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# RECORD

## No. 1446

*Highway Operations, Capacity, and Traffic Control*

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# High-Occupancy-Vehicle Systems and Freeway Operations

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# Transportation Research Record 1446

## Contents

# Foreword

The papers in this volume were presented at the 1994 Annual Meeting of the Transportation Research Board under the sponsorship of the Committees on Transportation System High-Occupancy-Vehicle (HOV) Systems Management, Freeway Operations, and Travelers Services. The papers cover a wide range of problems reflecting the concerns of both the theoreticians and the practitioners.

These specific areas of traffic operations are receiving considerable attention because of the emphasis on intelligent vehicle-highway systems (IVHS), provisions of the Intermodal Surface Transportation Efficiency Act (ISTEA), implications of the Clean Air Act Amendments, ever-increasing traffic congestion, and recognition of the importance of incident management for reducing nonrecurring traffic congestion.

Readers with an interest in HOV project and planning techniques will find papers on HOV lane evaluation, use of computer simulation models for HOV applications, HOV strategies and priority treatments on toll facilities and at ramp meters, conversion of mixed-use freeway lanes to HOV, and HOV marketing to build a constituency.

Those readers with a specific interest in freeway operations will find papers concerning ramp metering and increasing freeway ramp capacity, freeway service patrols, and design of emergency parking for restriped urban freeways.

# 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.

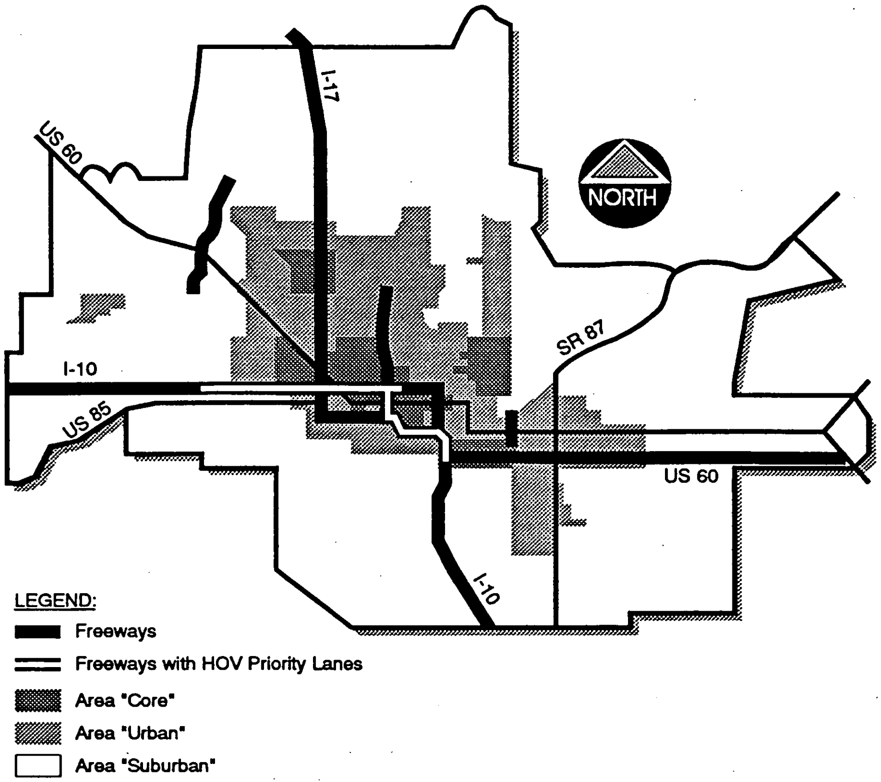


**FIGURE 1 Phoenix metropolitan area.**

## 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.

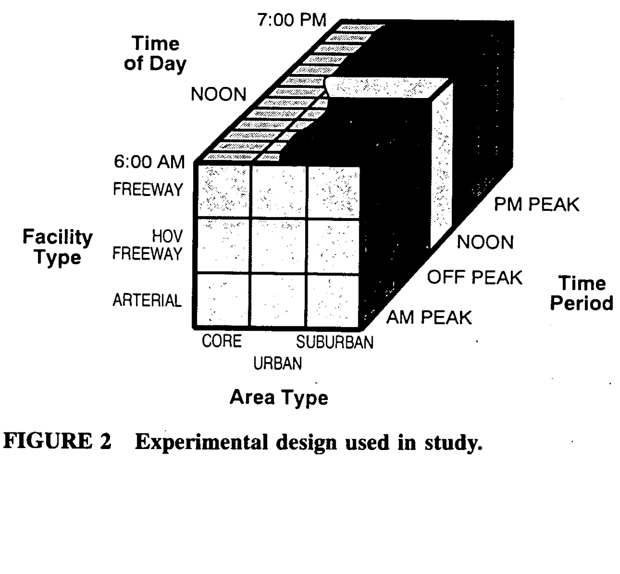


**FIGURE 2 Experimental design used in study.**

### 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 | | | |

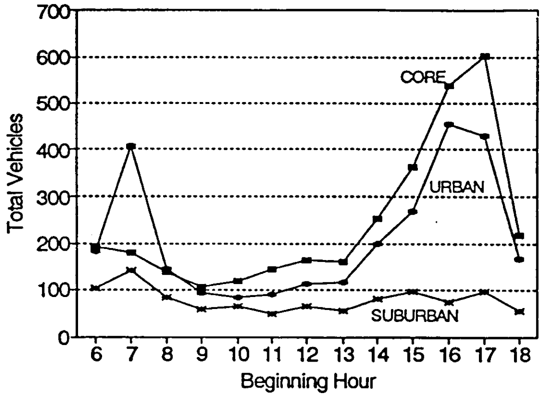


**FIGURE 3 Average volume on priority lanes by time of day and area type.**

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,

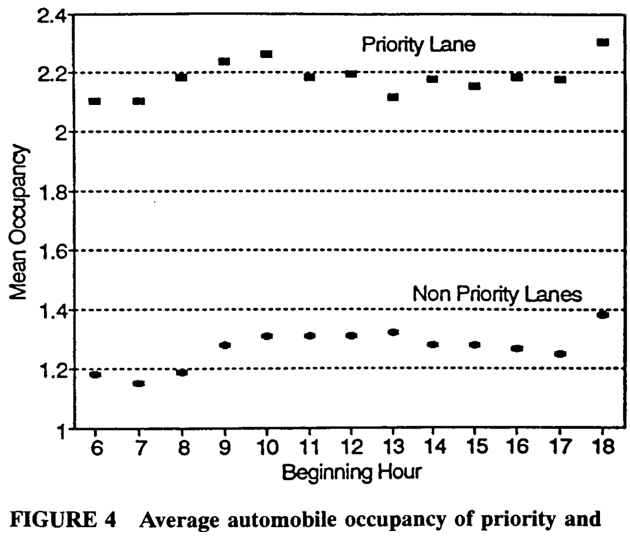


**FIGURE 4 Average automobile occupancy of priority and nonpriority lanes.**

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**

| | Vehicles/Lane/Hour | | Passengers/Lane/Hour | |
|---|---|---|---|---|
| Facility Congestion Level | HOV | Non-HOV | HOV | 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

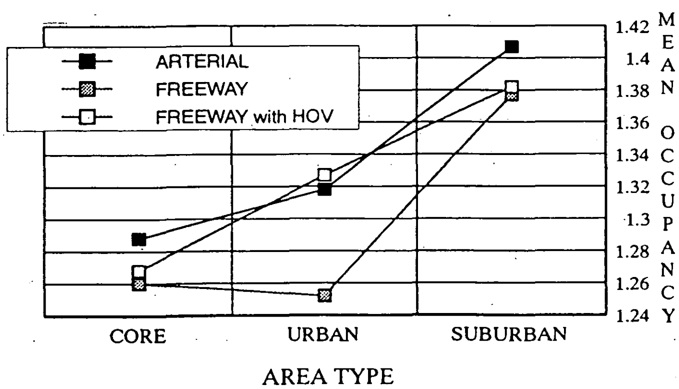


**FIGURE 5 Mean automobile occupancy versus area type and facility type.**

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.

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# Use of INTEGRATION Model To Study High-Occupancy-Vehicle Facilities

VINTON W. BACON, JR., DAVID J. LOVELL, ADOLF D. MAY, AND MICHEL VAN AERDE

A study was undertaken to assess the potential use of the INTEGRATION computer model to simulate high-occupancy-vehicle (HOV) facilities and to perform some preliminary investigations with the model. It was found that the model is capable of simulating a wide range of HOV facility types. Of those types tested, none was found that the model was not able to reasonably simulate. However, a few problems were encountered in using the model. First, the model works using units of vehicles, not passengers. It was found that this problem could be rectified by simple modification of some of the input and output files. Second, it is possible to indirectly model lanes whose status changes with time by creating an incident on a link that is to be closed for certain periods. Overall, the model seemed to accurately simulate HOV facilities. A number of runs were made on a simple straight-pipe network and a network that represents a portion of the Santa Monica freeway corridor in Los Angeles to determine if the results derived from INTEGRATION conform to what would be expected in the field. Initial analysis of the results from various sensitivity studies indicated that the model was accurately modeling the facilities in question. Because of the preliminary nature of the research, a number of recommendations for future research and some potential modifications to the model are given.

High-occupancy-vehicle (HOV) facilities are becoming an increasingly important tool to control urban freeway congestion and increase the person-carrying capacity of the road system. In fact, the federal government mandates that federal funds for added freeway lanes often can be spent only if the added lanes are HOV or auxiliary lanes. Because of the importance of these facilities, there is a need among transportation engineers and planners to develop analytical tools with which to determine their operating characteristics, effectiveness, and implementation strategies. Because priority treatment for HOV vehicles has been implemented only recently on a widespread basis, a limited number of before-and-after evaluation studies have been undertaken from which to extract meaningful information.

One very new and promising tool with the potential to address this need is the INTEGRATION computer simulation model, developed at Waterloo and Queen's Universities in cooperation with the Ontario Ministry of Transportation. INTEGRATION is unique among models of traffic behavior because it combines the ability to simulate deterministic traffic flow with the ability to replicate dynamic route choice behavior (traffic assignment). This allows the users to study the long-term effects of alternatives on the facility in question and on the surrounding street system. In addition, phenomena such as instantaneous traffic diversion in reaction to prevailing conditions and the provision of real-time route information to drivers can be studied. The INTEGRATION model can represent several different types of users, each having different access to real-time information, including HOV and non-HOV users.

V. W. Bacon, Jr., D. J. Lovell, and A. D. May, Institute of Transportation Studies, 109 McLaughlin Hall, University of California, Berkeley, Calif. 94720. M. Van Aerde, Civil Engineering Department, Queen's University, Kingston, Ontario K7L 3N6 Canada.

## PURPOSE AND SCOPE

The purpose of this paper is to investigate the feasibility of using the INTEGRATION computer simulation model for HOV facilities and to perform some preliminary investigations with the model. First, the model itself was tested to determine its capabilities as well as its strengths and weaknesses in simulating HOV facilities. Second, numerous simulation runs were made to assess the potential benefits of HOV facilities given various percentages of passengers in HOV vehicles. The first series of runs was made on a simple straight-pipe network. The next series of runs was undertaken using a subsection of the Santa Monica freeway corridor in Los Angeles. This network was coded in previous research by Gardes and May (*1*).

## SIMULATION OF HOV FACILITIES WITH INTEGRATION MODEL

### Simulated Vehicle Types

INTEGRATION has five classes of vehicles that may be used in the simulation. Table 1 contains descriptions of these five vehicle

**TABLE 1 Five Vehicle Types of INTEGRATION**

| Vehicle Type | Description |
|---|---|
| 1 | Background Vehicles - Route choice based on free-flow speed unless historic information or specified path trees are provided. |
| 2 | Guided Vehicles - Have access to real-time information at every node or at selected locations on which to base their route choice. |
| 3 | Drivers with Anticipatory Knowledge - Can use both real-time information and historical information. |
| 4 | Trav-Tek Vehicles - Have advanced route guidance systems within the vehicle. |
| 5 | Special Facility Users - Have exclusive access to selected links in the network (i.e. HOV vehicles). Can base route choice on specified path trees or on real-time information. |

types. These are discussed in more detail in the INTEGRATION user's manual (*2*). Type 5 vehicles, special facility users, can be considered HOV vehicles, and links in the network can be coded as HOV links. In this way, only HOV vehicles can use these HOV links. An additional feature of these vehicles is that they also can be given the route choice capabilities of Type 2 vehicles and can choose the shortest route to their destination, which may include both HOV and non-HOV lanes. The quality of information received by every vehicle type may be varied by using two parameters. The *F*- (frequency) parameter determines the frequency, in seconds, with which the information is updated. The *D*- (distortion) parameter, varying from −0.5 to 0.5, determines the accuracy of the information received. A *D*-parameter of 0 indicates perfect information, whereas movement away from 0 represents ever-increasing error levels.

## Input File Modification

Of the five required and four optional input files to the model, only four are of specific concern to HOV facilities. These nine input files are described in Table 2. In the creation of a typical mainline freeway HOV lane with a shared right-of-way, the first step is to modify input File 2, the link file. An original entry from the link file for the Santa Monica Freeway corridor network is as follows:

73 121 218 0.812 70 1700 5 0.35 1.0 1.0 0 0 0 0 0 1 Freeway EB

From left to right the columns represent link number, start node, end node, length (kilometer), free-flow speed (kilometer/hour), capacity (vehicle/hour/lane), number of lanes, platoon dispersion factor, the *A*- and *B*-parameters of the speed-flow curve, four columns for signal control, the HOV variable (a variable indicating whether real-time information is provided to this link), and a brief description of the link. This entry is copied and modified to produce the following entries:

73 121 218 0.812 70 1700 5 0.35 1.0 1.0 0 0 0 0 01 Freeway EB
257 121 218 0.812 70 1700 1 0.35 1.0 1.0 0 0 0 0 1 1 FW HOV EB

The three changes made are underlined and discussed below from left to right. First, a unique link number needs to be assigned to the new HOV link. Link numbers need not be sequential. The original link number was 73, and the new HOV link is assigned 257. Second, the number of lanes is changed to reflect the addition of an HOV lane. In this example, an HOV lane was added to the network. The last change is in the boolean variable that indicates whether a lane is an HOV lane or not. Switching this from 0 to 1 ensures that only Type 5 vehicles will use this link. The model ensures 100 percent compliance by not allowing for any cheating by non-HOV vehicles. However, the percentage of HOV vehicles can be changed to reflect any rate of expected violation of HOV lane usage.

Adding HOV links in the manner indicated above will simulate an HOV facility with no boundaries between HOV and non-HOV lanes. The HOV vehicles will be able to transfer between HOV and non-HOV links at any upstream node that is common to the two. The modified freeway links in this network were on average 0.44 km (0.26 mi) long. In reality, an HOV vehicle may switch between these links at any point. A more realistic model could have been achieved by dividing these links into smaller segments. To simulate an HOV facility with physically separated HOV and non-HOV lanes requires that the adjacent links not have the same upstream node numbers. This would require the creation of new nodes in input File 1, the node file. This was not attempted in this study. Using these methods, the model can simulate a facility with a continuous barrier, a series of discontinuous barriers, or no barriers at all.

HOV vehicles may be assigned specific routes that they must follow throughout the simulation. These are specified in the optional input File 8. This file is not recommended if the routing of HOV facilities is to be based on the attractiveness of HOV facilities versus non-HOV facilities. For that reason, this file was not used.

Input File 4 contains the origin and destination data. Because of the costly nature of these data, the file usually is generated synthetically using the program QUEENSOD, a supporting module of the INTEGRATION program. A sample entry from this file is given:

3 24 51 1500 1.0 0 3600 0.0 0.85 0.0 0.0 0.15

The first and second underlined values represent the origin and destination nodes for this entry. The third underlined value indicates the demand in vehicles per hour between the indicated origin and destination for the given period (0 to 3,600 sec in this example). The five underlined values on the right define the distribution of vehicle types for this origin-destination pair. In this entry 85 percent of the vehicles are Type 2 and 15 percent are Type 5. These five values must add up to 1. To be realistic, if the percentage of HOV vehicles is increased, the corresponding demand rate should be decreased to reflect the reduction in the total number of vehicles. This will be discussed in greater detail.

**TABLE 2 Nine Input Files of INTEGRATION**

| Input File | Description |
|---|---|
| * 1 (required) | Node File - Specifies x and y coordinates of all nodes in the network for purposes of graphical display. |
| * 2 (required) | Link File - Contains start and end nodes and physical characteristics of the links. |
| 3 (required) | Signal File - Signal timing plans. |
| * 4 (required) | Origin/Destination Traffic Demand File - Specifies demand rates for all O/D pairs for each time slice. |
| 5 (required) | Incident File - Includes length, severity and location of any incidents during the simulation. |
| 6 (optional) | Average Travel Times File - Provides average travel times for all links for use as historical information. |
| 7 (optional) | Time Series of Anticipated Travel Times - The same as file 6 except that travel time information is given for each user-specified time slice. |
| * 8 (optional) | Static Path Tree File - This file has the user-specified path trees for type 5 vehicles. |
| 9 (optional) | Time Series of Multipath Background Traffic Routings - The same as file 8 but used for type 1 vehicles. |

* Specific to HOV Studies

### Potential Modeling of HOV Facilities with INTEGRATION

*Network Possibilities*

By modification of the input files a wide variety of HOV facilities can be modeled with INTEGRATION. Any combination of links may contain HOV lanes to reflect HOV lanes of any length or at any part of the network. Any number of HOV or non-HOV lanes can be simulated. The analysis of a possible list of proposed HOV lane designations is feasible with the INTEGRATION model. Also, the simulation of HOV lanes is not restricted to freeways. The above discussion applies to arterial streets as well as freeways. By adding an additional link at an on ramp one can simulate priority bypass of ramp meters. The model also allows one to vary the traffic demands and HOV user levels over both individual origin-destination pairs and time slices.

*Lanes Whose Status Will Change with Time*

One potential problem is modeling lanes whose status will change throughout the simulation period. Examples of this are a shoulder lane that can be used during certain hours, lanes that are for HOV use only during certain hours, and reversible lanes. The link file does not provide for changes to be made to the physical structure of the network during the simulation period. One possible way around this problem would be to use input File 5, the incident file. The incident file allows for any number of lanes on a link (including portions of a lane) to be blocked for any period of time. Any number of incidents can be simulated. For example, to simulate a lane that switches from non-HOV to HOV for a certain period, one could set up two links, one for the HOV lane and one for the non-HOV lane. The entire link could be blocked for the period that the link is HOV to ensure that no non-HOV vehicles use the link during that period. Reversible lanes could be blocked in a similar manner.

*Vehicle-People Conflict*

Another potential problem is that the INTEGRATION model uses demand data that are measured in units of vehicles and not passengers. Of course, the decision of how many vehicles may use the HOV facility is not decided on a percentage basis but on an occupancy basis. Typically there are only two values that are chosen from when a cut-off level is selected: two or more persons per vehicle or three or more persons per vehicle. These two values will translate into three percentages that would be allowed onto the HOV facility.

As mentioned, if a study is conducted to determine the effects of altering the percentage of HOV passengers (or percentage of HOV vehicles), the number of vehicles must be altered to reflect the corresponding change in the total number of vehicles in the system. To accomplish this with the model, two steps were taken. First, a spreadsheet was used to calculate the change in the number of vehicles given the change in percentage of HOV passengers. Second, a simple computer program was written that can change the demand for all of the origin-destination pairs by any given percentage. This will be discussed in detail. It was believed that it would not be difficult to develop programs to automate this process.

The output from the model is also presented in terms of vehicles and not passengers. The process of manipulating the output files to reflect average passenger travel time as opposed to average vehicle travel time was also quite simple. Again, an average occupancy rate for HOV vehicles must be provided to the model.

## STUDIES USING STRAIGHT-PIPE NETWORK

In this section the simulation experiments conducted with the straight-pipe network are discussed and presented. The design of the experiment is discussed first followed by the presentation and interpretation of the numerical results.

### Design of Experiment

The first freeway network considered is a straight-pipe network consisting of a directional freeway 14.8 km (8.9 mi) long. The bottleneck itself is 0.8 km (0.5 mi) long and is located 0.8 km (0.5 mi) from the downstream end of the network. The purpose of the bottleneck and its location was to ensure that congestion would occur in the non-HOV lanes and that the queue would not block HOV vehicles from entering the HOV lane. With the HOV lane added, the network contains only 17 nodes and 32 links. The 17 nodes are all in a straight line. Between each pair of adjacent nodes there are two links—an HOV link and a non-HOV link.

The initial design of the freeway is a mixed-flow facility that has four lanes, except for the potential bottleneck, which has three lanes. A continuous lane is then added for the entire length of the freeway and will be analyzed as an added mixed-flow lane and alternatively as an HOV lane with varying HOV demand levels. All traffic demands originate at the upstream end of the directional freeway and have destinations at the downstream end.

Studies were made on this network using two levels of peak-hour demand: 8,000 and 10,000 persons per hour. For each demand level, the following investigations were made:

- Existing freeway design without an added lane;
- Existing freeway design with an added mixed-flow lane; and
- Existing freeway design with an added HOV lane and the percentage of passengers using HOV vehicles varying from 2 to 35 percent in 2 percent increments.

These three scenarios are shown in Figure 1. For simplicity the HOV vehicles were assumed to carry two persons each, and non-HOV vehicles were assumed to carry one person. Values above 32 percent were not studied because they represent a situation in which the travel times would be roughly equal between HOV and non-HOV lanes. There would be little benefit to constructing and operating the HOV facility in this manner.

### Presentation and Interpretation of Results

The results using the peak-hour demand of 8,000 persons per hour are shown in Figure 2. The average travel time for the entire length of the freeway under the existing design was 18.3 min and resulted in a total travel time of 2,440 passenger-hours. Similar

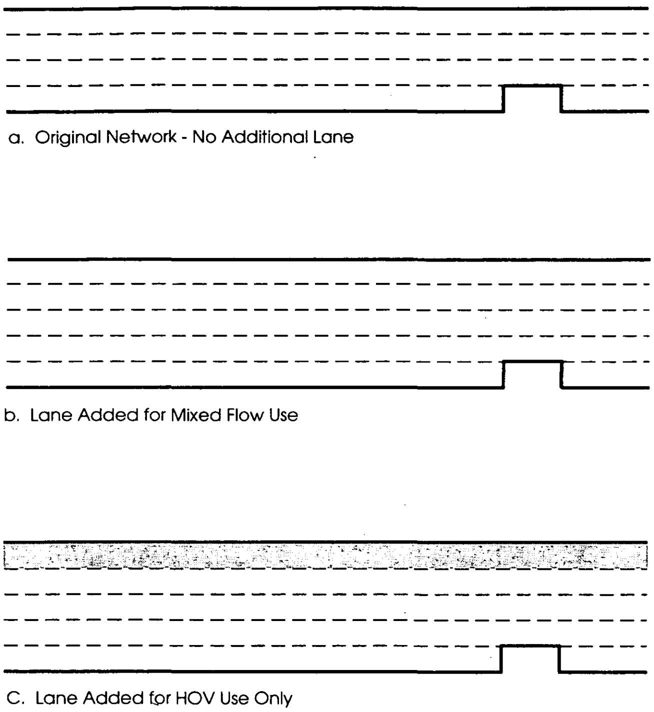


**FIGURE 1 Three straight-pipe scenarios.**

values for the existing freeway design with the added mixed-flow lane were 14.8 min and 1,979 passenger-hours. These values represented a reduction of 3.5 min in average trip travel time and 461 passenger-hours in total travel time with the added mixed-flow lane.

Similar results for the existing freeway design with an added HOV lane assuming HOV passengers varying from 2 to 32 percent in 2 percent steps are shown in Figure 2. The results conform to what would be expected in the field. At very low percentages of HOV passenger volume the HOV passengers enjoy a very low travel time. As this percentage increases and the HOV lane becomes more congested, their travel time increases. The travel times for non-HOV passengers and the system as a whole decrease as the percentage of HOV passengers rises for two reasons: the HOV lane is utilized better and the number of vehicles in the network is lower. A frequent argument against these system benefits achieved by HOV facilities is that more latent vehicular demand would be induced on the roadway; therefore the reduction in the total number of vehicles would not be as significant. Attempting to resolve this conflict is well beyond the scope of this paper.

Figure 3 shows the results with a demand of 10,000 persons per hour. The results are similar to those in Figure 2. As expected, HOV passengers benefit more at low percentages on the more congested network. Also, the difference between average travel times with and without an added lane is greater with the increased congestion. The average travel time savings associated with the added lane with 10,000 persons is 9.2 min versus 3.5 min for 8,000 persons. The total travel time savings increased from 461 to 1,532 hr.

## STUDIES USING SANTA MONICA FREEWAY CORRIDOR NETWORK

### The Network

A number of sensitivity studies were done to assess the model's ability to simulate HOV facilities on a more complex network. The Santa Monica Freeway corridor network was used for all of the following runs. This network consists of an 18.2-km (11.4-mi) section of the Santa Monica Freeway with two parallel and eight crossing arterial streets. The network contains 171 nodes and 308 links, and the simulation period is from 6:00 a.m. to 10:00 a.m.

### Design of Experiment

Two potential scenarios were examined using the network: adding an HOV lane to the entire eastbound freeway portion of the network and taking a lane away for conversion to an HOV lane. These were chosen to represent two scenarios with very different levels of congestion. Neither of these possibilities is actually expected to happen in the near future. Taking a lane away would be physically very simple but politically very difficult. In fact, there once was an HOV lane on the Santa Monica Freeway that was removed because of public opposition. Adding a new lane would be costly and likely encounter opposition.

These runs were made with the *F*- and *D*-parameters set at 10 and 0, respectively. These values means that the drivers have virtually continuous and perfect information about the travel times

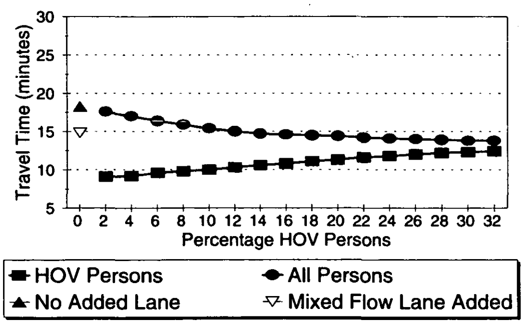


**FIGURE 2 Straight-pipe network with 8,000 persons.**

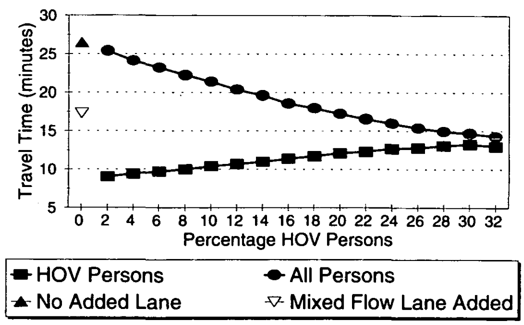


**FIGURE 3 Straight-pipe network with 10,000 persons.**

on the network. Because this network is simulating only recurring congestion, real-time information is essentially the same as historical information. Thus, this simulation represents the equilibrium that will be reached after the system is in place for some time and drivers have determined their shortest path. Another series of runs was done with the *F*- and *D*-parameters set to 60 and 0.2, respectively, to represent a poorer quality of information. The results were similar, except that travel times as a whole were slightly higher and there was significantly more variation in travel times with the poorer quality of information.

Data from California Department of Transportation (Caltrans) indicate that 10 percent of the vehicles on the freeway during the morning peak period contain two or more passengers, and the occupancy for HOV vehicles is 2.2 persons per vehicle. These data come from only a single count done in 1991. Using these figures, it was assumed that a single conversion from non-HOV to HOV would displace 1.2 vehicles and that the existing occupancy ratio for the network is 1.12 persons per vehicle. Because the original origin-destination file called for 191,097 vehicles, it was assumed that the network carries 214,029 passengers.

A spreadsheet was developed and used first to calculate the number of HOV and non-HOV passengers on the basis of the percentage of HOV passengers. Then the spreadsheet was used to calculate the number of both types of vehicles and the percentage of each on the basis of the assumed occupancy rates. The percentage of each vehicle type is then entered into the origin-destination pairs file of the INTEGRATION model. In addition, a vehicle adjustment factor is calculated for each percentile. This factor determines the amount by which the total number of vehicles must be adjusted to reflect the displacement of vehicles as a result of conversion from non-HOV to HOV. A program was written that automatically adjusts the demand data in the origin-destination pairs file by any given factor.

The model assigns traffic in a stochastic manner and the number of vehicles generated in the simulation often differs slightly from that specified in the origin-destination file. As a result the percentage of HOV vehicles and, hence, the percentage of HOV passengers in the simulation often differed slightly from the desired amount. For reasons of clarity, the *X*-axis in Figures 4 and 5 gives the desired percentages, not the actual percentages.

### Sensitivity Studies

Sensitivity studies were made by varying the proportion of HOV passengers from 0 to 22 percent in increments of 2 percent for both scenarios, adding and taking away a lane. The value of 22 percent was chosen as a stopping point because this value is beyond the point where the travel times converge for both studies. On the basis of data from Caltrans, the system actually has nearly 20 percent passengers in HOV vehicles. The results of these experiments are shown in Figures 4 and 5.

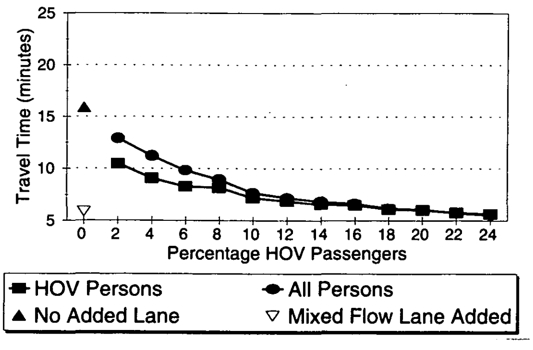


**FIGURE 4 Lane added to network: Santa Monica Freeway.**

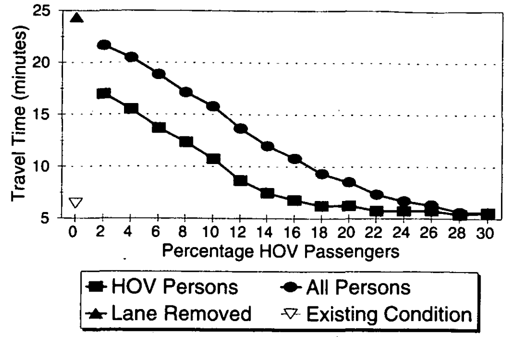


**FIGURE 5 Lane converted to HOV usage: Santa Monica Freeway.**

Figure 4 shows the results from the scenario in which an HOV lane was added to the existing network. Unlike the straight-pipe network, the travel times for HOV passengers actually decrease as the percentage of HOV passengers begins to rise. The reason for this change is likely that the congestion experienced by non-HOV vehicles affects the HOV vehicles as well. As the congestion is eased, travel times for both vehicle types improve. This is not the case with the straight-pipe network. Another difference between this network and the straight-pipe network is that the travel times for both vehicle types converge at a much lower percentage in the Smart Corridor network. [The Smart Corridor is a project under way on the Santa Monica Freeway to simulate various Intelligent Vehicle-Highway System (IVHS) strategies.] This convergence is expected for two reasons. First, the percentage of the freeway designated for HOV vehicles is much smaller in this example. Adding a lane creates a total of seven lanes at some points. Second, because the HOV vehicles are distributed across all origin-destination pairs evenly, many HOV vehicles take routes in which they do not use the HOV facility. One should also note that the travel times essentially have converged at 14 percent. At percentages of HOV passengers higher than 14 percent, the travel times for both types are essentially the same but continue to decrease because of the decreased number of vehicles on the network.

The results of taking a lane of the existing freeway and converting it to HOV are shown in Figure 5. The existing condition is assuming an HOV passenger percentage of 20 percent. Note that the results indicate that the percentage of HOV vehicles would have to increase to 26 percent before the average passenger time dropped below that of the existing condition. As with the straight-pipe network, the difference between HOV and non-HOV vehicles is greater under heavier congestion.

## FUTURE STUDIES

The overall assessment of the research is that the model is a powerful tool in the analysis of HOV facilities. The results of the sensitivity analysis are that the model gives results that conform with what would be expected in the field. However, the research conducted here is clearly preliminary in nature. Future research with the model is necessary to determine its accuracy and to enhance its capabilities. Some potential areas for future research are discussed below.

### Calibration with Actual Data

The test of any model is how well it predicts real-world conditions. Before-and-after study results of a real-world situation should be sought and compared with results from INTEGRATION. One possibility for this type of comparison is the I-80 corridor in the San Francisco Bay Area, where an HOV lane is in the process of being added. This network has been coded for INTEGRATION by researchers at the University of California at Berkeley. Also, efforts are under way to code in great detail a 9.3-mi section of the Santa Monica Freeway in Los Angeles.

### Calibration with Other Freeway Simulation Models

Studies could be done that compare the results of other freeway simulation models that incorporate HOV facilities with the results from INTEGRATION. The Santa Monica Freeway currently is being coded with FREQ-11, and comparisons of the two models are planned.

### Programs To Manipulate Input and Output Files

The process of using spreadsheets to generate values to be used by the origin-destination file was somewhat laborious. Efforts toward developing a program that can automatically alter this file on the basis of certain user-specified parameters (i.e., average occupancy) would ease the file preparation process. This program could generate a series of input files on its own. The program should allow the user to specify different HOV percentages for different origin-destination pairs. Also, the data are presented in this paper in terms of averages for all of the vehicles on the network. Programs could be written that disaggregate the origin-destination data into certain user-specified groups such as eastbound freeway travelers.

### Potential Modifications to INTEGRATION Program

A number of modifications could be made to the INTEGRATION model itself to enhance its capabilities to simulate HOV facilities. For example, a parameter of average vehicle occupancy for HOV vehicles could be added to the origin-destination pairs file. This would allow the program to directly calculate time savings on the basis of passengers and not vehicles. Signal optimization could also be done on a passenger basis. In addition, the model could also contain a growth factor that could determine the effect of various levels of latent demand generated by a reduction in vehicles caused by an increased percentage of HOV vehicles.

### Studies with Advanced Traveler Information Systems

As mentioned earlier, a powerful aspect of the INTEGRATION model is its ability to model varying levels of information provided to motorists. One could use the model to assess the potential benefits of an HOV facility alone and in combination with various levels of advanced traveler information systems.

## ACKNOWLEDGMENTS

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The authors thank Yonnel Gardes for the creation of the Santa Monica Freeway corridor network and for his assistance in understanding the use of the INTEGRATION model.

This paper is part of an effort to simulate various IVHS strategies on the Santa Monica Freeway corridor (I-10) in Los Angeles. This corridor is also known as the Smart Corridor because of the project of the same name that is under way on the corridor. Although much of the data used were obtained from the agencies involved in the Smart Corridor project, this research is not a part of the Smart Corridor project itself.

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# High-Occupancy-Vehicle Treatments on Toll Facilities

KATHERINE F. TURNBULL, KEVIN M. HALL, AND MICHAEL R. RINGROSE

The use of high-occupancy-vehicle (HOV) facilities in North America, especially those located on freeways and in separate rights-of-way, has been examined extensively over the last 20 years. Less consideration has been given, however, to the use of HOV treatments on toll facilities. The provision of priority measures for HOVs on toll facilities is a subject of growing interest among representatives from toll and transportation agencies in the United States, especially those that serve commuters in large urban areas. Like other types of urban transportation facilities, many toll roads, bridges, and tunnels are experiencing peak vehicular demands that exceed their current capacity. HOV treatments represent one potential technique for addressing many of these issues. In an examination of the national experience with priority measures for HOVs on toll facilities, the use of HOV pricing strategies and HOV priority treatments is explored. Information on the toll facilities operated by 21 toll agencies is examined. A total of 24 toll facilities currently utilize some type of HOV pricing strategy, and 14 projects that use HOV priority treatments were identified. Available information on the various projects is examined. The overview of the current use and status of HOV treatments on toll facilities should be of use to transportation professionals interested in exploring potential HOV applications on toll roads, bridges, and tunnels. As such, it represents a significant addition to the developing body of literature related to the application of HOV treatment in the United States.

The provision of priority measures for high-occupancy vehicles (HOVs) on toll facilities is a subject of growing interest among representatives from toll and transportation agencies in the United States, especially those that serve commuters in large urban areas. This paper provides a national overview of the experiences with HOV strategies and treatments on urban toll roads, bridges, and tunnels in the United States.

Like other types of urban transportation facilities, many toll roads, bridges, and tunnels are experiencing peak vehicular demands that exceed their current physical capacity. These demands often result in substantial congestion and delays for motorists. As a result, numerous transportation agencies are focusing on strategies and treatments for maximizing the efficiency of the existing systems, including priority measures for HOVs. There is a growing body of experience with HOV projects on freeways and in separate rights-of-way in cities throughout the United States. The evidence from those projects suggests that HOV priority treatments can be effective when properly planned and implemented (*1–3*).

Priority measures for HOVs on toll facilities are not new. A number of HOV projects undertaken during the past two decades have been on toll facilities (*2,4,5*). However, the experience with HOV strategies and treatments on toll facilities has not been explored extensively in previous studies of HOV projects (*2,4,5*). Thus, the focus of this paper is on HOV projects associated with toll facilities. The results should be of use to groups interested in the application of HOV strategies and treatments on toll roads, bridges, and tunnels.

The information presented in this paper was obtained through two methods. First, a state-of-the-art literature review was conducted to identify examples of HOV measures on toll facilities and to obtain basic information about those projects. A number of projects had been identified through previous research on HOV facilities conducted by the Texas Transportation Institute and other groups. In addition, a telephone survey was conducted of representatives from agencies responsible for toll roads, bridges, and tunnel facilities throughout the country. The survey was intended to verify and update the basic information gathered from the literature, to obtain additional information concerning the experiences with HOV strategies, and to identify other HOV projects that are in the planning stage.

This paper is divided into three major sections. Following this brief introduction, the second section provides more detailed information concerning HOV strategies and treatments on toll facilities in the United States, including a discussion of the characteristics of the HOV projects on different types of toll facilities, the use of HOV pricing strategies, and HOV priority techniques. Information obtained through the literature review and the telephone surveys from the various projects is summarized. The paper concludes with a brief summary of the major elements examined and the identification of areas for further research.

## HOV APPLICATIONS ON TOLL FACILITIES

A variety of HOV techniques have been applied on toll roads, bridges, and tunnels in the United States. Reduced travel times and increased travel time reliability can be provided to buses, vanpools, and carpools by altering the design and operation of certain elements of a toll facility. In addition to these design treatments, toll facilities may provide direct financial incentives for HOV use through lower toll charges or free passage. Thus, the various HOV applications on toll roads, bridges, and tunnels can be divided into two general categories: HOV pricing strategies and HOV priority treatments. Although both strategies may be used in combination, they are addressed individually in this section. Facilities using both techniques are also discussed, however.

To obtain current information on the status of HOV projects on toll facilities, a telephone survey was conducted with representatives from the agencies throughout the country responsible for planning and operating toll roads, bridges, and tunnels. The *1992*

K. F. Turnbull and K. M. Hall, Texas Transportation Institute, The Texas A&M University System, College Station, Tex. 77843-3135. M. R. Ringrose, BRW, Inc., Market Place Two, 2001 Western Avenue, Suite 400, Seattle, Wash. 98121.

*Membership Director* (*6*) of the International Bridge, Tunnel and Turnpike Association was used to identify both the agencies and the individuals included in the survey. In addition, literature on HOV projects and toll facilities (*2,4,7*) was reviewed to help ensure the inclusion of all relevant projects. Table 1 gives the toll agencies contacted and the current status of HOV applications on toll facilities in the United States. A total of 21 toll agencies were examined. As shown in Table 1, eight toll agencies are currently using some type of HOV pricing strategies and six are utilizing HOV priority treatments. Of these, four agencies are currently using both approaches.

The current use of both types of HOV techniques on toll facilities is examined in more detail in this section. As discussed, HOV pricing strategies are more commonly found with different types of toll facilities than HOV priority treatments. Then a brief overview that summarizes the extent of current applications is provided. The limited information available on project experiences is also reviewed.

## HOV Pricing Strategies

HOV pricing strategies provide lower toll charges or eliminate the toll charge altogether for HOVs. Thus, this approach gives a financial incentive to commuters to use buses, carpools, and vanpools. Pricing strategies also may be combined with other HOV priority treatments at toll plazas to provide both monetary and travel time benefits to HOV users.

Although they may not be explicit, toll facilities in general provide financial incentives for using multiple-occupant vehicles. Toll charges usually are collected on a per-vehicle basis, regardless of the number of occupants in a vehicle of a given type. Thus, in most cases, the toll per person drops as the occupancy of a vehicle using a toll facility increases. In this way, commuters who carpool or vanpool can reduce their daily out-of-pocket costs. It does not appear that this feature of toll facilities has been widely promoted or marketed, however, as a means to encourage the use of HOVs.

The general pricing strategies—reduced toll rates and toll-free access—are being applied to encourage greater use of carpools and vanpools on some toll facilities in the United States. With reduced toll rates the toll collected from qualifying HOVs is significantly lower than that for similar vehicles that do not have a sufficient number of occupants. With toll-free access, toll charges are not applied to qualifying HOVs.

Table 2 provides a summary of HOV pricing strategies on toll facilities in the United States, including agency, facility, route and location, year the HOV strategy was implemented, and the current status of the project. A total of 8 agencies and 24 toll facilities are listed. All but one of the projects are currently in operation.

As shown by Table 2, HOV pricing strategies are most common with toll facilities in California, Delaware, and New York. In addition, one toll facility in Massachusetts utilizes HOV pricing.

**TABLE 1 U.S. Toll Agency Experience with HOV Pricing and Priority Treatments**

| Agency | HOV Pricing | HOV Treatments | Neither |
|---|---|---|---|
| California Department of Transportation | X | X | - |
| Connecticut Department of Transportation[a] | - | - | X |
| Delaware River Port Authority | X | - | - |
| Delaware Turnpike Administration | X | X | - |
| E-470 Public Highway Authority - Denver, Colorado | - | - | X |
| Florida Department of Transportation | - | - | X |
| Golden Gate Bridge, Hwy. & Transp. District | X | - | - |
| Illinois State Toll Highway Authority | - | - | X |
| Indiana Department of Transportation | - | - | X |
| Maryland Transportation Authority | - | X | - |
| Massachusetts Port Authority | - | - | X |
| Massachusetts Turnpike Authority | X | - | - |
| New Jersey Expressway Authority | - | - | X |
| New Jersey Highway Authority | - | - | X |
| New York State Thruway Authority | X | X | - |
| Ohio Turnpike Commission | - | - | X |
| Oklahoma Turnpike Authority | - | - | X |
| Port Authority of New York & New Jersey | X | X | - |
| Triborough Bridge & Tunnel Authority | X | - | - |
| Pennsylvania Turnpike Commission | - | - | X |
| Virginia Department of Transportation | - | X | - |

[a]Connecticut operated toll facilities until the mid-1980's.

**TABLE 2 U.S. Toll Facilities with HOV Pricing Strategies**

| Facility | Route/Location | Year Implemented | Project Status |
|---|---|---|---|
| California Department of Transportation | | | |
| Antioch Bridge | SR 160, San Joaquin River | 1991 | current |
| Benicia-Martinez Bridge | I-680, Carquinez Strait | 1991 | current |
| Carquinez Bridge | I-80, Carquinez Strait | 1991 | current |
| Dumbarton Bridge | SR 84, San Francisco Bay | 1982 | current |
| Richmond-San Rafael Bridge | I-580, San Francisco Bay | 1989 | current |
| San Diego-Coronado Bridge | SR 75, San Diego Bay | 1977 | current |
| San Francisco-Oakland Bay Bridge | I-80, San Francisco Bay | 1970, 1971[a] | current |
| San Mateo-Hayward Bridge | SR 92, San Francisco Bay | 1989 | current |
| Vincent Thomas Bridge | SR 47, Los Angeles Harbor | Prior to 1989 | current |
| Delaware River Port Authority | | | |
| Benjamin Franklin Bridge | I-676, New Jersey/Philadelphia | 1971 | current |
| Betsy Ross Bridge | SR 90, New Jersey/Philadelphia | 1971 | current |
| Commodore John Barry Bridge | US 322, New Jersey/Philadelphia | 1971 | current |
| Walt Whitman Bridge | I-76, New Jersey/Philadelphia | 1971 | current |
| Delaware Turnpike Administration | | | |
| Kennedy Memorial Highway | I-95, Newark, Delaware | Oct. 1, 1993 | planned |
| Golden Gate Bridge, Hwy. & Transp. District | | | |
| Golden Gate Bridge | US 101, San Francisco Bay | 1975 | current |
| Massachusetts Turnpike Authority | | | |
| Massachusetts Turnpike | I-90, Boston/New York State | 1992 | current |
| New York State Thruway Authority | | HOV Rate-1980 | current |
| Tappan Zee Bridge | I-87, Hudson River | MOV Rate-1990[b] | current |
| Port Authority of New York & New Jersey | | | |
| Bayonne Bridge | SR 440, New Jersey/Staten Island | 1975 | current |
| George Washington Bridge | I-95, New Jersey/Manhattan | 1975 | current |
| Goethals Bridge | I-278, New Jersey/Staten Island | 1975 | current |
| Lincoln Tunnel | SR 495, New Jersey/Manhattan | 1970[c], 1975 | current |
| Outerbridge Crossing | SR 440, New Jersey/Staten Island | 1975 | current |
| Tri-Borough Bridge & Tunnel Authority | | | |
| Verrazano Narrows Bridge | I-278, New Jersey/Staten Island/N.Y.C. | 1986 | current |

[a]The pricing strategy on the San Francisco-Oakland Bay Bridge was initiated for buses in 1970 and extended to other HOVs in 1971.
[b]The MOV Rate applies to vehicles with 2 or more people and the HOV rate applies to vehicles with of more people.
[c]The contraflow bus lane was implemented in 1970 and the short HOV lane approaching the toll plaza was implemented in 1975.

Further, the majority of HOV pricing projects is on toll bridges. Of the toll facilities using HOV pricing strategies, 20 are located on bridges, 2 are associated with tunnels, and 2 are on highways. Information in Table 2 also indicates that HOV pricing strategies have been in effect on most of the toll facilities for many years, including those in Delaware, the New York and New Jersey area, and California, which were all implemented in the 1970s.

Table 3 provides additional information on the operating characteristics associated with each of the HOV toll pricing projects. Information is provided on the normal toll rate, the HOV toll charge, the definition and vehicle occupancy requirements for HOVs, and the hours that HOV pricing is in effect. The information indicates that a variety of pricing strategies are utilized on the 24 facilities. Five of the California toll bridges provide free passage for HOVs, whereas five give reduced rates for commuter buses. All of the other 14 toll facilities provide reduced rates for HOVs. The reduction in the toll charges for HOVs varies among the different facilities, however. For example, the four toll facilities operated by the Delaware River Port Authority provide a $0.50 savings for HOV users, whereas the six facilities operated by the Port Authority of New York and New Jersey provide a $3.50 savings for HOV users.

The purchase of prepaid tickets or tokens is required by many toll agencies to take advantage of the lower HOV rates. For example, an advance-purchase carpool ticket is required for HOV users on the six toll facilities operated by the Port Authority of New York and New Jersey. For $30 carpoolers may purchase 60 tickets for use over a 6-month period. This equates to a $0.50 charge for HOVs compared with the normal $4.00 toll.

The HOV definition also varies among the various projects. As noted previously, five of the California toll bridges provide lower toll charges only to buses, with carpools and vanpools paying the same rates as other automobiles. A 3+ carpool definition is used on most of the other 19 toll facilities. The two exceptions to this are the Tappan Zee Bridge in New York and the Kennedy Memorial Highway in Delaware. The Tappan Zee Bridge uses two different classifications for HOVs: multioccupant vehicles (MOV), which are classified as 2+ carpools, and HOVs, which are carpools with three or more occupants (3+). Both groups may purchase a toll ticket option that allows 60 trips within 105 days, which equates to a $1.00 charge—a significant savings over the regular $2.50 toll. An additional option of 20 tickets over a 30-day period may be purchased by HOVs.

The hours for which the reduced tolls for HOVs are in effect differ among the projects. On six facilities, the reduced tolls are provided to HOVs on a 24-hr basis. Facilities using the 24-hr designation include the Coronado Bridge in San Diego, the four bridges operated by the Delaware River Port Authority, and the Verrazano Narrows Bridge in New York City. Of the remaining 19 toll facilities, 11 offer the reduced HOV charges in both the morning and afternoon peak periods, whereas 7 provide the lower charges only in the morning peak period.

## HOV Priority Treatments

HOV priority treatments with toll facilities take a number of forms. These include HOV lanes over the length of the facility, HOV lanes at the approach to toll plazas, and toll booths reserved for use only by HOVs. An HOV lane on a toll facility represents a treatment similar to those commonly found on freeways. The HOV treatment could be an exclusive, concurrent, or contraflow lane. This approach provides travel time savings and travel time reliability to HOVs in congested travel corridors. The primary function of reserved lanes on the approach to a toll plaza is to allow HOVs to bypass the queues that form at toll plazas. Reserving specific toll plazas for HOVs provides a similar benefit by allowing HOVs to bypass queues and move more quickly through the toll plaza.

Table 4 gives the seven toll agencies reporting the use of HOV priority treatments; 12 priority treatments are currently in operation on toll facilities, although one project—the Kennedy Memorial Highway in Maryland—operates only when traffic conditions warrant. One project, encompassing the section of the Kennedy Memorial Highway in Delaware, is in the planning stage. Finally, the future of the Dulles Toll Road HOV lane, which was discontinued in 1992 after only a few months of operation, is unclear at this point.

Additional information on the types of priority treatments utilized with the various toll facilities and the operating characteristics of each are contained in Table 5. Of the 14 projects, 5 provide an HOV lane, 1 includes just an HOV toll booth, and 8 provide both reserved HOV toll booths and HOV lanes. Three of the toll road HOV lanes represent major HOV facilities. The HOV lanes on the San Francisco–Oakland Bay Bridge and the contraflow lane on SR-495 on the approach to the Lincoln Tunnel in New York City have been in operation since 1970. They represent two of the oldest and most heavily utilized HOV facilities in the country. Further, the HOV lanes on both the Bay Bridge and SR-495 connect with exclusive HOV toll booths, providing additional travel time savings to HOV users. In addition, the Bay Bridge provides financial incentives for HOV users because HOVs do not pay a toll. The 3.3-mi HOV lane on the Virginia Beach–Norfolk Expressway, which connects with the 8-mi HOV lane on I-64, provides a more recent example of a new HOV lane on a toll road.

As shown in Table 5, a toll booth reserved for HOV use without any other supporting HOV treatments is in the planning stage on the Kennedy Memorial Highway in Delaware. One toll both would be provided for carpools, vanpools, and buses during the morning and afternoon peak periods. The remaining eight toll facilities provide both reserved approach lanes and toll booths for HOVs. Although the hours of operation vary among the facilities, most are oriented toward the morning and afternoon peak periods.

The location of the HOV toll booths or toll approaches, or both, varies among the different toll facilities. Some use the outside lane, some use the inside lane, and some use different combinations. The George Washington Bridge and the Massachusetts Turnpike both use the outside lane for HOVs. On the other hand, the HOV lane is on the inside lane on the Kennedy Memorial Highway and the Virginia Beach–Norfolk Expressway. The Bay Bridge and the Tappan Zee Bridge use a combination of inside and outside lanes for the HOV treatments.

## Project Experience and HOV Utilization Levels

Little information is available through either the published literature or the telephone survey of toll agency representatives on the number of HOVs that use the different HOV pricing mechanisms and priority facilities, the impact these measures have had on influencing a change in commuting behavior, and the financial impacts of lower or free HOV rates on the toll agencies. Available

**TABLE 3 Operating Characteristics of HOV Pricing Strategies on U.S. Toll Facilities**

| Facility | Normal Toll Rate ($) auto | HOV Toll Rate ($) auto | HOV Definition | Hours of Operation |
|---|---|---|---|---|
| California Department of Transportation | | | | |
| Antioch Bridge | 1.00 | 0.10 | bus[a], 3+ carpool, motorcycle, vanpool | 5:00-10:00 a.m. 3:00-7:00 p.m. |
| Benicia-Martinez Bridge | 1.00 | 0.10 | bus[a], 3+ carpool, motorcycle, vanpool | 5:00-10:00 a.m. 3:00-7:00 p.m. |
| Carquinez Bridge | 1.00 | 0.10 | bus[a], 3+ carpool, motorcycle, vanpool | 5:00-10:00 a.m. 3:00-7:00 p.m. |
| Dumbarton Bridge | 1.00 | free | bus[b], 2+ carpool, motorcycles, vanpool | 5:00-10:00 a.m. 3:00-6:00 p.m. |
| Richmond-San Rafael Bridge | 1.00 | free | bus[a], 3+ carpool, motorcycle, vanpool | 5:00-10:00 a.m. 3:00-6:00 p.m. |
| San Diego-Coronado Bridge | 1.00 | free | bus[b], 2+ carpool, motorcycle, trucks | 24 hours |
| San Francisco-Oakland Bay Bridge | 1.00 | free | bus[b], 3+carpool, motorcycle[c], vanpool | 5:00-10:00 a.m. 3:00-6:00 p.m. |
| San Mateo-Hayward Bridge | 1.00 | free | bus[b], 2+carpool, motorcycle[c], vanpool | 5:00-10:00 a.m. 3:00-6:00 p.m. |
| Vincent Thomas Bridge | 0.50 | 0.50 | bus[d] | 24 hours |
| Delaware River Port Authority | | | | |
| Benjamin Franklin Bridge | 2.00 | 1.50 | bus, 3+ carpool | 24 hours |
| Betsy Ross Bridge | 2.00 | 1.50 | bus, 3+ carpool | 24 hours |
| Commodore John Barry Bridge | 2.00 | 1.50 | bus, 3+ carpool | 24 hours |
| Walt Whitman Bridge | 2.00 | 1.50 | bus, 3+carpool | 24 hours |
| Delaware Turnpike Administration | | | | |
| Kennedy Memorial Highway, Newark, DL. | 1.25 | $25.00/40 Passes/30 Days | bus, 2+ carpool | 6:30-10:00 a.m. 3:30-6:00 p.m. |

| | | | | |
|---|---|---|---|---|
| Golden Gate Bridge, Hwy. & Transp. District | | | | |
| Golden Gate Bridge | 3.00[e] | free | bus[f], 3+ carpool | 5:00-9:00 a.m.<br>4:00-6:00 p.m. |
| Massachusetts Turnpike Authority | | | | |
| Massachusetts Turnpike: Brighton-Alston Facility | 0.50 | $25.00/year[g] | bus[h], 3+carpool | 7:00-9:00 a.m.<br>3:30-5:30 p.m. |
| New York State Thruway Authority | | | | |
| Tappan Zee Bridge | 2.50 | MOV=1.00<br>HOV has book option[i] | bus, MOV=2+,<br>HOV=3+ carpool | 7:00-9:00 a.m. |
| Port Authority of New York & New Jersey | | | | |
| Bayonne Bridge | 4.00 | 0.50[j] | bus[k], 3+ carpool | 7:00-9:30 a.m. |
| George Washington Bridge | 4.00 | 0.50[j] | bus[k], 3+ carpool | 7:00-9:30 a.m. |
| Goethals Bridge | 4.00 | 0.50[j] | bus[k], 3+ carpool | 7:00-9:30 a.m. |
| Holland Tunnel | 4.00 | 0.50[j] | bus[k], 3+ carpool | 7:00-9:30 a.m. |
| Lincoln Tunnel | 4.00 | 0.50[j] | bus[k], 3+ carpool | 7:00-9:30 a.m. |
| Outerbridge Crossing | 4.00 | 0.50[j] | bus[k], 3+ carpool | 7:00-9:30 a.m. |
| Tri-Borough Bridge & Tunnel Authority | | | | |
| Verrazano Narrows Bridge | 6.00 | 1.25[l] | bus, 3+ carpool | 24 hours |

[a]Commuter buses pay only $0.10/crossing and are paid with commute bus scrip ticket(s) only.
[b]Commuter Bus service is allowed to pass free at any time of the day in designated lanes. Passage through staffed lanes requires toll-free commuter bus tickets.
[c]Motorcycles are required to display special permits to receive the HOV pricing on these bridges.
[d]Commuter buses pay only $0.20/crossing and are paid with commute bus scrip ticket(s) only.
[e]Non-HOV commuters may purchase an advance book option that allows 16 passages for $40.00 at an average cost of $2.50.
[f]Buses allowed to pass free during HOV hours of operation.
[g]May be as high as $75.00/year depending on length of travel prior to arriving to toll facility. HOV's receive a lower toll charge through the Car Pass Program.
[h]Bus pricing dependant upon number axles.
[i]Both MOV and HOV users may purchase a ticket option that allows 60 trips for 105 days at essentially a $1.00 a commute and HOV users may also purchase a smaller option of 20 tickets that are eligible for 30 days at $10.00.
[j]HOV discount requires the use of an advance-purchase carpool ticket that is eligible for 6 months for $30.00 and 60 tickets.
[k]Buses pay a straight fee of $3.00.
[l]Only Staten Island dwellers may be eligible for the Staten Island HOV Book Token that allows 24 trips for $30.00.

**TABLE 4 U.S. Toll Facilities with HOV Priority Treatments**

| Facility | Route/Location | Year Implemented | Status |
|---|---|---|---|
| California Department of Transportation | | | |
| Carquinez Bridge | I-80, Carquinez Strait | 1991 | current |
| Dumbarton Bridge | SR 84, San Francisco Bay | 1982, 1989 | current |
| San Diego-Coronado Bridge | SR 75, San Diego Bay | 1977 | current |
| San Francisco-Oakland Bay Bridge | I-80, San Francisco Bay | 1970, 1971 | current |
| San Mateo-Hayward Bridge | SR 92, San Francisco Bay | 1989 | current |
| Delaware Turnpike Administration | | | |
| Kennedy Memorial Highway | I-95 in Newark | 1993 | planned |
| Maryland Transportation Authority | | | |
| Kennedy Memorial Highway | I-95 in Baltimore | January 1993 | only when traffic warrants |
| Massachusetts Turnpike Authority | | | |
| Massachusetts Turnpike | I-90, Brighton-Alston in Downtown Boston | 1992 | current |
| New York State Thruway Authority | | HOV Rate - 1980 | |
| Tappan Zee Bridge | I-87, Hudson River | MOV Rate - 1990 | current |
| Port Authority of New York & New Jersey | | | |
| George Washington Bridge[a] | I-95, New Jersey/Manhattan | 1973, prior to 1980 | current |
| Holland Tunnel | I-78, New Jersey/Manhattan | 1985 | current |
| Lincoln Tunnel[b] | SR 495, New Jersey/Manhattan | 1970, 1975 | current |
| Virginia Department of Transportation | | | |
| Dulles Toll Road | Dulles Airport/Washington, D.C. | 1992 | suspended 1992[c] |
| Virginia Beach-Norfolk Expressway | SR 44, Virginia Beach/Norfolk | 1988, 1992[d] | current |

[a]HOV treatments are only on Upper Level approach. Police can operate a second lane when traffic warrants.

[b]1 Toll booth approach lane for buses and 3+ carpools and 1 contraflow bus lane.

[c]HOV facilities on the Dulles Toll Road may be re-instated in mid-1994.

[d]The HOV lanes on SR 44 were initially opened in 1988. After a temporary suspensions to allow for the completion of the HOV lanes on I-64, the lanes were re-opened in 1992

**TABLE 5 Operating Characteristics of HOV Priority Treatments on U.S. Toll Facilities**

| Facility | Treatments: Total # of Toll Booths | Treatments: HOV Booths | Treatments: HOV Toll Booth Approach Lanes | HOV Lanes/ (Kilometres) | HOV Definition | Hours of Operation |
|---|---|---|---|---|---|---|
| California Department of Transportation | | | | | | |
| Dumbarton Bridge | 7 | 1 | 1 | 1/(3.2) | bus, 2+ carpool, motorcycle, vanpool | 5:00-10:00 a.m. 3:00-6:00 p.m. |
| Richmond-San Rafael Bridge | 5 | 1 | 1 | 1/(8.0) | bus, 3+ carpool, motorcycle, vanpool | 5:00-10:00 a.m. 3:00-6:00 p.m. |
| San Diego-Coronado Bridge | 7 | 1 | 0 | 0 | bus, 2+ carpool, trucks, motorcycle | 24 hours |
| San Francisco-Oakland Bay Bridge | 20 | 2 | 2[a] | 4/(4.8) | bus, 3+ carpool, motorcycle[b], vanpool | 5:00-10:00 a.m. 3:00-6:00 p.m. |
| San Mateo-Hayward Bridge | 8 | 1 | 1 | 1/(3.2) | bus, 2+ carpool, motorcycle[b], vanpool | 5:00-10:00 a.m. 3:00-6:00 p.m. |
| Delaware Turnpike Administration | | | | | | |
| Kennedy Memorial Highway | 8 | 1[c] | 0 | 0 | bus, 2+ carpool | 6:30-10:00 a.m. 3:30-6:00 p.m. |
| Maryland Transportation Authority | | | | | | |
| Kennedy Memorial Highway | 9 | 0 | 0 | 1 | yet to be determined | when traffic warrants |
| Massachusetts Turnpike Authority | | | | | | |
| Massachusetts Turnpike | 14 | 1[d] | 1[e] | 0 | bus, 3+ carpool | 7:00-9:00 a.m. 3:30-5:30 p.m. |

**TABLE 5** *Continued*

| | | | | | | |
|---|---|---|---|---|---|---|
| New York State Thruway Authority | | | | | | |
| Tappan Zee Bridge | 13 | 2 | 3-4 | 0[f] | bus, 2+ carpool, 3+carpool | 7:00-9:00 a.m. |
| George Washington Bridge | 12[g] | 1 | 1 | 1/(0.4) | bus, 3+ carpool | 7:00-9:30 a.m. |
| Holland Tunnel | 9 | 1 | 1 | 1/(0.2) | bus, 3+ carpool | 7:00-9:30 a.m. |
| Lincoln Tunnel | 13 | 2 | 2[h] | 2[h]/(0.16[i]), (4.8[j]) | bus, 3+ carpool | 4:00-6:00 a.m.[i] 6:30-10:00 a.m.[j] |
| Virginia Department of Transportation | | | | | | |
| Dulles Toll Road[k] | 7 | 1 | 1[c] | 1/(19.3) | bus, 3+ carpool | 6:30-9:00 a.m. 4:00-6:30 p.m. |
| Virginia Beach-Norfolk Expressway (SR-44) | 7 | 0 | 0 | 1/(4.8) | bus, 2+ carpool | 5:00-8:30 a.m. 3:00-6:00 p.m. |

[a]2 Bypass lanes for HOV use during defined HOV hours of operation.
[b]Motorcycles are required to display a special permit.
[c]Planned.
[d]Another toll booth is planned to be implemented as reserved for HOV use.
[e]Approach lane is approximately 100 yards in length and is delineated with cones.
[f]The New York State Thruway Authority is planning an exclusive HOV lane but it is many years away from being implemented.
[g]Number of booths may vary somewhat depending on traffic conditions.
[h]Includes both the Contraflow Bus Lane and the HOV approach lane to the toll plaza.
[i]Bus lane that is open to 3+ carpools.
[j]Contraflow Bus Lane.
[k]Suspended in 1992.

Conversion Factor Used: 1km = 0.62 miles information obtained through the literature review and the telephone surveys with representatives from toll agencies is briefly reviewed in this section.

It appears that the use of HOV pricing and priority measures on toll facilities varies greatly among the different projects. For example, the HOV lanes on the Bay Bridge and SR-495 carry a significant number of vehicles and passengers. In 1992 the four HOV lanes on the Bay Bridge carried some 2,426 vehicles and 11,808 passengers during the morning peak hour (*2*). The contraflow bus lane on SR-495 carries an average of 725 buses and 34,685 passengers during the morning peak hour. Further, the new HOV lane on the Virginia Beach–Norfolk Expressway currently carries approximately 800 vehicles and 1,520 passengers (*2*).

Table 6 provides a summary of the monthly use of the free HOV toll booths on four toll bridges in California. The monthly number of HOVs ranges from a low of approximately 1,275 vehicles to a high of 370,989 vehicles. Table 6 also shows the total number of vehicles using the toll bridge and the percentage of free HOVs. The percentage of HOVs ranges from a high of 37 percent on the San Diego–Coronado Bridge in San Diego to 1 percent on the San Mateo–Hayward Bridge. However, it is important to note that these are monthly totals and that HOVs probably represent a higher percentage of total vehicles during the peak periods.

A few other toll agency representatives provided information on the use of reduced HOV pricing strategies. The representative from the Delaware Port Authority, which provides a $0.50 savings for 3+ carpools on four toll bridges, indicated that the carpool tickets were not well utilized by commuters. To receive the $0.50 savings, carpoolers must purchase prepaid tickets, which are good for a 30-day period. The representative noted that the purchase of these tickets had declined over the past year. On the other hand, the Triborough Bridge and Tunnel Authority reported selling over 1 million HOV commuter ticket books to carpoolers on Staten Island last year.

None of the representatives contacted during the telephone survey were able to identify the specific impact of the HOV priority pricing strategies on the general revenue stream of the toll agency. Most indicated that they did not think the HOV pricing programs had a major impact on the revenue collected from the toll facilities. The small impact was noted primarily because of the limited hours of operation for many HOV pricing strategies and the fact that the percentage of commuters taking advantage of the HOV pricing was relatively small.

Further, information was not available on the possible influence of the HOV toll strategies on changing individual commute modes. No before-and-after studies or other evaluations of the impact of implementing an HOV toll pricing project were identified. Thus, it appears that little information exists on the influence toll HOV pricing strategies and toll HOV priority treatments have had on encouraging greater use of buses, vanpools, and carpools.

A number of representatives provided information on the reasons for implementing the HOV toll projects. Many of the projects in California, Delaware, New York, and New Jersey were implemented in the 1970s in response to the energy crisis and the Organization of Petroleum Exporting Countries (OPEC) oil embargo. The focus of these projects was to encourage greater utilization of all forms of HOVs, to reduce gasoline consumption, and to better manage facilities that were at or near capacity. These are the same objectives of most recent projects as well. For example, the implementation of the HOV and MOV pricing strategies on the Tappan Zee Bridge was part of a regionwide transportation system management plan developed to help reduce travel times and congestion in the area. Other elements of the program included park-and-ride lots and ridesharing programs.

Although the experience has not been extensively documented, it appears that a number of the toll HOV projects examined are providing either travel time or financial incentives that are attractive enough to commuters to encourage them to use buses, vanpools, and carpools instead of driving alone. As discussed in the concluding section of this paper, it appears that additional research would be beneficial to further examine the influence of toll HOV strategies on changing commuter behavior and assisting with managing traffic congestion.

## CONCLUSION

A review of the national experience with priority measures for HOVs on toll facilities in the United States has been presented. The types of HOV projects examined included HOV pricing strategies and HOV priority treatments. Current examples of both techniques were examined and the limited information available on the experience with different strategies was reviewed.

On the basis of the information examined in this paper, it is evident that HOV pricing strategies and HOV priority treatments are being utilized with a variety of toll facilities in the United States. Although information on utilization levels and the influence on mode choice is limited, it appears that many of the toll HOV strategies are assisting with congestion management at toll plazas and are encouraging greater utilization of buses and car-

**TABLE 6 Monthly Use of Four California Toll Bridges**

| Facility | June 1992 Traffic Count | | |
|---|---|---|---|
| | Free (HOV) Vehicles Number | Percent | Total Vehicles |
| Dumbarton Bridge | 86,676 | 10% | 858,852 |
| San Diego - Coronado Bridge | 370,989 | 37% | 999,546 |
| San Francisco - Oakland Bay | 63,416 | 2% | 3,647,771 |
| San Mateo - Hayward Bridge | 1,275 | 1% | 1,073,862 |

Source: California Department of Transportation pools in certain corridors. Thus, information contained in this paper helps provide a better understanding of the current use of HOV pricing strategies and HOV priority treatments with toll facilities in the United States.

Further, the analysis also indicates that additional research would be of benefit to better document the experience with HOV strategies on toll facilities and to better understand the influence of the various projects. Areas for further research could include the examination of vehicle and passenger volumes at HOV and non-HOV toll plazas, the use of various HOV pricing methods and pricing levels, surveys of HOV users to determine the influence of the pricing strategies and priority treatments on encouraging a mode change, and the impact of reduced HOV tolls on agency revenue. This paper helps provide the first step for a more detailed examination of HOV treatments on toll facilities.

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# Public Attitudes Toward Conversion of Mixed-Use Freeway Lanes to High-Occupancy-Vehicle Lanes

JOHN GARD, PAUL P. JOVANIS, VIVEK NARASAYYA, AND RYUICHI KITAMURA

Increasing public concerns over air quality and traffic congestion call for a reevaluation of the idea of converting an existing mixed-use freeway lane into a high-occupancy-vehicle (HOV) lane. A study was undertaken of freeway HOV lane perceptions that included an extensive literature review, focus groups, and a survey of over 1,000 California residents. The telephone survey, conducted in May 1993, provided a quantitative assessment of public opinion toward HOV lanes and their conversion. The majority of respondents in the survey agreed that carpool lanes are a strong incentive to get people to carpool and that carpool lanes are fair to nonusers and those who cannot carpool. When given a choice of three HOV alternatives for a freeway that they use, shoulder rebuilding garnered support from 40 percent of the respondents, whereas building a new lane and lane conversion received 30 percent support. Respondents also expressed a strong preference for HOV lane conversion compared with more restrictive traffic management policies, such as road pricing, gas tax increases, and monthly parking surcharges. Interestingly, support for conversion did not vary much with socioeconomic characteristics or mode (carpool or drive alone. Respondents were more likely to support conversion if they believed freeway congestion would be better after the HOV lane was operating. These findings suggest that urban Californians may be more supportive of HOV lane conversions than was previously thought.

A common belief appears to have been formed that the conversion of an existing mixed-use freeway lane into a high-occupancy-vehicle (HOV) lane will not gain public acceptance. This belief presumably dates back to the ill-fated conversion attempt on the Santa Monica Freeway in the 1970s (*1*). All of the freeway HOV lanes implemented in California since then have been newly constructed lanes or conversions of medians and shoulders that were designated as HOV lanes from the first day of operation.

However, as metropolitan areas continue to grow and as demand for freeway capacity continues to increase, the conversion of existing lanes into HOV lanes is becoming a logical freeway operation scheme. Furthermore, with increasing public concerns about air quality and traffic congestion, it is conceivable that urban residents in California are now more receptive to the idea of converting an existing mixed-use freeway lane into an HOV lane. This calls for the reevaluation of public perceptions and attitudes toward HOV lanes in general and lane conversions in particular.

At the request of the California Department of Transportation (Caltrans) and the California Air Resources Board, researchers at the University of California, Davis, undertook a project to assess the public's perceptions of converting a mixed-use freeway lane to an HOV lane.

In late 1992 a literature review on HOV lanes and their conversion was prepared (*2*). This was followed by a series of focus groups to qualitatively assess public perceptions of HOV lanes. The results of the focus groups assisted in refining the telephone survey questionnaire. A computer-aided telephone interview (CATI) system was used to conduct the telephone survey in May 1993. This paper summarizes the literature review and focus group findings and describes the survey methodology and results. A more detailed description of the survey methodology and findings is contained in the project research report. (*3*).

## LITERATURE REVIEW

An immediate finding of the literature review was that very little research has been done on public perceptions and attitudes toward converting a mixed-use freeway lane into an HOV lane. However, numerous studies have examined public reactions to implementations of HOV lanes in general (*2*).

The anticipated lack of public acceptance generally is attributed to the probable increase in congestion in the remaining mixed-use freeway lanes that is likely to accompany a conversion.

Many researchers believe that public reaction today would be similar to that which occurred during the Santa Monica Diamond Lanes experiment. On March 15, 1976, the median lane in each direction of a 12-mi, eight-lane segment of the Santa Monica Freeway was reserved during peak traffic hours for the exclusive use of buses and carpools carrying three or more persons. After the implementation, carpool ridership increased by 65 percent, and bus ridership more than tripled (*1*). However, energy savings and air quality improvements were insignificant. Accidents increased significantly and noncarpoolers lost more time than carpoolers gained. Prompted by heated public outcry, poor press notices, and derisive new commentary, the project was terminated after only 21 weeks. The failure of this project forced the delay or cancellation of several other Caltrans-sponsored HOV lane projects.

A 1990 study in Washington State examined public opinion and behavior toward different HOV alternatives. A variety of questions were asked to gain insights into Seattle residents' views on current transportation problems and potential solutions. A majority of residents (57 percent) in the Seattle area would be inclined to support the conversion of an existing mixed-use freeway lane to an HOV lane if it were converted for peak hours only. About 39 percent

J. Gard, P. P. Jovanis, and V. Narasayya, Department of Civil and Environmental Engineering, Institute of Transportation Studies, University of California, Davis, Calif. 95616. R. Kitamura, Department of Transportation Engineering, Kyoto, Japan, and Institute of Transportation Studies, University of California, Davis, Calif. 95616.

of residents believed that a lane conversion would be very effective in easing traffic congestion on I-5 between Seattle and Tacoma. Of respondents who favored a lane conversion, the most often stated reasons for support included additional incentive to carpool and improved traffic flow (*4*).

The conclusions of the literature review are that most people have no strong opinion on HOV lanes and would be willing to give HOV lanes a try. It seems to be nearly unanimous that early and continued public involvement and support are necessary for the success of any HOV lane implementation.

## FOCUS GROUP SUMMARY

A series of six focus groups was conducted by Fairbank, Maslin, Maullin & Associates to explore public attitudes toward the potential conversion of mixed-use freeway lanes to HOV lanes. The focus groups were held in West Covina, San Francisco, and Anaheim, California, during October 1992 and January and February 1993 (*5*). At each site, one group consisted of those who currently drive alone to work, and the other consisted of those who rideshare (carpool, vanpool, or use public transit). All focus group participants commuted on freeways with HOV lanes. Each session lasted approximately 2 hr. The focus group participants expressed the following perceptions of HOV lanes and related ridesharing issues:

1. The main reason for ridesharing is economic. The availability of an HOV lane is a positive, although secondary, consideration.
2. HOV lanes currently are underutilized. Those who drive alone generally, but not exclusively, resent their presence.
3. Although the moderator used the term 'HOV lane' consistently, respondents tended to use the term 'diamond lane' or 'carpool lane' instead.
4. HOV lanes and current ridesharing incentives are not compelling enough to make a difference in driving decisions. Only two factors would really make people rethink the drive-alone decision adequate mass transit and painful economic disincentives.
5. Participants generally rejected the idea of building a new lane for HOV purposes. They believed that there were enough roads already and that this would be too costly and take too long. Focus group members also expressed concern that there would be significant delays to current traffic during construction.
6. Although most participants recognized that it would be far less costly (compared with building a new lane) to restripe existing lanes or rebuild a shoulder to create an HOV lane, they believed that the safety tradeoffs were too high. They were concerned that there would be no place to pull off the road when necessary and that emergency vehicles would have no way of moving through traffic.
7. Although acknowledged as the least expensive way to add an HOV lane to a freeway, the conversion of an existing lane to an HOV lane received only lukewarm support. Most participants believed that this option would only make the situation worse by forcing the same number of solo drivers into fewer lanes of freeway. Many drive-alone commuters were incensed by this proposal, vowing to fight it.
8. Once understood, the idea of creating an HOV lane network was greeted warmly. Many ridesharers expressed frustration over the sudden end of HOV lanes.
9. Congestion pricing, increasing parking fees, removing older cars from the road, and having solo drivers pay to use HOV lanes during rush hour were all strongly opposed. Most participants when forced to make a choice would agree to give up a mixed-use lane to HOV before accepting any of these alternatives.

## SURVEY METHODOLOGY

Strategic Consulting and Research (SCR) was hired to conduct a telephone survey of urban northern and southern California residents. SCR's CATI system was utilized to automate all skipping patterns and ensure that respondents were asked questions appropriate to their local freeways and their personal commuting patterns.

Before surveying began, the survey questionnaire was reviewed in detail by SCR. Care was taken to word each question in an unbiased manner. The large number of stated preference questions was randomly ordered using the CATI system to prevent fatigue bias (responses from later questions usually less accurate) or "order of alternative" bias (earlier-mentioned alternatives not chosen because of a respondent's lack of total recall).

A sample of 1,085 persons 18 years or older was taken from cities located adjacent to freeways with HOV lanes. The cities were sampled in proportion to their population with a few exceptions. Cities near HOV lanes with extraordinarily high or low HOV lane usage were oversampled by doubling the sampling for that city. Heavily populated cities such as San Francisco, Los Angeles, and San Diego were scaled down (to one-fifth of their population) to get a more geographically varied sample.

For selected cities, calls were made by first randomly selecting an active prefix for the city even if there was only one working number in the prefix. A randomly generated four-digit number is used as the last four digits of the phone number. The random selection of the last four digits ensures that there is no bias in the sampling that occurs from households with unlisted numbers.

Calling was conducted between 5:00 and 9:00 p.m. on weekdays and between 9:00 a.m. and 9:00 p.m. on Saturday and Sunday. When persons under the age of 18 answered the phone, interviewers asked to talk to one of their parents. There was a minimum of 2 days between callbacks to increase the likelihood of reaching residents who may have been away for a few days. Seven callbacks were made before the number was abandoned. This prevents a bias from households that do not spend much time at home.

To ensure that the survey was conducted in an unbiased manner and that all data collected are both consistent and accurate, surveyors were monitored on a random basis using a silent monitoring system. Completed surveys were randomly reviewed by a project supervisor for consistency and accuracy of responses. When inconsistent responses were identified, the supervisor recontacted the respondent to clarify the responses [see project report (*3*) for further methodologic details].

## SURVEY RESULTS

### Socioeconomic Characteristics

A total of 1,085 individuals made up the sample. Table 1 divides the sample by geographic region. In addition to the geographic

TABLE 1 Sampling Distribution by Geographical Region

| Region | Number of Respondents |
|---|---|
| Los Angeles Metropolitan Area | 460 (42.4%) |
| San Diego | 50 (4.6%) |
| San Francisco Bay Area | 575 (53.0%) |
| Total | 1085 (100%) |

distribution, other sample characteristics included the following: English was used to survey 92 percent of the respondents; females made up 55 percent of the sample; almost three-fourths (72 percent) of the respondents said they were employed; roughly 94 percent of the respondents had driver's licenses. In addition, about 60 percent of the respondents owned their own home.

On average, northern California respondents seemed to be slightly older, better educated, and more affluent than southern California respondents. A considerably higher percentage of Hispanics were interviewed in southern California. Vehicle ownership and housing type appear to be similar for both regions.

## Sampling Representativeness

In most surveys it is important that the sample resemble the population of interest. In this survey the subjects were purposely drawn from cities located near HOV lanes so that a substantial percentage of respondents would have some familiarity with HOV lanes. Therefore, it is reasonable to expect that for each county's sample, the socioeconomic characteristics and commuting habits will differ slightly from those found in the 1990 census for the county as a whole.

Nonetheless, they should bear some resemblance to one another. Table 2 compares the socioeconomic characteristics and commuting habits of each county's sample with comparable variables found in the 1990 census and the 1992 California Statistical Abstract. For each county, household size, percent dwelling units owned, and gender all were compared statistically using a *t*-test. The asterisk denotes statistical differences at the 95 percent confidence level.

Only data from Los Angeles, Orange, Alameda, Marin, and Santa Clara counties were compared with those of the census because of sample size limitations. The samples taken from San Diego, San Francisco, Riverside, Contra Costa, and San Mateo counties were too small for comparison with census data. Telephone survey responses generally result in an oversampling of large households because someone is more likely to be home in a larger household than in a small household. This helps explain why average household size for three of the five counties was statistically different from the 1990 census figure for that county. Women were oversampled (in all five counties), possibly because they are more likely to answer the phone than men. This bias resulted in statistically significant differences for two counties. Age and average household income are only qualitatively comparable because the survey asked only for their age or income category. Exact numbers have been estimated through interpolation. Average household income seems consistently low across counties relative to the census figures.

TABLE 2 Representativeness of Survey Sample by County

| Characteristic by County | Los Angeles | Orange | Alameda | Marin | Santa Clara |
|---|---|---|---|---|---|
| Sample Size | 221 | 194 | 200 | 79 | 219 |
| Household Size (Survey/1990 Census) | 3.48/ 2.91 * | 3.21/ 2.87 * | 2.83/ 2.59 * | 2.46/ 2.33 | 3.00/ 2.81 |
| % Dwelling Units Owned (Survey/ 1990 Census) | 53.5/ 48.2 * | 65.1/ 60.0 | 55.1/ 53.3 | 60.8/ 62.1 | 63.7/ 59.1 |
| Age (Survey/1990 Census) | 30.4/ 30.6 | 34.4/ 31.2 | 36.4/ 32.6 | 41.4/ 38.0 | 35.9/ 31.8 |
| Household Income (Survey/1990 Census) | 28,930 34,965 | 41,710 45,922 | 33,490 37,544 | 44,940 48,544 | 46,460 48,115 |
| Gender (%male) (Survey/1990 Census) | 43.0/ 49.9 * | 45.0/ 50.4 | 40.4/ 49.3 * | 39.2/ 49.5 | 48.2/ 50.7 |
| % Transit Users (Survey/1990 Census) | 10.4/ 6.5 | 2.1/ 2.5 | 10.5/ 10.0 | 13.0/ 10.3 | 5.1/ 3.0 |
| % Carpoolers (Survey/ 1990 Census) | 13.6/ 15.5 | 15.7/ 13.7 | 12.9/ 12.8 | 10.9/ 12.4 | 5.7/ 12.3 |

*Statistical differences at 95 percent confidence level.

In general, the proportions of transit users and carpoolers derived from census data would be expected to exceed those of the survey. This is because the census counts someone who drives alone and carpools as both. In the survey, they were forced to choose only one of the two. Despite this, transit user percentages exceeded the census percentages for the majority (four out of five) of counties. Two of the five counties had carpooler percentages that exceeded the census percentages.

Overall, it appears that the sample from each county generally resembles the county as a whole. There appear to be no important differences in socioeconomic or commute characteristics between each county's sample and the census. Differences that have been found to exist statistically generally are implicit limitations of this type of surveying (biases toward larger households and women). These differences are not expected to play a role in the analysis of data and identification of important perceptions of HOV lane conversions.

## Commute Characteristics

A total of 736 respondents stated that they were employed and commuted to work. Table 3 gives a breakdown of the modes they took to get to work.

Many respondents had both driven alone and either used public transit or carpooled to work within the 2 weeks before the survey. Table 4 illustrates average commute distance and differences in travel times for these individuals. Cells that contain dashes indicate a nonapplicable comparison. The Drive Alone/Carpool category has about the same travel times for each mode. One of the main reasons for carpooling is to save time. These respondents may have had ulterior motives for carpooling part time because they do not in fact save time by carpooling. The 16 commuters who both drive alone and used transit suffered greatly in travel time (18.44-min difference) when taking transit instead of driving alone.

## HOV Lane and Carpooling Characteristics

A series of questions was asked to test the respondents' exposure to HOV lanes and carpooling. Of the 132 respondents who had carpooled within 2 weeks of the telephone interview, money savings was by far the most common reason cited. Reduced travel time and company on the trip rated second and third, respectively, in terms of importance in the decision to carpool. Reasons such as no need to own a car, dislike driving, parking incentives, and employer incentives were not generally stated as important in the respondent's decision to carpool. These findings were consistent with results found in the literature review and focus groups: the main reason for carpooling is economic with secondary consideration given to travel time reduction through the use of HOV lanes.

Table 5 summarizes the 736 employed respondents' exposure to HOV lanes and ridesharing. About 39 percent of respondents said that their employer had provided them with information on HOV lanes. Only 16.7 percent of the respondents' employers had a subsidized vanpool program, whereas about 8 percent of the respondents indicated that they did not know. Employer-provided matching lists were accessible to 30.4 percent of the respondents. About 38 percent of the respondents' employers provided information on ridesharing programs.

## Opinions Concerning HOV Operations

A series of attitudinal questions was asked of all respondents to measure their opinions of HOV lanes. Table 6 summarizes responses to five attitudinal statements, partitioning the sample by region (i.e., NORCAL is the San Francisco Bay Area; SOCAL is southern California, including San Diego). The allowable responses were as follows: strongly agree (S.A. in Table 6), agree, neutral, disagree, and strongly disagree (S.D.).

**TABLE 3 Modes Taken to Work**

| Mode | Number of Respondents |
|---|---|
| Drive Alone | 569 (77.4%) |
| Bus, Train, or Trolley | 59 (8.0%) |
| Carpool | 86 (11.7%) |
| Walk | 12 (1.6%) |
| Bike | 7 (0.9%) |
| Other | 3 (0.4%) |
| Total | 736 (100%) |

**TABLE 4 Commute Characteristics of Respondents Who Had Driven Alone and Either Used Public Transit or Carpooled to Work Within Two Weeks of Survey Date**

| Variable | Drive Alone / Carpool | Drive Alone / Transit |
|---|---|---|
| # of Respondents | 68 | 16 |
| Commute Distance (miles) | 15.06 | 14.84 |
| Average Drive Alone Travel Time | 23.69 | 26.56 |
| Average Carpool Travel Time | 24.65 | ----- |
| Average Transit User Travel Time | ----- | 45.0 |
| Average Drive Alone Travel Time Savings | .96 | 18.44 |

TABLE 5 HOV Lane and Ridesharing Exposure

| Questions: | Yes | No | Not Sure |
|---|---|---|---|
| Has your employer provided you with any information on carpool lanes? | 288 (39.1%) | 432 (58.7%) | 16 (2.2%) |
| Has your employer provided you with any information on ridesharing programs? | 276 (37.5%) | 440 (59.8%) | 20 (2.7%) |
| Does your employer have a subsidized vanpool program? | 123 (16.7%) | 556 (75.5%) | 57 (7.8%) |
| Does your employer provide access to a carpool/vanpool matching list? | 224 (30.4%) | 456 (62.0%) | 56 (7.6%) |

TABLE 6 Participant Response to Selected Statements by Region

| <u>NORCAL</u> SOCAL Carpool lanes... | S.A. | AGREE | NEU-TRAL | DIS-AGREE | S.D. |
|---|---|---|---|---|---|
| are not fair to non-users and those who can't carpool. | 23 (4.0%) | 96 (16.7%) | 50 (8.7%) | 339 (59.0%) | 67 (11.7%) |
| | 12 (2.4%) | 86 (16.9%) | 46 (9.0%) | 314 (61.6%) | 52 (10.2%) |
| are a strong incentive to get people to carpool. | 75 (13.0%) | 330 (57.4%) | 51 (8.9%) | 103 (17.9%) | 16 (2.8%) |
| | 73 (14.3%) | 315 (61.8%) | 37 (7.3%) | 75 (14.7%) | 10 (2.0%) |
| are a safety hazard. | 12 (2.1%) | 83 (14.4%) | 38 (6.6%) | 374 (65.0%) | 68 (11.8%) |
| | 10 (2.0%) | 114 (22.4%) | 41 (8.0%) | 299 (58.6%) | 46 (9.0%) |
| regulations are generally poorly enforced. | 35 (6.1%) | 148 (25.7%) | 148 (25.7%) | 224 (39.0%) | 20 (3.5%) |
| | 33 (6.5%) | 168 (32.9%) | 116 (22.7%) | 178 (34.9%) | 15 (2.9%) |
| are underutilized. | 77 (13.4%) | 274 (47.7%) | 75 (13.0%) | 144 (25.0%) | 5 (0.9%) |
| | 41 (8.0%) | 252 (49.4%) | 61 (12.0%) | 145 (28.4%) | 11 (2.2%) |

The majority of all 1,085 respondents disagreed (653 disagreed and 119 strongly disagreed) with the statement that carpool lanes are not fair to nonusers and those who cannot carpool. This perception of carpool lanes as being "equitable" was held in both regions. An even higher percentage (645 agreed and 148 strongly agreed) of respondents supported the position that carpool lanes are a strong incentive to get people to carpool. Yet in general, carpoolers reported that the main reason for carpooling was money savings and not HOV lanes.

The majority of both southern and northern California respondents disagreed with the statement that carpool lanes are a safety hazard. Northern California respondents disagreed with this statement more often than southern California respondents (78.6 percent versus 67.6 percent). There was no consensus on the issue of carpool lane regulation enforcement in either region. Many respondents in both northern and southern California believed that carpool lanes are underutilized. However, a significant portion (more than 25 percent in each region) believed differently.

Some of these results are in contrast to what was found in the focus groups. Focus group members seemed to be more critical of HOV lanes in general. They believed that the lanes are currently underutilized and are a safety hazard. Some solo drivers resented the devotion of a lane to such a small minority of the cars on the road. Focus group members also criticized HOV lanes as being difficult to move into and out of. In general, the survey responses seemed more supportive of HOV.

It is difficult to definitively deal with the different inferences drawn from the two methods. Each focus group clearly contained opinion leaders, the majority of which were negative concerning HOV. Despite the best efforts of the moderator, this vocal minority could have influenced the expressed opinions of others. This is not unlike the public debate concerning HOV lanes in California: weak-to-moderate support by the majority but very strong opposition by a small minority.

## HOV Lane Addition Preferences

A series of questions was asked about the conversion of a mixed-use freeway lane to an HOV lane and respondents' perceptions of the attributes of various HOV alternatives. Specifically, the respondents were given three alternatives: (*a*) build a completely new carpool lane; (*b*) rebuild the shoulder, restripe the lanes, and make the additional lane a carpool lane; or (*c*) convert a general-use lane into a carpool lane. Table 7 summarizes their preferences to achieve a particular objective (e.g., least expensive).

The majority of respondents perceived the inexpensiveness of the lane conversion alternative (62.5 percent) relative to the two other alternatives. The build-a-new-lane alternative was chosen as the alternative that would make the biggest improvement in overall traffic flow. Interestingly, the lane-conversion alternative was chosen by 19.6 percent of the respondents for the given objective. When asked which alternative was, overall, the most preferable on a freeway respondents take, the rebuilding of the shoulder was preferred by a plurality of respondents (39.3 percent). The lane-conversion alternative tied with the build-a-new-lane alternative with about 30 percent support.

These results are similar to those of the focus groups. In both cases opinion varied on the best HOV lane addition alternative. A majority of the focus group members and survey respondents did perceive the inexpensiveness and low delay cost of the conversion alternative.

Table 8 divides the sample by region. Northern California respondents seemed slightly more receptive to HOV lane conversion than their southern California counterparts but less receptive to building a new lane for HOV purposes. A higher percentage of northern California respondents perceived the inexpensiveness of the conversion alternative. There were minor regional differences concerning perceptions of traffic flow improvement and delay time. Additional comparisons were made of carpoolers and solo drivers; surprisingly, there were virtually no differences in attribute perceptions between these two groups.

Several additional questions were asked to gauge respondents' reactions to and opinions of the conversion of a mixed-use freeway lane into an HOV lane. For example, "After an HOV lane conversion, do you think congestion in the remaining mixed-use lanes would be much better, better, about the same, worse, or much worse than before?" The responses can be found in the last column of Table 9.

Although about 57 percent of respondents anticipated that congestion would become worse, a surprising number of respondents (30.9 percent) though that congestion would be better or much better in the remaining lanes after an HOV lane conversion. Respondents with these perceptions may be expecting a significant number of solo drivers to begin carpooling, using the freeway at a different time, or using a different route.

Participants were asked whether they would support the conversion of a mixed-use freeway lane to an HOV lane if it were to complete an HOV lane network. The results showed strong support for the idea. About 67 percent supported it, 25 percent opposed it, and 8 percent were not sure. This is much stronger support than is shown in Table 7. Respondents were also asked whether an HOV lane conversion would help or hinder their commute. Although 20 percent said it would help, the majority (74 percent) said that it would not. When asked whether they would seriously consider taking an alternate route if a freeway they often used were to have a mixed-use lane converted into an HOV lane, the majority of respondents (69.7 percent) answered no.

Additional categorical analyses tested for independence between HOV lane addition preferences and several socioeconomic and commute characteristics. Table 9 demonstrates that the respondents who thought congestion would be much better, better,

**TABLE 7 Preferred HOV Lane Addition Alternative for Particular Objective (1,085 respondents)**

| Objective | Build a New Lane | Rebuild Shoulder | Lane Conversion |
|---|---|---|---|
| Least Expensive to Implement | 69 (6.4%) | 338 (31.1%) | 678 (62.5%) |
| Biggest Improvement in Overall Traffic Flow | 509 (46.9%) | 363 (33.5%) | 213 (19.6%) |
| Least Amt. of Traffic Delay & Const. Time | 88 (8.1%) | 359 (33.1%) | 638 (58.8%) |
| Overall Preference on Freeway You Take | 330 (30.4%) | 426 (39.3%) | 329 (30.3%) |

**TABLE 8 Preferred HOV Lane Addition Alternative for Particular Objective (575 NORCAL Respondents and 510 SOCAL Respondents)**

| Objective | NORCAL / SOCAL | Build a New Lane | Rebuild Shoulder | Lane Conversion |
|---|---|---|---|---|
| Least Expensive to Implement | NORCAL | 25 (4.3%) | 170 (29.6%) | 380 (66.1%) |
| | SOCAL | 44 (8.6%) | 168 (33.0%) | 298 (58.4%) |
| Biggest Improvement in Overall Traffic Flow | NORCAL | 271 (47.1%) | 196 (34.1%) | 108 (18.8%) |
| | SOCAL | 238 (46.7%) | 167 (32.7%) | 105 (20.6%) |
| Least Amt. of Traffic Delay & Const. Time | NORCAL | 41 (7.1%) | 185 (32.2%) | 349 (60.7%) |
| | SOCAL | 47 (9.2%) | 174 (34.1%) | 289 (56.7%) |
| Overall Preference on Freeway You Take | NORCAL | 162 (28.2%) | 223 (38.8%) | 190 (33.0%) |
| | SOCAL | 168 (32.9%) | 203 (39.8%) | 139 (27.3%) |

**TABLE 9 Congestion in Remaining Mixed-Use Lanes After HOV Lane Conversion versus HOV Lane Addition Preference**

| Congestion change.... | BUILD NEW LANE | REBUILD SHOULDER | CONVERT A LANE | TOTAL |
|---|---|---|---|---|
| MUCH BETTER | 12 | 12 | 23 | 47 |
| BETTER | 72 | 107 | 110 | 289 |
| ABOUT THE SAME | 39 | 42 | 52 | 133 |
| WORSE | 108 | 155 | 106 | 369 |
| MUCH WORSE | 99 | 110 | 38 | 247 |
| TOTAL | 330 | 426 | 329 | 1085 |
| Pearson Chi-Square= 51.068 | DF= 8 | Prob.= 0.000 | | |

or about the same generally favored the conversion alternative over the alternatives for the freeway they take. Similarly, those who thought congestion would be worse or much worse tended to choose either the new-lane or rebuild-the-shoulder alternative over the conversion alternative.

For mode, age, schooling, household income, reverse commuter status, and perceived traffic conditions, the hypothesis of independence could not be rejected. This implies that the mode taken to work is independent of the HOV lane addition preference. The fact that household income showed no dependence on HOV lane addition preference suggests that people are equally offended by or supportive of an HOV lane conversion regardless of income. The only other variable to display any sort of dependence on HOV lane addition preference was gender ($p = 0.0625$). Males tended to support the two other alternatives over the conversion alternative.

Respondents were offered only HOV alternatives; they were not given a "do-nothing" option. However, given that much of the freeway capacity expansion in coming years in California will be dedicated to HOV, the comparisons remain valid.

### Comparisons of HOV Lane Conversion to Transportation Demand Management Alternatives

To understand how HOV lane conversions compare with other transportation demand management (TDM) alternatives, four alternatives were presented to the respondents. The alternatives included congestion pricing ($0.10/mi), a monthly parking fee of $100, a gasoline tax increase ($0.10/gal), and an HOV lane conversion. The personal daily cost of the parking fee, congestion pricing, and the gasoline tax was calculated using the respondents' specified commute distance and the assumption of 25 mi/gal. Each alternative and its associated costs were randomly read to the respondents, who were instructed to rank the alternatives from favorite to least favorite. The results are given in Table 10.

The HOV-lane-conversion alternative was preferred by the most respondents (480 supporters). The gasoline tax was second with 407 supporters followed by congestion pricing (142 supporters) and finally, the monthly parking fee (56 supporters). The possibility exists that a respondent condition effect is partially responsible for the high level of HOV lane conversion preference. The large number of questions regarding HOV lanes may have influenced respondents' preferences.

Nonetheless, people may look upon HOV lane conversions with less resentment than such painful driving disincentives as congestion pricing, parking fees, and gasoline taxes. This is consistent with the findings of the focus groups. One focus group member characterized the choice as follows: "Which is worse, a kick in the stomach or a punch in the face?"

## SUMMARY

With increasing public concerns over worsening air quality and traffic congestion, it is conceivable that urban California residents are now more receptive to the idea of converting an existing mixed-use freeway lane into an HOV lane. This paper has summarized a study whose aim was to assess public attitudes and perceptions toward HOV lane conversions.

A literature review and six focus groups were conducted to support the design of a telephone survey. The telephone survey took place in May 1993. The target areas included the San Francisco Bay Area, Los Angeles, and San Diego. Cities located adjacent to freeways with HOV lanes were sampled. A CATI system was utilized to ensure that the 1,085 respondents were asked questions appropriate to their local freeways and their personal commuting patterns. Care was taken to construct an unbiased survey questionnaire and to have it implemented in an unbiased manner.

Respondents were asked a variety of questions about commuting, ridesharing, HOV lanes, and traffic conditions. About 77 percent of employed respondents reported that they drove alone to

**TABLE 10 Ranking of TDM Alternatives**

| TDM Alternative | 1st | 2nd | 3rd | 4th |
|---|---|---|---|---|
| Congestion Pricing | 142 | 260 | 349 | 328 |
| Monthly Parking Fee | 56 | 137 | 345 | 548 |
| Gas Tax | 407 | 328 | 217 | 137 |
| HOV Lane Conversion | 480 | 360 | 174 | 72 |

work, whereas 12 percent carpooled, and 8 percent took public transit. Money savings was the most common reason cited for carpooling. Solo drivers were generally older and had higher incomes than carpoolers or transit users.

Several attitudinal questions were asked of all respondents to measure their opinions of HOV lanes. A majority of the respondents agreed that carpool lanes are a strong incentive to get people to carpool and that carpool lanes are fair to nonusers and those who cannot carpool.

Respondents were given three alternatives for putting an HOV lane on a freeway: (*a*) build a completely new carpool lane; (*b*) rebuild the shoulder, restripe the lanes, and make the additional lane into a carpool lane; or (*c*) convert a general-use lane into a carpool lane. They were then asked, "Which alternative would you prefer on a freeway you take?" The rebuilding-of-the-shoulder alternative garnered support from 40 percent of the respondents, whereas the build-a-new-lane and lane-conversion alternatives both received 30 percent support. This level of support breakdown was similar across region, household income, age, commute modes, and schooling.

Participants were also asked whether they would support the conversion of a mixed-use freeway lane to an HOV lane if it were to complete an HOV lane network. The results showed strong support for the idea with 67 percent supporting it, 25 percent opposing it, and 8 percent unsure. Respondents were given four TDM alternatives and told to rank them by preference. The fact that the HOV lane conversion alternative was preferred over a gasoline tax, congestion pricing, and a monthly parking fee suggests that people may view HOV lane conversions with less resentment than these other driving disincentives.

There appear to be a great many variables affecting the respondents' choices regarding HOV lane addition preferences, possibly some that were not or cannot be measured. Overall, it appears that the public will be most receptive to a potential HOV lane conversion if the conversion completes an HOV lane network. Support will also be strong when the public is made to feel that the conversion will alleviate congestion. There seems to be no clear trend of HOV lane addition preference on the basis of socioeconomic or commuting characteristics.

Some of these conclusions are based on respondents' preferences in the abstract. The validation of these findings must await the actual implementation of an HOV lane conversion. The possibility exists that the informed opinions (having knowledge of cost, delays, traffic flow implications, etc., of the different HOV alternatives) of the respondents could be quite different. This possibility highlights the importance of public involvement in the planning process when different HOV lane treatments are considered.

Research on HOV lane conversions will continue at University of California, Davis. Additional surveying will be able to capture the effect of HOV experience and transit availability on HOV lane addition preference. Insights also may be gained into situations (in terms of proper implementation timing, freeway design, operation policies) in which an HOV lane conversion can be successful. Future research may also focus on developing a methodology for measuring changes in attitudes and perceptions associated with HOV lane conversions.

The results presented in this paper suggest that urban California residents may now be ready for HOV lane conversions. The results from actual HOV lane conversion implementations are necessary to validate these findings. Nonetheless, transportation professionals should not summarily dismiss the HOV lane conversion option.

## ACKNOWLEDGMENTS

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# HOV Lanes and Ramp Metering: Can They Work Together for Air Quality?

BILL R. SHOEMAKER AND EDWARD C. SULLIVAN

The analysis process used to assess the air quality impacts of high-occupancy-vehicle (HOV) lane and ramp metering projects is discussed, and the degree to which these popular measures are effective and compatible when jointly applied to improve freeway operations is examined. It happens that there exist subtle and potentially perverse interrelationships between HOV lanes and ramp metering. Also, in an environment of worsening congestion, ramp metering has a limited life. Proper management of these respective systems can occur only when they are administered with full acknowledgment of their mutual interdependence and with a long-term view of their relative potential.

Transportation agencies in California currently find themselves having great difficulty proving air quality conformity with regulations stemming from the Clean Air Act for the favored traffic management measures of the moment: high-occupancy-vehicle (HOV) lanes and ramp metering projects. These two traffic management measures become intimately related when they coexist, in which case the analysis procedure for evaluating air quality impacts becomes quite involved.

Figure 1 is an effort to illustrate the process of analysis and decision making required in the San Francisco Bay Area to gain approval for HOV lane and ramp metering projects at the regional level. The point of the illustration is to emphasize the complexity of the process and the key role of analytical modeling in informing the eventual decision for or against a project.

The purpose of this paper is to provide a perspective on this analysis process and to examine in detail the degree to which these popular measures are effective and compatible when jointly applied to improve freeway operations. The adequacy of the methodologies used to analyze such projects is also addressed. It is argued that there exist subtle and potentially perverse interrelationships between HOV lanes and ramp metering. It is essential to address these interrelationships directly so that proper decisions can be made regarding the times and places to deploy either or both of these traffic management options.

## RAMP METERING

Ramp metering projects attempt to hold traffic demand at freeway bottlenecks below their capacities, eliminating most mainline queue delays by imposing much smaller delays on vehicles temporarily held back on the ramps. Ramp metering also fills in naturally occurring gaps in the freeway traffic stream, resulting in smoother operation, greater flow rates, and less backup. Metering may also result in diversion of some very short trips from the freeways altogether.

Ramp metering is designed to reduce travel times and improve safety by eliminating stop-and-go driving conditions. The resulting higher speeds also reduce the carbon monoxide (CO) emissions along the freeway mainline. But, until recently, no one had thought much about the air quality consequences of the resulting on-ramp backups and the altered ramp acceleration behaviors.

The California Department of Transportation (Caltrans) recently performed air quality impact modeling to assess ramp metering projects along US-101 and Interstate 880 in the San Francisco Bay Area. Consideration was limited to the possibility of CO hotspots with no effort to determine areawide air quality impacts. In some instances, the modeled receptors next to proposed metered on ramps yielded CO excesses that rivaled those reduced excesses computed along the more smoothly operating freeway mainline.

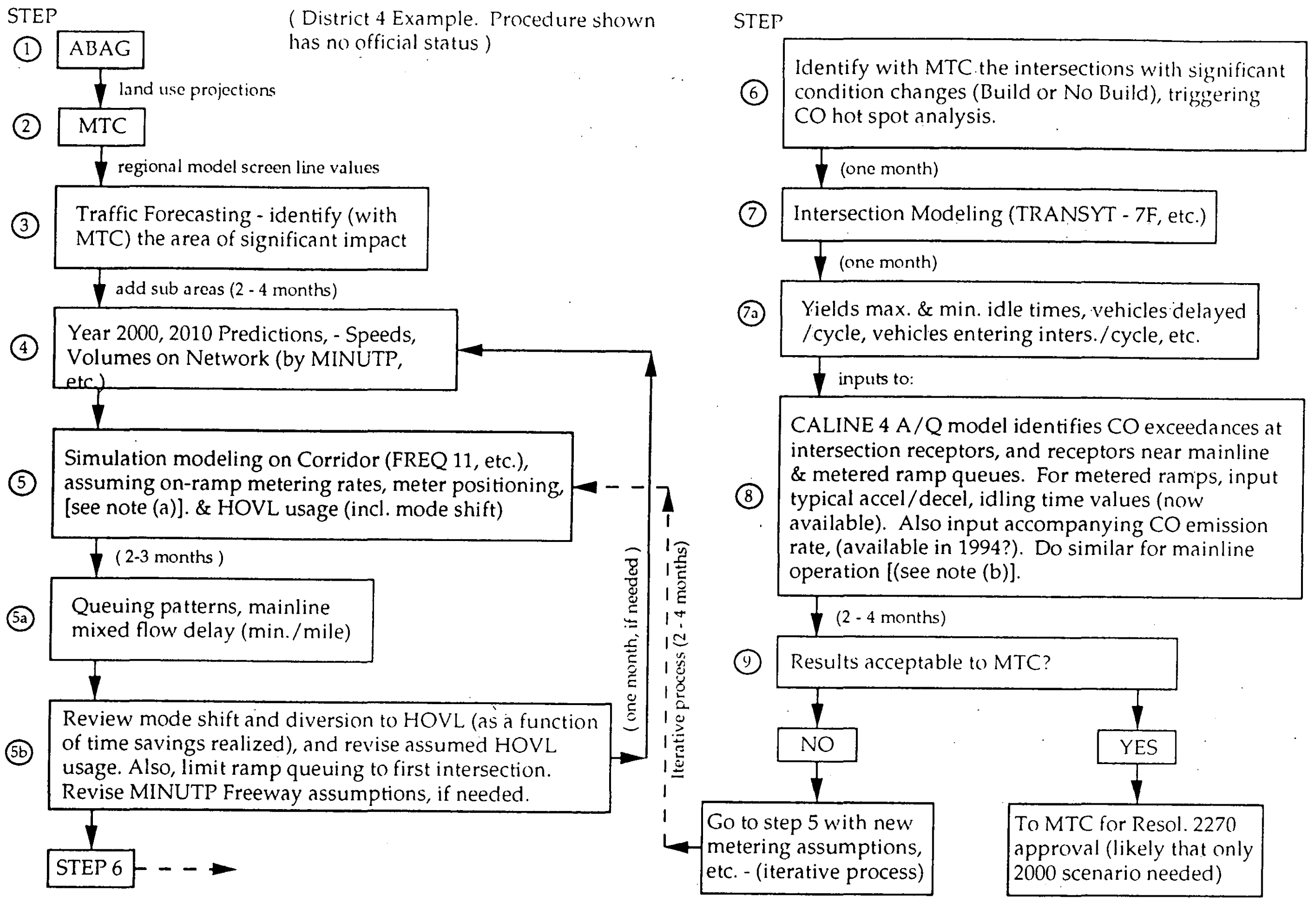
Initial (as yet unpublished) investigations by consultants to the California Air Resources Board (CARB) and Caltrans revealed very high tailpipe emission rates when stop bars and meters are positioned near the on-ramp merge locations. The shortened acceleration distances seemed to result in increased acceleration rates for entering cars and higher emission. However, another recently completed study for CARB and Caltrans found no consistent differences in acceleration behavior from reduced acceleration distances per se except on heavily congested mainline freeways without auxiliary lanes (*1*).

In any case, moving the stop bar back along the ramp to lengthen acceleration distances reduces available storage for metered traffic, resulting in little flexibility for setting future metering rates. Queuing is required to stop short of the adjacent street intersection, because cities do not permit metered traffic to overflow onto city streets. The solution, if possible, is to rebuild ramps to provide greater lengths and widths for vehicle storage or auxiliary lanes to facilitate merging, or both; however, financial and land availability constraints often render such improvements infeasible.

## HOV LANES

The theory behind the HOV lane program is that when mixed-flow traffic becomes sufficiently delayed, the time savings enjoyed by HOV lane users will promote carpool formation among the drivers of single-occupant vehicles (SOVs). There is some evidence that such a mode shift impact has occurred in some situations. For example, Pratt (*2*) reports reductions ranging from a few percent to over 20 percent in vehicles per person associated with vanpool and carpool increases on the Interstate-10 El Monte Busway, Shirley Highway, and the Houston transitways. However, significant mode shifts have not occurred to a marked degree at all installations.

B. R. Shoemaker, Office of Operations, California Department of Transportation, 111 Grand Avenue, Oakland, Calif. 94623. E. C. Sullivan, Department of Civil and Environmental Engineering, Cal Poly State University, San Luis Obispo, Calif. 93407.




Footnotes

(a) Metering and stop bar positioning critical (e.g.) placing at on-ramp nose results in short acceleration distance. The high acceleration rate needed results in very high CO emission rates. But placing farther upstream lowers acceleration rates, but means reduced storage.

(b) "Dynamic" modeling of the street network (i.e. simulation modeling similar to that already employed on the freeway by FREQ 11, etc.) will be available in two to five years. At present, only average link speeds are available. When queuing, accel/decel/idling profiles (including CO emission breakdowns) become available, the constant speed attributes of HOVL operation will become apparent in CO evaluations, - especially if an (area wide) burden analysis (i.e. total tailpipe emissions for the area) is run.

**FIGURE 1 Typical freeway project adding HOV lanes and ramp metering.**

The inconsistent results with regard to mode shift have a variety of explanations. Perhaps the major one is the necessity that, for fundamental mode shifts to occur, chronic congestion must exist with the prospect of only getting worse. Such congestion would not be alleviated, other than momentarily, by ramp metering or other operational improvements.

Figure 2 presents a summary of the varying success reported for a number of HOV facilities constructed across the country (*3–6*). The graph shows the first-year increases in carpooling related to the time savings per unit distance and the corresponding speed differences, assuming an HOV lane speed of 100 km/hr (60 mph). Unfortunately, the results for some installations are deceptive because the increase in HOV users often can be attributed to the migration of existing carpools from parallel arterials. In this regard, the only way to be sure of actual carpool formation is through a corridor-wide survey. This has been done in the case of the highly successful California State Route 55 operation in Orange County, thus ensuring that the more than doubling of HOV eligibles has indeed largely come from those who previously drove alone (*3,7*). In any case, shifting carpools from congested arterials to constant-speed HOV lanes offers air quality benefits, as will be explained.

A fact of life, however, is that the vacancies created by the migration of carpools to an HOV lane are typically back filled by SOVs, which may come from parallel arterials or from the mainline itself, having shifted from earlier or later periods. To the extent that back filling involves diversion from longer or more congested alternative routes, it may actually be beneficial for air quality, or the effect may be neutral if mostly time shifts are involved. However, if the new SOVs are composed of former transit riders, riders in newly generated trips, or former HOV riders from other periods, the incremental air quality consequences of back filling can be negative.

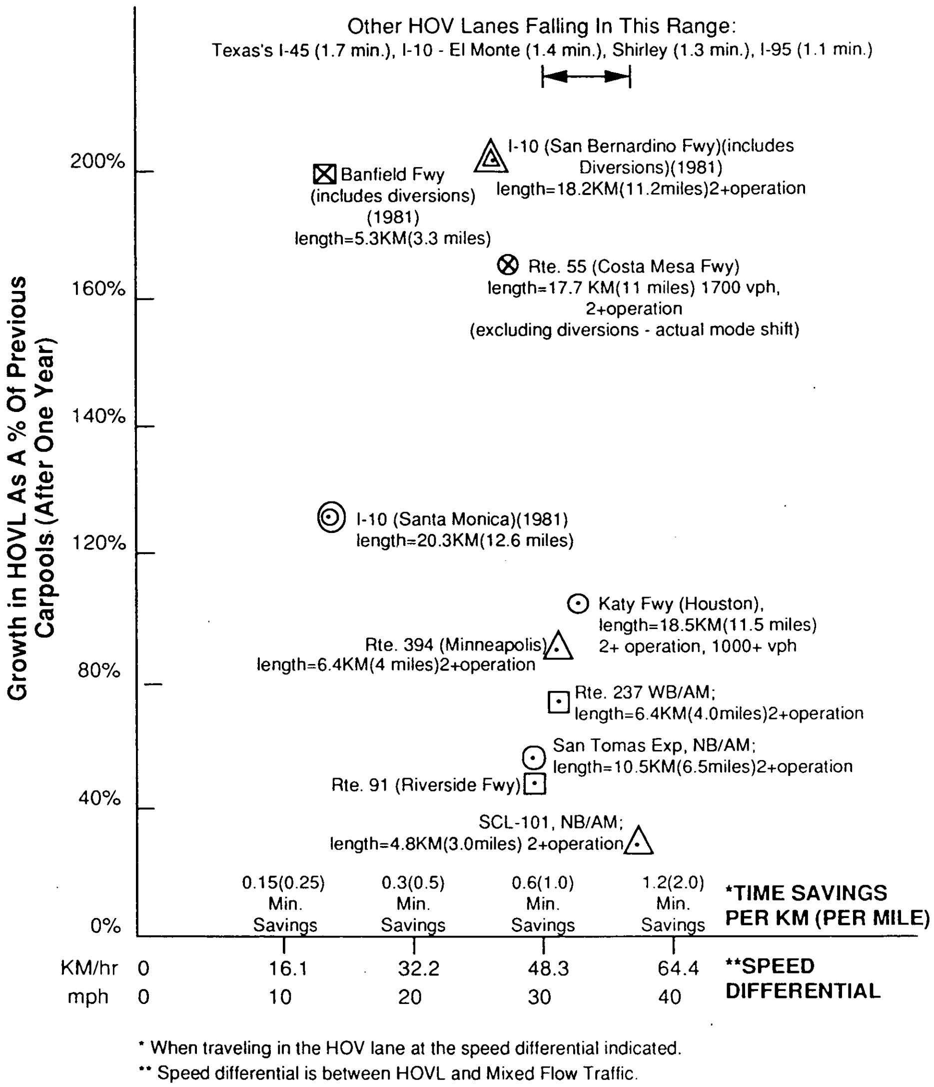



**FIGURE 2 HOV lane growth versus time savings for various facilities.**

Proving the air quality benefits of HOV lanes is problematic because the methodology developed thus far is largely inadequate for the task. Although traffic modeling for the freeway systems has achieved some success, modeling of the surrounding street network is still fairly primitive, viewed from the perspective of air quality impact determination.

What is needed, among other things, is an accurate assessment of the comparative traffic conditions to be experienced on the various routings from home to work. Planning models assign trips to these routings on the basis of the shortest travel times or costs. As a general rule, the higher the route speed, the lower the CO emission. For the moment the impact of CO emissions is the major hurdle in gaining project approval.

## WHAT IS THE PROBLEM?

In looking at tailpipe emissions, it is important to recognize that the emissions are not simply a function of the average speed on a journey from home to work. In reality, driving in congested areas means a great deal of speeding up, slowing down, lane changing, and idling. All of these operational modes have vastly differing instantaneous emission rates. It is only when these actual driving profiles under typical urban travel conditions are understood that a true picture of the air quality consequences of typical arterial and freeway congestion and of congestion mitigation measures becomes apparent.

Most planning models depict travel in terms of constant average speeds between major intersections. The fallacy here is that congested operations with accelerations, decelerations, and idle times can produce CO emissions that are much different from those that the average speeds imply. Unfortunately, most past empirical research to develop emission factors has focused on the average vehicle emissions produced throughout a complete driving cycle rather than on the disaggregate emissions associated with the individual modes of operation. In ongoing research, CARB and others are working to gain insight into the emission impacts of various driving modes experienced on arterials, freeways, and metered on ramps.

The magnitude of the problem of estimating disaggregate mode-specific emission factors should not be underestimated. The task is made considerably more difficult because of the need to cope with the varying emissions characteristics of the composite fleet on the road. Emissions characteristics vary with model, vehicle age, and factors such as the deteriorating efficiency over time of catalytic converters. The emission differences among various vehicles become amplified when the averaging effects of driving cycles are eliminated. Therefore, it may be years before the requisite disaggregate profiles of vehicle operation and emission rates have been agreed on and made available.

Meanwhile, there are continuing efforts to reduce, and perhaps some day eliminate, vehicle pollution emissions. Although solving the motor vehicle air pollution problem would simplify the analysis, the need for careful evaluation of the effectiveness and synergetic relationships of HOV lane and ramp metering projects would remain, with attention more focused on user benefits and other mobility impacts.

Work is proceeding to improve the dynamic modeling of traffic performance in mixed arterial and freeway networks, which will become increasingly relevant to the evaluation of HOV and ramp metering projects. The goal is to be able to realistically model the actual performance of traffic flowing through a network, including the accelerations, decelerations, and cruise and idle periods resulting from both traffic congestion and the various traffic control devices that operate throughout the network.

Fortunately, a great deal of progress has been made in traffic modeling over the past several years. A number of microscopic models now exist that can track individual vehicles through fairly large mixed freeway-arterial networks and provide quite realistic representation of the development, propagation, and eventual shrinkage of queues, along with plausible traveler diversion behavior in the face of recurring and nonrecurring congestion (*8–12*). Although not trivial, the goal of extending such traffic models to provide location-specific vehicle operational mode data for use as input to disaggregate mode-specific emission models as well as other impact models is within reach. Once these traffic models have been extended and the necessary mode-specific emission factors are made available for all the relevant pollutant species, the evaluation of HOV lanes and ramp metering projects and their systemwide air quality impacts on urban corridors will become a reality.

## DO RAMP METERING AND HOV LANES WORK TOGETHER?

With traffic operations centers utilizing camera and loop detector surveillance, one regularly seeks to optimize freeway operating conditions by varying metering rates at on ramps. This sounds sensible enough until it is realized that the HOV lanes can be part of the equation.

HOV lanes succeed in promoting mode shift only when they realize a significant time saving, on the order of a 0.5 min/km (1 min/mi). This value corresponds to mixed-flow traffic moving no faster than an average of 50 to 65 km/hr (30 to 40 mph). This seems to place the metering program goals at loggerheads with those of the HOV lane program, and it may be some time before there is a meeting of the minds on the proper roles of these two strategies.

On the other hand, if ramp metering can be tuned carefully so that the mainline freeway operates consistently in the range of 50 to 65 km/hr (30 to 40 mph), and if the extent of HOV systems is sufficient to provide the long journey lengths needed to produce significant cumulative travel time savings for HOV users, the promise of both of these traffic management strategies could theoretically be achieved together. Speeds in the range of 50 to 65 km/hr (30 to 40 mph) largely correspond to the upper end of freeway conditions at Level of Service E. This is exactly the range that yields the greatest traffic throughput on the mixed-flow lanes, assuming that traffic flow stability can be maintained and at the same time provides sufficient long-term incentives toward greater HOV participation.

Of course, the assumption that traffic flow stability can be maintained is a significant one. Under today's operating conditions, consistently maintaining stable flow near capacity is difficult. However, some of the new vehicle control technologies now being developed through the national Intelligent Vehicle-Highway System (IVHS) initiative may result in basic operational improvements that can make this requirement easier to achieve.

Bearing on this picture is the realization that in an atmosphere of worsening congestion, ramp metering has a limited life. Perhaps a fourth of the meters in Los Angeles already have become useless during the most congested periods of the day. This typically occurs when on-ramp queues start overflowing onto city streets and the meters have to be turned off.

With the support of FHWA and, thus far, with the support of the air quality monitoring agencies, both ramp metering and HOV lane programs have achieved considerable momentum. However, both programs are increasingly under attack, in part because of the inability to demonstrate convincingly that when properly designed and coordinated, these facilities represent the best practical strategy available for achieving improved air quality as well as increased user benefits. This situation may change after the needed planning tools discussed earlier are developed, which will enable a more scientific evaluation of the impacts of these programs and whatever synergetic relationships they may prove to have.

The short-run view perhaps should be that ramp metering with centralized monitoring (and HOV lane bypass of the meters) offers the greatest promise. As congestion worsens, however, and many meter locations become less effective because of excessive queue lengths, HOV lanes will become increasingly attractive as their trip time savings accrue.

Meanwhile, proper management of these respective systems can occur only when they are administered with full acknowledgment of their mutual interdependence and with a long-term view of their relative potential. An enormous investment is being made in both programs. It is important that their respective roles not be compromised. State and federal leadership in this regard is essential to establishing the necessary perspective. Otherwise, the situation could easily become competitive and counterproductive, resulting in a deterioration of public confidence and cooperation with either program.

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# Marketing a High-Occupancy-Vehicle Lane in a Suburban Setting: Long Island Expressway Experience

ARNOLD BLOCH, MARGARET CAMPBELL JACKSON, WAYNE UGOLIK, AND MEL COOPERMAN

A marketing effort was undertaken for implementation of a high-occupancy-vehicle (HOV) lane on the Long Island Expressway in Suffolk County, New York. The HOV lane was scheduled to open in spring 1994, but marketing efforts began considerably earlier in recognition of the lack of knowledge of the concept in the Long Island region. The marketing effort, like others in the nation, has had two major objectives: (*a*) to promote the project to key stakeholders as a workable highway improvement alternative to gain support and approval for the project; and (*b*) to promote the project to potential HOV lane users, so as to build a constituency and an adequate level of usage. The results of all these marketing efforts so far have been to (*a*) develop a constituency for HOV facilities on Long Island, (*b*) gain interest among employers in the HOV concept, (*c*) provide a coordinated marketing and informational program that can meet the needs of potential users even before implementation, and (*d*) add to the overall effort to meet suburban mobility needs with effective solutions that significantly address the issue of automobile occupancy.

High-occupancy-vehicle (HOV) projects have been successfully implemented and operated throughout the United States for more than 20 years. There are examples throughout the research literature of successful applications, resulting in such beneficial results as travel time savings for HOV lane users, increased people-moving capacity of highway facilities, and increased usage of transit and ridesharing options. With well over 30 projects and 300 mi in service in the nation, HOV lane options receive increasingly serious consideration as public transportation improvements throughout urban and suburban settings.

Still, HOV lanes remain difficult projects to promote. They are neither as provocative as a new rapid rail line nor as universally appealing as a new general-use highway facility. Instead, they have the appeal of being appropriate, which limits enthusiastic support. In other words, responses to these projects are as follows:

- To those who prefer more highways, the response is that financial, environmental, and community constraints no longer make it feasible to construct traditional new facilities. In addition, new highways are not a solution to the long-term congestion problem but may actually help increase congestion, because new capacity may draw new vehicular travel. Therefore, HOV lanes become the more appropriate alternative.

A. Bloch and M. C. Jackson. Howard/Stein-Hudson Associates, Inc., 10 E. 21st Street, New York, N.Y. 10010. W. Ugolik and M. Cooperman, New York State Department of Transportation, Region 10, State Office Building, Veterans Memorial Highway, Hauppauge, N.Y. 11788.

- To those who prefer rail lines, the response is that origins and destinations have become so diffuse that rail would serve only a fraction of the market. A major (and expensive) complementary system of feeder-distributor bus connections and park-and-ride lots would be necessary to serve most origin-destination (O-D) pairs, further implying a series of undesirable modal transfers. Therefore, HOV lanes become the more appropriate alternative.

Given that an appropriate choice is not necessarily one that wins widespread support, each new HOV lane project is an adventure in marketing. Marketing starts early—years before construction—and continues late—well past implementation. Marketing is undertaken for two main reasons: first to promote the project to key stakeholders as a workable (not simply an appropriate) alternative to gain their support and approval for the project and second to promote the project to potential HOV lane users so as to build a constituency and an acceptable level of usage. For both of these reasons, a concerted marketing effort has been undertaken since 1988 for the Long Island Expressway (LIE) HOV lane project, a project that was not planned to begin operation until the spring of 1994.

## LIE HOV LANE PROJECT

### History

The LIE began to take shape as a major highway link in the New York City metropolitan area in the 1940s by providing city residents with access to the Midtown Tunnel into Manhattan. By the early 1960s, it already extended beyond the city's eastern border into Nassau and Suffolk counties. It currently extends 70 mi (112 km) east from the tunnel to mid-Suffolk County. It is a six-lane, limited-access facility throughout.

The LIE serves as a major commuting route, not only linking the Manhattan central business district with much of the city and suburban areas, but also serving a considerable portion of so-called intra-island commuting trips—particularly those with both origins and destinations within Nassau and Suffolk counties. These two suburban counties have a combined population of about 2.7 million and total employment of about 1.4 million. Following a similar pattern as in most of the country, these counties grew throughout the first half of the 20th century as bedroom communities for New York City commuters. Over the past 30 years, they have become much more self-reliant. For example, 70 percent of the westbound (i.e., toward New York City) morning peak period commuters on the LIE in these two counties never enter New York City, having found service sector, retail, and manufacturing employment opportunities on Long Island itself.

### Current Conditions

Over the years, traffic and congestion on the LIE have grown steadily: average annual daily traffic exceeds 150,000 vehicles—more than twice the design standard. Delays and slow operating speeds are prevalent during the peak commuting periods in much of Nassau and Suffolk counties. State studies and a bond referendum in the late 1980s identified the prospect of constructing additional lane capacity in each direction along a 41-mi (65.6-km) stretch of the LIE from the New York City border to Exit 64 in western Suffolk. Through legislative action, a design and environmental study was initiated on a 12-mi (19.2-km) section of the LIE, to be followed shortly by a study of the entire 41-mi proposed project area. At the time of this writing, the 12-mi (19.2-km) section was under construction and scheduled to begin operation in spring 1994. The draft design and environmental impact statement study for the 41-mi (65.6-km) corridor was still being prepared as of April 1994.

State transportation officials identified HOV as a possible appropriate alternative for the new bidirectional capacity improvement. In support of the HOV lane option, former state Department of Transportation (DOT) Commissioner Franklin E. White asserted that the state cannot build its way out of congestion. In beginning to explore the HOV lane option, however, significant resistance and doubt were voiced from three major sources: business leaders; editorials in *Newsday*, the island's largest (and one of the nation's largest) daily newspapers; and elected officials. The types of issues raised are not unlike those voiced in other parts of the country:

- Long Islanders will not carpool; they are different from the rest of the country.
- There is neither a "central city" as such in Nassau or Suffolk nor many major employers. This situation will make it very difficult to generate ridesharing or transit-related use of an HOV lane system.
- The government should not force people to carpool, but should build additional capacity for everyone.
- The state should invest in new rapid rail systems in the LIE median. (Long Island already has the 100-year-old, 10-line Long Island Rail Road, the nation's busiest commuter railroad, which carries 70 million riders annually, primarily to and from Manhattan.)

It was clear to state officials that if the HOV option was shown to be a workable alternative following the design and environmental process, a marketing effort was needed to make HOV appealing to stakeholders and the public at large. The first order of business was to provide information to key stakeholders that would be useful in helping to promote and build support for the HOV lane concept. Key objectives were to show

- That HOV lane projects have been successfully implemented throughout the United States, including in suburban settings in areas dominated by single-occupant vehicle commuting;
- That a significant number of Long Islanders would be interested in ridesharing if travel time savings would accrue to them;
- That government was acting in a responsible, not overbearing manner, in promoting the HOV lane option versus new general-use lanes on the LIE;
- That the LIE primarily served a different (i.e., non-Manhattan) market than the Long Island Rail Road, meaning that new rail options would not meet most travel needs; and
- That an HOV lane system on the LIE could be operated, enforced, and managed effectively.

The second order of business was to appeal to potential users of the HOV lanes to whom the concept was not well known. (Although Manhattan commuters from Brooklyn, Queens, and New Jersey have had the benefit of HOV lanes at tunnel approaches for many years, these have served express bus riders, but not ridesharers or Long Island commuters.) The objectives were to

- Build anticipation and positive expectations for the upcoming HOV lanes,
- Define the elements and operations of the HOV lane system, and
- Relate the HOV lane to the travel needs of Long Islanders.

To undertake this two-pronged approach and fulfill the various objectives, the state DOT developed a strategic effort, shown in Figure 1. The remainder of this paper highlights the strategies and tools presented in Figure 1 and points to new directions to adopt.

## MARKETING HOV-LANE CONCEPT TO STAKEHOLDERS

### Strategy

The basic strategy in this effort was threefold:

1. To provide factual material to key stakeholders about the LIE HOV lane and other HOV operations around the country,

| | Marketing HOV as a *Concept* | Marketing HOV to *Potential Users* |
|---|---|---|
| Strategy | ▪ Basic Information on similar findings<br>▪ Cooperation and coordination<br>▪ Bring together diverse interests | ▪ Providing timely information<br>▪ Working through employees<br>▪ Tie in HOV to TDM, environmental and economic concerns |
| Tools | ▪ Driver Survey<br>▪ Conference/white paper<br>▪ Site visits<br>▪ Slide Show<br>▪ LIE/HOV Task Force | ▪ Outreach Options Matrix<br>▪ Focus Groups<br>▪ Employer Outreach Program<br>▪ Media Strategic Plan |

**FIGURE 1 Marketing directions for LIE HOV lane.**

2. To move the planning process out of the traditional departmental structure and into a forum of mutual cooperation and coordination with other agencies, and

3. To bring together diverse public and private interests early in the process as a way of encouraging buy-in and support for various aspects of the HOV-lane concept.

## Marketing Tools

### *Driver Survey*

In 1987–1988, a postcard survey was conducted. Over 130,000 postcards were distributed to automobile commuters on Long Island (primarily on the LIE itself). The return rate was nearly 30 percent. The survey was intended to provide O-D information. However, two questions were raised as a way of determining, in a preliminary way, the extent of an existing and potential market for HOV lanes. It was found that about 20 percent of LIE users were traveling in multiple-occupancy vehicles. Furthermore, an additional 20 percent said that they would consider ridesharing options if they could achieve travel time savings on the LIE. The primary use of this information was to show stakeholders that a sizable number of commuters were likely users of the HOV lanes, enough to create a sufficient nucleus for a successful operation.

### *Conference and White Paper*

In November 1989 the state DOT worked with a diverse set of sponsors (including a key state legislator, business groups, other state and county agencies, and the federal government) to hold a 1-day workshop on relevant transportation issues and solutions. The title of the workshop reveals its purpose and general agenda: Innovative Ideas for Keeping Long Island Mobile—Featuring an Update on Implementation of the Long Island Expressway Fourth Lane Project. Key traffic mitigation success stories included nationwide experience with transportation management associations (TMAs), travel demand management (TDM) techniques, and HOV programs—all key aspects in managing suburban congestion problems. Additional sessions and workshops focused on diverse topics, including the LIE HOV-lane concept, but also including freight movement issues, public-private partnerships, and other Long Island traffic corridors. Speakers and workshop leaders included elected officials, transportation officials from New York and other states, business leaders, TMA personnel, and others.

In preparation for this conference the state DOT had consultants prepare an informal report entitled *Moving People Out of Congestion: Considering the High Occupancy Vehicle Option on the Long Island Expressway* (*1*). The report recognized that the HOV-lane alternative was not well known to the public, even though elsewhere it was shown to be an effective method for improving highway capacity. It posed and answered such questions as Why consider the HOV-lane alternative for the LIE; Who uses HOV lanes; What is the proper setting for an HOV lane; and What are the key measures for success for an HOV lane? Its primary purpose was to show that other suburban areas had planned, implemented, and successfully operated HOV lane systems, achieving beneficial results.

### *Site Visits*

To encourage further understanding of HOV lane operations, including key enforcement issues, the state DOT both coordinated with and sponsored on-site visits for elected officials, planning officials, and law enforcement officials to some of the nation's HOV lane systems. The first visit, to the Washington, D.C., area in 1989, was arranged by a key state elected official. Subsequent visits to southern California and Hartford, Connecticut, were arranged by the state DOT. In all cases, the emphasis was on observing successfully operating HOV systems.

### *Slide Show*

Beginning in 1991, the state DOT developed various slide show presentations to explain the LIE HOV lane concept to stakeholders, including elected officials, business groups, and other civic and educational groups. The slide show (unpublished presentation) made the following case for HOV as the appropriate option:

> Another new lane in each direction of the LIE is needed. But new lanes in and of themselves are not the most effective solution. A four lane expressway will be congested as soon as it opens. . . . The most effective approach to maintaining long-term mobility is to combine the potential that highway expansion offers with the people-moving efficiency of transit. . . . This can be accomplished by reserving a new, fourth lane for . . . so-called high occupancy vehicles.

## LIE-HOV Task Force

The LIE-HOV Task Force was established in 1991 by the state DOT to provide advisory opinions on key HOV issues. The task force brings together government, the private sector, and other organizations; participants include elected officials, mass transit agencies, law enforcement agencies, environmental groups, the business community, the Automobile Club of New York; the Long Island Association (the region's largest business and civic group), and Long Island's nonprofit ridesharing group.

The task force is charged with the responsibility of charting a new course for the future travel needs of Long Islanders. Guided by the state DOT, the task force meets regularly to deal with developing recommendations for all major actions and policies needed to make HOV successful on Long Island.

The issues addressed by the task force have included (*a*) HOV operations such as enforcement, incident management, the HOV occupancy requirement, and HOV hours of operation; (*b*) park-and-ride lot planning; (*c*) ridesharing and transit programs; and (*d*) public outreach and education about the HOV concept and use of the HOV lanes. Through direct involvement in these key areas, task force participants became an integral part of the planning for LIE-HOV success and a solid, broad-based foundation supporting the implementation of HOV on the island.

The state DOT's prominence as the leader in developing this new HOV solution on Long Island was now shared with a much wider group with closer ties to communities, businesses, and the traveling public. Less than 1 year from the first meeting of the task force, major statements of support for HOV by task force participants were in the public domain.

As a result of formal task force resolutions, numerous actions and policies to support the successful operation of the first 12 mi

(19.2 km) of lanes were developed. These include, but are not limited to, the decision to operate the facility as a 2+ occupant HOV lane between 6:00 a.m. and 8:00 p.m. Monday through Friday, with general use at other times; a state DOT plan with Suffolk County Transit for new LIE express bus service that would utilize the HOV lanes; an enforcement plan to be implemented by the Suffolk County Police Department; and several park-and-ride improvement projects.

From its beginning the task force also maintained a keen interest in public outreach. Recognizing that a well-planned program of information and education is critical to the public's understanding and use of the HOV lanes, the task force asked the public Outreach Working Group to recommend an effective program. The process used to develop and implement that program will be taken up in the remainder of this paper.

## MARKETING HOV LANES TO POTENTIAL USERS

### Strategy

The strategy for marketing HOV lanes to potential users has evolved over time as the state DOT undertook preliminary data-gathering steps and began to incorporate the lessons learned in the marketing of the HOV lane as a concept. Three key objectives emerged:

1. To provide potential users with timely information at various stages of the process.
2. To focus on Long Island employees as the main target group for a marketing effort. As a result of this decision, a key direction was to reach employees directly at their job sites by promoting the LIE HOV concept to their employers.
3. To relate the LIE HOV lane to other innovative TDM methods and, in a larger way, to the overall goals of improving Long Island's environment, its economy, and its strength as a suburban residential community.

### Marketing Tools

#### *Outreach Options Matrix*

In early 1991, the state DOT asked its consultant to develop a set of outreach proposals intended to (*a*) inform the public, and commuters in particular, about HOV lane issues; (*b*) promote the HOV-lane concept; (*c*) tie informational and promotional efforts to actual milestone dates; and (*d*) coordinate the outreach activities of DOT and the LIE-HOV task force. Some 17 separate activities were identified. These included general publications (e.g., progress bulletins and newsletters); focus groups and surveys; workshops, seminars and a speakers' bureau; a hotline phone number and a roving field office; outreach to special groups and briefings to public officials; slide shows and videos; and press releases, editorial board briefings, key reporter contacts, and a media campaign. All of these had wide-ranging consequences in terms of costs, timing, direction, and joint participation among DOT officials, the task force, the consultant, and others.

In the end, it was from this first-cut identification of options that the two main directions that state DOT adopted were derived. Before they were selected, a separate activity was selected—also from this list—with the intent of quickly gathering important insights into the nature of what a marketing program should concentrate on. The activity selected was to conduct focus groups.

#### *Focus Groups*

In recent years, the focus group technique has been used as a means of identifying key issues and beginning the consensus-building process, particularly for complex projects and those requiring a strong public education and information campaign. A critical part of the successful design and implementation of the marketing effort was understanding the public's knowledge and perception of what an HOV lane is and how it works.

Three focus groups were conducted in late 1991: two with commuters and one with employers near the LIE corridor. The intent was for commuters to express their understanding of HOV lanes and related issues and concerns. Employers were encouraged to discuss efforts to encourage ridesharing and reduce vehicle trips to their work sites.

Participants were selected with the aid of the mailing list developed for the project, as well as additional lists of Long Island civic associations. For the commuter focus groups, civic association leaders were asked to suggest a member who regularly used the LIE for commuting and various other purposes. For the business focus group, representatives were invited who both were concerned with employee travel issues and had some decision-making influence in the firm.

A major finding from the commuter groups was their skepticism about the ability of the LIE HOV lanes to generate new carpools. Further probing during the sessions revealed that most people knew very little about the project, and in fact many were hearing about it in detail for the first time. Commuters and employers needed to understand how the lanes would work—particularly with respect to enforcement, incident management, and a clear understanding of entering and leaving the HOV lane—and how HOV lanes would save travel time. They all agreed that some traditional outreach methods—such as mass mailings and inserts in utility bills—would not reach the target market of commuters.

The commuter groups thought that the first point of contact should be employers. Results of the employer group showed that they were willing to help in this effort, with assistance from the state. Many of the employer group participants stated that they had tried to institute ridesharing programs on their work sites but found the process to be very slow. The employer group identified a number of high employment centers along the LIE corridor and suggested that the best way to promote ridesharing at their work sites would be to band together, either as business associations or by forming TMAs.

Everyone was in agreement that a major education process was necessary. They suggested that government could assist businesses by producing training videos for employee seminars.

#### *Employer Outreach Program*

On the basis of results of the focus groups, the state DOT decided to concentrate a significant portion of its informational activities to potential HOV users at the workplace. Working with the LIE-HOV task force (and actually under the sponsorship of that body, rather than the DOT itself), a program was developed to provide direct outreach to a number of Long Island employers who had a significant number of LIE commuters. The intent was to meet with key managerial officials from as many of the largest employers as could be managed before the first stage of the HOV lane began operating in the spring of 1994. This turned out to be approximately 200 firms. At these meetings, the officials would be presented with various visual materials that discussed TDM and employee trip reduction (ETR) goals in general, and the LIE HOV lane specifically. Using the materials that were distributed to them, employers would be encouraged to provide information to employees and take an active role in ETR objectives.

Consultants to the state DOT prepared the following types of materials for distribution to the employers:

- Introductory Video. A 10-min video was prepared that places TDM, ETR, and HOV goals in the context of
  - –Long Island's historical development,
  - –Preserving Long Island's precarious economic vitality,
  - –Working toward an improved environment, and
  - –Maintaining Long Island's quality of life.

  The video was intended to introduce these concepts to company executives and to their employees if the firm desired. The video takes a somewhat lighter approach than the original slide show, emphasizing a quick delivery and a strong set of visual images. For example, in the original slide show (unpublished presentation) congestion is treated as follows: "Unless something is done, congestion will continue to worsen, as traffic volumes on the LIE increase and traffic speeds decline in more areas for longer periods of time." In the video (*2*), the same idea is expressed: "We spend more and more time just getting there, and the trip becomes more and more stressful. Long Island is truly a community of places—but why does it have to seem that everyone is out on the road at the same time as you?" The video also used computer simulation to explain such key HOV operational issues as entry and exit, enforcement, and incident management.

- Informational brochures. Two brochures were prepared for distribution to employers (*3*).

  One was entitled *Keeping Long Island on the Go! Reducing Congestion is Good Business*. It sets the tone of a growing suburban congestion problem on Long Island and then explains what the state DOT is doing to alleviate the problem. The centerpiece is what businesses themselves can do.
  - –The second brochure provided more specific detail about the LIE HOV lane project, highlighting its many aspects, but in particular the actions of the LIE-HOV Task Force.

- Commuter transportation fact book. A three-hole looseleaf notebook was prepared for use by an existing or potential employee transportation coordinator (ETC). The following eight fact sheets were prepared:
  - –How to create an ETC for the firm,
  - –HOV lanes and park and ride,
  - –Managing the firm's parking supply,
  - –Ensuring carpool and vanpool continuity,
  - –Guaranteed-ride-home program,
  - –Transportation days,
  - –Getting involved in a TMA, and
  - –Alternative work schedules.

  Each fact sheet gave basic information and a list of contacts for more information. The notebook was wide enough to allow the ETC to add other related materials to it.

- Posters and handouts. Posters and handouts were prepared for display throughout the firm and distribution to employees.

State DOT and the LIE-HOV task force decided to use Long Island's nonprofit ridesharing promotion services organization, Long Island Transportation Management, Inc. (LITM), as the entity to reach out to employers. Their staff was given a training session and outreach efforts began in early 1993.

Initial results from the effort were not promising: for every 10 firms contacted, only one scheduled a meeting with LITM. Within 6 months, the success rate improved to one meeting scheduled for every four calls. What seemed to help was an emphasis by LITM on discussing ETR requirements in the Clean Air Act perspective, a message to which most were responsive.

As a result of these experiences, the approach was revised. The total number of expected individual meetings was lowered from 200 to 80. The additional 120 firms were to be reached through different formats, including the following:

- Presentations to chambers of commerce and industrial associations. Meetings of these groups usually involve representatives from 10 to 30 firms each.
- Direct mailing of seminar material to select firms identified by LITM through their phone contacts.
- Additional outreach to firms not located near the LIE corridor. Although these firms might not derive direct benefit from the initial 12-mi HOV section that was scheduled to open in spring 1994, they might benefit from subsequent stages of development of the LIE-HOV lane system. Although it would not produce initial benefits to the peak period usage of the Stage 1 HOV lanes, this approach would expand the knowledge base about HOV and supporting actions that employers can take to reduce vehicle trips by their employees.

### *Media Campaign*

State DOT asked its consultants to prepare a media strategic plan for the HOV lane. The central message to be delivered was "moving people to their destinations, not simply moving more vehicles." Slogans, such as "Putting the Express Back Into the Expressway" were to be incorporated. The audience to be reached, in order of priority, includes the following:

- LIE commuters;
- Other highway commuters;
- Other Long Island drivers;
- Long Island employees and employers (a lower priority for the media campaign because the Employer Outreach Program is their main approach);
- Educational facilities;
- Local agencies, elected officials, and interest groups; and
- General public.

Media options include the following:

- Press kits
- Briefings
- Speakers
- Direct mail
- Bus advertising
- Billboards
- Newspaper advertising
- Newspaper supplements
- Public service announcements (PSAs)
- Radio advertising
- Television advertising

The options were described and costed out and eventually grouped into the following strategic approaches:

- Minimum strategy. Initial and basic set of options that maximizes noncommercial sources (e.g., press kits, editorial board meetings, and speakers).
- Low-level strategy. Provides higher-quality information to the media for use in noncommercial formats and for reaching out to crucial radio and television (TV) markets, but in a low-cost mode. Options include a premium press kit (with brochure, videos, audiotapes, photos, and graphics), radio PSAs, and cable TV ads (taking advantage of free air time offered to state DOT by a local cable station).
- Moderate-level strategy. Combines previous strategies with distribution of materials to direct audiences, modest print advertising, and commercial radio advertising during drive time periods.
- High-level strategy. Combines all other strategies with newspaper supplements, exterior bus advertising, billboard advertising, and more extensive newspaper advertising.

The proposed scheduling and costing of these strategies through 1995 (with the anticipated opening of the first section of the HOV lane assumed to be spring 1994) has the objective of maintaining a basic level of information before and after implementation, punctuated by a moderate level of media outreach 1 month before the opening and a high level of media outreach 3 months after implementation. The reason for saving the high outreach level until shortly after implementation is to allow for a period for operational issues to work themselves out and for word of mouth and media reporting to have some effect.

As a result of this plan, the state DOT has adopted and (adapted) a media campaign that combines print, radio, and TV advertising. Although the available budget is limited, widespread outreach is anticipated through the use of

- Print media. A series of weekly informational advertisements in local community weeklies, beginning up to 2 months before commencement. The ads will include the following: basic operational information, a "why HOV" report, advice on starting a carpool, and statements from HOV users in other urban areas.
- Radio advertising. Paid drive time ads on three local commercial stations.
- Cable TV advertising. Four separate messages to be produced and shown on local 24-hr cable news station three times a day: 6:00 to 7:00 a.m. (prerush hour), midday, and after 9:00 p.m.

## FOLLOW-UP

The state DOT will act on an important recommendation from the LIE-HOV task force that involves establishing an implementation and feedback mechanism to assemble information on actual usage of the LIE-HOV lanes, as well as gathering public comments concerning the various HOV improvements.

As part of its efforts to gather direct feedback from the public about the HOV lanes, DOT will hold additional focus groups and consider conducting commuter surveys 6 months to 1 year after opening the Stage 1 LIE-HOV lanes. The information gathered from these approaches would then be used in subsequent marketing programs to keep promoting positive messages about HOV on Long Island.

It is also expected that the media campaign will be extended for several years after the initial opening of the LIE-HOV lanes. The extended program would include key messages about LIE HOV, ridesharing and vanpooling, transit, and options other than driving alone. Also, as employers begin to implement Employee Commute Options (ECO) programs, as required by the federal Clean Air Act, the media program could be expanded to help promote the ECO programs and instill such potential messages as "Ridesharing Saves the Earth," "Rideshare to Clean the Air," and "To Pool is Cool."

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# Coordinating Ramp Meter Operation with Upstream Intersection Traffic Signal

BIN HAN AND ROBERT A. REISS

Freeway entrance ramp meters are commonly located immediately downstream of a signalized intersection. As a result of the cyclic operation of the intersection signal, traffic tends to enter the ramp in platoons; hence the ramp traffic arrival rate is nonuniform within each signal cycle. Conventionally, the metering rate is uniform over a period longer than a signal cycle. Hence, nonuniform arrival traffic onto the ramp may lead to insufficient use of ramp storage capacity and cause unnecessary delay to ramp traffic. The possibility of employing a two-level variable metering rate to reduce delay at a ramp meter signal is investigated. The problem is modeled as minimizing total ramp delay $D$ with two variables: $M1$, the metering rate in the first level, and $s$, the switching point. It is pointed out that $D$ is a convex function in $M1$ for fixed $s$, but not convex in $s$ for fixed $M1$. An optimization method is proposed that will lead to the optimum $M1$ and $s$. The ramp capacity is kept unchanged. Example results indicate that ramp delay can be reduced by using the optimum metering rates and metering rate switching point.

In the past 30 years, freeway entrance ramp meters have been installed in the United States and elsewhere to regulate ramp traffic onto freeways and reduce congestion. A number of different ramp metering systems have been developed, ranging from the simplest local fixed-time operation to more advanced types such as an integrated traffic-responsive control system.

In most cases, especially in urban areas, ramp meters are located immediately downstream of a signalized intersection. As a result of the cyclic operation of the intersection signal, traffic tends to enter the ramp in platoons as each signal phase releases a stopped queue; hence the ramp traffic arrival rate is nonuniform within each signal cycle. Even though sophisticated ramp metering systems can adjust ramp metering rates on the basis of traffic conditions, metering rates are usually uniform over a period longer than a signal cycle. Therefore, in each cycle, nonuniform arrival traffic may lead to insufficient use of ramp storage capacity, since the ramp meter may be "starved" during the intervals between platoons and overloaded after the platoons arrive. Delay to ramp traffic may be unnecessarily greater than it should be. Delay may be reduced by varying the metering rate to adapt to the upstream intersection signal release pattern. For example, instead of being uniform, the metering rate could be increased when the platoon arrives and decreased after it is served without changing the number of vehicles that can be released onto the freeway in a cycle. However, to reduce potential disturbance to the freeway, ramp traffic as well as freeway traffic should be considered together in determining the higher metering rate.

So far only limited research on the coordination of ramp meter operation and upstream intersection traffic signals has been reported (*1,2*). In this paper the possibility of employing a variable metering rate to reduce the delay at a ramp meter signal is investigated. The example results indicate that ramp delay could be minimized by using the optimum metering rates and metering rate switching point.

Dunn Engineering Associates, 66 Main Street, Westhampton Beach, N.Y. 11978. R. A. Reiss, B. Han, Parsons Brinckerhoff, 33 Comac Loop, Ronkonkoma, N.Y. 11779.

## MODELING RAMP METER OPERATION

Figure 1 shows a typical freeway entrance ramp—intersection traffic signal configuration. Figure 2 shows a representative profile of ramp traffic arrivals. $T1$ represents the interval in which the service road receives the green signal (travel time from the intersection to the ramp is not considered in this analysis because the dynamics of the ramp traffic is the focal point rather than the platoon dispersion between the upstream traffic signal and the ramp meter) and through Movement 1 proceeds; a portion of this flow (Flow Rate $q1$) enters the ramp (the remainder continues along the service road). During $T2$, side street left-turn Movement 2 receives the green signal and a portion of this flow (Flow Rate $q2$) enters the ramp. $T3$ represents the interval in which a portion of side street right-turn Movement 3 proceeds to the ramp at a flow rate of $q3$. Usually a uniform metering rate $M$ is used to regulate the ramp traffic. To make sure that the ramp queue clears after each cycle, $M$ should satisfy the following condition:

$$M \cdot (T1 + T2 + T3) \geq q1 \cdot T1 + q2 \cdot T2 + q3 \cdot T3 \quad (1)$$

The left-hand side of expression 1 is the maximum number of vehicles that can enter the freeway with the selected metering rate,

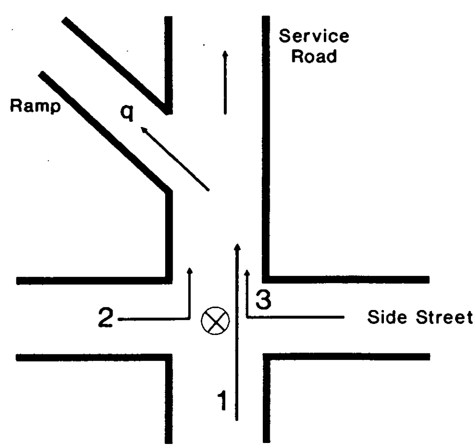


**FIGURE 1 Typical freeway-intersection signal configuration.**

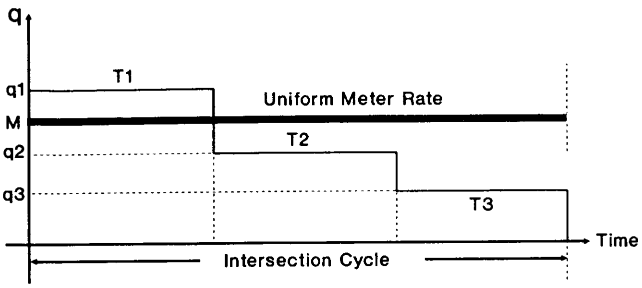


**FIGURE 2 Ramp arrival rate.**

$M$. Under this condition, the queue length should be 0 at the beginning of each cycle. On the other hand, $M$ should be subject to the practical minimum and maximum metering rates, $M\text{min}$ and $M\text{max}$:

$$M\text{min} \leq M \leq M\text{max} \tag{2}$$

The metering rate $M$ satisfying Conditions 1 and 2 represents a typical existing scenario.

The proposed technique is shown in Figure 3. Instead of a uniform metering rate $M$, $M1$ should be used for $s$ sec before it is changed to $M2$ for the remaining part of the cycle. $s$ is called the switching point and satisfies the following condition:

$$0 \leq s \leq T1 + T2 + T3 \tag{3}$$

To keep the same maximum number of vehicles that can enter the freeway, the following constraint is imposed:

$$M1 \cdot s + M2 \cdot (T1 + T2 + T3 - s) = (T1 + T2 + T3) \cdot M$$

$$M2 = [(T1 + T2 + T3)\,M - M1 \cdot s] \div (T1 + T2 + T3 - s) \tag{4}$$

Although there are unknown variables $M1$, $M2$, and $s$, $M2$ can be expressed as a function of $M1$ and $s$ by Equation 4. Therefore, only two variables need to be specified: $M1$ and $s$. $M1$ should satisfy the following constraints:

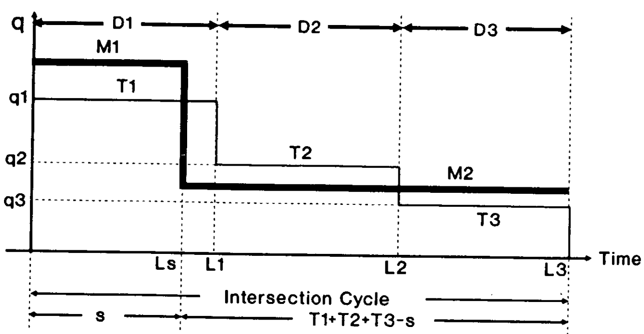


**FIGURE 3 Variable metering rate.**

$$M\text{min} \leq M1 \leq M\text{max}$$

$$M\text{min} \leq M2 = [(T1 + T2 + T3)\,M - M1 \cdot s] \div (T1 + T2 + T3 - s) \leq M\text{max} \tag{5}$$

The following notation is used:

$Ls$ = ramp queue length at switching point $s$;
$L1$ = ramp queue length at time $T1$;
$L2$ = ramp queue length at time $T1 + T2$; and
$L3$ = ramp queue length at time $T1 + T2 + T3$.

The objective function is the total delay to ramp traffic, which can be expressed as

$$D = D(M1,s) = 1/2(D1 + D2 + D3) \tag{6}$$

where $D1$, $D2$, and $D3$ are the total delay to ramp traffic in intervals $T1$, $T2$, and $T3$, respectively.

Under this formulation, the problem has been modeled as a two-dimensional minimization problem:

Minimize $D(M1,s)$

subject to Constraints 3, 4, and 5, assuming that $M$ is known and satisfies Constraints 1 and 2.

## OPTIMIZATION METHOD

An investigation of the functional properties of $D(M1,s)$ indicates that although $D$ is convex or quasi-convex in $M1$, it is not necessarily convex in $s$. However, since the switching point $s$ should normally be an integer, there would be a limited number of possible choices for $s$. For example, if the cycle time is 120 sec (which is usually the maximum cycle length for most intersection signals), there would be only 121 points for $s$ to be considered. Hence a direct search on $s$ can be made to minimize $D$ for a fixed $M1$, whereas a one-dimensional optimization method such as a golden section search, suitable for a convex or quasi-convex function, can be used for minimizing $D$ for a fixed $s$. Hence the following minimization method can be employed to locate the optimum value of $M1$ and $s$ where $D\text{min}$ is the current minimum value for $D$ and $M1\text{min}$ and $s\text{min}$ are the current values for $M1$ and $s$ that produce $D\text{min}$.

Step 1. Set $s = 0$, $s\text{min} = 0$, and set $D\text{min}$ to the maximum number that can be stored in the computer. Go to Step 2.

Step 2. For the given $s$, use the golden section search method to locate the local minimum $D$, subject to Constraint 5. If $D < D\text{min}$, the current values of $M1$ and $s$ are used for $M1\text{min}$ and $s\text{min}$. Increase $s$ by 1. Go to Step 3.

Step 3. If $s$ is not greater than the cycle length ($T1 + T2 + T3$), go to Step 2. Otherwise stop, and the optimum solution point is at $M1\text{min}$ and $s\text{min}$.

## SIMULATION TEST

To demonstrate the potential benefit of employing a variable metering rate, a simulation test was conducted using a simple Paradox for Windows program. For a time period $T$, if the initial queue length is $L0$ and the ramp volume and metering rate are $q$ and $M$, respectively, the queue length at the end of $T$ is simply given by

$$L_T = \begin{cases} L0 + (q - M) \cdot T & \text{if } L0 + (q - M) \cdot T > 0 \\ 0 & \text{otherwise} \end{cases}$$

The delay to the ramp traffic incurred during $T$ is the area under the queue length curve.

The program uses the following parameters to calculate the queues and delays:

| | | |
|---|---|---|
| $T1$ = 50 sec | $T2$ = 30 sec | $T3$ = 40 sec |
| $q1$ = 800 vehicles/hr (vph) | $q2$ = 500 vph | $q3$ = 300 vph |
| $M$min = 300 vph | $M$max = 1,000 vph | $M$ = 600 vph |

Under the control of a uniform meter rate of 600 vph, the total ramp delay is 162.96 vehicle-sec, and the maximum ramp queue length is 2.78 vehicles.

Using the proposed technique, the total ramp delay can be minimized to 6.82 vehicle-sec (a 96.5 percent reduction) at $s$ = 50 sec, $M1$ = 800 vph, with the maximum ramp queue length reduced to 0.36 vehicle (87 percent shorter). Also, $M2$ = 457 vph. As in the case of a uniform metering rate, the ramp queue clears at the end of the cycle.

Figure 4 shows the contour of total ramp delay $D$ as a function of ramp meter rate $M1$ and switching point $s$. Figure 5 plots the evolution of the ramp queue length as a function of time within the intersection cycle.

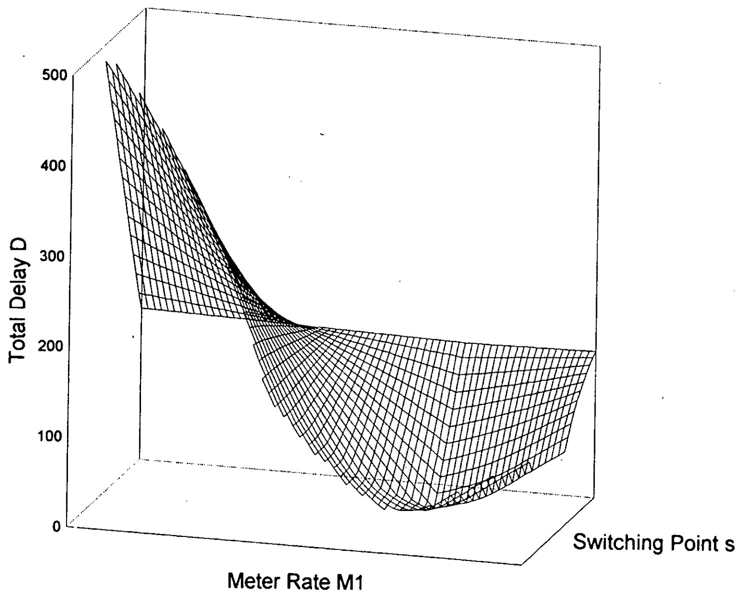


**FIGURE 4 Ramp delay $D$ as function of $M1$ and $s$.**

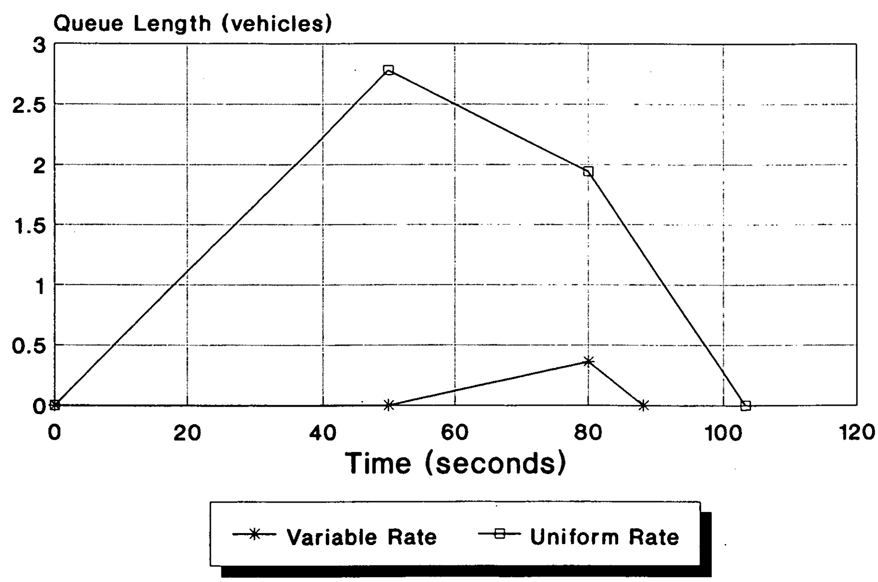


**FIGURE 5 Evolution of ramp queue length.**

## DISCUSSION OF RESULTS

It can be seen from Figure 5 that under the control of a uniform metering rate, a queue forms in the first time period *T*1 when there are heavy vehicular arrivals; therefore more delay results afterward. The proposed technique, however, uses a metering rate equal to the arrival rate in *T*1 for the whole length of *T*1; therefore no ramp queue occurs during *T*1. Although the metering rate is reduced for *T*2 and *T*3, the ramp delay would not increase since the queue left at the end of *T*1 is 0 and the arrival rates in *T*2 and *T*3 are much lower. Also, the ramp queue clears sooner.

## CONCLUSION

It can be seen from the simulation test that ramp delay and maximum ramp queue length can be reduced by applying a variable metering rate instead of a uniform one.

Because the ramp capacity remains the same in each cycle, the maximum number of vehicles released to the freeway remains constant; therefore, the disturbance of ramp traffic to freeway traffic caused by a variable metering rate should be small. To reduce this disturbance, the higher metering rate *M*1 should be determined by considering both the freeway traffic and the ramp volume. *M*1 should also be determined so that a minimum spacing between vehicles released by the ramp meter can be realized.

If ramp traffic is very heavy, the ramp has to operate at the maximum metering rate so that the queue does not spill back to the upstream intersection.

The proposed technique is a first step toward microscopically modeling the complicated freeway-arterial coordination problem. It has the potential to be extended and adapted for a real-time advanced traffic management system. Additional research is needed to further quantify the benefits, test the practicality of the approach via field measurements, and develop a technique for determining parameters of the arrival rate profile.

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# Case Studies of U.S. Freeway-to-Freeway Ramp and Mainline Metering and Suggested Policies for Washington State

ELDON L. JACOBSON AND JACKIE LANDSMAN

To mitigate increasing traffic congestion and to improve highway safety, state departments of transportation have come up with some innovative strategies for optimizing the efficiency of congested freeway sections. Two such strategies are freeway-to-freeway ramp metering and mainline metering. Freeway-to-freeway ramp metering involves installing traffic signals (either on the side of the roadway or overhead) on the ramps found at freeway-to-freeway interchanges. Mainline metering involves installing traffic signals (usually overhead) on the mainline of a freeway. Some examples of freeway-to-freeway ramp metering in the United States, namely, in Minnesota and California, are examined and the advantages and disadvantages of freeway-to-freeway ramp metering are discussed. The implementation and operational issues of the only known operating example of mainline metering in the western United States are also discussed. A complete and thorough analysis should take place before the installation of any freeway-to-freeway or mainline metering system. This analysis is needed to ensure that safety is maintained and that environmental concerns are addressed. The suggested policy on freeway-to-freeway ramp metering is to install meters on freeway-to-freeway ramps where system performance and efficiency would be improved. The suggested policy on mainline metering is to install mainline meters on freeways approaching bottleneck locations where analysis indicates that improved traffic operations would result. Guidelines for both metering types are given.

During the past few decades, traffic patterns have changed dramatically as commuters have moved farther away from central business districts and into the suburbs in search of, among other things, affordable single-family housing. This trend has contributed to the increase in suburban traffic congestion and also has resulted in longer commutes and an increase in total highway miles traveled. To mitigate the increasing congestion and to improve highway safety, state departments of transportation have come up with some innovative strategies for optimizing the efficiency of congested freeway sections. Two such strategies are freeway-to-freeway ramp metering and mainline metering.

Freeway-to-freeway ramp metering consists of installing traffic signals (either on the side of the roadway or overhead) on the ramps found at freeway-to-freeway interchanges. Mainline metering consists of installing traffic signals (usually overhead) on the mainline of a freeway.

The operational success of a number of freeway-to-freeway ramp and mainline metering systems currently installed around the country is discussed. Policies and guidelines concerning the installation and operation of freeway-to-freeway ramp metering and mainline metering for Washington State are suggested.

E. L. Jacobson, Washington State Department of Transportation, c/o Washington State Transportation Center, 1107 NE 45th St., Suite 535, Seattle, Wash. 98105-4631. J. Landsman, FHWA, 211 Main Street, Room 1100, San Francisco, Calif. 94105.

## FREEWAY-TO-FREEWAY RAMP METERING CASE STUDIES

Examples of freeway-to-freeway ramp metering are increasing throughout the United States. The majority of the installations are found in California and Minnesota. In addition, Washington State currently has two freeway-to-freeway ramp metering operations at the Swamp Creek interchange north of Seattle (northbound (I-405 to southbound I-5 and southbound SR-525 to southbound I-5). The Tacoma, Washington, area will have its first freeway-to-freeway ramp metering operation in the spring of 1994 at the SR-512 interchange on I-5 (westbound SR-512 to southbound I-5). The Vancouver, Washington, area is planning to install ramp metering at the SR-14 interchange (westbound SR-14 to southbound I-5). The following sections document in greater detail the status of a number of freeway-to-freeway metering sites.

### Los Angeles, California

In Los Angeles, where a large number of typical ramp metering installations are operated, only a few interchanges have freeway-to-freeway ramps that are metered. The first was at the interchange of I-5 and I-110 (southbound I-5 to southbound I-110). Additional freeway-to-freeway ramp metering operations have been set up with the completion of the new Century Freeway.

The direct connection between southbound I-5 and southbound I-110 (see Figure 1) typically supported high traffic volumes. When one of the two lanes on this facility had to be closed because of regular rock slides, queues on the southbound I-5 connector became the norm [with maximum traffic volumes of 2,300 vehicles per hour (vph) for the single lane]. In May 1992, after a solution to the slide problem was found, the second lane was reopened, and a two-lane ramp metering operation was installed on the connector to help manage the heavy traffic flow onto southbound I-110. With the reopened lane, flow during the off-peak period (when the meters are off) has improved considerably, and virtually no queuing on I-5 is caused by this movement. However, when the meters are on during the peak period, considerable queues still occur on the connector [with almost 1 km (0.5 mi) of two-lane storage available] and on southbound I-5 (although the queues are now somewhat shorter because of the storage provided by the reopened lane). The two-lane metering is turned on during

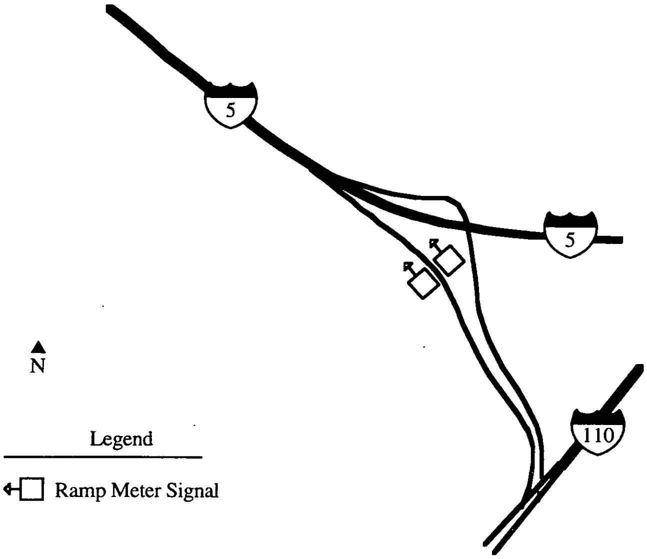


**FIGURE 1 Interchange of I-5 and I-110, Los Angeles.**

the morning peak period. Although the metering is set to operate at a maximum of 1,800 vph for the two lanes, actual maximum traffic volumes are around 1,600 vph. There is no high-occupancy-vehicle (HOV) bypass lane on this ramp.

Traffic flow on southbound I-110 at the interchange may have improved slightly with the metering (no before-and-after study has been done yet), but before the additional lane was opened, the I-5 connector itself acted as a meter onto I-110. Because only one lane of traffic was allowed onto southbound I-110, a serious bottleneck was avoided at this location. However, if the widened connector had not been metered, the additional traffic accessing I-110 probably would have seriously impeded southbound I-110 traffic and would have caused extensive queuing on southbound I-110.

### Minneapolis, Minnesota

Minneapolis has the largest number of freeway-to-freeway ramp metering operations in the United States. Its two earliest installations were activated in 1971 at the interchange of Trunk Highway (TH) 36 and I-35E (eastbound and westbound TH-36 to southbound I-35E). Since then, an additional 25 freeway-to-freeway ramp metering installations have been activated throughout the Minneapolis–St. Paul metropolitan area. Most commonly, the Minnesota Department of Transportation (MnDOT) has initiated the metering in conjunction with other roadway improvements. MnDOT's primary objective often has been to encourage route diversion away from onerous merges, especially where alternative routes have been identified. Another objective is to manage and control the queuing at certain interchanges. Several in-depth case studies follow. Some of these cases involve metered on ramps upstream of the freeway-to-freeway ramp metering, so some vehicles may be metered twice on one trip.

#### *Eastbound I-94 to Southbound TH-65*

In 1974 ramp control was initiated from eastbound I-94, a six-lane freeway, to southbound TH-65, a four-lane freeway (see Figure 2), to reduce the heavy congestion that was occurring downstream of this location and to improve the flow of the corridor in general. Before implementation, the two-lane ramp had carried 1,080 vph during the p.m. peak hour. After the metering was turned on and both lanes had been metered, the volumes on the ramp dropped to 690 vph during the p.m. peak. MnDOT estimates that over two-thirds of the reduction is caused by route diversion. Typical delays on the ramp are over 1 min, but they can reach up to 8 min with 0.5-km (0.25-mi) queues.

The last in-depth analysis of this metering operation showed that even though volumes had increased by 17 percent, the southbound peak-hour speeds on TH-65 had increased by 29 percent since metering had been initiated. This high performance level on the freeway has led to few complaints and high driver compliance with the metering. The study also found that peak-period accidents had been reduced by 21 percent since the system began operation.

#### *Eastbound and Westbound I-494 to Southbound and Northbound I-35W*

All four I-494 ramps were metered to the four-lane I-35W in 1975 as part of the Urban Corridors Demonstration Program in Minneapolis. The volumes on these ramps were consequently reduced by approximately 20 to 25 percent after metering had been initiated. Volumes on the ramps to northbound I-35W (see Figure 3) have been reduced from 650 to approximately 500 vph, and queuing associated with this volume has not been a problem. Average delays are less than 1 min. However, the I-494 ramps to southbound I-35W (see Figure 4) maintain higher volumes and, consequently, longer queues. In particular, the eastbound to southbound movement resulted in queues that backed up ahead of the ramp and extended onto the shoulder of I-494. This situation created a further problem when some drivers attempted to cut in at the last moment, rather than wait in line. To mitigate this problem, the ramp was widened to two lanes to increase storage capacity. The westbound to southbound movement experienced similar problems; however, in that situation widening was not possible. The ramp is monitored closely by operators so that the metering rate can be increased when a problem begins to develop.

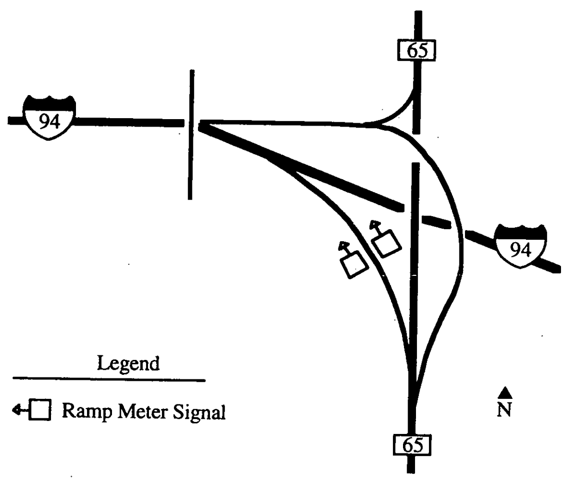


**FIGURE 2 Interchange of I-94 and TH-65, Minneapolis.**

Metering at this location is considered to be partly responsible for the 38 percent increase in speeds on northbound I-35W, as well as for an increase in speed on southbound I-35W. Even with the problems described above, the number of accidents at this location has decreased.

*Eastbound and Westbound TH-13 to Northbound I-35W*

The two direct connector ramps (see Figure 5), eastbound and westbound TH-13 to northbound I-35W, were incorporated into the freeway management system as part of the Urban Corridors Demonstration Program. Although the volumes were not extremely high on these ramps before metering (690 vph eastbound to northbound and 510 vph westbound to northbound), the eastbound-to-northbound ramp was limited by its low-speed cloverleaf design. After metering had been initiated, volumes decreased by approximately 100 vph on each ramp. Average vehicle delays range between 3 and 4 min; however, these vehicle delays are highly dependent on the status of alternative routes. When an incident occurs that prevents or discourages diversion, delays at this interchange can reach 15 min, with queues on the shoulders for up to 1 mi. Because TH-13 is not a high-volume roadway, the ramp metering has not demonstrated a safety problem.

Just downstream of this interchange, northbound I-35W crosses the Minnesota River. By metering the TH-13 direct connectors,

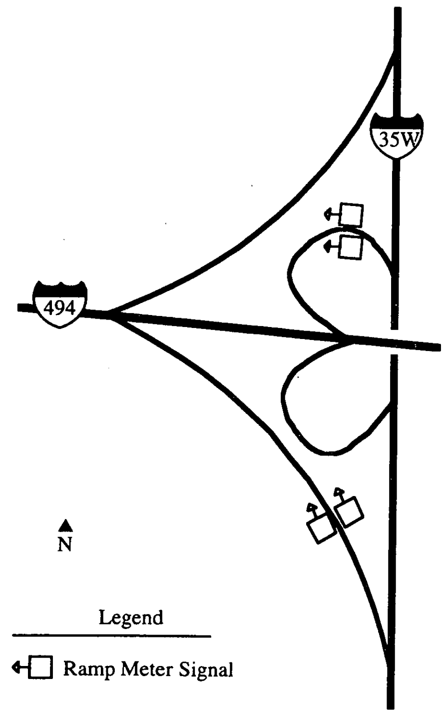


**FIGURE 4 Interchange of I-494 and I-35W (southbound metered ramps), Minneapolis.**

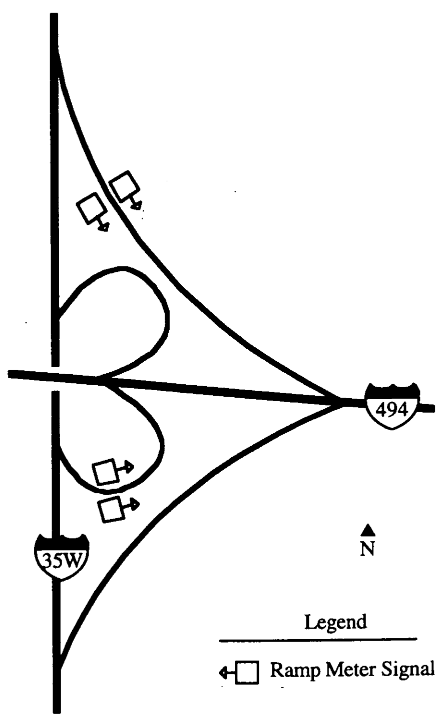


**FIGURE 3 Interchange of I-494 and I-35W (northbound metered ramps), Minneapolis.**

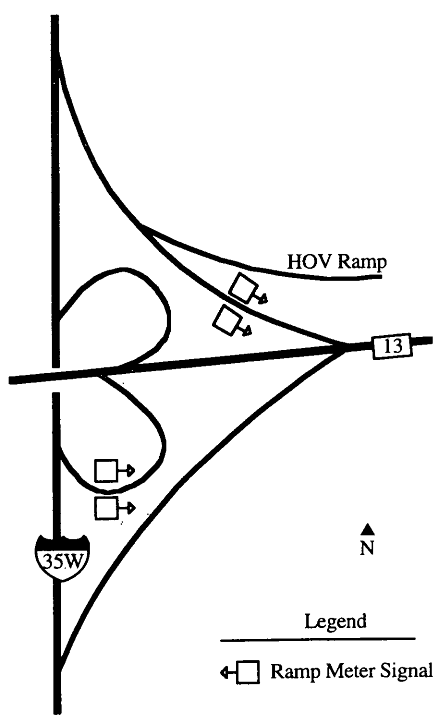


**FIGURE 5 Interchange of I-35W and TH-13 (east half of interchange), Minneapolis.**

MnDOT has kept this corridor open with a minimum of congestion over the bridge. The metering is considered essential to providing optimal flow through the section and has met with high motorist compliance in spite of queuing on the ramps.

## San Diego, California

San Diego began using freeway-to-freeway ramp metering in 1971; the first installation was at the interchange of SR-15 and SR-94 (southbound SR-15 to westbound SR-94). Since then, three more installations have been added, two of which feed SR-94 and the third I-8. The initial justification for these installations was to better manage the queuing and the delay that was occurring at these interchanges and to better manage the freeway system in general. A more detailed description of two of these locations follows.

### *Southbound SR-67 to Westbound I-8*

The most recent direct connector metering installation in San Diego (1985) (see Figure 6) is at the interchange of SR-67 and I-8 (southbound SR-67 to westbound I-8). This three-lane metering was installed to relieve congestion on I-8 just downstream of the interchange and to improve traffic flow throughout the area. Before metering, this section of I-8 was frequently congested with long queues that extended upstream from the interchange. Since the metering was turned on, the flow downstream on I-8 has averaged 2,500 vehicles per hour per lane (vphpl), and speeds have averaged 100 km/hr (60 mph). Average weekday traffic has dropped from 37,000 vehicles before metering was installed to 30,000 vehicles after metering was activated.

This freeway-to-freeway ramp metering operates almost as mainline ramp metering. Because SR-67 ends at a city arterial street, which is just downstream of the metering location, the majority of the traffic on southbound SR-67 at the I-8 interchange uses the connector to access westbound I-8. There is no HOV bypass lane at this location. There is almost unlimited storage length, because the queues occur on the freeway mainline of SR-67. During the peak hour the maximum metered traffic volume is 2,300 vph for the three lanes.

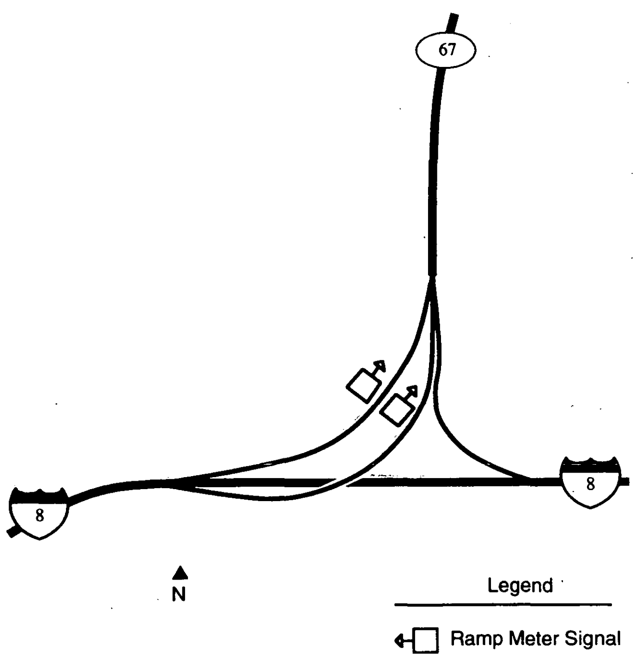


**FIGURE 6 Interchange of I-8 and SR-67, San Diego.**

Although no formal before-and-after study has been completed, the consensus within the Traffic Systems Branch of the California Department of Transportation (Caltrans) is that the metering strategy at this interchange has been very successful. The effectiveness of the metering was clearly demonstrated a number of years ago when an electrical malfunction caused the meters to discharge cars more rapidly onto I-8 than the normal metering rate. Queues of several miles formed on I-8 because of this malfunction, causing long delays for those traveling westbound on I-8, as well as for those attempting to reach I-8 from the southbound SR-67 ramp. Although the event was not planned, it served to educate the public on the benefits of metering, and consequently public acceptance improved considerably.

Because SR-67 ends at I-8, the problem of traffic on SR-67 speeding by metered, stopped traffic has not occurred. On ramps to southbound SR-67 upstream of the SR-67/I-8 interchange are not currently metered.

### *Westbound SR-94 to Southbound SR-94 (Extension of Southbound SR-125)*

The metering for this direct connector (see Figure 7) was turned on in May 1978 to relieve some of the congestion and queuing through the SR-94 interchange. In addition, metering was added to the cross street feeding the southbound SR-125 on ramp, which merges with the westbound SR-94 direct connector just before their confluence with southbound SR-125. Metering on both routes is operated by an automated, traffic-responsive system on the basis of mainline volumes, so the metering is typically on only during peak periods. To encourage carpooling and to improve bus service through the interchange, the direct connector also features a peak-period, inside HOV lane in addition to the two regular lanes. During the off peak, the HOV lane is not used as a travel lane. On ramps to westbound SR-94 upstream of the SR-94/SR-125 interchange are not currently metered. All three lanes (including the HOV lane) are metered.

When the metering on the direct connector was first activated, the ramp carried approximately 1,900 vph during the peak hour, with an average wait of 1 min and a maximum wait of about 3 min. Today the daily volume on the three-lane ramp is approximately 28,000 vehicles (peak-hour volume of 2,900 vph), and the maximum wait during the peak period can exceed 10 min. In spite of the high ramp delays, there have been very few complaints, and responses to the metering have continued to be positive. Caltrans reasons that public acceptance has remained high largely because of the level of service provided on the freeway, in particular, the high speeds that are maintained beyond the metering. The time savings attributed to metering are purported to be up to 20 min for some home-to-work commute trips. Queues do extend back on the connector because of the metering; however, these queues also existed before the metering, and no safety problems have surfaced because of the metering itself.

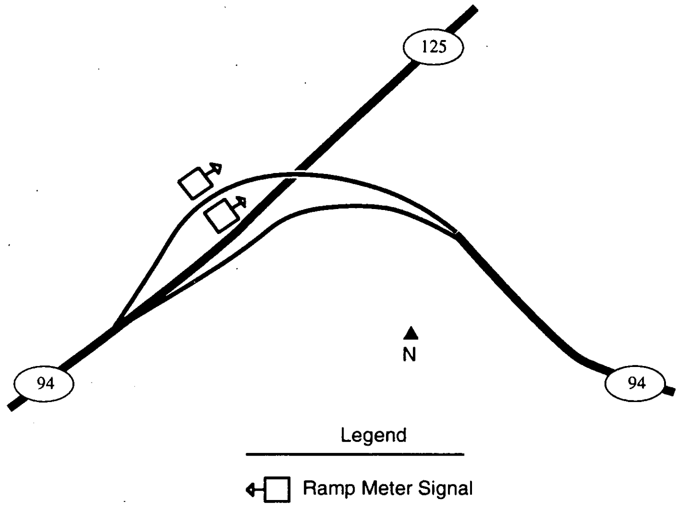


**FIGURE 7 Interchange of SR-94 and SR-125, San Diego.**

### Discussion of Case Studies

So far, Caltrans' policy has been to be very selective in instituting freeway-to-freeway ramp metering, and all the installations it has initiated thus far have been successful not only operationally, but also in the public's opinion. Because of the public's increased frustration with traffic congestion, a high level of acceptance has been shown for traffic management strategies that improve the overall quality of the commute. When negative feedback has been encountered, Caltrans has tried to remedy the situation. Caltrans has not done much in the way of public education for its ramp metering system. It has instead relied on improved system operation to communicate the benefits of freeway-to-freeway ramp metering. Most of Caltrans' districts have a strong relationship with the traffic reporting media, and these ties have been used to educate the media, and consequently the public, about the strategies under way.

MnDOT has the most extensive system of freeway-to-freeway ramp metering, and its continued use of this management strategy is an indicator of its faith in the strategy's effectiveness. MnDOT has conducted several studies that have quantified the benefits of this type of metering. It has been concluded that, on average, throughput downstream of the metering increases by 300 to 400 vphpl, speed increases by approximately 27 percent, and total accidents decrease by 38 to 40 percent. The Minnesota freeway system consists of a typical spoke-and-wheel design; thus, at least one alternative route is usually available for most trips. Route diversion has been encouraged in especially congested areas with strategic metering placement. MnDOT has maintained strong public support through a concentrated public information effort, along with strong media support.

## MAINLINE METERING CASE STUDY

The only known operating example of mainline metering in the western United States is westbound I-80 approaching the San Francisco–Oakland Bay Bridge. Two locations in the eastern United States with mainline metering are the Baltimore Harbor Tunnel in Maryland and the Hampton Roads Bridge-Tunnel in Virginia (*1*). Mainline metering was apparently first implemented in the New York City area by the local Port Authority in the early 1960s. The Boston, Massachusetts, area plans to install mainline metering on I-90 approaching the Harbor Tunnel. Washington State Department of Transportation (WSDOT) is studying the possibility of installing mainline metering on the highway approaching the Tacoma Narrows Bridge.

### San Francisco, California

*Westbound I-80 at San Francisco–Oakland Bay Bridge*

This mainline metering facility located westbound I-80 at the San Francisco–Oakland Bay Bridge (see Figure 8) is a unique system because the meters are located just downstream of a 22-bay toll plaza. Westbound traffic approaching the bridge passes through the toll plaza and is then metered so that the 22 lanes of traffic can be narrowed to five lanes as efficiently as possible. HOV lanes that allow HOVs to bypass the traffic queues are also provided (*2*).

The metering helps delay extensive queuing during the peak period; however, queues during this time are inevitable, and wait time at the metered area can reach 30 min. On the other hand, with the meters off, queuing occurs on the bridge instead of at the metered area and the delays exceed those that occur when the metering is on. Public opinion of this metering has been quite good, considering the long delays. Motorists apparently realize that the metering does save them time. One peripheral benefit of the metering system is that heavy vehicles are able to reach normal speed before arriving at the uphill grade that approaches the bridge. Before the metering system was installed, trucks had a tougher time because the bottleneck occurred near the bottom of the uphill grade.

The San Francisco–Oakland Bay Bridge mainline metering is operated during peak traffic periods, which vary depending on traffic volumes. The metering is operated also outside peak periods whenever the traffic volumes reach a preselected level or

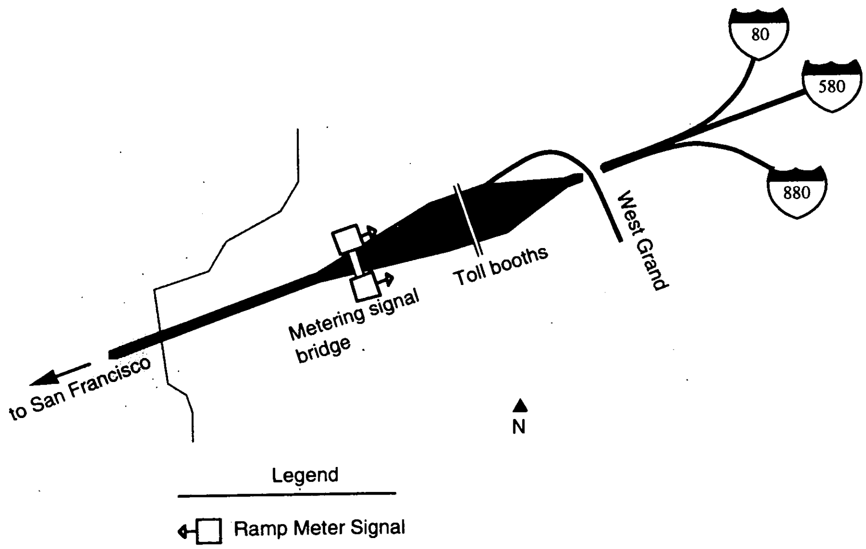


**FIGURE 8 Mainline metering on I-80, Oakland (westbound direction).**

when an incident on the bridge blocks the traffic lanes. Thus, tow trucks can bypass the traffic queue created by the metering and get to incidents quickly, thereby allowing them to clear the roadway faster. Emergency vehicles likewise avoid being stuck in the usual queues that form upstream of an incident location. The metering is turned on and off by the local Caltrans traffic operations center.

## Discussion of Case Study

Mainline metering has both advantages and disadvantages. The main advantage is better traffic operations downstream of the metering. A disadvantage is the possible political opposition from some motorists traveling the corridor. So far mainline metering has been implemented or planned for locations approaching a major traffic bottleneck, such as a bridge or tunnel.

### *Implementation Issues*

One of the theories behind implementing mainline metering before a bottleneck section is that metering maintains a more orderly progression through the constrained section. This, in effect, increases the traffic capacity and flow through the bottleneck. The conditions that exist at most bottlenecks today consist of heavy weaving and braking maneuvers, which are often dictated by aggressive drivers who jockey for a better position in the queue and force others to brake or weave out of the way. Mainline metering can smooth this traffic flow and improve the operational efficiency of the system, not just downstream of the meters, but for the system as a whole.

Another possible use of mainline metering involves the equitable distribution of delay. If most of the on ramps on a mainline for which metering has been proposed have ramp metering that causes drivers to wait in line, the equitable approach is to meter the mainline upstream of the ramp metering so that the mainline drivers also have to wait in line. However, the drivers passing through the mainline metering would probably be traveling farther.

As an example, if mainline metering were installed on southbound I-5 south of Marysville (in Washington State north of Seattle), three traffic lanes would feed into three traffic lanes. Given the normal, maximum metering rate of 900 vphpl, the freeway downstream of the mainline metering would have very little congestion (maximum capacity of 2,000+ vphl). The metering capacity could be increased by allowing two vehicles to pass during each green cycle or by widening the road to install additional metered lanes. The unused freeway downstream capacity would allow more traffic to be metered onto the freeway at downstream on ramps. Of course, upstream queues would probably develop. The queue lengths would vary depending on the approaching traffic volumes.

Some possible long-term land use impacts also may be associated with mainline metering. If a corridor contained ramp metering but no mainline metering, people might move farther from the suburban area to avoid the metering, continuing sprawl. Conversely, if a corridor contained both mainline metering (with its ensuing traffic backup) and ramp metering, a person's choice of where to live would be influenced by factors other than freeway metering.

Because it can be associated with social engineering, this kind of mainline metering should be instituted only with the approval of the local metropolitan planning organization (MPO) to encourage growth in the desired locations. WSDOT policy encourages coordination of these types of public policy decisions with the local MPO.

In either use of mainline metering—improving bottleneck flow and system efficiency or encouraging certain trip and land use patterns—politics plays a large role. In fact, political opposition may well be the largest obstacle to employing mainline metering. Most current sentiments are that mainline metering is too controversial and that highways should not be obstructed by meters. A rigorous and extended educational campaign would most likely be necessary to make the potential benefits known to those in decision-making positions and to convince them that mainline metering is a workable traffic management strategy.

*Operational Issues*

One of the critical components of the successful operation of a mainline metering system is the safety of the traveling public. Fortunately, there are numerous examples of toll plaza operations that function almost identically to mainline metering. In fact, the signing for mainline metering would be similar to that required for mainline toll booths. Mainline toll booths are common in other parts of the country and have been installed in Washington State before. Some of these traditional toll facilities often operate as unintentional mainline meters. This is especially true when the number of toll booths is insufficient for the traffic flow, creating traffic queues.

Because traffic queues are possible at a mainline metering installation, the ideal location for mainline metering is at the end of long, straight stretches of freeway where approaching drivers would have a good view of the queue's end. It also would be possible to have signs actuated by queue loop detectors that could warn of extended queues. A variable message–speed limit sign at the southbound entrance to the Golden Gate Bridge warns approaching drivers of the traffic conditions ahead at the toll plaza. This arrangement could be emulated for mainline metering.

To encourage increased bus ridership and the formation of carpools and vanpools, an HOV lane should be built to allow HOVs to bypass the mainline metering traffic queue. The HOV lane should extend from the mainline metering upstream to the rear of the worst anticipated traffic queue.

Metering of the HOV lane should also be considered. Some areas of California meter the on-ramp HOV lanes at the same location as the general-purpose lanes. Metering is an excellent tool for making enforcement of the HOV lane efficient and safe. Other areas of California do not meter the HOV lanes. In Washington State there is one metered HOV lane (the northbound on ramp to the I-5 express lanes at Pike Street in Seattle), which operates in conjunction with the Metro bus tunnel on ramp to the express lanes.

Some of the issues related to mainline metering concern drivers' expectations. Most drivers do not expect a traffic light on a freeway; therefore, mainline metering would require some adjustment time and probably some educational marketing strategies. Presumably, mainline metering would operate in coordination with and during the same hours as ramp metering; the metering would be turned off the rest of the time.

## SUGGESTED POLICIES AND GUIDELINES FOR WASHINGTON STATE

The operational success of a number of freeway-to-freeway ramp metering systems currently installed around the country and the successful installation of a mainline metering system in San Francisco, California, have been discussed. The lessons learned from these real-life examples are invaluable and have been heavily drawn on in the development of suggested policies and guidelines for the installation and operation of freeway-to-freeway ramp metering and mainline metering in Washington State. However, a complete and thorough analysis should take place before the installation of any freeway-to-freeway or mainline metering system in Washington State. This analysis is needed to ensure that safety is maintained and that environmental concerns are addressed. In addition, in the majority of cases, the traffic impacts of these types of metering systems should be evaluated on a regional level and should be incorporated as part of an overall, areawide congestion management plan.

### Freeway-to-Freeway Ramp Metering

The suggested policy on freeway-to-freeway ramp metering is to install meters on freeway-to-freeway ramps where system performance and efficiency will be improved.

Suggested guidelines for freeway-to-freeway ramp metering include the following.

- Consider and implement freeway-to-freeway ramp metering where recurring congestion is a problem or where route diversion should be encouraged. Installation of the meters should be accompanied by a marketing and publicity campaign.
- Consider route diversion only where suitable alternative routes exist to avoid diverting drivers through residential neighborhoods. Normally, route diversion is not the intention of freeway-to-freeway ramp metering. Instead, freeway-to-freeway ramp metering should be installed to improve the mainline flow and on-ramp merge or to help multiple ramps merge into one ramp. If the intent of the metering is route diversion, then consider trailblazers or appropriate signing to educate drivers on preferred alternative routes.
- Avoid metering vehicles twice within a short distance. If ramp meters are installed within 5 km (3 mi) upstream of a freeway-to-freeway ramp, the freeway-to-freeway ramp should not be metered.
- Avoid metering single-lane, freeway-to-freeway ramps that feed traffic into an add lane. Because the maximum single-lane metering rate is usually 900 vph (although it can be increased by allowing two vehicles per green cycle), an add lane with a capacity of over 2,000 vph would be underutilized.
- Do not install meters on a freeway-to-freeway ramp unless analysis ensures that the mainline flow will be improved, so that people using the freeway-to-freeway ramp are rewarded for waiting in line at a metering installation.
- Install meters on freeway-to-freeway ramps where two or more ramps merge before feeding onto the mainline and congestion on the ramps occurs regularly (four or more times a week during the peak period).
- If traffic queues that impede mainline traffic develop on the upstream mainline because of freeway-to-freeway ramp metering, increase the metering rate to minimize the queues on the upstream mainline or provide additional storage capacity.
- Monitor and control freeway-to-freeway ramp meters by the appropriate traffic management center.
- Whenever possible, install meters on roadways that are level or have a slight downgrade, so heavy vehicles can easily accelerate. Also, install meters where the sight distance is adequate for drivers approaching the metering to see the queue in time to safely stop.

### Mainline Metering

The suggested policy on mainline metering is to install mainline meters on freeways approaching bottleneck locations where analysis indicates that improved traffic operations will result.

Suggested guidelines for mainline metering systems include the following.

- Whenever possible, install meters on roadways that are level or have a slight downgrade, so heavy vehicles can easily accelerate.

- Install meters where the sight distance is adequate for drivers approaching the mainline metering to see the queue in time to safely stop.
- Provide an HOV lane that allows HOVs to bypass the mainline metering traffic queue. The HOV lane should extend from the mainline metering upstream to the rear of the worst anticipated traffic queue.
- Perform an extensive marketing and publicity campaign before installation of mainline metering in Washington State.

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# Integrated Real-Time Ramp Metering Model for Nonrecurrent Congestion: Framework and Preliminary Results

GANG-LEN CHANG, JIFENG WU, AND STEPHEN L. COHEN

An integrated real-time ramp metering model for nonrecurrent freeway congestion among link flows has been developed and tested in this study. The core concept of the proposed algorithm is to capture the dynamic traffic state evolution with a two-segment linear flow-density model. To be implemented in real time, an effective solution algorithm has been proposed for determining the time-varying metering rates. The entire algorithm has also been integrated with INTRAS, the most well-known freeway simulation model, for conducting simulation experiments. Preliminary research results indicate that the proposed integrated control model is promising because its effectiveness increases with the severity of accidents and the level of congestion. The model execution time is also sufficiently short for potential real-time operations.

Ramp metering is a widely recognized potential control strategy for alleviating freeway congestion. Over the past several decades, traffic engineers have proposed and designed various ramp metering algorithms. One of the pioneering studies on this subject is the so-called time-of-day control proposed by Wattleworth and Berry (*1*) and further developed by Wattleworth (*2*) and Papageorgiou (*3*). The time-of-day control uses a linear programming model to generate the pretimed metering rates on the basis of the freeway capacity and regular daily traffic demands. Most other existing ramp metering studies are based on the concept of local traffic-responsive control, such as the percent occupancy strategy (*4*). The two well-known local traffic-responsive strategies are the demand-capacity method that is similar to the traditional occupancy-based strategy and the linear feedback strategy in ALINEA (*5*). Other conventional local traffic-responsive strategies include speed control metering and gap acceptance merge control. These two methods, along with the pretimed metering and the demand-capacity strategy, have been implemented in the microscopic freeway simulation model INTRAS (*6*). Although they all can be used to improve freeway congestion to some extent, all of these strategies have some limitations. Because the time-of-day strategy is based on past traffic patterns without consideration of actual current traffic condition, it obviously cannot be expected to be effective if nonrecurrent congestion occurs because of incidents. Although local traffic-responsive strategies do respond to actual traffic conditions, they do not impose metering rates on those ramps far upstream of the incident location because they cannot respond until the congestion reaches the detectors that control them.

In view of the deficiencies of time-of-day as well as local control, several studies on integrated traffic-responsive strategies have been proposed in recent years. Most of them have been grounded on optimal control theory, which usually leads to a large-scale nonlinear optimization problem. The most common approach is to employ the linear-quadratic optimization technique based on the minimization of a quadratic performance functional that penalizes deviations from nominal values of traffic status (*7–9*). Another way to approximately solve such a large-scale nonlinear optimization problem is the hierarchical decomposition algorithm presented by Papageorgiou (*10,11*). This method consists of three functional layers: an optimization layer based on steady-state traffic distribution patterns, an adaptation layer, and a direct control layer that implements local feedback controls. Because both link density and speed have been used as status variables and the dynamic model describing mean link speed evolution is rather complex, these nonlinear optimal control-based methods, although accurate in addressing the problem, generally require considerable computation effort for solution. Through analytical linearization of the nonlinear models, a linear regulator formula has been proposed by Payne et al. (*7*) for interconnected traffic-responsive ramp metering control. However, this linear regulator model (and linearization schemes for the nonlinear models described) is not applicable to the incident control case because the deviations from nominal conditions are large, hence the controls required to return to the nominal condition are also large and not describable with linear approximations.

Because the existing optimization-based models are generally too complex for on-line application, some heuristic areawide ramp metering algorithms also have been proposed. For instance, Koble et al. (*4*) developed an incident-specific ramp metering strategy by explicitly predicting the shock wave frontage induced by the incident. More recently, Nihan et al. (*12*) reported a predictive ramp metering algorithm that has been tested on line with very good accuracy and is especially effective for lightly congested flow conditions. Other heuristic strategies include the extended local traffic-responsive control in the FRECON2 model developed by University of California at Berkeley and the areawide demand-responsive ramp metering system of the I-5 corridor in Seattle, Washington. Although so many approaches have been developed, so far not one has been proved adequate for real-time freeway control and operations. Hence, it is still a challenging task to develop more effective real-time control strategies.

This paper reports the development of a new integrated real-time ramp metering algorithm. The first section describes the problem in integrated ramp metering control; the next section presents dynamic traffic models and an optimal control process; and the following section addresses some critical issues, such as the optimization of ramp metering rates, the estimation of the

G-L. Chang and J. Wu, Department of Civil Engineering, University of Maryland, College Park, MD 20742. S. L. Cohen, IVHS Division, HSR-10, FHWA, 6300 Georgetown Pike, McLean, Va. 22101.

traffic status, and the prediction of system model parameters. The next section presents an efficient algorithm for real-time applications. For preliminary evaluation and implementation, the proposed algorithm is integrated with INTRAS. The following section reports some numerical results with respect to its performance evaluation against several other ramp metering strategies. The final section summarizes conclusions and recommendations.

## PROBLEM DEFINITION

An effective real-time ramp metering system should be (*a*) responsive and capable of determining the metering rates in real time according to the current traffic status and (*b*) effective in coordinating all interacting ramps so as to achieve a global system optimum. Conceivably, to be responsive, the on-line traffic status information must be obtainable; to be effective in coordination, the employed optimization model should realistically capture the dynamic interactions among ramp and freeway flows.

Consider a general freeway section, including a number of on ramps and off ramps as shown in Figure 1. Suppose that it can be conceptually divided into $N$ small segments (links), and that each small segment contains at most one on ramp and one off ramp. The control time period is divided into a series of equal intervals. Before the presentation of the modeling structure, the definitions of all variables involved are summarized in Table 1.

Generally, previous and current traffic volume data $q_i(k)$, $r_i(k)$, $s_i(k)$ can be obtained from any surveillance systems. However, the traffic status variables and model parameters need to be estimated indirectly from the surveillance data, including volume and occupancy. Hence, given the dynamic travel demand pattern $\{q_0(k), D_i(k), \theta_i(k)\}$ and incident factors $\{\sigma_i(k)\}$ in advance, the ultimate challenge is to determine the real-time metering rates $R_i(k)$ so as to achieve a global system-optimum status.

## MODEL FORMULATION

### Freeway Traffic Status Dynamics

Suppose that an equilibrium flow-density relation $Q_i(k) = Q_i[\rho_i(k)]$ exists for each freeway link $i$; then the traffic status on a segment can be described simply by the mean link density. A dynamic equation for density evolution according to the flow conservation law can be formulated as follows:

$$\rho_i(k) = \rho_i(k-1) + [q_{i-1}(k) + \delta_i^{on}R_i(k) - \delta_i^{off}\theta_i(k)Q_i(k) - q_i(k)]T/L_i l_i \qquad i = 1, 2, \ldots, N \qquad (1)$$

where $\delta_i^{on}R_i(k)$ and $\delta_i^{off}\theta_i(k)Q_i(k)$ are, respectively, the expected flow rates entering and exiting link $i$ through on ramps or off ramps.

The transition flow rate, $q_i(k)$, between adjacent links $i$ and $i + 1$ can be approximated with the weighted sum of two segment boundary flows: $[1 - \delta_i^{off}\theta_i(k)]Q_i(k)$ and $Q_{i+1}(k) - \delta_i^{on}R_{i+1}(k)$. The two weight factors are denoted by $\alpha_i(k)$ and $l - \alpha_i(k)$, respectively. Thus,

$$q_i(k) = \alpha_i(k)[1 - \delta_i^{off}\theta_i(k)]Q_i(k) + [1 - \alpha_i(k)][Q_{i+1}(k) - \delta_{i+1}^{on}R_{i+1}(k)] \qquad i = 1, 2, \ldots, N-1 \qquad (2)$$

and $q_N(k)$ is just the downstream boundary flow rate of freeway link $N$, so it can be computed with

$$q_N(k) = Q_N(k) - \delta_N^{off}\theta_N(k)Q_N(k) \qquad (3)$$

The parameters $\alpha_i(k)$ in Equation 2 play an important role in capturing the interrelations between adjacent segment flows.

Incorporating Equations 2 and 3 into Equation 1 leads to the following equation:

$$\begin{aligned}\rho_i(k) = {} & \rho_i(k-1) + [T/(L_il_i)]\alpha_{i-1}(k)[1 - \delta_{i-1}^{off}\theta_{i-1}(k)] \cdot Q_{i-1}(k) \\ & + [T/(L_il_i)\{1 - \alpha_{i-1}(k) - \alpha_i(k) - \delta_i^{off} \\ & \times [1 - \alpha_i(k)]\theta_i(k)\} \cdot Q_i(k) \\ & + [T/(L_il_i)][\alpha_i(k) - 1] \cdot Q_{i+1}(k) \\ & + [T/(L_il_i)]\alpha_{i-1}(k\delta_i^{on} \cdot R_i(k) \\ & + [T/(L_il_i)][1 - \alpha_i(k)]\delta_{i+1}^{on} \cdot R_{i+1}(k) \\ & i = 2, 3, \ldots, N-1\end{aligned} \qquad (4a)$$

For $i = 1$ and $N$,

$$\begin{aligned}\rho_1(k) = {} & \rho_1(k-1) + [T/(L_1l_1)] \cdot q_0(k) \\ & + [T/(L_1l_1)][\alpha_1(k) - \delta_1^{off}\theta_1(k) \\ & + \delta_1^{off}\alpha_1(k)\theta_1(k)] \cdot Q_1(k) \\ & + [T/(L_1l_1)][\alpha_1(k) - 1] \cdot Q_2(k) \\ & + [T/(L_1l_1)]\delta_1^{on} \cdot R_1(k) \\ & + [T/(L_1l_1)]\delta_2^{on}[1 - \alpha_1(k)] \cdot R_2(k)\end{aligned} \qquad (4b)$$

$$\begin{aligned}\rho_N(k) = {} & \rho_N(k-1) + [T/(L_Nl_N)]\alpha_{N-1}(k)[1 - \delta_{N-1}^{off}\theta_{N-1}(k)] \\ & \cdot Q_N(k) - [T/(L_Nl_N)]\alpha_{N-1}(k) \cdot Q_N(k) \\ & + [T/(L_Nl_N)]\alpha_{N-1}(k)\delta_N^{on} \cdot R_N(k)\end{aligned} \qquad (4c)$$

Hence, given the parameter values $\{\alpha_i(k)\}$, it can be seen that if $Q_i(k)$ is a linear function of $\rho_i(k)$, the density evolution equation (Equation 4) should also be a linear dynamic system. Now, assuming that a linear flow-density relation holds,

$$Q_i(k) = [w_i + u_i\rho_i(k)]\sigma_i(k) \qquad (5)$$

in which the parameters $w_i$ and $u_i$ depend on the range of density $\rho_i(k)$, and $\sigma_i(k)$ is the incident factor representing capacity reduction as a result of incidents. If no incident occurs on link $i$, $\sigma_i(k)$ should equal 1.

To facilitate the presentation, the following two new vector variables are defined:

$$\rho(k) = [\rho_1(k), \ldots, \rho_N(k)]^T$$

$$\mathbf{R}(k) = [R_1(k), \ldots, R_N(k)]^T$$

Then, from Equations 4 and 5, the following matrix form for the dynamic linear density equation is obtained:

$$\rho(k) = \rho(k-1) + \mathbf{A}_1(k)\rho(k) + \mathbf{A}_2(k)\mathbf{R}(k) + \mathbf{a}(k) \qquad (6)$$

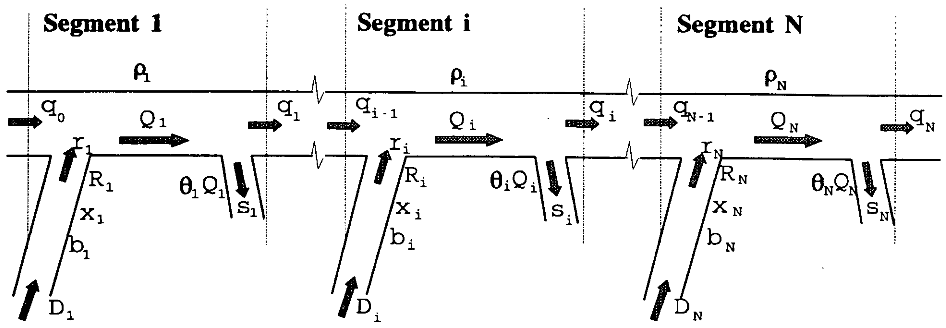


**FIGURE 1 General freeway section and its major arguments.**

where $\mathbf{A}_1(k) = [a_{ij}^1(k)]$ is an $N * N$ matrix with its elements given by

$$a_{11}^1(k) = [T/(L_1 l_1)][-\alpha_1(k) - \delta_1^{\text{off}}\theta_1(k) + \delta_1^{\text{off}}\alpha_1(k)\theta_1(k)]u_1\sigma_1(k)$$

$$a_{12}^1(k) = [T/(L_1 l_1)][\alpha_1(k) - 1]u_2\sigma_2(k)$$

$$a_{1j}^1(k) = 0 \qquad \text{for } j = 3, 4, \ldots, N$$

$$a_{i,i-1}^1(k) = [T/(L_i l_i)]\alpha_{i-1}(k)[1 - \delta_{i-1}^{\text{off}}(k)]u^{i-1}\sigma_{i-1}(k)$$

$$a_{i,i}^1(k) = [T/(L_i l_i)][(1 - \alpha_{i-1}(k) - \alpha_i(k) - \delta_i^{\text{off}}\theta_i(k) + \alpha_i(k)\delta_i^{\text{off}}\theta_i(k)]u_i\sigma_i(k)$$

$$a_{i,i+1}^1(k) = [T/(L_i l_i)][\alpha_i(k) - 1]u_{i+1}\sigma_{i+1}(k)$$

$$a_{i,j}^1(k) = 0 \qquad \text{for } j = 1, \ldots, i-2, i+2, \ldots, N; \quad i = 2, \ldots, N-1$$

$$a_{N,N-1}^1(k) = [T/(L_N l_N)]\alpha_{N-1}(k)[1 - \delta_{N-1}^{\text{off}}\theta_{N-1}(k)] \times u_{N-1}\sigma_{N-1}(k)$$

$$a_{N,N}^1(k) = -[T/(L_N l_N)]\alpha_{N-1}(k)u_N\sigma_N(k)$$

$$a_{N,j}{}^1(k) = 0 \qquad \text{for } j = 1, 2, \ldots, N-2$$

$\mathbf{A}_2(k) = [a_{ij}^2(k)]$ is an $\mathbf{N} * \mathbf{N}$ matrix with its elements given by

$$a_{1,1}^2(k) = [T/(L_1 l_1)]\delta_1^{\text{on}}$$

$$a_{1,2}^2(k) = [T/(L_1 l_1)][1 - \alpha_1(k)]\delta_2^{\text{on}}$$

$$a_{1,j}^2(k) = 0 \qquad \text{for } j = 3, 4, \ldots, N$$

$$a_{i,i}^2(k) = [T/(L_i l_i)]\alpha_{i-1}(k)\delta_i^{\text{on}}$$

$$a_{i,i+1}^2(k) = [T/(L_i l_i)][1 - \alpha_i(k)]\delta_{i+1}^{\text{on}}$$

$$a_{i,j}^2(k) = 0 \qquad \text{for } j = 1, \ldots, i-1, i+2, \ldots, N; \quad i = 2, \ldots, N-1$$

$$a_{N,N}^2(k) = [T/(L_N l_N)]\alpha_{N-1}(k)\delta_N^{\text{on}}$$

$$a_{N,j}^2(k) = 0 \qquad \text{for } j = 1, 2, \ldots, N-1$$

$a(k) = [a_1(k), \ldots, a_N(k)]^T$ is an $\mathbf{N} * 1$ vector with its elements given by

$$a_1(k) = [T/(L_1 l_1)] \cdot q_0(k) + [T/(L_1 l_1)] \times [-\alpha_1(k) - \delta_1^{\text{off}}\theta_1(k) + \alpha_1(k)\delta_1^{\text{off}}\theta_1(k)]w_1\sigma_1(k) + [T/(L_1 l_1)][\alpha_1(k) - 1]w_2\sigma_2(k)$$

$$a_i(k) = [T/(L_i l_i)]\alpha_{i-1}(k)[1 - \delta_{i-1}^{\text{off}}\theta_{i-1}(k)]w_{i-1}\sigma_{i-1}(k) + [T/(L_i l_i)][1 - \alpha_{i-1}(k) - \alpha_i(k) - \delta_i^{\text{off}}\theta_i(k) + \alpha_i(k)\delta_i^{\text{off}}\theta_i(k)]w_{i\delta i}(k) + [T/(L_i l_i)][(\alpha_i(k) - 1]w_{i+1}\sigma_{i+1}(k)$$

$$\text{for } i = 2, 3, \ldots, N-1$$

$$a_N(k) = [T/(L_N l_N)]\alpha_{N-1}(k)[1 - \delta_{N-1}^{\text{off}}\theta_{N-1}(k)] \times w_{N-1}(k)\sigma_{N-1}(k) - [T/(L_N l_N)]\alpha_{N-1}(k)w_N(k)\sigma_N(k)$$

Suppose that matrix $[\mathbf{I} - \mathbf{A}_1(k)]$ is invertible; then the dynamic density relation (Equation 6) can be reformulated into a canonical form

$$\rho(k) = \mathbf{A}(k)\rho(k-1) + \mathbf{B}(k)\mathbf{R}(k) + \mathbf{d}(k) \qquad (7)$$

where

$\mathbf{A}(k) = [\mathbf{I} - \mathbf{A}_1(k)]^{-1}$;

$\mathbf{B}(k) = [\mathbf{I} - \mathbf{A}_1(k)]^{-1}\mathbf{A}_2(k)$; and

$\mathbf{d}(k) = [\mathbf{I} - \mathbf{A}_1(k)]^{-1}\mathbf{a}(k)$.

### Ramp Traffic Status Dynamics

Another major traffic status variable is the mean number of vehicles (content), $X_i(k)$, occupying each on ramp $i$. According to flow conservation law, the content change from Interval $k-1$ to $k$ is given as

$$x_i(k) = x_i(k-1) + [d_i(k) - R_i(k)]T$$

In a matrix form, it becomes

$$\mathbf{X}(k) = \mathbf{X}(k-1) + \mathbf{E}(k)\mathbf{R}(k) + \mathbf{D}(k) \qquad (8)$$

TABLE 1 Definitions of Relevant System Variables

| | |
|---|---|
| Network geometric and physical data | |
| $L_i$: | physical length of segment i |
| $l_i$: | number of lanes contained in segment i |
| $\rho^{cr}$: | critical mean density value at which link flow rate reaches its maximum |
| $\rho^{max}$: | jam density value for freeway links |
| $w_i$, $u_i$: | parameters of equilibrium freeway flow-density model for link i |
| $R_i^{max}$: | maximum metering rate for on-ramp i |
| $R_i^{min}$: | minimum metering rate for on-ramp i |
| $b_i$: | vehicle storage capacity of on-ramp i |
| Designed parameters for modeling analysis | |
| T: | duration of one time interval |
| M: | number of time intervals involved in a time horizon for optimization |
| N: | number of subsegments divided for the entire freeway section |
| Dynamic traffic demands | |
| $q_0(k)$: | flow rate entering the upstream boundary of the freeway section during interval k |
| $D_i(k)$: | flow rate entering the upstream on-ramp i during interval k |
| $\theta_i(k)$: | proportion of turning traffic at off-ramp i during interval k |
| Traffic volumes | |
| $q_i(k)$: | flow rate entering freeway link i+1 from link i during interval k |
| $Q_i(k)$: | mean flow rate of freeway link i during interval k |
| $r_i(k)$: | actual flow rate entering the freeway from on-ramp i during interval k |
| $s_i(k)$: | actual flow rate exiting the freeway at off-ramp i during interval k |
| Incident information | |
| $\sigma_i(k)$: | capacity reduction parameter, with $[1-\sigma_i(k)]100\%$ representing the reduced percentage of capacity for link i due to incidents |
| Dynamic model parameters | |
| $\alpha_i(k)$: | parameter to represent the interaction between flows of link i and i+1 during interval k |
| Traffic status variables | |
| $\rho_i(k)$: | mean density of link i during interval k |
| $x_i(k)$: | mean number of vehicles (content) at on-ramp i during interval k |
| $Q_i(k)$: | mean flow rate on freeway link i during interval k |
| Control variables to be solved | |
| $R_i(k)$: | metering flow rate for on-ramp i during interval k |

where

$$\mathbf{X}(k) = [x_1(k), \ldots, x_N(k)]^T$$

$$\mathbf{E}(k) = \mathrm{diag}[-T\delta_1(k), \ldots, -T\delta_N(k)]$$

$$\mathbf{D}(k) = [T \cdot D_1(k)\delta_1(k), \ldots, T \cdot D_N(k)\delta_N(k)]^T$$

So far, Equations 7 and 8 have represented the interrelations between freeway evolution dynamics and the ramp control variable $\{R_i(k)\}$. The appropriate objective function will now be defined.

## Objective for Ramp Metering Control

As in most traffic control strategies, the primary purpose of ramp metering is to alleviate freeway congestion, both recurrent and nonrecurrent, and thus improve its performance. Several measures of effectiveness (MOEs) have been proposed in the literature to evaluate the operational performance, such as total throughput, total vehicle-miles, average speed, and total delay. Theoretically, the total traffic throughput (TTT) is relatively more appealing than others and thus is chosen as the control objective of this study. TTT is defined as the total number of vehicles discharging from the freeway section over the control period of interest. For the example freeway section shown in Figure 1, the total throughput is given by

$$TTT = \sum_k \left[ \sum_i^{N-1} \delta_i^{\text{off}} \theta_i(k) Q_i(k) + Q_N(k) \right] T$$

$$= T \sum_k \left[ \sum_{i=1}^{N-1} \delta_i^{\text{off}} \theta_i(k) u_i \sigma_i(k) \rho_i(k) + u_N \sigma_N(k) \rho_N(k) \right]$$

$$+ T \sum_k \left[ \sum_{i=1}^{N-1} \delta_i^{\text{off}} \theta_i(k) w_i \sigma_i(k) + w_N \sigma_N(k) \right] \quad (9)$$

### Model Constraints

The essential constraints for optimizing ramp metering rates are the dynamic traffic evolution equations (Equations 7 and 8). The other constraints are the physical lower and upper bounds for the mean link density values, the metering rates, and the ramp contents:

$$0 \leq \rho_i(k) \leq \rho^{\max} \qquad i = 1,2, \ldots, N \quad (10)$$

$$R_i^{\min} \leq R_i(k) \leq R_i^{\max} \qquad i = 1,2, \ldots, N \quad (11)$$

$$0 \leq x_i(k) \leq b_i \qquad i = 1,2, \ldots, N \quad (12)$$

Note that an additional operational constraint is required that pursues the implementation of sufficiently large, if necessary, metering rates so as to prevent ramp queues from spilling back to surface streets. This objective may conflict with the total freeway throughput when traffic demand is high. It has to be temporarily ignored if the mainline freeway operational MOE is the primary consideration. When improvement on the entire network is the ultimate goal, ramp metering control only is not enough, and additional control measures, including real-time diversion control and signal timing coordination at surface street intersections, must also be considered for achieving optimal control. This type of more complex control issue at the corridor network level has been approached by Chang et al. (*13*).

### Optimal Control Model

Theoretically, the optimal time-varying ramp metering rate for the entire control period can be solved in one step. In practice, however, considering both the required computational effect for real-time operations and the dynamic nature of all key time-varying parameters, it is recommended that each optimal control mode be executed over a relatively shorter period and updated with the feedback information from surveillance systems. Supposing that a time horizon comprising $M$ consecutive intervals is chosen as one control period, an optimal control model can be formulated as follows:

Maximize objective function Equation 9

subject to Equations 7, 8, 10, 11, and 12 (13)

However, before applying this optimization model, all unknown model coefficients and parameters involved in Model 13 must be identified. In particular, current link densities must be estimated so that a proper linear-form flow density model (Equation 5) can be calibrated.

## STATUS ESTIMATION AND DYNAMIC PARAMETER PREDICTION

### Traffic Status Estimation

It is notable that traffic status information [$\rho(t-1)$ and $\mathbf{X}(t-1)$] at the beginning of interval $t$ must be estimated for the optimization model Equation 13. Several methods are available in the literature for dealing with such issues. For instance, Kalman filtering is one of the most efficient approaches for system status identification and has been extensively applied in traffic control. The single segment estimation (SSE) approach developed by Payne et al. (*14*) is an example application of the Kalman filtering technique for estimating link densities and on-ramp queuing lengths with point volume and occupancy data from surveillance detectors. The SSE approach can be directly utilized in this study.

### Parameters Updating and Prediction

In addition to the traffic status information, the time-varying parameters $\{\alpha_i(k)\}$ in Model 13 must be identified before the execution of the models. At each instant, since the parameters' current and previous values can be obtained from the traffic surveillance data, some type of time-series model such as the autoregressive moving average (ARMA) model (*15*) can be calibrated and applied to predict the future parameter values.

More specifically, at interval $t$, given the $r_i(k)$, $s_i(k)$, $q_i(k)$, and $Q_i(k)$ for all $i$ from the on-line traffic surveillance system, the parameters $\alpha_i$ can be updated according to Equation 2:

$$\alpha_i(t) = \frac{q_i(t) - [Q_{i+1}(t) - \delta_{i+1}^{\text{on}} r_{i+1}(t)]}{[Q_i(t) - \delta_i^{\text{off}} s_i(t)] - [Q_{i+1}(t) - \delta_{i+1}^{\text{on}} r_{i+1}(t)]}$$

With the following simple autoregressive model AR(m) of $m$ lags, the future parameter values $\{\alpha_i(k)\}$ can be obtained through a time-series recursive prediction:

$$\alpha_i(k) = \sum_{j=1}^{m} \delta_j(k) \alpha_i(k-j) \quad (14)$$

However, because of the dynamic nature of the model coefficients $\delta_j(k)$, before performing prediction, these $\delta_j(k)$, $j = 1, \ldots, m$, should be updated with the current $\alpha_i(k)$. Such an updating process can be executed with the application of a linear least-squares algorithm or the Kalman filtering technique.

Note that to update the above model parameters with Kalman filtering, it is convenient to assume that all $\delta_j(k)$ follow a random walk model. In this way, a canonical status space dynamic model can be set up as

$$\delta_j(k) = \delta_j(k-1) + w_j(k) \qquad j = 1,2, \ldots, m$$

$$e_i(k) = \sum_{j=1}^{m} \delta_j(k) e_i(k-j) + v_i(k)$$

where $w_j(k)$ and $v_i(k)$ are Gaussian white noise with known variance-covariance matrices. Then the parameter updating is given by

$$\delta_j(k) = \delta_j(k-1) + K_j\left[e_i(k) - \sum_{n=1}^{m} \delta_n(k-1)e_i(k-n)\right]$$

where $K_j$ is the associated Kalman gain.

With the new coefficients $\{\delta_j(k)\}$ the future parameter values $\{\alpha_i(t)\}$ can thus be predicted with Equation 14.

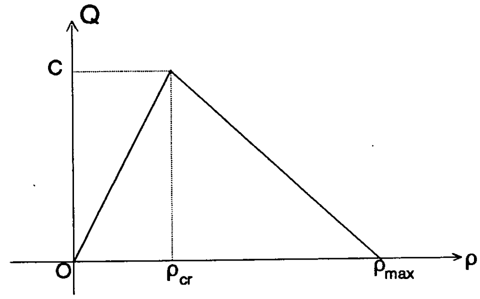


**FIGURE 3 Two-segment linear flow-density model.**

## SUCCESSIVE LINEAR PROGRAMMING ALGORITHM

Having established the modeling concepts, an integrated algorithm procedure for computing real-time ramp metering rates is shown in Figure 2. The basic logic governing this algorithm is the rolling horizon concept that was first introduced to traffic control by Gartner (*16*) and further utilized by Chang et al. (*17*).

One of the most important aspects of this real-time algorithm framework is the feedback control. At each step, the model computes the optimal ramp metering rates for the next $M$ intervals, that is, a set of $R(t)$, $R(t+1)$, . . . , $R(t+M-1)$ is computed. The control system will then process the comparison between the predicted and detected traffic conditions so as to determine the acceptability of those future metering rates. As shown in Figure 2, if the projected traffic flows at interval $t$ are consistent with the on-line surveillance data, one may accept the computed metering rates for subsequent intervals; otherwise, the optimization procedure for the next time horizon is repeated after the parameters are updated and prediction with the new surveillance data is executed.

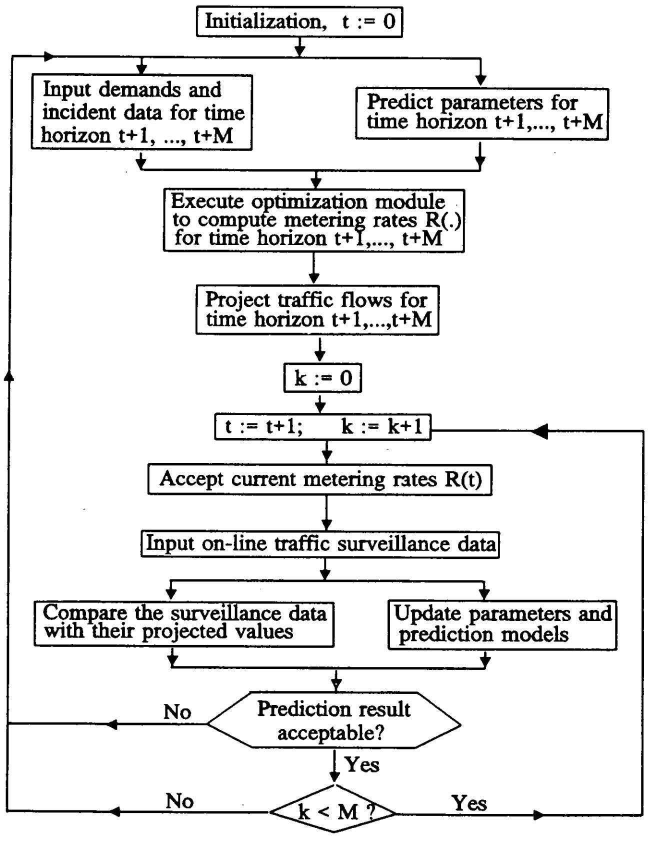


**FIGURE 2 Flow chart of the real-time ramp metering control logic.**

Now turning to the central part of the ramp metering algorithm, consider the optimal control model Equation 13 and the dynamic constraints Equations 7 and 8. It seems to be a linear programming problem with respect to variables $\rho(k)$, $\mathbf{X}(k)$, and $\mathbf{R}(k)$, $k = t+1$, . . . , $t+M$. However, Equation 13 is not pure linear programming because the coefficient matrices of the density dynamic constraint Equation 7 depend on the range to which the density $\rho(k)$ belongs. A linear-form dynamic equation is derived under the condition that a linear flow-density relation (Equation 5) holds. Therefore, before the linear programming techniques are applied, a piecewise linear flow-density model must be calibrated.

According to recent research studies reported in the literature (*18,19*) a two-segment linear flow-density function, as shown in Figure 3, is reasonable for representing freeway traffic flows. Thus for any freeway link $i$, Equation 5 has two sets of parameters $w_i(k)$ and $u_i(k)$ corresponding to the two density ranges $[0,\rho^{cr}]$ and $[\rho^{cr},\rho^{max}]$ for calibrating the linear function.

Now it is clear that the corresponding boundary constraints for $\rho_i(k)$ should be added when a linear dynamic Equation, such as Equation 7, is used. To apply a linear programming model for such a unique optimal metering model and dynamic constraints, a special technique is proposed, successive linear programming (SLP) algorithm, which enables the model to be executed sufficiently fast for real-time applications. All principal steps of the proposed SLP algorithm are summarized as follows:

- Step 1.1 According to the current traffic status and metering flows, add the corresponding lower- and upper-bound constraints for $\rho_i(k)$, $i = 1,2,\ldots,N$; $k = t+1,\ldots,t+M$, to the LP Model 13.
- Step 1.2 Compute the coefficient matrices of the linear density dynamic equation according to the current linear flow-density models.
- Step 1.3 Solve the resulting linear programming model to obtain a set of solutions $\rho(k)$, $X(k)$, and $R(k)$ and the corresponding objective function value.
- Step 2 Check whether some $\rho_i(k)$ equals $\rho^{cr}$. If not, stop with the current LP solution. Otherwise, go to Step 3.
- Step 3 Change the lower- and upper-bound constraints for those $\rho_i(k) \approx \rho^{cr}$ into the other range and modify the correspond-

ing parameters in the linear flow-density models and the coefficient matrices of the linear density dynamic equation constraints.

Step 4 Solve the updated LP model to obtain a new set of solutions and its corresponding objective function value.

Step 5 Check whether the objective function value has been improved. If not, stop with the current LP solution; otherwise, return to Step 2.

A more detailed discussion of the properties and performance of the proposed SLP algorithm can be found elsewhere (*13*). Not all LP problems generated by the algorithm can guarantee a feasible solution. If there is no feasible solution, any local traffic-responsive strategy can be applied instead at this iteration step, so as to continue the algorithm procedure. In the simulation tests performed here, it was found that such infeasible LPs occur only rarely; hence it has only a slight impact on the performance of the algorithm. To show the potential effectiveness of the models and strategy developed in this study, a simulation experiment is presented in the next section.

## NUMERICAL TESTS

### Field Network and Surveillance Detectors Assignment

To evaluate the proposed model and algorithm, a section of the I-5 corridor in Seattle, Washington, was selected as the field network for simulation tests. As shown in Figure 4, this corridor network contains 9 on ramps, 6 off ramps, and one parallel arterial (SR-99) as well as 14 crossing surface streets. In this simulation test, exactly one full set of loop detectors was placed close to each node for freeway links. To minimize the use of detectors, each detector station was located at the on-ramp upstream merging point or the off-ramp downstream diverting point, depending on the node configuration. In addition, two detectors were placed near the upstream and downstream boundaries of each on ramp, and one detector was placed near the upstream boundary of each off ramp. Because all ramps in this network have one lane, one detector is sufficient for each ramp station.

### Simulation Design

In this simulation test, an incident was assumed to occur on freeway Link 7 → 8. Simulation tests were then performed for four different traffic conditions with different demand levels, incident severity, and duration. This simulation plan was based on a research report of a simulation study of coordinated signal control strategies by Farradyne Systems Inc. (*20*).

The following six on-ramp control strategies were specified to investigate their MOEs regarding freeway performance, given an identical control operation on the surface streets:

1. Strategy O: baseline case operation, no ramp metering;
2. Strategy A: close one on ramp immediately upstream of the incident site;

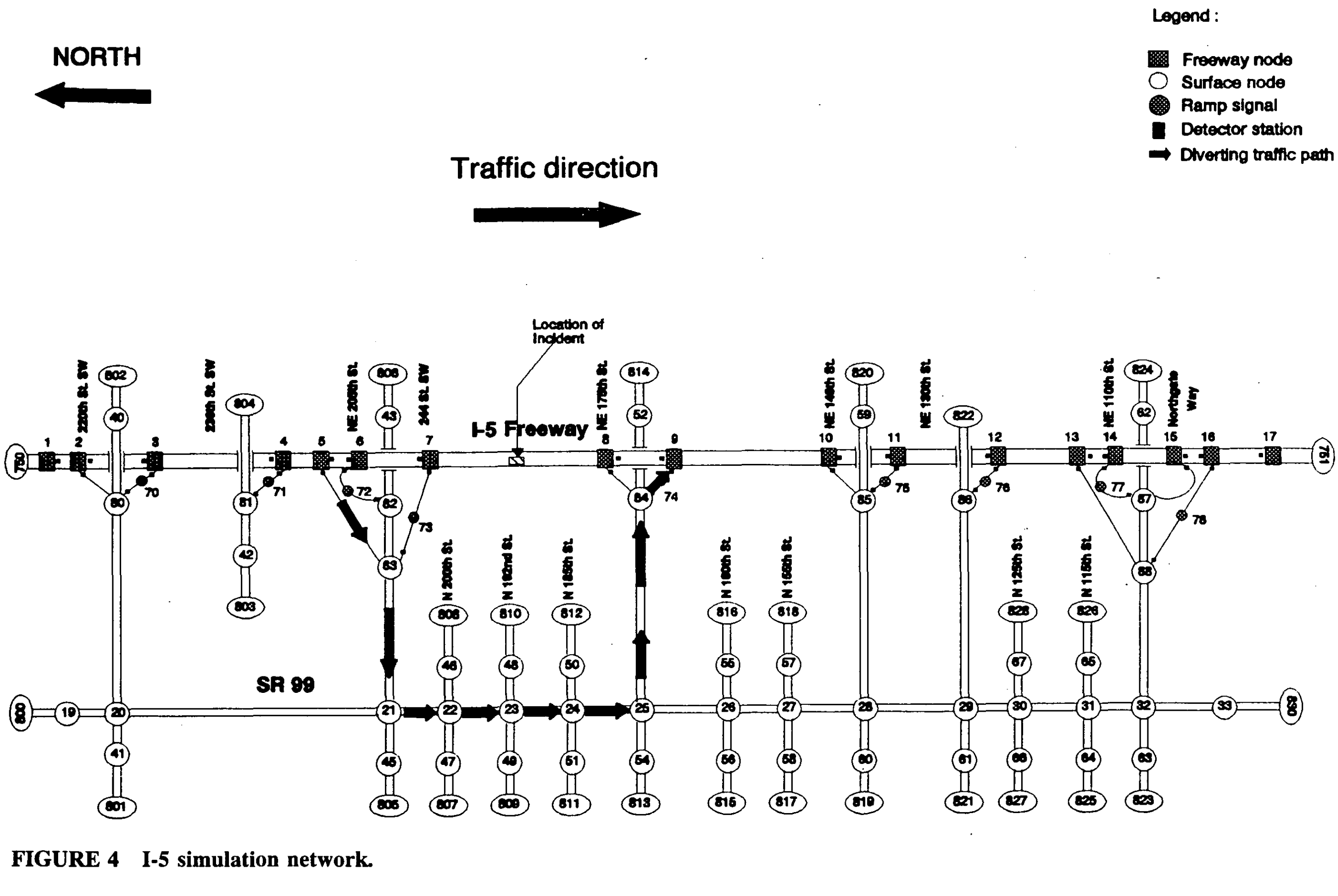


**FIGURE 4 I-5 simulation network.**

3. Strategy B: close two on ramps immediately upstream of the incident site;
4. Strategy C: local demand-capacity ramp metering;
5. Strategy D: Areawide ramp metering algorithm integrated with INTRAS and tested by Farradyne Systems, Inc. (*20*); and
6. Strategy S: Real-time metering with the SLP algorithm developed by the authors.

Each ramp metering strategy was implemented over four kinds of traffic conditions that are of different entry volume levels or different incident and traffic diversion patterns, or both. The following four test cases of traffic conditions are given:

Case 1. A total of 60 percent of the peak-hour volume [more concrete data and test results can be found elsewhere (*21*)], low incident level (i.e., one lane blockage, 10 percent rubberneck factor for other lanes, 10-min duration), 10 percent diversion from mainline to the diversion route as highlighted in Figure 5.
Case 2. A total of 60 percent of the peak-hour volume, high incident level (i.e., two lanes blockage, 20 percent rubberneck factor for other lanes, 20-min duration), 30 percent diversion from mainline to the diversion route.
Case 3. A total of 100 percent of the peak-hour volume, low incident level (i.e., one lane blockage, 10 percent rubberneck factor for other lanes, 10-min diversion from mainline to the diversion route).
Case 4. A total of 100 percent of the peak-hour volume, high incident level (i.e., two lanes blockage, 20 percent rubberneck factor for other lanes, 20 min duration), 30 percent diversion from mainline to the diversion route.

The simulation runs of all the six strategies over these four traffic conditions amount to 24 cases, which were named sequentially as follows:

| | | |
|---|---|---|
| O1, O2, O3, O4 | A1, A2, A3, A4 | B1, B2, B3, B4 |
| C1, C2, C3, C4 | D1, D2, D3, D4 | S1, S2, S3, S4 |

### Simulation Procedures

The simulation time for each of the 24 INTRAS runs was 35 intervals (35 min) over three periods as follows:

Period 1. A 5-min duration under normal traffic conditions without incident,
Period 2. A 20-min duration with an incident occurring at the beginning and lasting for 10 or 20 min. At the beginning of this period, diversion was performed at the off ramp immediately upstream of the incident location (freeway Node 5) by manual adjustment of turning percentages at intersections along the diversion route.
Period 3. A 10-min duration representing the recovery period after the incident has been removed from the freeway. After the removal of the incident, the turning percentages were reverted to those values before the incident, as specified in the first subinterval.

### Simulation Results

As shown in Table 2, the TTT produced under Strategy 6 (with the SLP algorithm) is notably superior to those with other control strategies in all four cases of traffic conditions. The performance of the proposed SLP strategies can be examined further through the results shown in Figure 5, where the improvement in TTT increases with the level of congestion and the severity of the incident.

The simulation results with all other MOEs from the INTRAS output are also examined. For the mainline freeway operations, among the six strategies except baseline Strategy O, Strategy S has produced the following:

- The highest vehicle-miles and speed as well as the lowest vehicle-minutes and delay when both volume and incident levels are high (Case 4);
- The second-highest vehicle-miles but the lowest speed, highest vehicle-minutes and delay when volume level is high but incident level is low (Case 3);
- The second-highest vehicle-miles, medium speed and delay, but the second-highest vehicle-minutes when volume level is low but incident level is high (Case 2); and
- The highest vehicle-miles, second-highest speed and medium delay, but the second-highest vehicle-minutes when both volume and incident level are low (Case 1).

As a byproduct of the INTRAS output, these MOEs for the entire corridor network also have been obtained. Compared with the six strategies except baseline Strategy O, Strategy S has produced the following:

- The highest vehicle-miles, medium speed and delay, but the highest vehicle-minutes when both volume and incident levels are high (Case 4);
- The second-lowest vehicle-miles and speed as well as the highest vehicle-minutes and second-highest delay when volume level is high but incident level is low (Case 3);
- The second-highest vehicle-miles and medium speed but the second-highest vehicle-minutes and delay when volume level is low but incident level is high (Case 2); and
- The highest vehicle-miles, medium speed and delay, but the second-highest vehicle-minutes when both volume and incident level are low (Case 1).

In summary, the proposed SLP approach has shown convincing improvement over all other strategies for freeway operation in the case of heavy traffic and high incident level. However, its improvement under low congestion is not so significant as to justify the use of such a sophisticated method. In addition, with the entire corridor as the objective, no substantial improvement can be achieved with any algorithm under any of the cases. This actually implies that for contending with nonrecurrent congestion, one should view the entire corridor as a control system and perform both ramp metering and diversion control as studied by Chang et al. (*13*).

## CONCLUSIONS

This study has developed an integrated ramp metering model with a piecewise linear dynamic optimal control function and an effi-

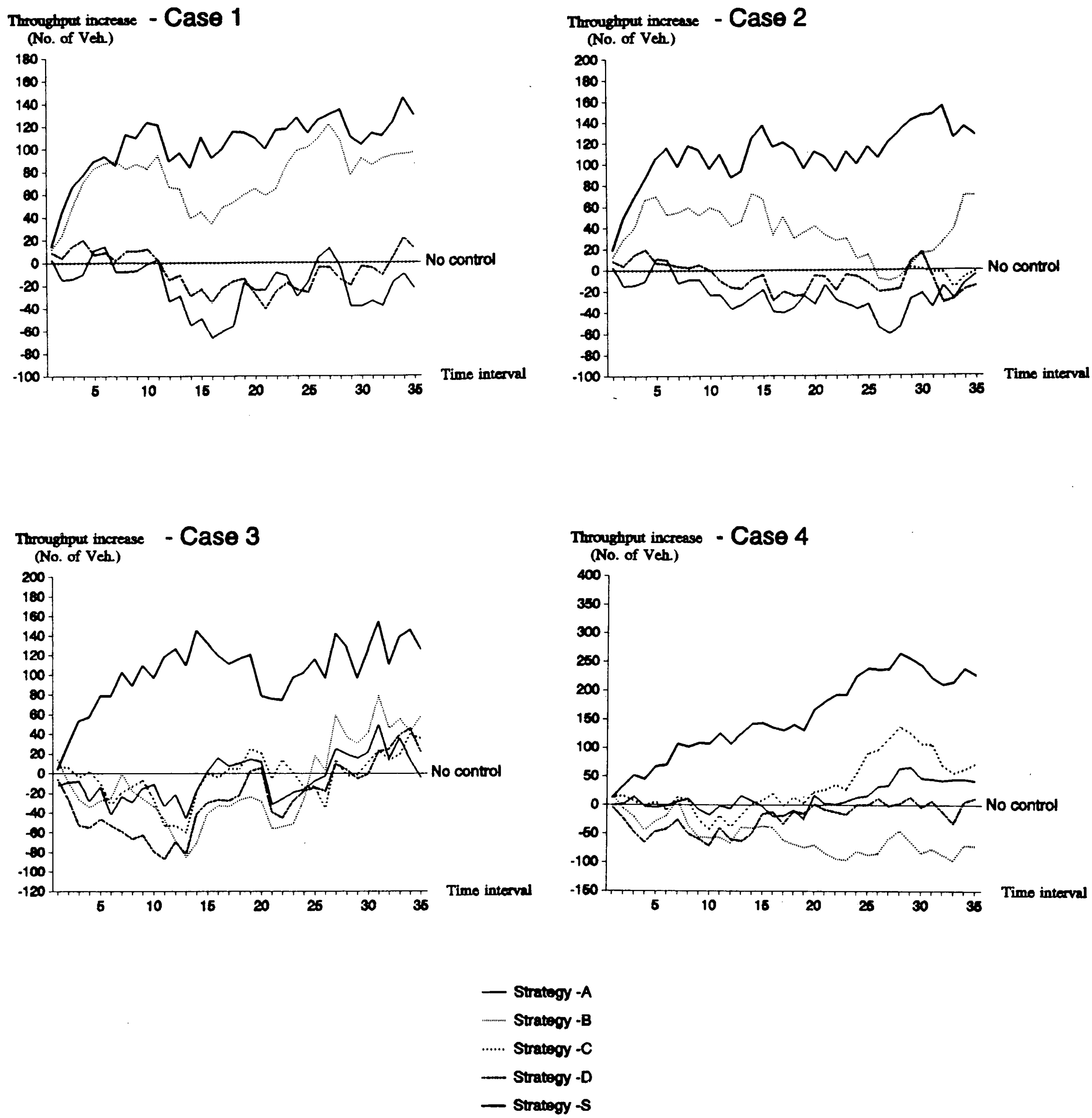


**FIGURE 5 Cumulative throughput increases versus no control.**

cient algorithm for real-time applications. Numerical tests of the proposed model and the SLP algorithm on a typical freeway corridor with INTRAS simulation demonstrated that the integrated control strategy with the proposed SLP algorithm outperforms all other strategies in total freeway throughput and in other MOEs, including total vehicle-miles, total vehicle-minutes, and average speed and delay under both high-volume and high-incident conditions. However, no significant performance can be achieved with any ramp metering strategies if the entire corridor network is concerned. Hence, although it is reasonable to conclude that the SLP algorithm is a promising strategy for real-time freeway nonrecurrent congestion control, integration with proper diversion control will be necessary to lead the entire corridor to optimum status.

**TABLE 2 Simulation Results of Total Freeway Throughput**

| Control Strategy | Case 1 | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|
| Strategy -O | 2927 | 2991 | 4535 | 4220 |
| Strategy -A | 2904 | 2987 | 4531 | 4263 |
| Strategy -B | 3024 | 3062 | 4593 | 4149 |
| Strategy -C | 2927 | 2990 | 4571 | 4293 |
| Strategy -D | 2939 | 2976 | 4557 | 4232 |
| Strategy -S | 3057 | 3120 | 4662 | 4449 |

NOTE: Values given are numbers of vehicles.

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# Comparative Evaluation of Adaptive and Neural-Network Exit Demand Prediction for Freeway Control

EIL KWON AND YORGOS J. STEPHANEDES

Reliable on-line predictors that can accurately predict freeway demand in real time are of critical importance in developing optimal control systems for freeway corridors. New freeway exit demand predictors have been developed using two prediction approaches: model-based adaptive-parameter and backpropagation neural network-based prediction. The adaptive-parameter predictor requires prespecified models with parameters determined on line using the Kalman filter. Two such models are formulated. The first model is developed for normal weekdays and requires both historical and current-day measurements. The second model is designed for situations in which no historical information is available. Neural network-based prediction does not require a prespecified functional form that relates traffic measurements to predicted flow. However, an appropriate network structure and training method need to be determined before the network is trained. A three-layer backpropagation neural network was trained with the same data that are used to determine the historical pattern for the adaptive-parameter predictor. The new predictors were tested with real data from the I-35W freeway during a 2-week period and their performance was compared with that of the urban traffic control system (UTCS)-2 predictor. The error indexes from the two new predictors are very close and substantially better than those from UTCS-2 under the same conditions.

The most advanced concept for optimal freeway control that has been proposed in the literature employs a hierarchical structure. In such a structure, the overall control problem is decomposed into components, such as demand prediction, network optimization, and direct control (*1,2*). The main principle is that, on the basis of predicted demand, optimization determines optimal control strategies over a short period. Because of the discrepancies between predicted demand and actual traffic volume, these strategies are further adjusted by direct control in real time. However, the lack of reliable algorithms that can predict freeway demand in real time has forced traffic engineers to adopt reactive control strategies. To be sure, most traffic-responsive ramp metering systems currently in operation employ automatic rate selection procedures that are based on past freeway data. Ramp metering rates are selected from a predetermined library using previously collected data, generally 1 min old, from detectors on the main freeway, thereby reacting to freeway conditions rather than acting to prevent congestion. Similarly, in urban network traffic control, the inaccuracy of existing on-line predictors, such as the third-generation urban traffic control system (UTCS), has led to the development of purely reactive control systems (*3*).

Addressing the need for reliable real-time prediction, earlier work by the authors developed a method for adaptive prediction of demand diversion at freeway entrance ramp areas. This method determines the parameters in the prediction models on line using the extended Kalman filter (*4,5*). This paper assesses the effectiveness of two approaches for on-line prediction of freeway exit demand. To accomplish this, it develops an extension of the model-based adaptive-parameter prediction method previously developed by the authors and neural network-based prediction. Two models are formulated for adaptive-parameter prediction, depending on the availability of historical information. Further, a three-layer backpropagation neural network is trained with the same data used for extracting the historical demand pattern for the adaptive-parameter predictor.

The resulting predictors were tested with real data from the I-35W freeway exit ramps in Minneapolis, Minnesota. The test data were collected during two periods, a normal weekday period and a Thanksgiving holiday period. The performance of each predictor was compared with that of the UTCS-2 predictor.

E. Kwon, Center for Transportation Studies; Y. J. Stephanedes, Department of Civil Engineering, University of Minnesota, Minneapolis, Minn. 55455.

## BACKGROUND

Most traffic prediction algorithms developed to date use a functional form that relates the traffic measurements to the predicted flow with a set of parameters. Such model-based algorithms can be categorized into four classes, depending on the method used for determining the model parameters, such as, off or on line, and the type of data used, that is, historical and current-day data versus current-day data only (Table 1). The most common predictors use constant parameters determined off line with historical data. For example, the parameters in the demand predictor of the second generation of UTCS-2 are determined off line using a representative data set collected from the location in question. The UTCS-2 predictor employs both historical and current-day measurements. Using current-day traffic measurements, the UTCS-2 predictor tries to correct for the traffic deviations from the average historical pattern. In contrast, the UTCS-3 predictor, employing only current-day measurements, uses the interpolation between the most recent smoothed and unsmoothed measurements as the predicted value. Off-line determination of parameters and use of only current-day measurements for prediction are also featured by later research that focuses on freeway mainline volume and occupancy prediction (*6–8*). These models, mostly ARIMA-type Box-Jenkins time series models, assume that demand prediction is a point process and use purely statistical techniques to identify the stochastic nature in the observed data.

The above constant-parameter algorithms treat demand prediction as an open-loop process and employ historical demand pat-

TABLE 1 Traffic Demand Prediction Algorithms

| | CURRENT-DAY & HISTORICAL DATA | CURRENT-DAY DATA ONLY |
|---|---|---|
| **OFF-LINE CALIBRATION (CONSTANT PARAMETERS)** | UTCS-2 (FHWA, 1973) | UTCS-3 (Lieberman, 1974)<br>Time-Series Models<br>- Ahmed (1979,1983)<br>- Moorthy (1988) |
| **ON-LINE CALIBRATION (VARIABLE PARAMETERS)** | Okutani & Stephanedes (1984)<br>Stephanedes & Kwon (1989, 1992) | |

terns to predict the current-day trend. Therefore, the accuracy of these algorithms depends on the similarity between the trend of the historical data used for the determination of the parameters and that of the actual measurements. Although the algorithms that use only current-day measurements are more responsive to current traffic variations, inherent time lags characterize prediction with those algorithms (*9*). Further, under normal traffic conditions, the algorithms employing historical information as reference provide better prediction than those that use only current-day measurements (*9*).

Updating the prediction parameters in real time with filtering was first introduced by Okutani and Stephanedes (*10*), who applied the Kalman filtering algorithm to 15-min volume prediction in urban networks. Recent research by the authors combines behavioral modeling and the extended Kalman filter. In this approach, the prediction model parameters represent the behavioral state of traffic flow. The nonstationary random walk process describes the time-dependent state evolution of the model parameters, and the extended Kalman filter updates the model parameters. This approach employs both historical data and current-day measurements and was applied to predict the traffic diversion in freeway entrance ramp areas (*5*).

Recent developments in the area of neural networks provide a new dimension in traffic prediction. Unlike the above model-based predictors, the neural network-based approach does not require a prespecified functional form for prediction. A large data set is needed to identify a set of parameters associated with each link of the neural network. The neural network learns by adjusting the parameters of each link in the direction of desired output (*11*). Although the neural network-based prediction approach, using mostly the backpropagation network, has been studied by researchers in other areas, only limited research has been conducted in predicting traffic demand in real time.

In this research, an adaptive-parameter predictor that predicts freeway exit demand at 5-min intervals is developed first. The predictor consists of two prediction models. The first, developed for normal traffic conditions, uses both historical data and current-day measurements. The second model employs only current-day measurements and is designed for applications in which substantial discrepancies exist between historical demand patterns and actual measurements as a result of unexpected events or holidays. In both models, the parameters are estimated on line using the most recent prediction error. Second, a neural network-based predictor is developed by training a three-layer backpropagation neural network with the same data used in developing the adaptive predictor. The trained network uses both current- and previous-day measurements to predict freeway exit demand at 5-min intervals. The resulting predictors were tested with real data collected from the I-35W freeway section and their performance was compared with that of the UTCS-2 predictor. The model formulation, training method, and test results are described in this paper.

## DEVELOPMENT OF ADAPTIVE-PARAMETER PREDICTOR

A model-based freeway-exit demand predictor is developed by extending the adaptive prediction approach previously developed by the authors for freeway-entrance demand. This approach determines the parameters in the prediction model in real time using the Kalman filtering algorithm and thus requires a prediction model that relates the traffic measurements to the predicted flow. Two models are formulated to predict the exit demand by using the data collected from the ramp in question. The first model is developed for normal traffic conditions, such as normal weekdays without incidents or unexpected events, and uses both historical data and current-day measurements collected from the exit ramp in question; for example,

$$V_t = \sum_{i=1}^{t} V_i^H - \theta_{1,t} V_{t-1} - \theta_{2,t} \sum_{i=1}^{t-2} V_i \tag{1}$$

where

$V_t$ = predicted exit demand for $t$th time interval;
$V_t^H$ = historical average exit volume for $t$th time interval;
$V_t$ = current-day measurements at $t$th time interval; and
$\theta_{1,t}$, $\theta_{2,t}$ = parameters to be updated in real time.

The model is based on the findings from an extensive analysis of the Twin Cities freeway data, indicating that cumulative exit ramp volume exhibits limited daily variations during weekdays in normal traffic conditions (*5*). Prediction reflects the current traffic trend by applying time-variant weights on the current-day exit volume measurements in the previous interval and on the cumulative exit volume before that interval. The weights are updated on line by a Kalman filter and the most recent prediction error.

The second model is designed for situations in which substantial discrepancy between historical demand pattern and actual traffic volume exists, such as during incidents or holidays, so that the historical data are no longer meaningful for prediction. The model updates the moving average of current-day exit volume measurements with a time-variant parameter determined on line with a Kalman filter; that is,

$$V_t = \theta_t\left(\sum_{i=1}^{N} V_{t-i}\right)/N \qquad (2)$$

where

$V_t$ = predicted exit volume for $t$th interval;
$V_t$ = current-day exit volume for $t$th interval;
$N$ = number of periods considered (here, $N = 4$); and
$\theta_t$ = parameter to be updated in real time.

This model adjusts the moving average of current-day measurements to reflect the current traffic pattern. Because the model does not require historical data and the parameter is estimated on line, no prior knowledge of exit demand trends is necessary for prediction.

The adaptive prediction approach considers the model parameters as status variables representing the behavioral status of traffic flow at a given interval, and the Kalman filter algorithm identifies the optimal unbiased estimates of the behavioral status in real time using the most recent prediction error. The status evolution of the model parameters, $\theta$, is assumed to follow the nonstationary random walk process; that is,

$$\theta_{t+1} = \theta_t + w_t \qquad (3)$$

where $w$ denotes noise. The random walk process has been successfully applied to model physical systems that are subject to rapid variation (*12*). Using the prediction models as observation equations, the Kalman filter continuously updates the model parameters by recursively determining the minimum variance estimates of the prediction parameters. The Kalman filter is based on the theory developed by Kalman (*13*) and was intended for the status identification of a linear dynamic system. The procedure for updating the model parameters via the Kalman filter is summarized as follows:

1. Initialize algorithm ($k = 0$) with any prior knowledge of model parameters for each ramp:

$$\theta_{t/t} = \theta_0 \qquad \Sigma_{t/t} = \Sigma_0$$

where $\Sigma_{t/t} = E[(\theta_t - \theta_{t/t})(\theta_t - \theta_{t/t})^T]$.

2. Set the model parameters $\theta_{t+1/t} = \theta_{t/t}$.
3. Predict the exit ramp demand $V_t$ using prediction Model 1 or 2 with the parameters $\theta_{t+l/t}$
4. Measure actual exit ramp volume $V_t$ and obtain prediction error $e_t$, where $e_t$ = [measured value]$_t$ − [predicted value]$_t$.
5. Update model parameters $\theta_{t+l/t}$ using gain and error;

$$\theta_{t+1/t+1} = \theta_{t+1/t} + K_{t+1}e_t \qquad (4)$$

where

$K_{t+1} = \Sigma_{t+1/t}S^T_{t+1}[S_{t+1}\ \Sigma_{t+1/t}S^T_{t+1} + s_t]^{-1}$ is the gain vector,
$\Sigma_{t+1/t} = \Sigma_t + q_t$, the covariance matrix;
$S_{t+1} = [\partial V/\partial\theta]^T$ with $\theta = \theta_{t+1/t}$;
$V$ = prediction Model 1 or 2;
$\Sigma_{t+1/t+1} = (I - K_{t+1}S_{t+i})\ \Sigma_{t+1/t}$, the updated covariance matrix;
$E[w_tw_j^T] = q_{tj}$, the covariance of state noise vector;
$E[v_tv_j^T] = s_{tj}$, the covariance of observation noise vector; and
$w$, $v$ = zero-mean Gaussian white noise sequences for state Equation 3 and prediction Model 1 or 2, respectively.

6. Let $t = t + 1$ and return to Step 2.

## DEVELOPMENT OF NEURAL NETWORK-BASED PREDICTOR

An artificial neural network is an abstract simulation of a real nerve system. It is determined by the connection between neurodes, the transfer function used by the neurodes and the weight change law that controls training of the network (*11*). Owing to their self-organizing and adaptive features without a prespecified functional form representing a physical system, neural networks have become a popular alternative to the traditional model-based approaches in various areas of science and engineering. In this research, a three-layer backpropagation neural network (BNN) is designed and trained to predict freeway exit demand at 5-min intervals. The three-layer backpropagation network, the most widely used network in the area of prediction, has one hidden layer linking input and output layers. The following weight change law, also called the generalized delta rule, is used to adjust the weight associated with each connection link between neurodes:

$$\Delta w_{i,j,k} = \beta E_i X_i + \alpha \Delta w_{i,j,k-1}$$

where

$\Delta w_{i,j,k}$ = change in the weight for link $ij$ for $k$th iteration;
$E_i$ = error for neurode $i$; for example, the difference between desired and actual outputs;
$X_i$ = input for neurode $i$;
$\alpha$ = momentum constant; and
$\beta$ = learning rate.

As noted in the weight change law, the backpropagation training algorithm requires two parameters—learning rate and momentum constant—whose values need to be specified before training. Further, the number of neurodes in the hidden layer should be determined before training starts. The values of these training parameters and the input-output structure substantially affect the performance of the neural network.

First, the input-output structure of the backpropagation neural network is determined. Although a neural network does not require a prespecified functional form for prediction, the type of output, that is, the value to be predicted, and the input to the network need to be specified before the network is trained. The neural network, trained with real data, is expected to have learned the inherent pattern that may exist between the inputs and the output. In this research, it is assumed that the freeway exit demand is affected by both upstream and downstream traffic conditions from the ramp in question. Table 2 summarizes the input-output structure used in the BNN predictor developed in this research. As indicated in Table 2, the BNN predictor uses both current- and previous-day measurements upstream, downstream, and at the ramp in question. A total of 80 input and one output data are identified for the proposed BNN predictor.

Second, the training method for the proposed BNN predictor is determined to achieve the best prediction performance. As dis-

**TABLE 2 Input-Output Specifications for BNN Predictor**

| | | Ramp in question | Upstream 3 entr. ramps 3 exit ramps | Upstream 3 mainline locations | Downstream 2 mainline locations |
|---|---|---|---|---|---|
| INPUT | Current day | Volume at t-1, Cumulative volume at t-1, t-2 | Volume at t-1, Cumulative volume at t-1, t-2 | Volume at t-1 | Volume at t-1 |
| | Previous Day | Volume at t, t-1, Cumulative volume at t, t-1, t-2 | Volume at t, k-1, Cumulative volume at t, t-1, t-2 | Volume at t, t-1, Cumulative volume at t | Volume at t, t-1, Cumulative volume at t |
| OUTPUT | Currenttday | Volume at t | | | |

cussed earlier, the performance of the BNN predictor substantially depends on the training method, that is, values of the training parameters, such as learning rate, momentum, and the number of neurodes in the hidden layer. However, no theory is available that can determine the best set of these values for any given problem. In this research, a sensitivity analysis is conducted on these parameters with real data collected from the test section. An example ramp that shows a typical exit demand pattern in the test section is selected and the sensitivity of the BNN-based prediction with respect to various values of the training parameters is analyzed for the selected ramp. Finally, a set of training parameters with the best prediction performance is selected. The resulting training parameters are used to train the BNN predictor for all other ramps in the test section.

## TESTING AND COMPARISON WITH UTCS-2 PREDICTION

The performance of the new predictors was tested with the real data collected from the I-35W northbound freeway in Minneapolis, Minnesota. Further, the results were compared with those of the UTCS-2 predictor using the same data. The test freeway section and the location of the loop detector stations operated by the Traffic Management Center, Minnesota Department of Transportation, are illustrated in Figure 1. As a result of the detection system configuration, only 5-min exit ramp–mainline volume data were available from each detector station. Four exit ramps of the test section were selected and their 5-min exit volume was collected during a 2-week period, November 12 through 23, 1989. The data from the first week, November 12 through 16, were used to determine the historical demand pattern for the adaptive-parameter predictor. Data from the first week also were used to train the BNN predictor. The resulting predictors were applied to predict the exit demand of the selected ramps in the second week, November 19 through 23.

The exit ramps selected for testing are also indicated in Figure 1, in which ramp notation indicates the traffic movement and cross street; for example, 94NX represents the northbound exit ramp at 94th Street. In particular, 94NX and 66NX ramps are typical low-volume ramps in the test section. Demand at the 82NX ramp is high relative to the other ramps, and the 78NX2 ramp is the busiest, serving as the exit to westbound I-494 freeway. For evaluating the performance of the predictor, the mean absolute error (MAE) and the mean square error (MSE) are calculated for each prediction. These are defined as

$$\mathrm{MAE} = \frac{\sum_{t=1}^{N} |(\mathrm{Measured})_t - (\mathrm{Predicted})_t|}{N}$$

$$\mathrm{MSE} = \frac{\sum_{t=1}^{V} |(\mathrm{Measured})_t - (\mathrm{Predicted})_t|^2}{N}$$

where $N$ denotes the number of predictions.

### Prediction with On-Line Adaptive-Parameter Predictor

First, the adaptive-parameter predictor was tested with the data collected from the four exit ramps in the test section. For each ramp, the exit volume of three normal weekdays, November 19 through 21, was predicted with the first prediction model using both current-day measurements and the historical data for every 5-min interval from 6:00 to 9:00 a.m. each day. For each day's prediction, the average exit volume of the previous week, that is, November 12–16, at the same interval was used as historical data. The following set of the initial parameter values was used for all exit ramps in the test section:

$$\theta_{1,0} = 1.0, \quad \theta_{2,0} = 1.0, \quad s_0 = 5.0,$$

$$\Sigma_0 = \begin{pmatrix} 10 & 5 \\ 3 & 15 \end{pmatrix} \quad q_0 = \begin{pmatrix} 30 & 5 \\ 10 & 25 \end{pmatrix}.$$

The remaining two days, November 22 and 23, were Thanksgiving holidays, and prediction was performed with the second prediction model without historical data because a substantial discrepancy exists between holiday traffic demand and normal weekday traffic patterns. The following initial parameter values were used:

$$\theta_0 = 1.0, \Sigma_0 = 5.0, s_0 = 7.0, q_0 = 10.0.$$

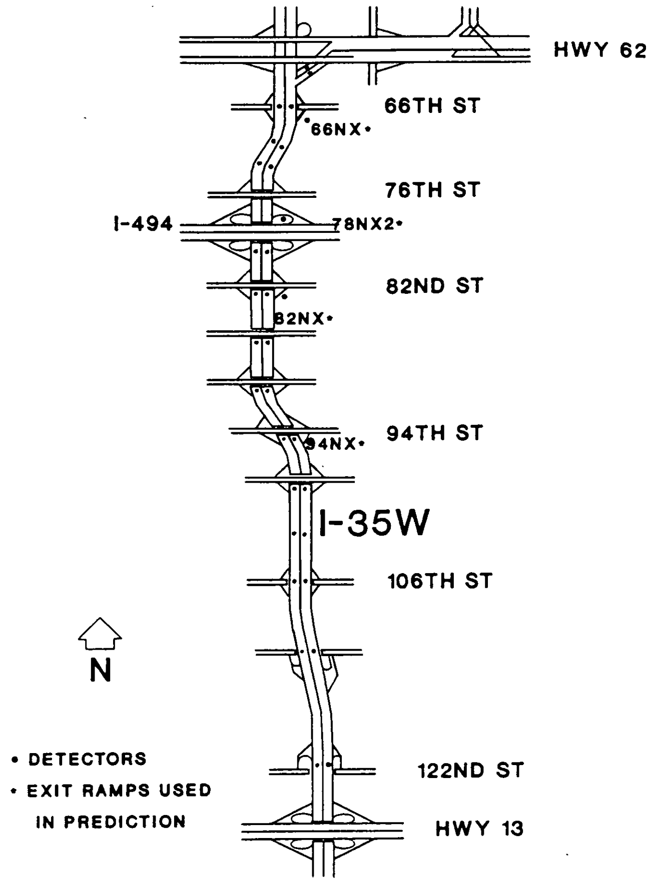


**FIGURE 1 Location of test freeway section (I-35W, northbound, Minneapolis, Minnesota).**

The initial parameter values for both models were determined by conducting limited sensitivity analysis with real data for each model. The prediction results from the two models are summarized in Table 3.

### Prediction with BNN Predictor

Determination of the appropriate values for the training parameters, that is, learning rate, momentum, and the number of the hidden neurodes, is of critical importance in developing neural network-based predictors. In this research, the values of training parameters were determined by conducting a sensitivity analysis on those parameters with the real data collected from the test section. The 82NX exit ramp, located in the middle of the test freeway section, is the example ramp for this analysis. For each parameter, three values were selected:

1. Number of hidden neurodes: 50, 30, 10;
2. Learning rate: 0.05, 0.03, 0.01; and
3. Momentum: 0.7, 0.5, 0.3.

The proposed BNN predictor was trained for the example ramp with the above parameters using the real data collected from the test section. A total of 136 patterns, each with 80 inputs and one output, were developed using the data from the first week (November 12–16) for this training. The training of the BNN was performed using the NeuroShell 2 software, developed by Ward Systems Group. The training was stopped when no error improvement was made after 10,000 iterations.

First, the proposed BNN was trained with varying numbers of the hidden neurodes while the other two parameters remained same. The trained networks were applied to predict the exit demand of the example ramp for three days in the second week (November 19–21). Table 4 summarizes the prediction results of the proposed BNN predictor trained with different numbers of hidden neurodes. In particular, the network trained with 30 hidden neurodes was consistently the best performer in terms of MAE and MSE, but the differences are not substantial. Because the time necessary for training the network increases with the number of hidden neurodes, 30 neurodes were considered adequate. Following the same procedure, three values of learning rate and momentum constant were tested and evaluated, and the results are summarized in Tables 5 and 6. On the basis of these results, the structure of the proposed BNN predictor is determined to be 80-30-1 with a learning rate of 0.05 and a momentum of 0.5.

The proposed BNN with the above structure was trained for each exit ramp in the test freeway section with the data from the first week (November 12–16). After the training, the trained network was applied to predict the exit demand of the first three days of the second week (November 19–21). The last two days of the second week (November 22–23) were the Thanksgiving holidays and were not included in this prediction. Table 3 includes the prediction results with the BNN predictor for each ramp during the 3-day period.

### Prediction with UTCS-2

The second-generation UTCS predicts the next-control-interval (5–15 min) traffic volume at each detector location in real time on the basis of the measurements from the same location only. The UTCS-2 demand prediction equation of UTCS-2 is as follows (*9,13*):

$$V_t = m_t + \gamma(m_t - \gamma f_{t-1}) + (1 - \alpha) \sum_{s=0}^{t-1} \alpha^s (f_{t-s-1} - m_{t-s-1})$$

$$+ \gamma(1 - \alpha) \sum_{s=0}^{t-2} (f_{t-s-2} - m_{t-s-2})$$

where

$V_t$ = predicted volume at time $t$,
$m_t$ = Fourier series approximation of historical volume at time $t$ for each measurement location,
$f_t$ = measured volume at time $t$, and
$\alpha$, $\gamma$ = constants computed off line using representative volume data from the location in question.

For each ramp, to determine the best set of UTCS-2 parameter values, $\alpha$ and $\gamma$, a sensitivity analysis was conducted on those parameters with the real data collected from that ramp. The parameter values that result in the best prediction are summarized in Table 7. Table 3 includes the UTCS-2 prediction results for each ramp in the test section. For purposes of comparison, the

**TABLE 3 Prediction Error Comparisons**

Prediction Error Comparison, 94NX

| | Day 1 | | Day 2 | | Day 3 | |
|---|---|---|---|---|---|---|
| | MAE | MSE | MAE | MSE | MAE | MSE |
| UTCS-2 | 5.0 | 45.9 | 4.2 | 29.2 | 5.3 | 45.8 |
| MODEL 1 | 4.2 | 30.9 | 3.6 | 19.3 | 4.0 | 28.9 |
| BNN | 4.5 | 37.0 | 4.0 | 25.5 | 3.7 | 22.9 |

Prediction Error Comparison, 78NX2

| | Day 1 | | Day 2 | | Day 3 | |
|---|---|---|---|---|---|---|
| | MAE | MSE | MAE | MSE | MAE | MSE |
| UTCS-2 | 10.9 | 175.9 | 16.6 | 372.8 | 12.1 | 197.8 |
| MODEL 1 | 6.5 | 77.8 | 11.4 | 178.6 | 8.1 | 105.4 |
| BNN | 7.6 | 94.3 | 9.1 | 122.3 | 8.3 | 97.8 |

Prediction Error Comparison, 82NX

| | Day 1 | | Day 2 | | Day 3 | |
|---|---|---|---|---|---|---|
| | MAE | MSE | MAE | MSE | MAE | MSE |
| UTCS -2 | 6.4 | 60.2 | 8.9 | 121.2 | 6.4 | 60.2 |
| MODEL 1 | 5.9 | 26.9 | 6.3 | 57.2 | 4.5 | 26.9 |
| BNN | 5.2 | 42.3 | 5.2 | 41.6 | 4.8 | 33.5 |

Prediction Error Comparison, 66NX

| | Day 1 | | Day 2 | | Day 3 | |
|---|---|---|---|---|---|---|
| | MAE | MSE | MAE | MSE | MAE | MSE |
| UTCS-2 | 3.6 | 22.8 | 3.6 | 21.0 | 3.7 | 23.5 |
| MODEL 1 | 3.0 | 11.7 | 3.6 | 12.5 | 3.7 | 22.5 |
| BNN | 3.1 | 14.9 | 3.0 | 14.2 | 3.6 | 18.3 |

**TABLE 4 BNN Prediction Results with Different Numbers of Hidden Neurodes for 82NX**

| Learning rate = 0.05 | | Number of neurodes in hidden layer | | |
|---|---|---|---|---|
| Momentum = 0.5 | | 52 | 30 | 10 |
| Nov. 19 | MSE | 46.89 | 42.3 | 45.4 |
| | MAE | 5.49 | 5.18 | 5.36 |
| Nov. 20 | MSE | 43.04 | 41.55 | 38.41 |
| | MAE | 5.41 | 5.2 | 5.01 |
| Nov. 21 | MSE | 35.28 | 34.83 | 37.49 |
| | MAE | 4.79 | 4.93 | 4.85 |

**TABLE 5 BNN Prediction Results with Different Learning Rates for 82NX**

| Hidden Neurodes = 30 | | Learning rate | | |
|---|---|---|---|---|
| Momentum = 0.5 | | 0.05 | 0.03 | 0.01 |
| Nov. 19 | MSE | 42.3 | 44.49 | 44.91 |
| | MAE | 5.18 | 5.42 | 5.43 |
| Nov. 20 | MSE | 41.55 | 41.78 | 41.99 |
| | MAE | 5.2 | 5.27 | 5.32 |
| Nov. 21 | MSE | 34.83 | 33.09 | 33.46 |
| | MAE | 4.93 | 4.83 | 4.84 |

**TABLE 6 BNN Prediction Results with Different Momentum Values for 82NX**

| Hidden neurodes = 30 | | Momentum | | |
|---|---|---|---|---|
| Learning rate = 0.05 | | 0.7 | 0.5 | 0.3 |
| Nov. 19 | MSE | 43 | 42.3 | 43.56 |
| | MAE | 5.25 | 5.18 | 5.32 |
| Nov. 20 | MSE | 42.17 | 41.55 | 41.77 |
| | MAE | 5.27 | 5.2 | 5.26 |
| Nov. 21 | MSE | 33.46 | 34.83 | 34.09 |
| | MAE | 4.82 | 4.93 | 4.89 |

same historical volume used in the adaptive-parameter predictor was also used as the historical volume for the UTCS-2 predictor, that is, as the value for $m_t$ in the above model.

### Test Results

As indicated in Table 3, the new predictors, that is, the adaptive-parameter (Model 1) and the BNN predictors, resulted in almost the same level of accuracy in terms of MAE and MSE. The MAE from the adaptive-parameter predictor (Model 1) for three normal weekdays ranges from 3.0 to 11.4 vehicles per 5 min, whereas the MAE from the BNN predictor is between 3.7 and 9.1. The adaptive-parameter predictor uses only the data collected from the ramp in question, whereas the BNN predictor uses the upstream and downstream measurements in addition to the ramp data. Both predictors performed consistently better than the UTCS-2 predictor; this improvement was larger in the case of MSE and is probably the result of the higher proportion of large errors in the UTCS-2 prediction. Figures 2 and 3 show typical prediction examples resulting from Model 1 and the BNN predictor for the 78NX2 ramp on November 19 and for the 82NX ramp on November 20, 1989. As indicated, the UTCS-2 predictor tends to fluctuate, depending on the prediction results of the previous interval, whereas Model 1 tries to capture the trend in the current-day exit volume without a substantial time lag. The prediction with the BNN does not exhibit substantial time lag but tends to

**TABLE 7 Parameter Values in UTCS-2 Prediction**

| Exit Ramp | alpha | gamma |
|---|---|---|
| 66NX | 0.001 | 0.89 |
| 78NX2 | 0.001 | 0.97 |
| 82NX | 0.001 | 0.94 |
| 94NX | 0.001 | 0.92 |

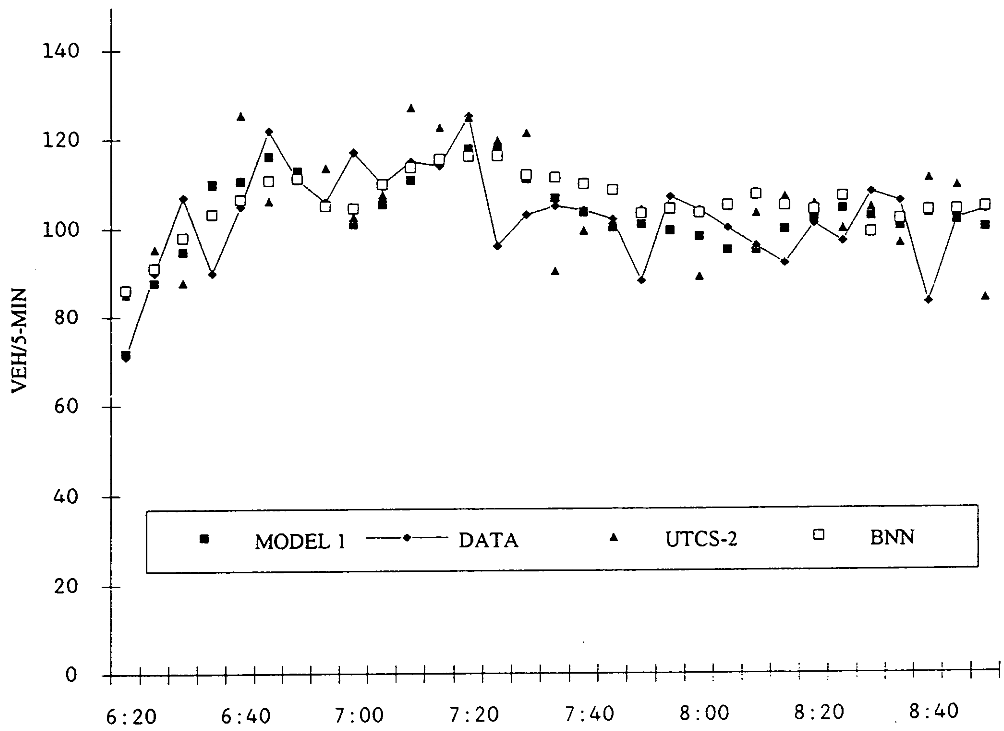


**FIGURE 2 Prediction results at 78NX2 ramp on November 19, 1989.**

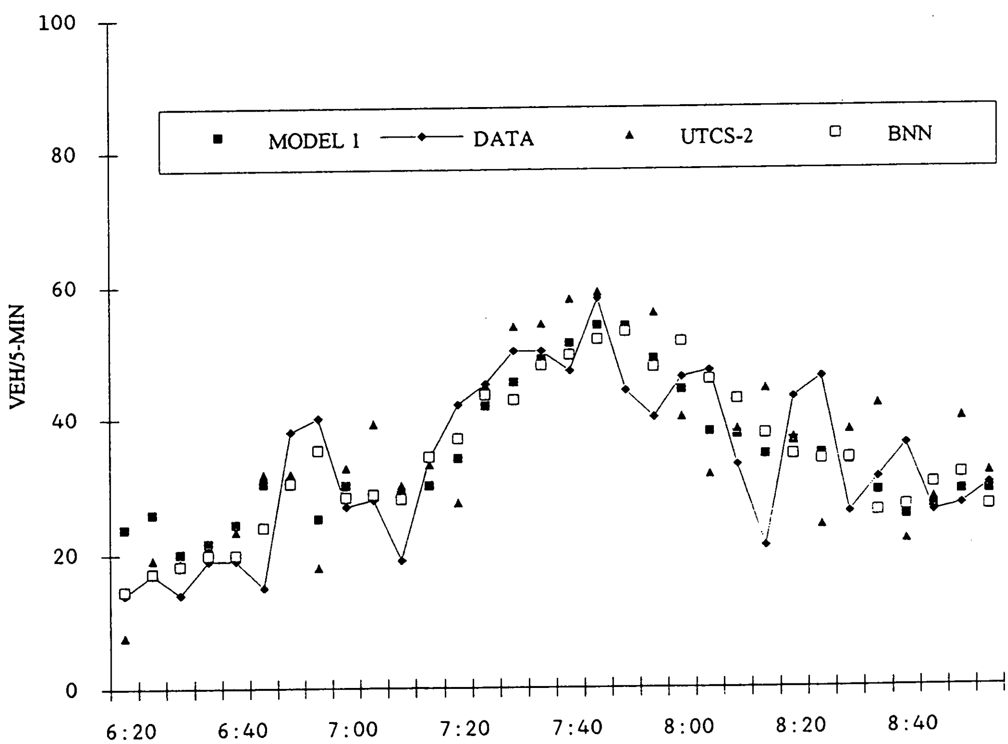


**FIGURE 3 Prediction results at 82NX ramp on November 20, 1989.**

TABLE 8 Predictor Error for Holidays with Model 2

| | Day 4 | | Day 5 | |
|---|---|---|---|---|
| | MAE | MSE | MAE | MSE |
| 78NX2 | 3.9 | 24.3 | 6.1 | 75.6 |
| 82NX | n/a | n/a | 5.1 | 28.2 |
| 66NX | n/a | n/a | 6.0 | 48.0 |

without historical data

be less adaptive to the demand fluctuation compared with the adaptive-parameter predictor.

The prediction results from 2 days over the Thanksgiving holiday with the second model of the adaptive-parameter predictor using only current-day measurements are summarized in Table 8; the table indicates an MAE range between 3.9 and 6.1 vehicles per 5 min. Figure 4 shows the prediction results with Model 2 for the 78NX2 ramp on November 23, 1989, a Thanksgiving holiday. In addition, Figure 5 shows the performance comparison between Models 1 and 2 for the 78NX2 ramp on November 19. As indicated, prediction with Model 2, without using historical data, tends to follow the measurements at the previous interval. This can cause a large amount of error when substantial fluctuations exist in traffic demand, as indicated in Figure 5. The prediction error for Models 1 and 2 of the adaptive-parameter predictor do not propagate through time, and this indicates the adaptability of prediction.

## DISCUSSION OF RESULTS

New freeway exit demand predictors are developed using two different prediction approaches: model-based adaptive-parameter and backpropagation neural network-based prediction. The adaptive-parameter predictor uses the data collected from only the exit ramp in question; the neural network-based predictor also uses the traffic measurements collected from other locations, including those upstream and downstream from the ramp. Prediction Model 1 and the BNN predictor use historical and current-day measurements, but the second adaptive prediction model is developed for the case in which no historical information is available. The new predictors are tested with real data from the I-35W freeway section, and their performance is compared with that of the UTCS-2 predictor. The error indexes from the two new predictors are very close and consistently better than those from the UTCS-2 predictor under the same conditions.

The adaptive-parameter prediction approach determines the parameters in the prediction models in real time using a Kalman filter with the most recent prediction error. In this approach, an appropriate functional form of the prediction model must be determined to relate the traffic measurements to the predicted traffic volume. Although the on-line parameter adaptation tries to minimize the prediction error, the accuracy of the prediction largely depends on how closely the selected model represents the actual traffic demand process. The models formulated in this research use only the volume data collected from the ramp in question,

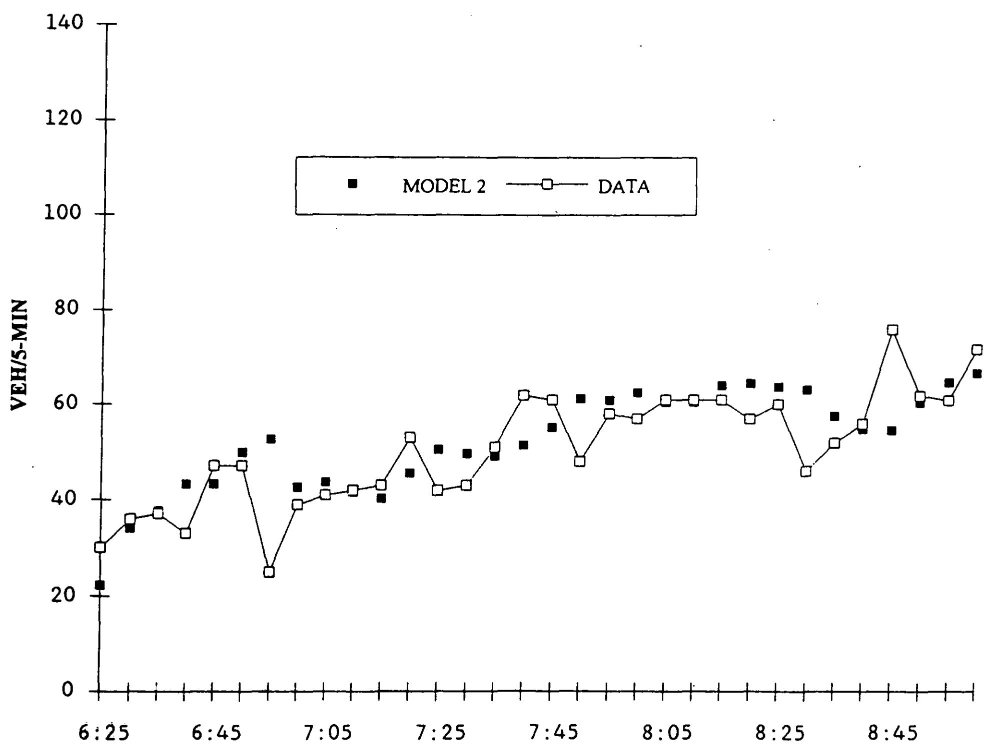


FIGURE 4 Prediction results at 78NX2 ramp on November 23, 1989.

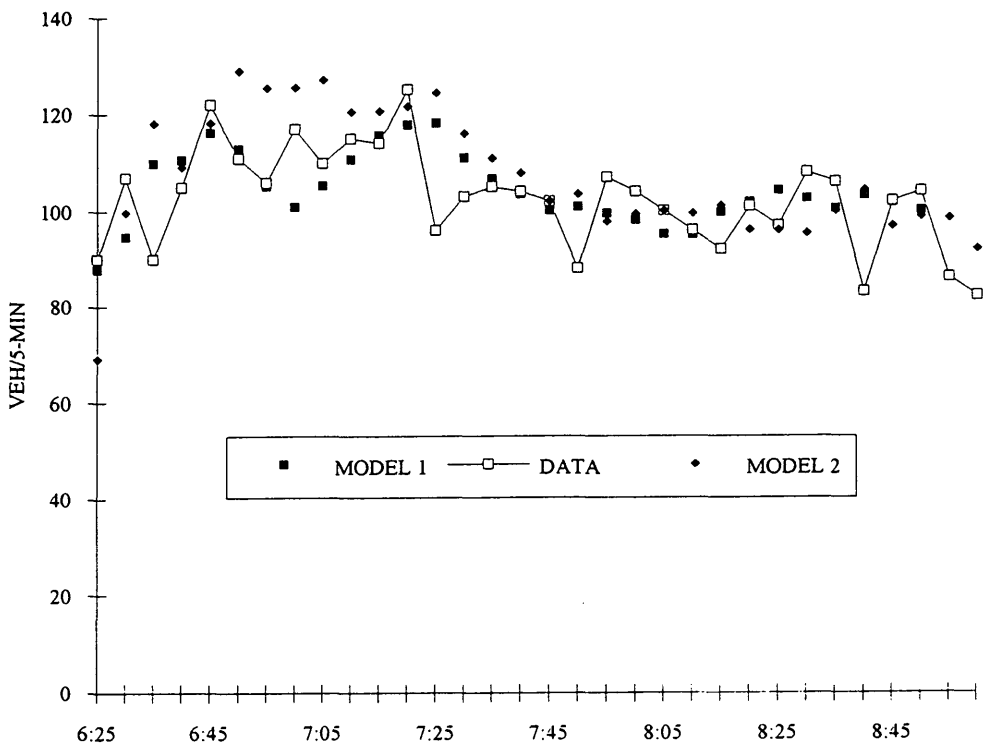


**FIGURE 5 Prediction results at 78NX2 ramp on November 19, 1989.**

and efforts to include additional information, such as upstream and downstream volume data, have not improved the prediction results significantly.

Unlike the model-based approach, the backpropagation neural network-based prediction does not require a predefined functional form for the given traffic demand process. However, the performance of the BNN predictor substantially depends on the network structure including the input-output specifications and the training method, that is, the values of the training parameters, such as learning rate and momentum. Although the selection of input and output values for a given network may be less difficult than the determination of an appropriate functional form for the adaptive-parameter approach, no robust theory is available that can determine the best training procedure for a given problem. The comparison of results from the limited testing conducted in this research indicate that, with the same amount of historical data, the BNN predictor requires less time and effort than the adaptive-parameter predictor and produces almost the same level of performance. However, prediction with the BNN tends to be less adaptive to demand fluctuations than prediction with the adaptive prediction approach because the BNN prediction error is not reflected in the prediction at the next interval unless the network is retrained with new data.

Current research seeks to combine the two approaches and to develop a comprehensive, hierarchical prediction algorithm that is more reliable and adaptive to the underlying traffic demand. In addition, research to develop new metering thresholds for ramp control reflecting the predicted exit demand volume is also ongoing. Finally, future phases of this research will address the need for developing optimal control algorithms that can determine metering rates on the basis of predicted demand.

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# Survey of Efforts To Evaluate Freeway Service Patrols

MICHELLE MORRIS AND WILSON LEE

Some program administrators believe that there is no need to evaluate their service patrol programs unless funding is threatened. However, all programs should be evaluated to some extent to ensure that resources are used optimally. Before conducting an evaluation, program administrators should ask specific policy questions and clearly link the study to these questions. Therefore, it is recommended that larger programs perform comprehensive evaluations in which appropriate measures of effectiveness directly correspond with policy questions. Appropriate measures of effectiveness include the following: public perception, safety benefits, operating statistics, congestion delay, air quality and energy consumption benefits, and benefit-cost ratios. Approximately 32 service patrol programs in the United States and Canada were surveyed and the nature of the programs and the means by which their administrators are evaluating them were analyzed. All programs are very popular with motorists. Most programs keep some form of operating statistics, and several have conducted comprehensive evaluations, with benefit-cost ratios ranging from 2:1 to 36:1. Several upcoming studies also are discussed. If studies to date are any indication, service patrols are cost-effective programs to reduce incident-related congestion. If additional evaluations in large areas produce positive results, it is recommended that FHWA initiate programs and provide guidelines and training for large metropolitan areas with extreme congestion. Finally, it is recommended that states or regions coordinate similar programs and include them as part of a larger incident management program.

Transportation engineers have attributed over 50 percent of all urban freeway congestion to traffic incidents (*1*). In recent years, transportation policy makers have placed greater emphasis on more innovative and low-cost transportation alternatives. With the emphasis of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) on making existing facilities more efficient, freeway service patrols, or roving tow truck programs, have become an increasingly popular approach. These vehicles are dedicated to quickly clearing incidents such as accidents and stalls to reduce congestion delays and keep traffic moving. Whereas Chicago's program has been operating since 1960, many new programs have been launched in the 1990s.

These programs are very popular with the motoring public. One motorist phoned the Metropolitan Transportation Commission (personal communication) to talk about the Freeway Service Patrol in the San Francisco Bay Area:

> I had blown a tire and was waiting on the phone about 15 seconds when one of your drivers. . .Bob, rolled up and changed my tire—he could not have been more professional or courteous. It was raining out there. He was working real close to the slow lane where the trucks are going by, and just did an outstanding job. (He) spoke to me about tires and safety, and had me back on the road in no time. . . . Again, excellent program; it's the best utilization of my tax dollars. . .and it keeps the freeways clear.

Metropolitan Transportation Commission, 101 Eighth Street, Oakland, Calif. 94607.

Public response is certainly one way to measure the effectiveness of service patrols. What other measures of effectiveness are transportation officials using to evaluate freeway service patrols? A survey of program administrators yielded varying answers: from counting the number of assists to conducting comprehensive studies calculating a benefit-cost ratio.

In the following section, measures of effectiveness used to evaluate freeway service patrols are discussed. Next, the results are presented of a telephone survey of most U.S. service patrols and one from Canada, which show the measures of effectiveness they use. Also reviewed are existing comprehensive evaluations of freeway service patrols and forthcoming studies. Finally, evaluation efforts to date are assessed and recommendations are made.

## MEASURES OF EFFECTIVENESS

There are a variety of ways to measure the effectiveness of service patrols, both quantitatively and qualitatively. Possible categories include public perception, safety benefits, selected operating statistics, congestion delay, air quality and energy consumption benefits, and benefit-cost ratios. The use of these measures was investigated in a survey and literature search of evaluation efforts. Motorists who are helped by service patrols often provide feedback to program managers in the form of phone calls, letters, or questionnaires, which are all indications of public perception. Many people support the service and its funding because they value the help they received or the security of knowing the service exists.

Motorists feel safer because trained tow truck drivers help them with car trouble and consequently save them from having to walk along the freeway to get help. Furthermore, when stalled vehicles are removed from the freeway quickly, other motorists may avoid secondary accidents. Many programs collect data, such as number and type of assists, and calculate statistics to evaluate their services. Location of service areas or hours of operation may be evaluated if other factors, such as time of assist, also are recorded.

Some programs use more sophisticated means of evaluating their services. For instance, a benefit-cost ratio may be calculated to determine whether a program is cost-effective. Benefits generally are calculated by determining the vehicle-hours of delay reduced by a service patrol multiplied by a particular dollar value of time. In his report, Finnegan (*2*) suggests other units of measure, as shown in Table 1.

## NATIONWIDE SURVEY OF SERVICE PATROL PROGRAMS

In June and July 1993, a telephone survey of service patrol administrators around the United States and Canada was conducted

**TABLE 1 Products and Units of Measure**

| Product | Unit of Measure |
|---|---|
| 1) Reduced peak period congestion | Hours of reduced delay<br>Dollar value of reduced delay<br>Increase peak period freeway speeds<br>Increase traffic volume |
| 2) Improved air quality and reduced fuel consumption | Pounds of reduced vehicle emissions<br>Gallons of reduced fuel consumption<br>Dollar value of reduced fuel consumption |
| 3) Reduced secondary accidents | Number of accidents avoided<br>Dollar value of avoided accidents |
| 4) Excellent service (i.e. reduced motorist anxiety, stress, and discomfort) | Distribution of responses to motorist survey questions<br>Motorist survey comments, letters, and phone calls |

to determine the nature of their programs and find out what they are doing to evaluate their programs. The operations portion of the survey was modeled after a survey by *The Urban Transportation Monitor (3)*. A total of 32 service patrol programs in the United States and Canada were identified. In addition to the 26 service patrol programs surveyed, California's six Freeway Service Patrol (FSP) programs were included.

The programs surveyed varied from a small, one-truck operation in Haywood County, North Carolina, to large operations such as the 51-vehicle ''Minutemen'' program in Chicago and the 138-tow truck FSP in Los Angeles. The survey was broken down into five sections. Operations information was requested first, such as the number of vehicles, hours of operation, and sponsorship. The second section asked about the cost of each program and its funding sources. The third section examined various operating statistics collected and how they were utilized, and the fourth section asked questions about public perception. Finally, evaluation efforts that had been completed or were in progress were surveyed. Specific information about service patrol programs with six or more vehicles is summarized in Table 2. Although all four programs in North Carolina are counted separately in the 32 total patrols, they are combined in Table 2. Surveyed programs with five or fewer vehicles include

- Golden Gate Bridge, San Francisco, California—four heavy tows;
- Howard Franklin Bridge Courtesy Patrol, Tampa/St. Petersburg, Florida—two heavy tows;
- Hoosier Helper, northeast Indiana—two pickups and three vans;
- Motorist Assist, St. Louis, Missouri—five pickups;
- Motorist Assist, Kansas City, Missouri—four pickups;
- Courtesy Patrol, New Jersey Turnpike, New Jersey—three vans;
- Pittsburgh, Pennsylvania—three regular tows;
- Courtesy Patrol, Fort Worth, Texas—two pickups and one sander/utility truck;
- Highway Helper, Seattle, Washington—1 van;
- Road Ranger, Seattle, Washington—three vans; and
- Emergency Patrol, Toronto, Ontario, Canada—three pickups.

The following sections describe some interesting key findings from the survey.

## Operations

In this survey it was discovered that there is a variety of ways to operate freeway service patrols. The sponsors and centerline kilometers patrolled are shown in Figure 1. With the exception of a few bridge patrols and units that respond only to major incidents, most vehicles patrol continuously. Communications systems, hours of operation, and type of vehicles vary by program. Some programs, such as the Chicago Minutemen, are able to handle almost any type of incident with their equipment; however, because of the expense of big rig tows, most programs operate regular tow trucks, pickup trucks, or vans. Since pickup trucks are less expensive to purchase and operate, over 50 percent of the programs have them in their vehicle fleet.

Communications systems were an important component of operations for all service patrols. All programs reported having a two-way radio communications system, and 19 programs also reported having cellular phones. The San Francisco Bay Area and Los Angeles FSPs also have automatic vehicle location (AVL) systems and mobile data terminals (MDTs)—small on-board computers—to assist with dispatch and data collection. Minneapolis and Houston are planning AVL systems. Indiana's Hoosier Helper also uses MDTs.

## Program Funding and Costs

The 32 service patrols vary greatly in the types of funding they receive, as shown in Table 2. Fifteen receive only state department of transportation (DOT) funds, and nine additional programs receive funding from their state DOTs as well as other sources, which may include federal ISTEA funds. For three patrols that operate on bridges and turnpikes, money comes from toll receipts. Three patrols are privately sponsored. Samaritania funds its patrols through corporate sponsors, and two radio stations in Seattle sponsor patrols. These sponsors advertise on the tow trucks. Finally, two programs are funded by other sources, including federal ISTEA funds. Most patrols do not charge motorists for the service; however, three programs charge for gasoline, and Washington State's Incident Response program bills the party at fault in major incidents.

**TABLE 2 Selected Service Patrol Survey Results**

| STATE | California | California | California | California | California | California | California | Colorado | Illinois |
|---|---|---|---|---|---|---|---|---|---|
| LOCATION | San Francisco Bay Area | Los Angeles | Riverside | San Diego | Orange County | Sacramento | Bay Bridges except Golden Gate Bridge | Denver | Chicago |
| PATROL NAME (Year Initiated) | Freeway Service Patrol (1992) | Freeway Service Patrol (1991) | Freeway Service Patrol (1993) | Freeway Service Patrol (1993) | Freeway Service Patrol (1992) | Freeway Service Patrol (1992) | none (1936) | Mile-High Courtesy Patrol (1992) | Emergency Traffic Patrol "Minutemen" (1960) |
| SPONSOR(S) | Caltrans, CHP, Metropolitan Transportation Commission SAFE | Caltrans, CHP, L.A. Co. Metro. Trans. Authority | Caltrans, CHP, Riverside Co. Transportation Commission | Caltrans, CHP, SANDAG | Caltrans, CHP, Orange Co. Trans. Authority | Caltrans, CHP, Sacramento Trans. Authority | Caltrans | Colorado DOT | Illinois DOT |
| PATROL PROVIDER | outside contractor | outside contractor | outside contractor | outside contractor | outside contractor | outside contractor | in-house | outside contr. & state patrol | in-house |
| CENTERLINE KILOMETERS PATROLLED | 177 | 568 | 34 | 39 | 77 | 43 | not available (n/a) | 43 | 127 |
| NO. OF VEHICLES | 36 tow trucks | 138 tow trucks | 8 tow trucks | 8 tow trucks | 12 tow trucks | 6 tow trucks | 13 heavy tows | 4 reg. tows, 2 pickups | 3 heavy tows, 36 reg. tow, 11 pickups, 1 car |
| TYPE OF PATROL | peak commute | peak commute | peak commute | peak commute | peak commute | peak commute | day & night | peak commute | day & night |
| ESTIMATED ANNUAL ASSISTS | 70,000 | 250,000 | 18,000 | 18,000 | 45,000 | 10,000 | 45,900 in 1992 | 12,000 | 100,000 |
| FUNDING SOURCE(S) | State FSP, MTC SAFE, ISTEA, Federal Construction Funds | State FSP, Local Sales Tax | State FSP, Local Match | State FSP, Local Match | State FSP, Local Match | State FSP, ISTEA, Local Match | Maintenance Budget and Tolls | Maintenance Budget and Federal Monies | Gasoline Taxes and DMV Fees |

## Data Collection

A total of 29 of the 32 programs surveyed collect operating statistics on the number of assists performed. Although it covers the entire state of Washington, the Incident Response program performed only 292 assists in 1992 because the team is on call to handle large incidents only. On the other hand, Chicago and Los Angeles handle over 100,000 incidents a year. Almost all patrol administrators collect data on the date, time, location, and vehicle problem. In addition, they usually collect data on the vehicle type, miles patrolled, and additional tows required. Because managers do not have common definitions for the data collected, it is difficult to compare data across programs. All patrols keep records in the form of daily drivers' logs; 16 patrols survey motorists with comment cards given after each assist.

The programs differ greatly in the intervals between reports, from weekly to annually. Although most programs collected data on a regular basis, they did not necessarily make reports on a regular basis. Nine of the patrols made reports as needed, and two programs had never prepared a status report.

## Public Perception

Program administrators gauge the public's perception through surveys, letters, and phone calls. Almost all programs receive feedback from the public, and an overwhelming majority of the responses have been positive and supportive. Many agencies believe that the service patrols are the best public relations activity they have. A comment from a pleased motorist said it all: "He came. He saw. He help[ed]." A total of 16 of the 32 programs survey motorists at the time of assist, and all programs have received numerous letters and phone calls. So far, no survey has been administered to obtain feedback from nonusers. Such a survey could be used to rally additional political support for programs.

## Other Evaluation Criteria

Several questions on the survey addressed other evaluation criteria for freeway service patrols. Of the 32 programs, only a few had calculated a benefit-cost ratio as shown in Table 3 (*4–8*). However, these ratios cannot be directly compared because the survey showed that administrators calculate program costs differently. For example, although all programs included operating costs, some did not include administrative costs. All benefits included a dollar value for reduced delay, but researchers valued time at different rates. Although other benefits may have been included in the ratios, reduced delay was always the most significant.

Many program administrators apparently see no need to have more comprehensive evaluation efforts. One administrator even said that the program does not need to justify its existence. "It would be like saying that you have to justify the need for snow plows during the winter." Another said, "We *know* we're doing a good job, no doubt about it." For other programs, the only stated purpose of evaluation was to justify funding for existing service or to examine the possibilities of expansion.

TABLE 2 *Continued*

| STATE | Minnesota | New Jersey | New York | North Carolina | Texas | Washington | Washington D.C. | Washington D.C. | 10 States |
|---|---|---|---|---|---|---|---|---|---|
| LOCATION | Minneapolis | New Jersey | New York City | Charlotte, Winston-Salem, Greensboro, Haywood County | Houston | Statewide | Washington D.C. & Baltimore | Washington D.C. | 11 Metropolitan Regions |
| PATROL NAME (Year Initiated) | Highway Helper (1987) | Emergency Service Patrol (1993) | Commuter Assistance Teams (1990) | Motorist Assistance Patrol (1992) | Motorist Assistance Program (1986) | Incident Response (1990) | Emergency Traffic Patrol (1989) | Safety Service Patrol (n/a) | Good Samaritan (1978) |
| SPONSOR(S) * Managing Organization | Minnesota DOT | New Jersey DOT | New York State DOT | North Carolina DOT | *TexDOT, Sheriff Dept., METRO, Car Dealers, Cell. Phone | Washington DOT | Maryland DOT | Virginia DOT | *Samaritania and Corporate Sponsors |
| PATROL PROVIDER | in-house | in-house | in-house | in-house | in-house & outside cont. | in-house | in-house | in-house | Samaritania, Inc. |
| CENTERLINE KILOMETERS PATROLLED | 113 | 39 | 97 | 293 | 225 | entire state | 644 | 1448 (includes highways and streets) | varies |
| NO. OF VEHICLES | 6 pickups | 8 vans & trucks | 6 pickups | 8 pickups | 9 vans | 9 pickups | 8 reg. tow, 6 vans on-call | 2 heavy tow, 2 regular tow, 14 pickups, 3 vans, 2 other | Number of vans varies by region |
| TYPE OF PATROL | all day | all day | peak commute | all day | all day | on-call | peak commute | all day | peak commute |
| ESTIMATED ANNUAL ASSISTS | 13,000 | not available | 4,200 | not available | 22,800 | 292 in 1992 | 17,000 | 40,000 | not available |
| FUNDING SOURCE(S) | Traffic Manage. Budget | ISTEA | Maint. Budget | Maintenance Budget, Federal construction funds, Gasoline tax | TexDOT, Sheriff Dept., METRO, Car Dealers, Cell. Phone | Maintenance Budget | Maint. Budget | Maintenance Budget (Gas Taxes) | Corporate Sponsors |

### Statewide Efforts To Evaluate FSPs

California and North Carolina have made an effort to coordinate their service patrol programs statewide, including evaluations. North Carolina coordinates four service areas and has plans for a statewide evaluation. California FSPs have formed a partnership that consists of the California Highway Patrol (CHP), the California Department of Transportation (Caltrans), and a local agency in each region to sponsor the service patrol. In the San Francisco Bay Area, the private tow contractors who provide the service are considered a fourth partner, with two tow representatives participating on the FSP technical advisory committee. In all six California FSP programs, the agencies sign a memorandum of understanding that outlines the duties of each agency, drawing on the strengths of each. Although each FSP is controlled and operated locally, all programs share information and ideas through a formal statewide committee and an informal network. In addition to the larger statewide committee, an evaluation committee and a funding allocation committee have been formed to address specific areas of the statewide program. Smaller programs benefit from evaluation studies conducted by the larger programs. The public benefits from this coordination by being able to access similar services throughout the state.

The California FSP Evaluation Committee was established in response to state legislation to prepare a comprehensive evaluation of the FSP program statewide. The committee coordinates the evaluation efforts of different areas, standardizes data collection statewide, and plans to extrapolate the results of local studies to the entire state.

## COMPREHENSIVE EVALUATION STUDIES

Several programs already have completed comprehensive evaluation studies: the Emergency Traffic Patrol in Chicago, FSP in Los Angeles, the service patrols in Seattle during the 1990 Goodwill Games, the Mile-High Courtesy Patrol in Denver, various patrols in Houston, and the Motorist Assistance Patrol in Charlotte, North Carolina. These studies are summarized below.

### Emergency Traffic Patrol in Chicago

Begun in April 1960, Chicago's Emergency Traffic Patrol—better known as the Minutemen—has grown to a fleet of 51 vehicles, including 39 heavy and light tow trucks, 11 pickups, and a supervisor's car. In addition to the Emergency Traffic Patrol's major incident response team and roving patrol, Chicago has established a freeway traffic management program that includes the Traffic Information Program, with 1,800 loop detectors on over 160 km (100 mi) of highway, and the Traffic Systems Center, which feeds traffic and incident information to the media (*5*).

In October 1990, Cambridge Systematics completed a study for the Trucking Research Institute on the incident management programs (*5*). This evaluation determined that the entire Chicago Freeway Traffic Management Program, including the Emergency Traffic Patrol, had a benefit-cost ratio of 17:1. The program costs were composed of capital, operations, maintenance, labor, and overhead totaling $5,549,290 (1990 dollars) annually. Benefits were estimated using models developed by FHWA (*9*) to calculate

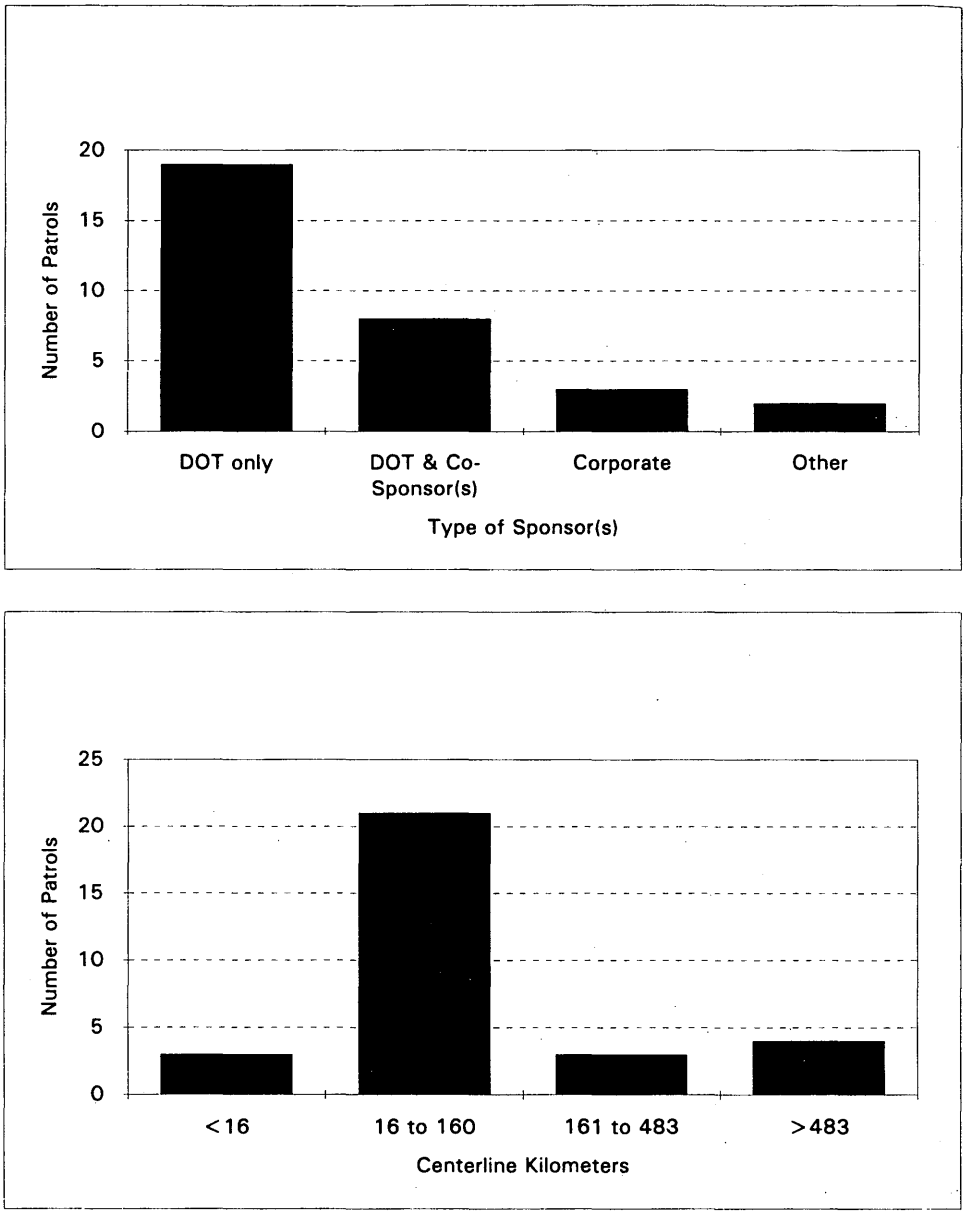


**FIGURE 1 Service patrol operations: (*top*) service patrol sponsors; (*bottom*) centerline miles patrolled.**

**TABLE 3 Benefit-Cost Ratios**

| Location | Program | Benefit-Cost Ratio | Year |
|---|---|---|---|
| Charlotte, NC *(4)* | Motorist Assistance Patrol | 7.6:1 | 1993 |
| Chicago *(5)* | Emergency Traffic Patrol | 17:1 | 1990 |
| Denver *(6)* | Mile-High Courtesy Patrol | 13.5:1 to 18.4:1 | 1993 |
| Houston | Motorist Assistance Program | 19:1 | 1993 |
| Houston *(7)* | Motorist Assistance Program | 7:1 to 36:1 | 1991 |
| Houston *(8)* | Freeway Courtesy Patrols | 2:1 | 1973 |

vehicle-hours of delay before and after implementing the program. This delay was translated to travel time savings with time valued at $10/person-hr. A second benefit-cost ratio of 11:1 was calculated for an alternative ''partial incident management'' program (i.e., a major incident response team only, on-call for large incidents and hazardous materials). Inputs to the model included type and duration of incidents with and without the program. The Cambridge Systematics study stated that the effectiveness of Chicago's program is based on years of personal relationships within agencies involved in incident management and recommended establishing institutional agreements through an ''integrated regional incident management program'' (*5*).

### Freeway Service Patrol Evaluation in Los Angeles

In June 1992, Finnegan of the Los Angeles County Metropolitan Transportation Authority (MTA) completed a study of freeway service patrol assists in Los Angeles (*2*). At the time of the study, MTA contracted with private tow operators for 88 tow trucks to patrol 346 km (215 mi) of freeway in Los Angeles during the peak periods. This program, a joint project of MTA, CHP, and Caltrans, began operating in July 1991 (*2*).

Finnegan evaluated the program's economic impact (137 new jobs), compiled the results of motorist surveys (92 percent rate the service as excellent; 7 percent, good), and calculated statistics on operations. By May 1992, over 130,000 motorists had been assisted, and FSP was performing over 700 assists per day at a cost of $43 each.

In addition, he developed the FSP Assist Model to help public officials make optimum use of the resources available. This model uses miles of freeway, accident rates, and average annual daily traffic to estimate FSP assists. The model accounts for 54 percent of the variance in total daily assists between different freeway segments. On the basis of the concepts of a deterministic queuing model used to quantify congestion for incidents, he concluded that public officials could improve cost-effectiveness by maximizing the number of assists and reducing the incident response times (*2*).

### Service Patrols in Seattle and Tacoma at 1990 Goodwill Games

In 1990, the Washington Tow Truck Operators Association provided six tow truck patrols for two weeks in Tacoma, Washington, during the Goodwill Games. Washington State Patrol (WSP) officers in six specially equipped jeeps also provided service in Seattle. In March 1991, Mannering and Hallenbeck of the Washington State Transportation Center published a report for the Washington State Department of Transportation (WSDOT) describing the impacts of these 12 service patrol vehicles (*10*).

Data were collected from the WSP computer-aided dispatch system that consisted of incident report forms completed for each assist and a survey of motorists who returned a prepaid postage card to WSDOT. Researchers compared data before and during the Goodwill Games to determine changes brought about by the congestion mitigation efforts. This study found a decrease in incident duration within the study area, with service patrols reaching incidents an average of over 5 minutes sooner than regular tow service. Although the study did not compute a benefit-cost ratio or decrease in vehicle delay, the researchers concluded that if the service patrols decreased the time for incident detection, initial response, and (in many cases) incident clearance as measured in the study, they did improve traffic performance. Additionally, motorists like the service (*10*).

### Courtesy Patrol Pilot Program in Denver

The Mile-High Courtesy Patrol in the Denver metropolitan region was implemented on a pilot basis from September 1992 through February 1993 and remains operational. An agreement between Colorado DOT and the Colorado State Patrol was formed to provide the patrol. Local contractors of the American Automobile Association (AAA) are under contract to provide the tow service. Covering 43 centerline km (27 mi) of freeway, AAA operates four tow trucks and Colorado State Patrol officers run two 4-wheel-drive vehicles.

Cuciti and Janson of the University of Colorado at Denver performed a comprehensive evaluation in June 1993 for the Colorado DOT (*6*). Four objectives of the study were to (*a*) collect data on assists, (*b*) evaluate public perception of the patrols, (*c*) calculate a benefit-cost ratio, and (*d*) determine which type of patrol was more effective, AAA or state patrol (*6*).

To gather information on public perception, every motorist was given a comment card after being assisted. A total of 99 percent of the 550 motorists who returned comment cards said the service was a good use of their tax dollars. Many motorists acknowledged the benefits of better traffic flow, less congestion, and good public relations for law enforcement and other government agencies.

In addition, Cuciti and Janson calculated a benefit-cost ratio by examining a segment of Interstate 25 before and after the Mile-High Courtesy Patrol began service. They used a deterministic queuing model to estimate vehicle delay involving four phases (detection, response, service, and queue dissipation). By varying the reduced capacity assumed when an incident blocked traffic lanes, they found that the courtesy patrol reduced, on average, 78 to 98 vehicle-hr of delay per incident in the morning peak period and 71 to 75 vehicle-hr in the afternoon peak.

They valued travel time savings at $10/vehicle-hr and estimated the total program costs to be between $110,000 and $130,000 in the 6-month evaluation period. A 6-month travel time savings was estimated to be $1.8 million to $2 million. Using the information above, Cuciti and Janson calculated a benefit-cost ratio of 13.5 to 18.4:1 for the range of program costs and delay per incident. Their evaluation recommended establishing a permanent program, extending the operating hours, and patrolling areas with narrow or nonexistent shoulders. They did not determine which service mode was more effective—state patrol or AAA—because there were advantages and disadvantages in each (*6*).

### Motorist Assistance Program in Houston, Texas

Houston's Motorist Assistance Program (MAP) began in 1986 as a joint project between the Harris County Sheriff's Department and the Houston Automobile Dealers' Association. Now the program includes three more sponsors: Texas DOT, Metropolitan Transit Authority of Harris County (METRO), and Houston Cellular Telephone. The current program has nine vans operated by Harris County sheriff deputies patrolling 225 km (140 mi) of freeway.

Texas Transportation Institute prepared an annual report for Texas DOT and METRO for Houston's MAP in 1991. From August 1, 1989, to July 31, 1991, MAP performed more than 24,000 assists (*7*). Researchers estimated the benefits of a reduction in vehicle-hours of delay by using methods developed by FHWA (*11*). They calculated delay for lane and shoulder incidents for seven routes with and without MAP. For the average duration of an incident without MAP, they used an upper-limit assumption of a 20-min reduction as a result of MAP (*12*). They calculated 3,102,576 vehicle-hr saved, resulting in $38 million saved by motorists, and assumed a value of time at $12/vehicle-hr. A conservative 5-min reduction per incident would result in a reduction of 607,392 in vehicle-hr of delay, equating $7.4 million. Costs included labor salaries, benefits, and vehicle costs, yielding an average cost of $85.67 per incident. The benefit-cost ratio was estimated to be between 7:1 and 36:1, depending on average response times used. In addition to the benefit-cost ratio, the study addresses the importance of public acceptance. With 12 representative examples of public appreciation letters attached to the report, it shows that the MAP program is well liked by the motoring public (*7*).

### MAP in Freeway Reconstruction Area in Houston

Texas Transportation Institute recently completed a study for Texas DOT to evaluate MAP on the Southwest Freeway (U.S. Highway 59) in Houston, Texas. Conducted by Paul Hawkins with William McCasland as the principal investigator (unpublished data), the study evaluated the impact of using two MAP vans on the Southwest Freeway versus having no MAP service. The study was conducted from August 1991 to July 1992 during a period of heavy reconstruction on the freeway that eliminated most shoulders, with MAP vans patrolling from 6:00 a.m. to 10:00 p.m.

To evaluate the service, Hawkins used computer model FREQ10 to simulate traffic on the freeway, modeling incidents by reducing the freeway capacity. He simulated incidents with one lane blocked and incidents on shoulders and calculated the difference in delay with and without MAP. He found that depending on the location, removing some incidents actually increased delay during certain periods because the incidents acted as a meter, increasing the efficiency of the freeway. However, for the approximately three-quarters of the 17 incidents modeled, MAP reduced the delay experienced by motorists.

Taking all 17 case studies into account, the vans demonstrated a 19:1 benefit-cost ratio. A total cost of $196,483 was calculated, including equipment, drivers, and Texas DOT administrative costs. Total benefits of $3,700,000 included a small cost savings to assisted motorists who did not have to pay for additional help and the larger cost savings of reduced delay to other motorists on the freeway. The majority of the savings came from clearing incidents that blocked one lane of the freeway. Although this study showed significant benefits from MAP, Hawkins recommended that each candidate freeway for a service patrol be investigated separately because factors that affect the benefits, such as traffic volumes and accident rates, vary in different areas.

### Service Patrols in Houston in Early 1970s

One of the earliest studies on service patrols was completed in 1974 for the Texas Highway Department by Fambro of the Texas Transportation Institute (*8*). In 1973, the Texas Highway Department (now Texas DOT) provided courtesy patrols consisting of tow pickup trucks in Houston. Although Fambro calculated a benefit-cost ratio of 2:1 and recommended that the program continue, service was later discontinued until MAP began patrolling in 1986 (*8*).

### Motorist Assistance Patrol in Charlotte, North Carolina

In 1993, Mooney of FHWA and Kirk with the North Carolina Department of Transportation (NCDOT) performed an evaluation of the Motorist Assistance Patrol in Charlotte, North Carolina, for NCDOT (*4*). This study evaluated the service of three pickup trucks, which performed a total of 12,600 assists a year. They calculated a benefit-cost ratio of 7.6:1 on the basis of the reduction in vehicle-hours of delay calculated using FREWAY3, a computer model developed by FHWA (*4*).

## UPCOMING STUDIES

In addition to these existing studies, several other efforts are under way to determine the effectiveness of service patrols. These studies include one on the FSP in the San Francisco Bay Area, an FHWA study on incident detection issues, and one on the Highway Helper program in Minneapolis.

### FSP in the San Francisco Bay Area

During 1993 in the San Francisco Bay Area, the FSP had 29 roving tow trucks patrolling 177 centerline km (110 mi) of freeway during peak commute hours. This program is jointly sponsored by the Metropolitan Transportation Commission Service Authority for Freeways and Expressways (MTC SAFE), CHP, and Caltrans. Private tow companies provide the service under contract with MTC SAFE. Caltrans has contracted with Partners for Advanced Transit and Highways (PATH), with Haitham Al-Deek of the University of Central Florida at Orlando and Pravin Varayia of the University of California at Berkeley as principal investigators, to conduct an evaluation of the program.

The purpose of this study is to evaluate the effectiveness of FSP in reducing incident congestion by developing a benefit-cost ratio. The benefits will be calculated as the cost savings of vehicle-hours of delay, and costs will include tow contractor and agency administrative costs. The researchers will quantify other benefits such as reduction in air pollutants and fuel use, but these factors will not be included in the benefit-cost ratio.

To collect data, students drove in five specially equipped cars on an 11.8-km (7.3-mi) stretch of Interstate 880 freeway. They collected data during the morning and afternoon commute hours for 5 weeks before and after FSP service was added in 1993. These researchers have collected one of the most comprehensive data sets, which includes the following:

1. Incident data from direct observation, the CHP computer-aided dispatch system, AAA dispatch logs, and tow companies operating on the freeway segment. Over 1,200 incidents were observed in the pre-FSP data collection.

2. Loop detector data from 340 mainline, 16 off-ramp, and 57 on-ramp loops.
3. Tach vehicle data from five tach cars, including global positioning system data.
4. Truck weigh station data. Two stations, one in each direction of I-880, provided truck counts and weights at different times of the day.

PATH researchers plan to write a computer program to calculate the cumulative recurring and nonrecurring congestion for each incident on the basis of a deterministic queuing model. They also will sort incidents into broad categories, and average characteristics will be calculated for each category for both the before and after data. If, on average, the incident duration decreases with FSP, congestion delay will most likely decrease. MTA in Los Angeles is planning a similar study. Caltrans plans to include the study results in a statewide FSP evaluation report with policy recommendations to be released in December 1994.

### FHWA Study on Incident Detection Issues

FHWA has contracted with Ball Systems Engineering Division, with Pete Payne as principal investigator, to conduct a study of incident detection issues (unpublished data). The team consists of researchers at California Polytechnic State University (Cal Poly) at San Luis Obispo led by Ed Sullivan; the University of Maryland, under the direction of Gang-Len Chang; and the University of California at Irvine with Stephen G. Ritchie. The study will develop and test a new generation of incident detection algorithms for use in the nation's freeway traffic management centers. An additional goal of the study is to develop a tool, supported by Cal Poly, that would allow users to analyze the impacts of incidents on freeways. The team plans to use data from federal sources (Highway Performance Monitoring System), state accident data bases, FSP in the San Francisco Bay Area, and the PATH study mentioned earlier to develop and verify the model.

This tool will be a personal computer program that will allow the user to try different scenarios at a specific site. It will predict the frequency of incidents by type and the expected duration of each type. It also might be used to model the effects of the freeway service patrols by varying the response time to incidents. Thus, planners may use results to determine where it would be cost-effective to implement service patrols. The impact analysis tool is scheduled to be available by the end of 1994, and the incident detection algorithm work will continue through 1997 (Payne, unpublished data).

### Highway Helper in Minneapolis

In Minneapolis, Sue Groth and Glen Carlson with the Traffic Management Center of Minnesota DOT are evaluating the Highway Helper program, which uses six pickup trucks operating all day on weekdays. They plan to assess the benefits of time savings and calculate a benefit-cost ratio, This study was to be completed by the spring of 1994 (unpublished data).

## ASSESSMENT OF EVALUATION EFFORTS

In assessing the evaluation efforts of service patrol program administrators throughout the country, appropriate measures of effectiveness are noted, comprehensive versus limited studies are considered, program and evaluation goals are examined, and an attempt is made to not generalize the results. On the basis of this survey and existing evaluation studies, appropriate measures of effectiveness include public perception, safety benefits, selected operating statistics, congestion delay, air quality and energy consumption benefits, and benefit-cost ratios. The survey results show the extent to which program administrators use these measures of effectiveness. Because service patrol programs are so popular, public perception is the easiest criterion to measure. Most program administrators receive letters and phone calls praising their programs. The second most common form of evaluation is selected operating statistics. Although most program administrators collect data on assists, it is not clear whether their statistics are used to evaluate existing service or merely to count the number of assists performed. Many programs do not regularly prepare reports using their statistics. Measuring safety benefits, congestion delay, fuel consumption, and air quality impacts is more difficult and requires costly data collection.

This difficulty is exhibited in the studies mentioned. In the Chicago study, which includes the entire incident management program, it is difficult to isolate the effects of the service patrols. Other methods, such as Los Angeles' regression model, are not able to account for all variables affecting FSP service. Also, this model relates only to a specific area and could not be applied to service patrols in other cities. In several studies, researchers make assumptions about critical variables such as response and clearance time at an incident because these variables are difficult to measure. Methods using models must be carefully calibrated, which often requires extensive data collection. Nevertheless, models used to calculate delay caused by incidents are evolving, as shown by the PATH study in the San Francisco Bay Area. In addition to improving methodologies, administrators should evaluate service patrols against other options to manage incidents and improve traffic performance.

The evaluation of service patrol programs ranges from limited to comprehensive. The scope of the evaluation should depend on the size and cost of the program, the goals of administrators, and policy questions administrators need to answer. Although all program administrators should evaluate their programs to some extent, more comprehensive evaluations only for larger programs are recommended; this can justify the expense of more costly evaluations as a way to ensure that resources are being allocated efficiently.

Various transportation officials have different goals and needs for evaluating service patrols. Goals include ensuring continued funding, adequate resources, and sufficient personnel. Many of the DOT programs are a part of their regular maintenance operations, and program administrators may feel no need to evaluate the service patrols unless funding is threatened. Politicians authorizing funding for the programs may be interested in quantified benefits as well as public perception. This may apply to other program administrators as well. According to McDade, evidence of the value of the service patrols to the operating and sponsoring agencies has been seen in the form of hundreds and thousands of letters, cards, and notes of appreciation from those who are served every year (*14*).

In California, where each FSP is run by a partnership of the state DOT, the highway patrol, and the metropolitan planning organization (MPO), individual agencies may have different evaluation needs. Needing to justify the funds spent for the project on the basis of its goals of reducing congestion, the MPO may require a more comprehensive evaluation. However, program administrators in an MPO also must balance paying for an evaluation versus putting additional trucks on the road. The evaluation needs of all three agencies are balanced through the California statewide evaluation committee. Agencies around the state join efforts, eliminating extra costs.

Finally, program evaluators must be careful not to apply the results of evaluations to other areas or programs that are not appropriate. Some measures of effectiveness are dependent on specific factors, such as freeway geometry, traffic volume, and the effectiveness of incident detection and response, and should not be generally applied.

## CONCLUSIONS

On the basis of these assessments of evaluation efforts of service patrol programs, several conclusions are drawn and recommendations are made. Before conducting an evaluation, program administrators should ask specific policy questions and clearly link the study to these questions. To optimize current resources, existing areas of service and hours of operation should be evaluated. The policy questions also should correspond directly to the measures of effectiveness chosen. For example, if congestion relief and improvement in air quality are goals of the program, vehicle-hours of delay and air quality impacts should be studied. Traffic conditions also change over time, and evaluation plans should provide regular monitoring on some level.

There are definitely advantages to coordinating with other agencies and programs and being part of a larger incident management program. The partnership arrangement used in California's FSP programs provides the institutional structure for agencies to cooperate and draw from the strengths of each. Statewide committees in California allow similar programs to combine resources and focus on specific goals, such as evaluating the programs and maintaining adequate funding. In the case of Chicago, where service patrols are the most visible part of a larger incident management program, a positive evaluation can create a constituency for the entire program (*13*).

If studies to date are any indication, service patrols are cost-effective programs to better utilize existing freeways and reduce incident-related congestion. The largest service patrol programs are located in the Chicago; Washington, D.C.; San Francisco; and Los Angeles areas. If evaluation results in these large areas show that they are meeting these goals, as the Chicago program has, it is recommended that FHWA initiate programs and provide guidelines and training for large metropolitan areas with extreme traffic congestion.

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# Emergency Parking Areas Along Restriped Urban Freeways

JAMES H. BANKS

Research related to the design of emergency parking areas along restriped urban freeways is documented. Several issues involved in designing such facilities are discussed; performance of existing emergency parking areas on the Santa Ana Freeway in Los Angeles County is documented; and dimensions for emergency parking areas based on the use of normal freeway shoulders are recommended. Extensive videotaping of the existing emergency parking areas revealed that they are little used, probably because they are too small and inconspicuous. Meanwhile, an analysis of accident records provided no evidence of safety problems associated with them or with the lack of normal shoulders on the freeway section in question; however, because of the lack of use of the parking areas, this does not necessarily indicate that the existing dimensions are adequate. The amount of space involved in use of normal shoulders was found to be widely variable; however, emergency parking areas with total lengths of 190 to 240 m should accommodate a majority of the maneuvers observed.

Increasing traffic congestion on urban freeways has led to use of a number of low-cost measures intended to increase capacity. One such measure is to restripe the freeway to convert shoulder areas to traveled way. This concept has been addressed by McCasland (*1*) and Urbanik and Bonillo (*2*) and is the subject of ongoing research funded by NCHRP. This concept has yet to be accepted as desirable and is used only in extreme circumstances; nevertheless, its use is increasing.

Restriping raises important safety and operational issues. This is especially true when it involves use of the right shoulder because it leaves no room for disabled vehicles to pull off the road. One possible solution is to provide emergency parking areas at intervals along restriped freeways. These provide limited capability to remove disabled vehicles without the cost or other impacts of a full-scale widening project.

To date, emergency parking areas have been provided in only a few cases and there is no guidance as to their proper geometric design or optimum spacing. The purpose of the research described in this paper was to document the performance of six existing emergency parking areas located on the northbound Santa Ana Freeway (Interstate 5) in the La Mirada–Santa Fe Springs areas southeast of Los Angeles and to develop information that will provide a rational basis for the design of such facilities.

## PERFORMANCE OF EXISTING EMERGENCY PARKING AREAS

Very few emergency parking areas have been constructed to date. In addition to those on the Santa Ana Freeway, several have been constructed alongside Interstate 66 in northern Virginia; however, no published information on the performance of the Virginia facilities could be found. Because the six parking areas on the Santa Ana Freeway could be studied conveniently, it was decided to confine the study of existing emergency parking areas to them.

At the outset it was expected that experience with these existing parking areas would provide considerable insight into the proper design of such facilities. Particular questions were how extensively they were used, whether drivers using them were experiencing obvious difficulties in entering or exiting them, and whether there was evidence of an unusual incidence of accidents involving them.

Answers to these questions were sought by means of extensive video surveillance of the parking areas, an analysis of accident records, and a survey of the professional opinions of California Department of Transportation (Caltrans) maintenance workers and California Highway Patrol (CHP) officers familiar with them.

### Usage

Approximately 87 hr of videotaping was carried out over 44 days between June 29 and August 28, 1992, at three of the six existing emergency parking areas on the Santa Ana Freeway for which vantage points were available. These sites are located in a section for which the right shoulder has been restriped to provide an auxiliary lane between interchanges and are intended primarily to provide parking at emergency call boxes. Their dimensions are documented in Figure 1. In all cases, videotaping was carried out during the morning peak period, between 6:30 a.m. and 8:30 a.m. Only one case of use of an emergency parking area was observed. From this experience, it was concluded that usage of the parking areas is quite low, probably because they are rather inconspicuous.

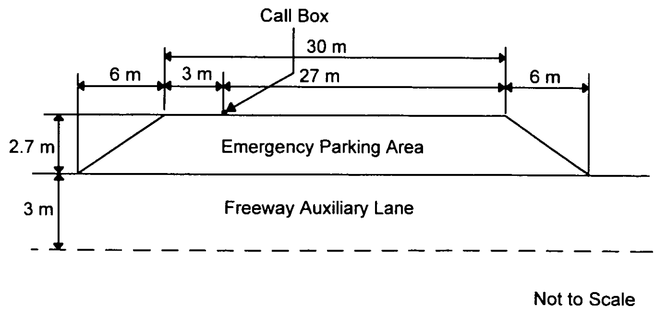


**FIGURE 1 Dimensions of existing emergency parking areas on the Santa Ana Freeway.**

Civil Engineering Department, San Diego State University, San Diego, Calif. 92182-0189.

### Accident Experience

Accident records contained in the Traffic Accident Surveillance and Analysis System (TASAS) data base were examined to determine whether there were obvious safety problems associated with the operation of the emergency parking areas or evidence of accidents involving disabled vehicles that were unable to reach a parking area. TASAS reports for the period January 1 through December 31, 1991, were examined for a 5.6-km section of the northbound Santa Ana Freeway containing the existing emergency parking areas.

All accidents within a distance of 0.08 km of the midpoint of an emergency parking area were examined in detail. In no case was there any indication that use of an emergency parking area was involved in an accident. This is not surprising, given the low level of usage, and certainly should not be interpreted as evidence that the design of the existing emergency parking areas is adequate.

In addition, TASAS reports were scanned to identify all accidents in the section involving stopped vehicles. It was found that 24.5 percent of the accidents did involve stopped vehicles. Comparison with the percentages of stopped-vehicle accidents occurring in the southbound lanes of the same section of the Santa Ana Freeway, which has a normal shoulder, indicated that this rate of stopped-vehicle accidents was not unusual. Once again, however, sample sizes are far too small to support general conclusions.

### Experience of Maintenance and Law Enforcement Personnel

Expert opinion concerning the existing emergency parking areas was sought through a written survey of Caltrans maintenance personnel and CHP officers familiar with them. Respondents were asked whether the emergency parking areas were useful to them in their work, who else used them and for what purposes, whether there were any safety or operational problems associated with the current design of the parking areas, and how their design could be improved. It had originally been intended to survey 12 to 15 individuals from each organization; however, after contacts with supervisory personnel, it became apparent that very few people were familiar with the existing parking areas. In the end, questionnaires were distributed to six Caltrans maintenance employees and one CHP officer. Surveys were returned by the CHP officer and five of the six maintenance employees; however, only four of the questionnaires returned by maintenance employees were usable.

Respondents indicated that the emergency parking areas were useful to them in their work. The CHP uses them for traffic stops and to remove disabled vehicles and vehicles involved in accidents from the traffic lanes. Caltrans maintenance employees use them to set up signs, remove litter, repair water systems, prune and load landscape cuttings and debris, and set lane closures. Maintenance employees further reported that in restriped sections that lack emergency parking areas, they are required to set up lane closures for even such routine maintenance activities as litter removal. In addition, respondents reported that the emergency parking areas were used by motorists for emergency repairs and various types of discretionary stops.

Several maintenance personnel reported that the emergency parking areas were too short for them to reenter the freeway safely and that in some cases they were too short to accommodate both disabled vehicles and tow trucks. Also, the maintenance employees stressed that normal shoulders should be retained wherever possible, stating that emergency parking areas are not adequate replacements for normal shoulders for many of their activities.

## DESIGN OF EMERGENCY PARKING AREAS

### Issues

Major issues in the design of emergency parking areas are their spacing and dimensions (lengths, widths, and tapers). The cost of emergency parking areas and their impact on the restriped freeway depend on both their dimensions and spacing. Their safety and operational efficiency depend largely on their dimensions.

Emergency parking areas are intended to serve as partial substitutes for normal shoulders, many of whose functions can be performed by relatively small, widely-spaced parking areas. Maintenance activities, non-vehicle–related emergency stops, repair of nondisabled vehicles, and stops of traffic violators all involve some discretion on the part of the driver as to where they take place. Many such stops can be accomplished by exiting the freeway altogether. On the other hand, total disablement of vehicles and accidents occur at random locations and often involve considerable difficulties in moving vehicles. In these cases, emergency parking areas are of value only if they are in the immediate vicinity of the incident.

Optimum spacing of emergency parking areas, unless dictated by some other consideration such as emergency call box spacing policies (as might be the case in California urban areas) depends on the size of the parking area and the desired tradeoff between cost and the probability that the parking area is available in the case of a nondiscretionary stop. This probability is roughly the fraction of the roadside occupied by parking areas, which can easily be computed for any given set of parking area dimensions and spacings.

Appropriate dimensions for emergency parking areas depend on vehicle dimensions and the behavior of drivers exiting and entering them. Widths are primarily dependent on vehicle dimensions and should be adequate to accommodate all vehicles of legal width. The legal width of the largest trucks is 2.6 m. On the basis of this measurement, a minimum width of 3 m, similar to the existing California standard for normal freeway shoulders, is desirable for emergency parking areas.

Required lengths and taper angles are less obvious. The overall maneuver involved in pulling into an emergency parking area and subsequently returning to the freeway includes the following stages:

1. Deceleration in the right lane of the freeway;
2. Diverging onto the emergency parking area;
3. Deceleration within the parking area to a stop;
4. Acceleration within the parking area from a stop;
5. Merging into the right lane of the freeway; and
6. Acceleration in the right lane of the freeway.

Stages 2 through 5 correspond to the design elements of the parking area; Stages 2 and 5 correspond to the tapers at the upstream and downstream ends; and the total of Stages 3 and 4 correspond to the length of its full-width portion.

### Use of Normal Freeway Shoulders

Distances required for each of these stages are best determined by observing actual driver behavior. Because the study of the existing emergency parking areas on the Santa Ana Freeway provided almost no insight into the use of these facilities, it was necessary to rely on a study of use of normal freeway shoulders. This involved analysis of videotapes from several previous freeway studies to determine the distances involved. As these videotapes were originally produced for other purposes, they were not always ideal for studying shoulder use; nevertheless, it was possible to identify about 20 cases for which the distances involved in stopping, starting, or both, could be determined.

Two methods were used to measure distances from these tapes. The first involved deriving a relationship between distances measured on the screen and those on the ground (*3*). As it turned out, this method could be used at only one site. The other method was to mark the beginning and end of the vehicle maneuver on the video screen and make measurements of the times it took several vehicles to cover this distance. If traffic was free flowing, average speeds were assumed to be in the range of 85 to 100 km/hr, and the distance was computed using an assumed average speed. Neither of these methods is very accurate. This was not very important, however, because the distances involved in shoulder-related vehicle maneuvers varied widely, and only an approximate idea of them was needed.

Where possible, four separate distances were measured. These included the diverge, defined as the distance covered between the times that the right front and left rear wheels left the traveled way; the deceleration distance on the shoulder; the acceleration distance on the shoulder; and the merge, defined as the distance covered between the times the left front and right rear wheels entered the traveled way. In some cases it was not possible to distinguish between diverging and deceleration on the shoulder or between acceleration on the shoulder and merging, and in these cases the total stopping or starting distance was measured. In other cases, it was possible to measure either the stopping distance or the starting distance, but not both.

Figures 2 through 6 present cumulative distribution curves for these measurements. From these one can see that the distributions of total stopping distance, total starting distance, and total distance used are relatively uniform. That is, there is in each case a break point indicating the tail region of the distribution, but below this break point the cumulative distribution curve is nearly a straight line, indicating that all distances are equally likely. Breakpoints are about 120 m for total stopping distance, 180 m for total starting distance, and 240 m for total shoulder distance used. The breakpoint for total distance used is not equal to the sum of those for total starting distance and total stopping distance because the longest starting and stopping distances did not necessarily occur for the same vehicles and because in some cases either starting or stopping distance was measured, but not both. Cumulative distribution curves for diverge and merge distances are more nearly S-shaped. In both cases, the bulk of the distribution falls between 30 and 45 m, although the distribution of merge distances is more spread out than that of diverge distances.

Median distances were 45 m for merging, 40 m for diverging, 60 m for total stop, 85 m for total start, and 190 m for total distance used. The median values of starting and stopping distances do not add up to that of total distance because in some cases either starting or stopping distance was measured, but not both.

## CONCLUSIONS AND RECOMMENDATIONS

From the foregoing it may be concluded that emergency parking areas are useful in cases in which freeway shoulders are converted to traveled way and that they can substitute for some but not all functions of normal shoulders. In particular, they are not effective substitutes for the full range of maintenance activities.

The existing emergency parking areas on the Santa Ana Freeway appear to be too small. Not only are their usage rates very low, probably as a result of the fact that they are small and inconspicuous, but their dimensions are considerably less than the distances typically used in pull-off-pull-on maneuvers on normal

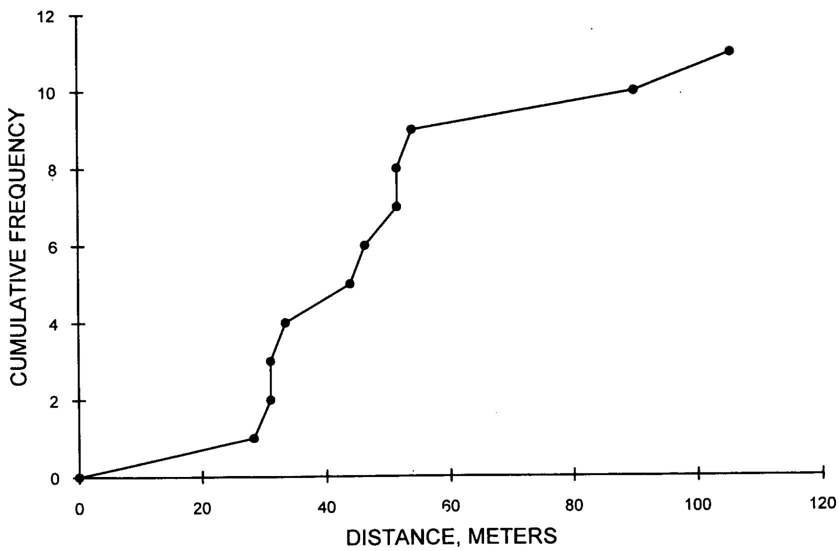


**FIGURE 2 Cumulative distribution: diverge distances.**

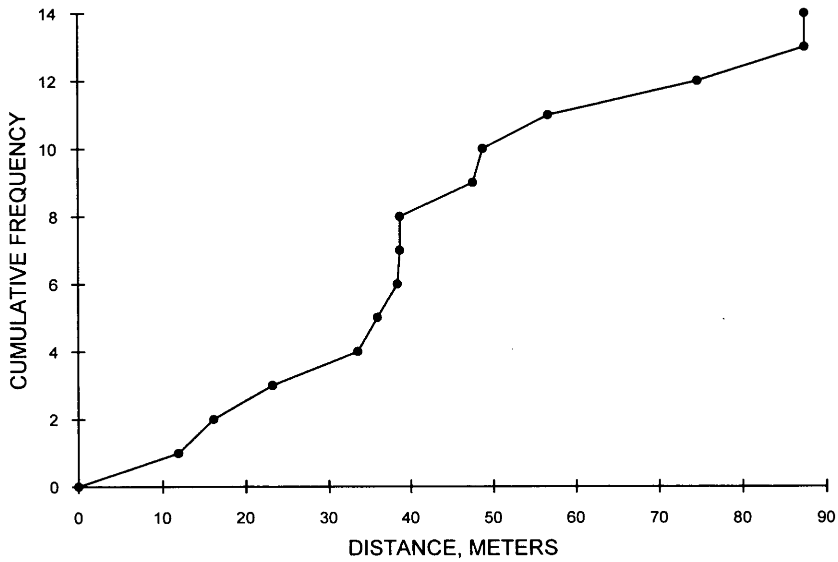


**FIGURE 3 Cumulative distribution: merge distances.**

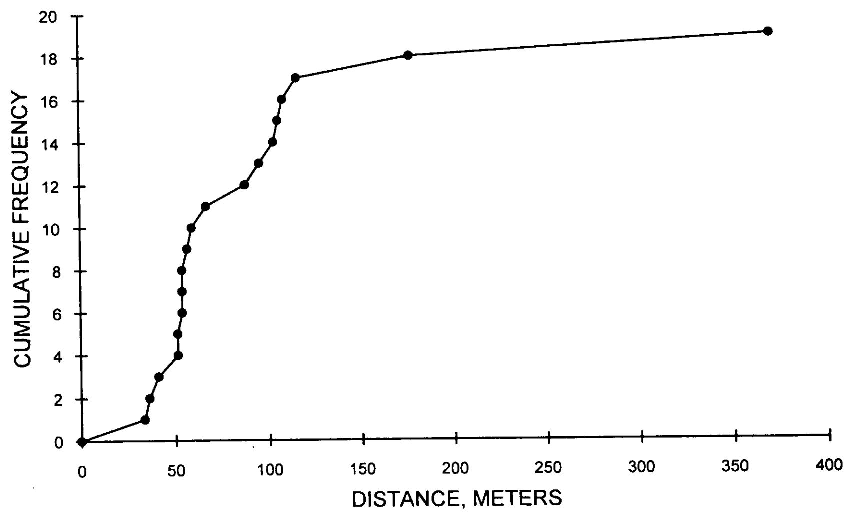


**FIGURE 4 Cumulative distribution: stopping distances.**

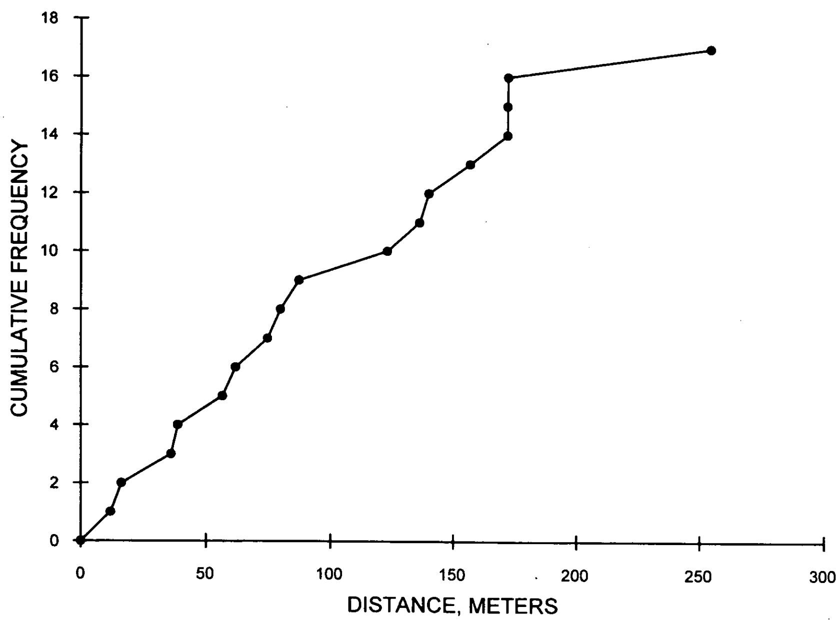


**FIGURE 5 Cumulative distribution: starting distances.**

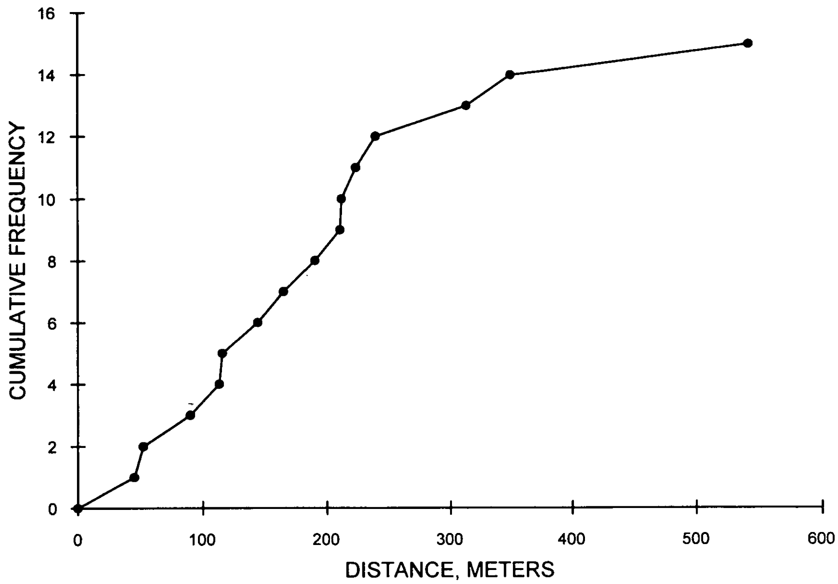


**FIGURE 6 Cumulative distribution: total shoulder distance used.**

shoulders. Observations of the use of normal freeway shoulders indicate that parking areas with overall lengths of 190 to 240 m should be adequate. Figures 7 and 8 give recommended dimensions of 190- and 240-m emergency parking areas incorporating emergency call boxes. The 190-m design is based on median distances observed on normal shoulders, and the 240-m design is based on upper break-point distances.

Where call boxes are installed, as in most urban areas of southern California, it is recommended that an emergency parking area be established at each box. This will result in a spacing of approximately 0.4 to 0.8 km. For the range of emergency parking area dimensions recommended here, a spacing of 0.8 km will result in 25 to 30 percent of the roadside being occupied by some part of an emergency parking area and 10 to 20 percent by the full-width parking area. For the 0.4-km spacing, these percentages will double.

Finally, there is no evidence that the existing emergency parking areas are involved in an unusual number of accidents. In fact, no accidents involving them were identified. The most likely explanation for this lack of accident experience is their low usage rates; however, it should not be concluded that the dimensions of the existing emergency parking areas are necessarily adequate to provide safe operation.

## ACKNOWLEDGMENTS

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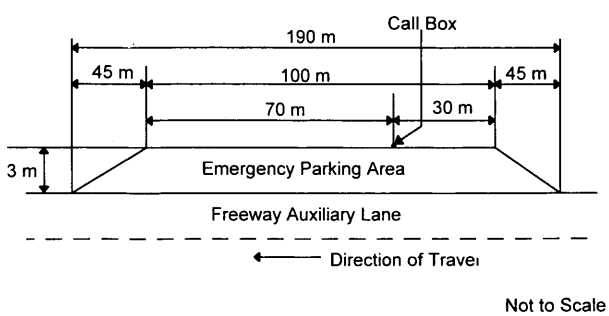


**FIGURE 7 Recommended dimensions for 190-m emergency parking areas.**

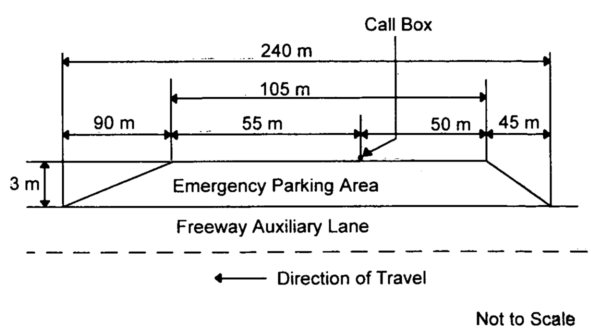


**FIGURE 8 Recommended dimensions for 240-m emergency parking areas.**

Highway Patrol; research assistant John Pham; and video crew members Bob Danila and Carl Segura.

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