOV ramps. There are three sets of priority ramps located within the core area.

Examination of the links sampled in the vicinity of these ramps indicates that these are high-violation-rate locations. Therefore,

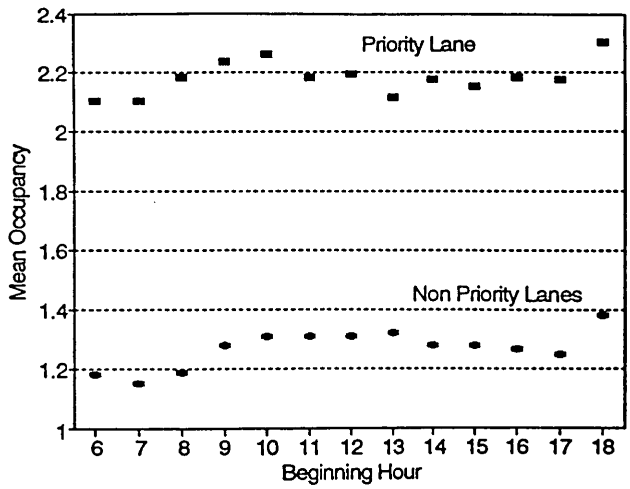

FIGURE 4 Average automobile occupancy of priority and nonpriority lanes.

TABLE 5 Duncan's Grouping for Priority-Lane Violations by Area Type

Duncan Grouping	Mean	N	Area Type
A	8.52%	78	Core
B	4.29%	78	Urban
C	3.08%	52	Suburban

the high violation rates may not be associated with travel time advantages for those traveling on the freeway but with advantages to be gained by traveling on alternative ramps and arterial streets.

As stated previously, the overall violation rate of priority lanes is approximately 6 percent. A study by Rutherford et al. (*2*) reports the violation rates of various facilities in other regions. The violation rate in the Phoenix metropolitan region appears to be lower than those in other more congested regions across the country. The highway patrol emphasizes enforcement of the 2+-person requirement for HOV lanes.

EFFECTIVENESS OF HOV LANES

To evaluate priority-lane effectiveness, two values have been calculated in this study, automobile occupancy and vehicle occupancy. Automobile occupancy is defined as the average occupancy considering only the private automobile classification. Vehicle occupancy is the average occupancy considering all vehicles on the facility. A mean occupancy was used for each vehicle type as shown in Table 6.

Automobile and vehicle occupancy for both HOV and non-HOV lanes on freeways with HOV lanes and for all lanes on freeways without HOV lanes is given in Table 7, which indicates that the occupancies on priority lanes are considerably higher than those of the adjacent nonpriority lanes.

The evaluation of the impact of HOV facilities on air and noise pollution has been of interest to many transportation professionals. However, as Turnbull et al. (*3*) point out, there is a general lack of consensus regarding the most appropriate measures to use in this evaluation.

Most evaluations of HOV lanes are in the form of before-and-after studies, which are structured to examine the same location before and after the implementation of the HOV lane. That situation is somewhat different from that of the HOV lanes in the Phoenix area, because these lanes were constructed mostly with new freeway segments. Using the data collected for this study, three different measures of effectiveness are presented to evaluate the HOV facilities.

Effect of Congestion on HOV Lane Usage

A review of the data indicates that facilities with traffic flowing at or below 1,400 vehicles per hour per lane are in an uncongested state. As the flow rate increases over 1,400, congestion begins to increase. Some facilities may exist in an uncongested state most of the day, incurring congestion only during the peak hours. Table

TABLE 6 Mean Occupancies for Each Vehicle Classification

	HOV Lane		Non-HOV Lane	
Vehicle Type	Mean Occupancy	Percentage	Mean Occupancy	Percentage
Passenger Vans	10.5	0.2	5.8	0.5
Light Trucks	2.2	4.3	1.3	4.6
Medium Trucks	2.0	0.7	1.1	2.9
Heavy Trucks	2.0	0.2	1.1	5.2
Motorcycles	1.1	5.8	1.1	0.4
Recreational Vehicles	2.2	1.6	1.3	0.2
Buses	30(AM)/40(PM)	0.9	30(AM)/40(PM)	0.2

1. Average occupancy of Van Pools as provided by Regional Public Transportation Authority
2. Average occupancy of Buses as provided by "Phoenix Metropolitan Area Quarterly Transit Ridership Report," 1992, Phoenix Transit System.

All other values are estimated.

TABLE 7 Automobile and Vehicle Occupancy for Freeways

Facility	Lane	Mean Auto Occupancy	Mean Vehicle Occupancy
Freeways With HOV Lanes	priority	2.162	2.383
Freeways With HOV Lanes	non-priority	1.247	1.327
Freeways Without HOV Lanes	all	1.288	1.357

TABLE 8 Variation in Number of Passengers per Lane per Hour and Vehicles per Lane per Hour by Freeway Congestion

Facility Congestion Level	Vehicles/Lane/Hour HOV	Vehicles/Lane/Hour Non-HOV	Passengers/Lane/Hour HOV	Passengers/Lane/Hour Non-HOV
Congested	474	1712	1135	2147
Uncongested	140	913	343	1240
All	238	1147	575	1505

8 shows how vehicles per lane and passengers per lane differ between those hours when the non-HOV lanes are congested and those hours when the non-HOV lanes are not congested.

The data indicate that the number of passengers per lane in the HOV lane of congested facilities is much higher than the passengers per lane on uncongested facilities. Even when adjacent freeway lanes are congested, the flow rate of 474 vehicles per hour indicates that the HOV lane is operating at a very acceptable level of service. The number of vehicles on the congested non-HOV lanes is approximately three times the number of vehicles in the adjacent HOV lane, yet these lanes are carrying only two times as many passengers as the adjacent HOV lanes.

Mode Shift Effects

Figure 5 shows that the average automobile occupancy of freeways with HOV lanes is greater than that of freeways without HOV lanes. In the urban area this is a significant difference. One possible explanation for this difference in automobile occupancy may be the propensity for drivers to change their driving habits because of the presence of the HOV facility. If drivers were not changing their habits, one would expect the occupancy rates of both facilities to be similar. In fact, in the suburban area type the occupancies are similar. However, in the suburban area there is little advantage to using the HOV lane because the freeway operation is relatively uncongested. This analysis suggests that in the Phoenix area, there is a real mode shift from single-passenger automobiles to higher-occupancy vehicles.

Another possibility is that carpools have shifted from non-HOV freeways and arterials to HOV freeways to take advantage of the HOV lanes. Adjacent facilities were not sampled in this study. Further work could test these hypotheses.

Persons Utilizing HOV Lanes

Another way to evaluate the effectiveness of HOV lanes is to tabulate the number of people being carried in the priority and nonpriority lanes. Even though the raw volume of vehicles in the priority lane is typically lower than that in the adjacent lanes, the occupancy of these vehicles is considerably higher. If the priority lane carries more people than the adjacent lanes, it is supposed that this is a more efficient means of automobile travel because the priority lane is less likely to incur delay as a result of congestion.

Table 9 shows the average vehicles and passengers per lane for those facilities with HOV lanes. These values are the weighted average for the entire 13-hr data collection period. As shown in Table 9, priority lanes carry, on average, less than half the passengers carried on the nonpriority lanes.

A tabulation of the number of persons carried on all HOV facilities was performed to determine whether there were any periods during which the HOV lanes carry more persons than the adjacent non-HOV lanes. The results indicate that systemwide there were none. The HOV lanes came closest in volume to the non-HOV lanes from 4:00 to 6:00 p.m., when both HOV and non-HOV lanes were carrying their highest volumes.

An analysis was also performed to identify individual segments where the person flow rate in the HOV lane was greater than that on the adjacent nonpriority lanes. Six locations were identified, as shown in Table 10. All six locations are heavily congested during

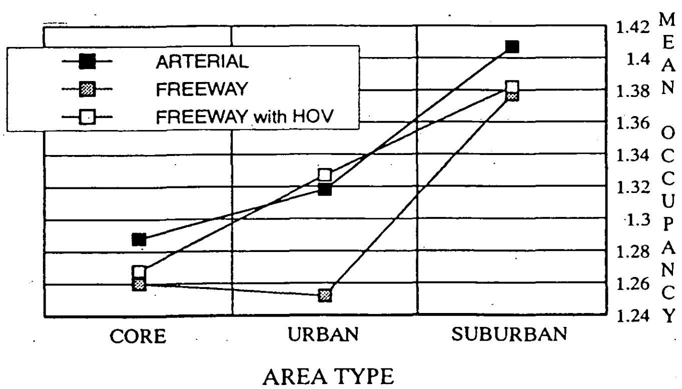

FIGURE 5 Mean automobile occupancy versus area type and facility type.

TABLE 9 Lane Passenger Volume by Area Type (Freeways with HOV Lanes)

	Vehicles/Lanes/Hr		Passengers/Lane/Hr	
	HOV Lane	Non-HOV Lane	HOV Lane	Non-HOV Lane
Core	262	1170	609	1504
Urban	227	1172	573	1516
Suburban	81	602	208	850

TABLE 10 Lane Passenger Volume by Time of Day

		Passenger/Lanes	
Location	Time of Day	HOV Lane	Non-HOV Lane
I-10/48th St. Eastbound	4:00 - 5:00 PM	2064	1779
I-10/48th St. Eastbound	5:00 - 6:00 PM	2685	1640
I-10/Broadway Eastbound	4:00 - 5:00 PM	2119	2001
I-10/Broadway Eastbound	5:00 - 6:00 PM	1997	1597
I-10/10th St. Eastbound	5:00 - 6:00 PM	2106	1992
I-10/67th Ave. Eastbound	7:00 - 8:00 AM	1813	1483

the peak hours. At these locations it appears that the HOV lane is highly effective, allowing those people using the HOV lane to travel at reasonable speeds. During the remainder of the day, the priority lanes are not heavily used, but the extra capacity is not needed to maintain high speeds.

The person flow rate of HOV lanes would increase significantly if there were more express bus service on the freeways. There are fewer than 10 eastbound and westbound express buses on I-10 during the evening peak hour. Yet these 10 buses carry nearly 15 percent of the peak-hour passengers on the busiest section of the HOV system.

SUMMARY OF EFFECTIVENESS OF HOV LANES

A review of the results of these three analyses shows that HOV lanes become very effective in periods of high congestion on the adjacent freeway lanes. During periods of low congestion, the number of people on the HOV lane drops to a much smaller percentage of the total freeway traffic.

On the basis of the analysis it appears that freeways with HOV lanes have much higher automobile occupancy than those without HOV lanes. It is reasoned that the cause of this increase in occupancy is a shift of single-occupancy vehicles to higher-occupancy modes of travel along HOV facilities in the urban area type.

If the goal of an efficient transportation system is to increase overall person-carrying capacity it would appear that HOV lanes are very effective in moving large volumes of people at relatively uncongested speeds. When the freeway is operating below the capacity of the nonpriority lanes, the HOV lanes are little used and little needed. They become effective when the adjacent freeway lanes become overloaded. More express bus service would increase their efficiency further. Although the Phoenix-area HOV system may not, in large part, be effective by some of the more traditional measures of effectiveness, the system has been successful in encouraging higher vehicle occupancies and improving HOV travel.

REFERENCES

1. *Guide for Estimating Urban Vehicle Classification and Occupancy.* Urban Planning Division, FHWA, U.S. Department of Transportation, Sept. 1980.
2. Rutherford, G. S., R. K. Kinchen, and L. N. Jacobson. Agency Practice for Monitoring Violations of High-Occupancy-Vehicle Facilities. In *Transportation Research Record 1280,* TRB, National Research Council, Washington, D.C., 1990, pp. 141–142.
3. Turnbull, K. F., R. H. Henk, and D. L. Christiansen. *Suggested Procedures for Evaluating the Effectiveness of Freeway HOV Facilities.* Report DOT-T-92-01. FHWA, U.S. Department of Transportation, 1992.

Publication of this paper sponsored by Committee on High-Occupancy-Vehicle Systems.