1232

TRANSPORTATION RESEARCH RECORD

Urban Traffic Systems and Operations

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1989

Transportation Research Record 1232
Price: $18.50

modes
1 highway transportation
2 public transit

subject area
54 operations and traffic control

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Printed in the United States of America

Library of Congress Cataloging-in-Publication Data
National Research Council. Transportation Research Board.

Urban traffic systems and operations.
p. cm.—(Transportation research record, ISSN 0361-1981 ; 1232)
ISBN 0-309-04960-1
1. Traffic engineering. 2. City traffic. I. National Research Council (U.S.). Transportation Research Board. II. Series.
TE7.H5 no. 1232
[HE333]
388.3'1—dc20 90-34796
CIP

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Transportation Research Record 1232

Contents

Foreword

This record is a compendium of papers related by their focus on urban traffic systems. The papers are sponsored by the Committees on Freeway Operations, Transportation System Management, Parking and Terminals, Communications, and Traffic Signal Systems, and by the Task Force on High-Occupancy Vehicle Systems. The topics presented cover a wide range of issues—from making speed estimates from single-vehicle detectors to the lessons to be learned from existing high-occupancy vehicle systems.

Aspects of predicting or influencing levels of performance for freeways are examined in the first three papers in this record. Gall and Hall propose logic for an incident-detection algorithm for distinguishing between congestion caused by recurrent bottleneck situations and congestion caused by incidents. Hall and Persaud identify a bias in estimating vehicle speeds from data obtained from single-detector locations. Jacobson et al. describe an algorithm developed by the Washington State Department of Transportation for calculating ramp-metering rates in real time based upon systemwide traffic conditions.

The next two papers examine maintenance and reconstruction activities on freeways and how the traffic performance can be predicted and managed. Zhang et al. describe a modeling methodology using a simulation model for predicting freeway performance under different maintenance/reconstruction plans. Krammes and Ullman investigate strategies that have been employed successfully by highway agencies to manage traffic during urban freeway reconstruction projects.

The many issues of parking and park-and-ride lots are the theme of the next four papers. Williams discusses the use of a transportation management program to mitigate the traffic impacts of a large expansion of the University of Washington stadium. The major elements of the plan included public transit incentives, a park-and-ride system, shuttle bus service from satellite parking lots, restricted parking zones, and a marketing program promoting the nonautomobile modes. The management of parking and traffic mitigation policies to discourage solo driving and encourage transit, ridesharing, cycling, and other alternatives is examined by Higgins. Loudon et al. examine the relationship between parking and air quality and evaluate alternative methods for reducing emissions in terms of parking space equivalents. Noel discusses the frequently neglected aspects of the implementation and operation of park-and-ride lots including, among other issues, liability, leasing, funding, marketing, and fee structures.

Providing routing information to drivers is examined in a paper by Blum and Van Aerde. They describe a route-guidance concept that can be integrated with traffic control models using either historic traffic volume data or in real-time mode with the appropriate vehicle-roadway communication link and illustrate a prototype implementation of the concept.

The concept of using freeway ramp-metering techniques to reduce demand on highly congested surface street systems is evaluated through simulation techniques by Rathi and Lieberman.

In the final paper, Cechini discusses the lessons that have been learned from various high-occupancy vehicle facilities and issues related to design and enforcement, occupancy, times of operation, and marketing.

Distinguishing Between Incident Congestion and Recurrent Congestion: A Proposed Logic

ANA I. GALL AND FRED L. HALL

A key element of freeway traffic management systems (FTMSs) is the detection of incidents. The problem with most incident-detection algorithms is that they do not detect incidents as such; rather they detect congestion, whether it is caused by an incident (incident congestion) or by a recurrent bottleneck situation (recurrent congestion). The purpose of this paper is to present a logic for distinguishing between incident congestion and recurrent congestion. The logic uses 30-sec volume and occupancy summaries at each FTMS detector station to classify traffic operations into one of four states. If congestion is detected at one detector station, the cause of this congestion is defined on the basis of the traffic state at the downstream detector station. Results from a preliminary evaluation of the proposed logic are promising.

Freeway traffic management systems (FTMSs) have been in operation for more than 20 years. A key element of such systems is the detection of incidents. Incidents, including accidents, spilled truck loads, and stalled cars (*1*), can be defined as random events that may disrupt the orderly flow of freeway traffic. Incidents can be detected through a variety of methods. One method that has become increasingly important to the effective management of freeway facilities is the automatic detection process. This process uses computer algorithms to monitor data from presence detectors at regular time intervals to evaluate the nature of traffic operations and to identify the presence of a capacity-reducing incident.

Several incident-detection algorithms are in use. Differences among the algorithms are due either to the different underlying logics or to the different detection criteria. The detection criteria refer specifically to the rules used to declare the occurrence of an incident. Despite these inherent differences, most algorithms share a common problem: they do not detect incidents as such; rather they detect congestion, whether it is caused by an incident (incident congestion) or by a recurrent bottleneck situation (recurrent congestion). Consequently, false alarms are a prevalent problem. What is needed is a means to distinguish between recurrent and incident congestion. In this paper, a proposed logic to achieve this is presented, and the results from a feasibility test of the logic are provided. The proposed logic would complement current incident-detection algorithms and thus improve their performance.

Included in this paper are a description of the logic, a description of the study site and of the data base for the feasibility test, a discussion of the calibration process, the results from the feasibility test, and conclusions.

DESCRIPTION OF PROPOSED LOGIC

The proposed logic grew largely out of the current research in incident detection at McMaster University (*2*). The core of the logic is the realization that traffic operation downstream of a permanent bottleneck differs from that downstream of an incident-caused (or temporary) bottleneck. This realization is not new. Wattleworth and Berry (*3*, p. 2) noted that "two types of freeway operation result from these two types of bottlenecks." Levin and Krause (*4*) and Levin, Krause, and Budrick (*5*) recommended that traffic behavior at permanent bottlenecks be investigated during incident conditions to distinguish between incident and incident-free shockwaves.

For purposes of this discussion, it is assumed that congestion has already been detected at a station, and further, that it has been detected on the basis of the single-station logic described in the previous reference, although this is not an essential assumption. The focus in this paper is solely on the problem of deciding whether that congestion has been caused by an incident or whether it is recurrent congestion. The presentation of the logic is divided into two parts: the first deals with classifying traffic operations into traffic states on the basis of variables describing the traffic stream, and the second uses this information to distinguish the cause of the congestion.

The first step of the logic, shown in Figure 1, classifies traffic operations on the freeway facility into one of four possible traffic states on the basis of two variables—volume and occupancy. These variables are obtained from electronic detectors, located at intervals along the facility. Occupancy, a measure of concentration, is defined as the percentage of time a detector is occupied by a vehicle (or vehicles) during the reporting interval.

Figure 1 was developed using the understanding of traffic operations relationships discussed by Persaud and Hall (*2*). As part of that discussion, they found that uncongested operations on a flow-occupancy (or volume-occupancy) plot tend to cluster tightly about a line, the lower bound of which can be established fairly clearly, in Figure 1. Athol (*6*) also found the same pattern. The maximum uncongested occupancy is defined as OCMAX. A volume-occupancy data pair located to the left of the boundary line, and left of OCMAX is classified as State 1, or uncongested. If the volume-occupancy data pair lies to the right of (or below) the boundary line and

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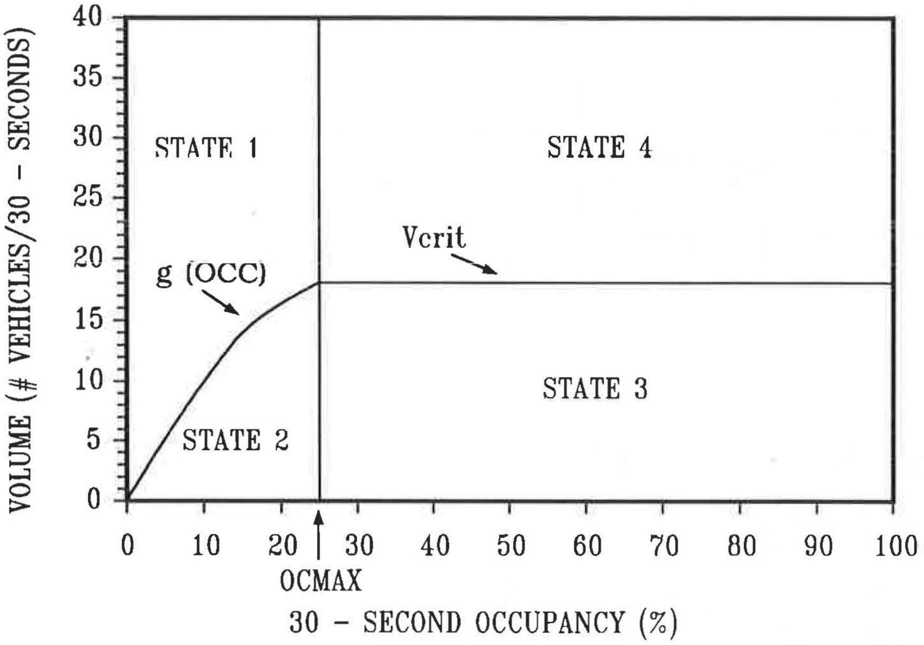

Note: $g(occ) = k * b * occupancy^{a}$, $0.0 < k < 1.0$
k, a, b and Vcrit are station-specific parameters

FIGURE 1 An illustration of the volume-occupancy template for traffic state classification.

left of OCMAX, it is classified as State 2, one type of congested operations. To the right of OCMAX are two states: State 3, the second type of congested operations, and State 4, which reflects traffic operations downstream of a permanent bottleneck in a section of roadway operating at or near capacity with accelerating speeds. State 3 can be distinguished from State 4 by Vcrit (which is defined later). In view of this, only stations downstream of an entrance ramp will include a State 4 region in their station-specific volume-occupancy template.

In Figure 2, the first part of the logic is depicted in decision tree form. One additional traffic state, State −1, has been included in Figure 2. This state identifies those sampling intervals for which detector data are missing (as denoted by either volume or occupancy recorded as −1). For the FTMS data we have used, each detector station contains two detectors to measure speed data as well. Hence data from the downstream detector are used whenever data from the upstream loop detector are missing. In the first portion of the decision tree, this screening process is depicted. Only in the event that both detectors fail to record data will the traffic state be classified as −1.

If congested operations are detected (identified by States 2 or 3) at a detector station, *i*, then the logic shown in Figure 3 is used. This second part of the logic focuses on evaluating the traffic operations at Detector Station $i + 1$, to identify the cause of the congestion detected at Station *i*.

It is important to note that although the logic uses freeway data from adjacent detector stations to establish the cause of congestion, the logic is not similar to the standard comparative algorithms. Instead, the logic relies on the freeway data from a single detector station to characterize the traffic operations there and looks downstream of the congested detector station to find the cause of this congestion. Also, the logic need be applied only to those freeway sections known to be bottlenecks. At these locations false alarms can arise because of recurrent congestion, and thus at these locations distinguishing the cause of congestion is required.

It also is important to note that the main focus of this discussion is not congestion detection, so only a very simple test for that is provided here (identification of either State 2 or State 3 at a detector station). Incident detection at a single station, discussed briefly by Persaud and Hall (*2*), is the focus of other ongoing research. The focus in this paper is identifying the cause of the congestion once it has been detected.

Before discussing the second step of the logic, it is necessary to review the patterns defining both incident congestion and recurrent congestion within the context of Figure 1. In the case of incident congestion, the typical pattern is as follows: an incident will reduce roadway capacity, causing traffic to queue upstream of the incident. Therefore, traffic operations upstream of the incident will be State 3 (after perhaps a brief move into State 2). Downstream of the incident site, however, the volume is reduced but the roadway capacity is normal. Hence, traffic conditions will either be in State 1 if the detector is located sufficiently downstream of the incident to allow vehicles to resume desired speeds or in State 2 if vehicles are still accelerating back to the desired speed (*7,8*). Even if there is an entrance ramp between the incident site and the downstream detector, operations downstream will still most likely

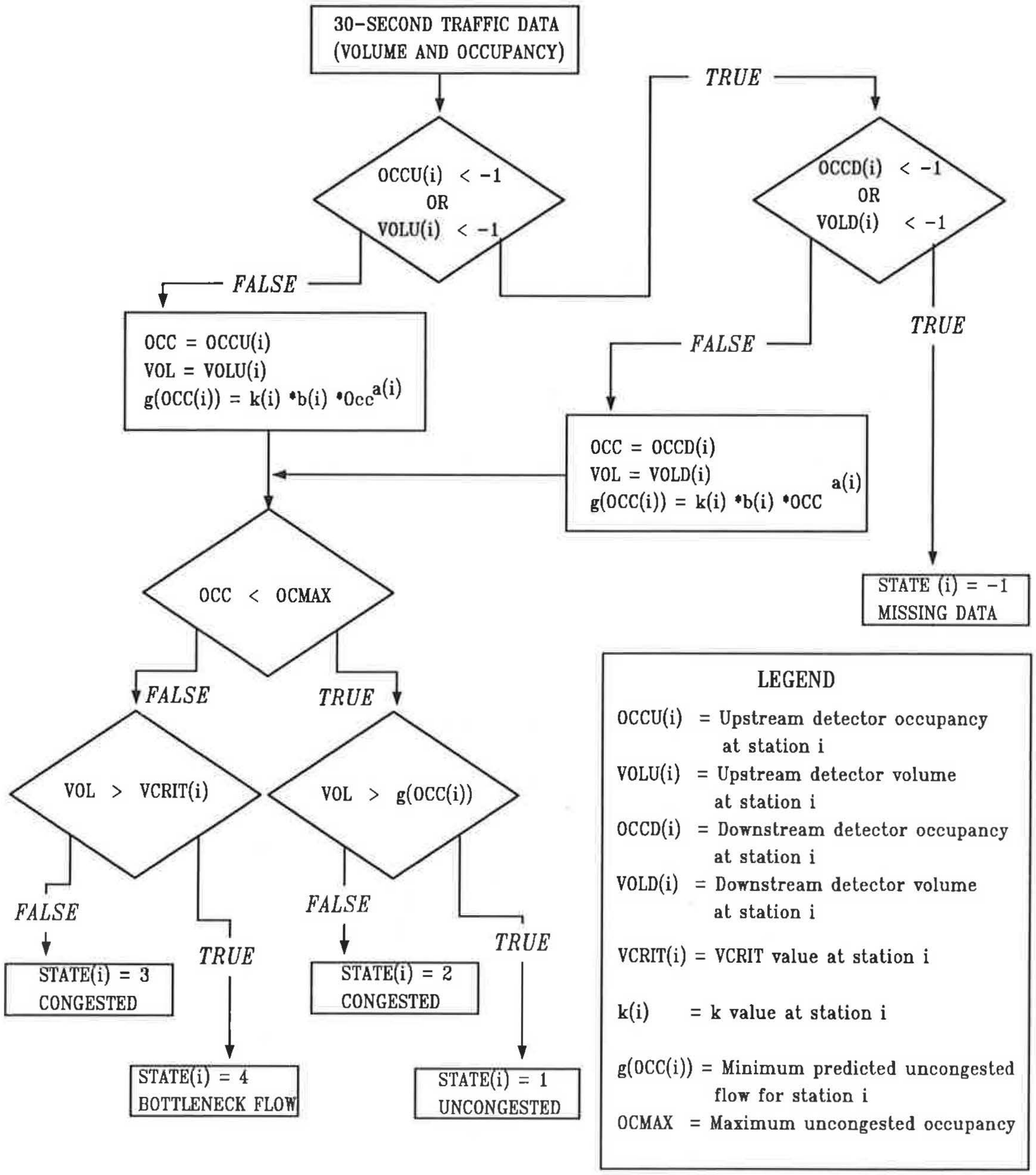

FIGURE 2 Traffic state classification decision tree.

be in States 1 or 2. Only if the ramp feeds more traffic than the reduction in capacity caused by the incident would this statement not be true.

In the case of recurrent congestion, the pattern is different from the previous one. The simplest mental picture of this situation is a high-volume entrance ramp merging with a roadway that is already near capacity. The volume arriving at the bottleneck (i.e., the section of roadway immediately downstream of the entrance ramp) exceeds its capacity, causing traffic to queue upstream. Traffic operations upstream of the bottleneck site will be in State 3 (or perhaps briefly in State 2) identical to the incident congestion pattern. However, downstream of the merge point (the point where ramp traffic merges with mainline traffic), traffic flow will be at or close to capacity (State 4). Once again depending on the distance between the downstream detector and the merge point, vehicles may or may not be back to the desired speed. If they are, operations will be near the left edge of State 4. If they are not, the occupancies will be increased (for any given flow rate) by the reduced speeds, leading operations to be toward the right of State 4.

The logic depicted in Figure 3 is based on these two patterns. Beginning at the first detector station, *i*, and moving in the direction of flow, the traffic state at each detector station is evaluated on the basis of the volume and occupancy values. If the traffic state is 1, proceed to the next detector station, *i* + 1, and repeat the procedure. If the traffic state is either 2 or 3, traffic operations are congested. It is now

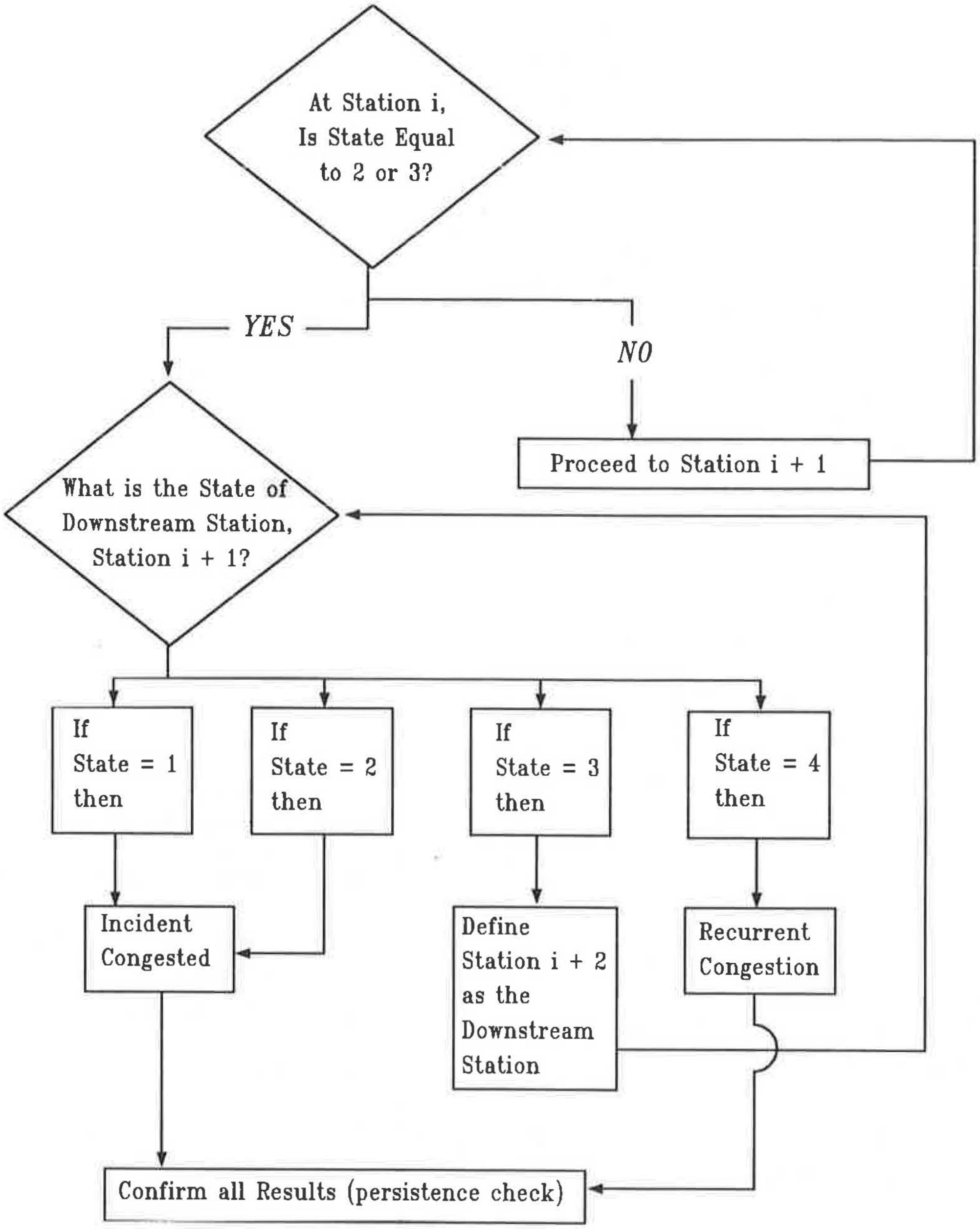

FIGURE 3 Flow chart for distinguishing between recurrent congestion and incident congestion.

necessary to evaluate the traffic state at the downstream detector station, $i + 1$. Three conditions at the downstream station are possible. If the downstream state is either 1 or 2, then it is highly likely that a capacity-reducing incident has occurred between Stations i and $i + 1$. If the downstream state is 4, then it is highly likely that the congestion is due to either an input of extra volume or a lane drop located between Stations i and $i + 1$. If the downstream state is 3, then the cause of the congestion is further downstream; proceed to Station $i + 2$. If the logic is used to complement a current incident-detection algorithm, then once congestion has been detected at a detector station, this logic would be used to evaluate only the downstream detector stations to identify the cause of the congestion.

DESCRIPTION OF THE STUDY SITE AND DATA BASE

The study site selected for a feasibility test of the proposed logic is a portion of the eastbound Queen Elizabeth Way (QEW) in Mississauga, Ontario (Figure 4). The prime reason for the selection of this portion of the QEW was its geometrics. The QEW is fairly flat, three lanes are maintained throughout the section, and the entrance ramps at Highway 10 and Cawthra Road cause recurrent congestion during the morning peak period. This portion of the QEW is approximately 3.2 km long and includes five detector stations. Each detector station is comprised of a pair of inductance loop detectors in each lane. Three traffic variables—average speed

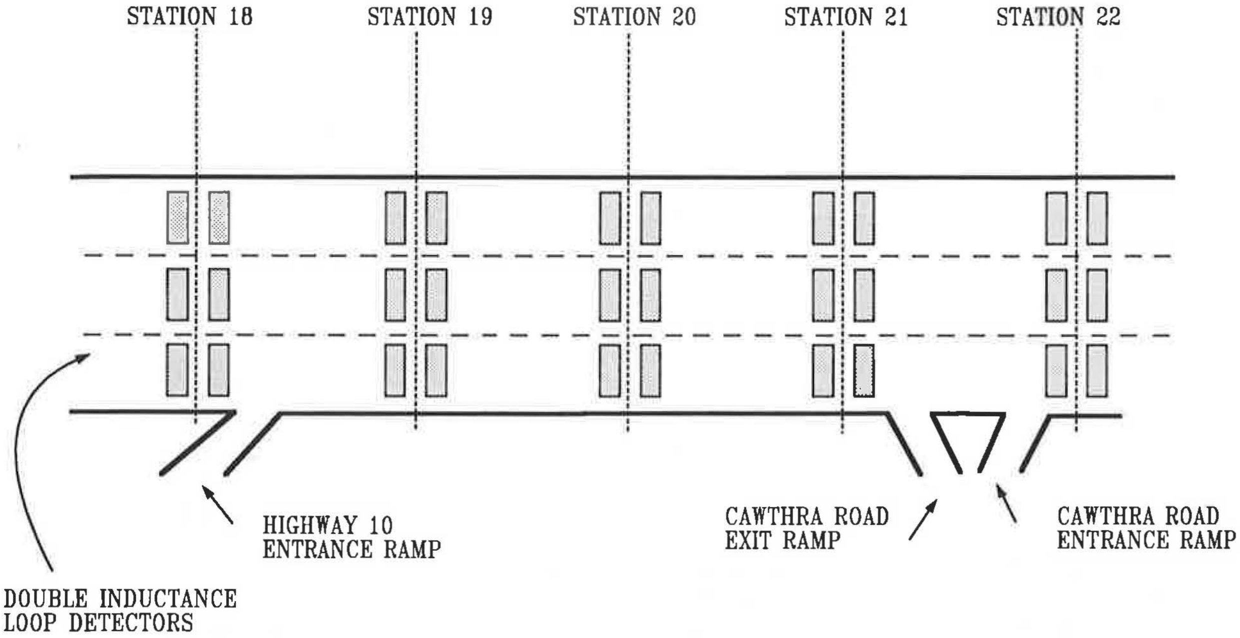

FIGURE 4 Schematic of study site—portion of eastbound Queen Elizabeth Way in Mississauga, Ontario.

(km/hr), volume (number of vehicles), and occupancy (percent)—are summarized at 30-sec intervals 24 hr a day at each of the three lanes.

Although the FTMS facility on the QEW measures freeway data daily, it does not regularly store these data. Before commencing the research for this paper, a few days of data had been stored on magnetic tapes for related research, and these form the basis for this test. The data base includes 2 incident-free days, September 30, 1987, and October 1, 1987, and 1 day, November 19, 1987, in which two incidents were recorded. Each data set contains 24 hr of 30-sec summaries of average speed, volume, and occupancy. Only the median lane data were used in the analysis, primarily because trucks are prohibited from using the median lane. Consequently, volume counts were used directly without conversion to passenger car units. Therefore this test depends strongly on the assumption that any incident or bottleneck will cause a queue in the median lane that grows at least as fast as queues in the other lanes. The use of only the median lane relies on the concept referred to as "lane sympathy." Dudek and Messer (*9*) found that

> although there is a degree of sympathy of speed between lanes regardless of volume, stoppage waves do not necessarily move in unison on each lane of a freeway . . . for the incidents studied, stoppage waves were first detected on either the median or the middle lanes, or both, in 98 percent of the cases.

In light of Dudek and Messer's observation, the assumption does not seem to be unreasonable.

CALIBRATION

To use the proposed logic, a volume-occupancy template (as in Figure 1) is required for each detector station in the study site. The calibration of the station-specific template involves the calibration of the function $f(\text{occ})$ and the parameters k, OCMAX, and Vcrit. As previously mentioned, $f(\text{occ})$ is a function that defines the line along which uncongested volume-occupancy data tend to lie. The parameter k is a value (between 0 and 1) that will produce the boundary line defined by $g(\text{occ})$. OCMAX is defined as the maximum occupancy for uncongested operations. Vcrit refers to the critical volume by which State 3 and State 4 are distinguished.

The function $g(\text{occ})$, which defines the minimum uncongested volume threshold in Figure 1, is defined as

$$g(\text{occ}) = k * f(\text{occ})$$

where $f(\text{occ}) = b * \text{occupancy}^a$

Depending on whether a multiplicative or additive error structure is assumed for the model, linear or nonlinear estimation techniques will be appropriate. The additive form was assumed, that is

$$f(\text{occ}) = b * (\text{occupancy})^a + e$$

This form of the model is intrinsically nonlinear in the parameters. Hence, the parameters, a and b, must be estimated using nonlinear techniques.

To estimate the parameters of $f(\text{occ})$, a sample of volume-occupancy pairs reflecting uncongested traffic operations is required. Because 2 days of incident-free data were available, it was decided to use these data in the estimation procedure (treating each day separately). The purpose of using the 2 days of data was to evaluate the sensitivity of the parameters. From each 24-hr period, 20 hr of data were used. The morning peak period from 6 a.m. to 10 a.m. was excluded because most of these data reflected congested traffic operations. The data were screened first for missing values (that is, any variables recorded as -1) and then screened to remove congested data. Congested data were defined as data in which occupancies exceeded a maximum uncongested occupancy threshold, OCMAX, and speeds were less than some minimum speed threshold. A visual inspection of volume-occupancy plots indicated that an OCMAX value of 25 percent was appropriate for all five detector stations. The threshold speed was different for each station, but generally about 65 km/hr. The values used for OCMAX and the minimum speed threshold are preliminary. More work will be done to derive station-specific values for these parameters.

The resulting uncongested data sets were then used as input to a nonlinear parameter estimation program. Each of the two uncongested data sets had between 1,500 and 1,800 volume-occupancy pairs. Generally, smaller data sets could be used, but larger data sets are preferred to reduce the variance of the residuals and thus improve the precision of the parameter estimates. As shown in Table 1, the two estimates for each parameter differed. These differences were tested using a standard statistical test with a confidence level of 95 percent, and it was found that generally the probability of the occurrence of this difference exceeded 5 percent, and therefore, could not be attributed to chance. This result suggests there are significant day-to-day changes in the traffic characteristics, implying that some updating technique for the parameters is required. In practice, estimates of the parameters could be obtained from available uncongested data, but the parameters should be updated on-line. In the feasibility test, no updating technique was employed; hence, the parameters of the function $f(\text{occ})$ were treated as fixed values. The parameter estimates used in the feasibility test were arbitrarily selected as those derived using Data Set 2.

The second part of the calibration process dealt with determining an appropriate value for k. Different values of k (where $0 < k < 1$) were tested such that the resulting line, $k * f(\text{occ})$ would be a lower bound for 95 percent of all volumes observed at a given occupancy value. Generally, a k value of 0.8 was found to be appropriate for all five detector stations. It appears that results are not particularly sensitive to k. This parameter will likely not need to be calibrated individually for each station.

In finding an appropriate value for OCMAX, the data from the two incident-free days were examined and volume-occupancy plots produced. Using these plots, a maximum occupancy value of 25 percent was set for OCMAX. At present, the parameter OCMAX is not station-specific. This may change as more work is done.

The focus of the final part of the calibration process was to determine an appropriate value for Vcrit. State 4 is applicable only to stations located immediately downstream of an entrance ramp; hence, the definition of Vcrit as a minimum discharge volume. The mean discharge volume corresponded to 19 vehicles/30 sec (2,280 vph), so the minimum discharge flow, Vcrit, was set at 16 vehicles/30 sec (1,920 vph) to provide a lower bound.

FEASIBILITY TEST OF PROPOSED LOGIC

The long-term objective for an evaluation of the logic is to compare the identification of the types of congestion made by the proposed logic with the FTMS operator's perception of the traffic conditions along the facility. This comparison could not be accomplished at present, however; but a feasibility test was conducted with the available data.

The best method for achieving the long-term objective is an on-line evaluation, but it was not possible to schedule such an evaluation at this time for several reasons: (a) the FTMS communications system is currently being upgraded; (b) traffic flow during the summer months is lighter than normal; (c) due to bridge construction upstream of the study site, traffic patterns and volumes have been altered; and (d) during the summer months, the FTMS facility is staffed only from 6 a.m. to 9 a.m. For these reasons, it was also impractical to collect more data at this time.

An off-line test was not possible because of insufficient data. The available data represent only 2 days of incident-free operation and 1 day with two recorded incidents. Further, for the incident data, only a minimal incident log is kept by the FTMS operators as part of the daily FTMS operations record. The operators record an incident only if the incident required a response. Hence, not all incidents are recorded. As part of the daily FTMS operations record, the operators identify the time congestion appeared and dissipated. From conversations with one operator, it was confirmed that this congestion period refers specifically to recurrent congestion that appears upstream of the Highway 10 bottleneck. The time period recorded is subjective as each operator may define "congestion" differently. Given the amount of stored data available and the limited information about these data, a full off-line evaluation was not possible. Therefore, only a pre-

TABLE 1 SUMMARY OF ESTIMATED PARAMETERS FOR THE FLOW MODEL

Data Set	Station 18	Station 19	Station 20	Station 21	Station 22
#1	a = 0.8400 b = 2.2410	a = 0.8436 b = 1.6921	a = 0.7882 b = 1.8360	a = 0.8492 b = 1.5950	a = 0.7800 b = 2.4170
#2	a = 0.8350 b = 2.5070	a = 0.8325 b = 1.6900	a = 0.8344 b = 1.6950	a = 0.8108 b = 1.7570	a = 0.8155 b = 2.2810

liminary off-line evaluation with the available data was performed, in the nature of a feasibility test.

The two objectives for this feasibility test are (a) to determine whether the logic can correctly identify the recurrent congestion that occurs daily, and (b) to see whether the logic can identify the incident congestion in the third day's data. The limited information provided by the operators was used to evaluate the logic. With respect to recurrent congestion, the logic was deemed successful if it could identify the operator-labeled congestion as recurrent. With respect to incident congestion, the logic was deemed successful if the incident congestion identified corresponded to a recorded incident. Two time periods from each data set were selected for evaluation, a morning peak period (6:00 a.m. to 10:00 a.m.) and an afternoon period (2:00 p.m. to 6:00 p.m.). A tentative persistence check (of three consecutive 30-sec intervals) was set to confirm identifications made using the logic.

The results (Table 2) show that the recurrent congestion portion of the logic was a clear success. For the 2 incident-free days, the congestion detected was identified as recurrent. Also, recurrent congestion was identified only at the two bottleneck locations and only during the morning peak period (6 a.m. to 10 a.m.). The time of day (not summarized in Table 2) was comparable to the time period in which recurrent congestion is known to be present along the study site.

The incident congestion portion of the logic did not meet with similar success. Although several short periods of incident congestion were identified, an average of one short period every 4 hr, these identifications did not correspond to any recorded incident. Two issues arise: the first is a possible explanation of why the recorded incidents did not cause any identifiable congestion, and the second deals with the incident congestion that was identified.

To understand why the recorded incidents were not found, we must examine the incident data more closely. With respect to the second recorded incident, its location is ambiguous and may have been upstream of the study area.

As indicated in Table 3, the first incident was very short. It seems likely that this short-duration incident did not impede traffic operations enough to cause congestion to reach the

TABLE 2 RESULTS OF PRELIMINARY EVALUATION

Data Set	Time Period	Recurrent Congestion Identifications	Incident Congestion Identifications
30 09 87	6:00 am to 10:00 am	At both bottlenecks	1 at Station 20 See Note 1
	2:00 pm to 6:00 pm	None	See Note 2
01 10 87	6:00 am to 10:00 am	At both bottlenecks	1 at Station 20 See Note 1 1 at Station 21 See Note 1
	2:00 pm to 10:00 am	None	See Note 2
19 11 87	6:00 am to 10:00 am	At both bottlenecks	1 at Station 19 See Note 3
	2:00 pm to 6:00 pm	None	1 at Station 20

Note 1: These identified incident congestion periods were of short duration and were declared after recurrent congestion was identified at both bottlenecks.

Note 2: Several periods of congestion were detected at Station 20, but due to missing data at Station 21, it was not possible to identify the type of congestion.

Note 3: Incident congestion was identified at Station 19 prior to the identification of recurrent congestion at the Highway 10 bottleneck. An incident was logged 4 minutes prior to the identification of incident congestion but the incident was recorded as occurring downstream of Station 19 at Cawthra Road.

TABLE 3 INCIDENT INFORMATION

Data Set	Start Time Logged	Location	End Time Logged
19 11 87	6:35 am	E/B left lane west of Cawthra	6:37 am
19 11 87	8:53 am	E/B left lane at Hwy. 10	9:05 am

detectors. Manual review of the data revealed that the pattern defining incident congestion was present, but did not persist beyond the persistence requirement, and was followed immediately by the pattern defining recurrent congestion.

Because the first recorded incident occurred at the onset of recurrent congestion, the data from the 2 incident-free days were also manually reviewed at the same location at approximately the same time. The incident-free data revealed a similar incident congestion pattern before recurrent congestion was firmly established. Thus, the result of the first manual check is not as positive as it might seem.

As previously mentioned, the incident congestion identifications did not correspond to any recorded incident. As summarized in Table 2, incident congestion was identified at Station 20 and Station 21 during the morning peak period of both incident-free days. These stations are located upstream of the Cawthra Road bottleneck. The queue from this bottleneck can, and often does, extend beyond Station 20. The incident congestion identified here may have been produced by the stop-and-go nature of operations within a queue. During the second time period (2 p.m. to 6 p.m.), it was not possible to identify the cause of congestion identified at Station 20 due to missing data at Station 21. Recorded incidents are incidents that require a response. Consequently, these recorded incidents do not constitute all the incidents that may have occurred at the study site during the 3 days. It is possible that the incident congestion identifications corresponded in fact to incidents that required no response.

The results from the feasibility test are positive but far from complete. The long-term objective can best be realized through an extensive on-line evaluation. Such an evaluation was not possible but will be performed in the near future.

CONCLUSIONS

The proposed logic, as described in the paper, makes it possible to distinguish between congestion due to an incident and congestion due to a bottleneck. The core of the logic is extremely simple but, we believe, quite accurate. The simplicity of the logic makes it feasible to implement.

The empirical results are promising, but, as a result of lack of field validation and limited data, are not conclusive. A more rigorous test of the proposed logic is needed and is planned.

It is important to note that although this logic uses data from adjacent stations to establish the cause of congestion, the logic is not similar to the standard comparative algorithms. Instead, this algorithm relies on the data from a single station to identify the state of traffic there and looks downstream of a congested situation to find the cause.

ACKNOWLEDGMENT

Most of the research for this paper was performed under a contract with the Ontario Ministry of Transportation. The authors wish to acknowledge this financial support as well as the assistance of Colin Rayman, Mike Young, Hoi Wong, Emmanuel Morala and others in the Freeway Traffic Management Section in making the freeway traffic data available. The authors also acknowledge the support of the Natural Sciences and Engineering Research Council of Canada.

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Publication of this paper sponsored by Committee on Freeway Operations.

Evaluation of Speed Estimates Made with Single-Detector Data from Freeway Traffic Management Systems

FRED L. HALL AND BHAGWANT N. PERSAUD

Freeway management systems that rely on single-detector data acquisition generally use a simple equation to calculate speeds. In this paper, the validity of that equation is tested using data from two locations in Ontario, collected using paired-detector speed traps. The results show that the equation gives biased estimates of speeds over a major portion of the range of operating conditions. Discussion of possible causes demonstrates that at least two key assumptions underlying the equation are not met by actual traffic. This result has important implications not only for operation and design of freeway traffic management systems, but also for theoretical work, such as that on speed-flow relationships.

Freeway traffic management systems (FTMSs) acquire data from the roadway and process these data to identify and respond to problems and to notify motorists of those problems. If some aspects of the data are unreliable, then the response decisions and the information given motorists may well be faulty. This paper investigates speed, one variable produced by most FTMSs.

The reason for focusing on speed is that even though speed is an important variable, not all systems measure it directly. Its importance lies in the fact that it is both a potential indicator of problems on the roadway and a good measure of system effectiveness in terms of travel times across a section of road. Further, if there is any intention of informing motorists of travel times across particular sections of a road, accurate speed data are desirable.

The FTMS data acquisition systems are based on the use of vehicle detectors in the roadway, with stations perhaps 0.8 km apart. Some systems and locations use closely spaced (e.g., 6-m separation) pairs of detectors that are capable of calculating speeds on the basis of the time taken to cross the gap between the detectors. Other systems or locations consist of only single detectors at a station. The single-detector stations are able to measure flow rates and the percentage of time the detector is occupied by a vehicle (occupancy), but not speed. Speed must be calculated on the basis of the measured variables. In these cases, one needs to be sure that the calculation procedures are reliable.

In this paper, the accuracy and reliability of the normal calculation procedures are investigated, using data obtained from two systems with paired detectors, which therefore provide direct measurement of speeds. First, the source of the data that will be used for these analyses is described; then, the current procedure for calculating speed is identified and tested with the data. Because problems with the current procedures will be identified by the analysis, possible explanations are examined, including a discussion of a new interpretation of freeway traffic flow, based on catastrophe theory. The implications of these results for traffic flow theory will be considered; and finally, conclusions will be presented.

DATA SOURCE

The data were obtained from two separate FTMSs along Queen Elizabeth Way (QEW) in Ontario, Canada. Both systems recorded volume counts, occupancies, and speeds every 30 sec, 24 hr a day.

The first system is at the Burlington Skyway, a portion of the QEW that goes over the entrance to Hamilton Harbour. Because of the need to allow shipping to clear the skyway, it consists of a 3-percent grade for roughly 1.2 km, symmetrically about the shipping canal. At the time these data were recorded, the system was collecting data at each of only six southbound and six northbound stations, although the full FTMS will incorporate more stations. Data have been used from three stations with different grades, but the bulk of the analysis has been done with data from a level station (NB7) just before the beginning of the skyway structure. It is worth noting that extended congestion arises on the skyway only during incidents.

The second system from which data were used is the Mississauga FTMS, eastbound on the QEW approaching Toronto. This is a relatively flat section of roadway on which there is recurrent daily congestion from commuter traffic because of several heavily used entrance ramps (which are metered as part of the FTMS).

TEST OF SPEED CALCULATION PROCEDURES

Calculation of Speeds

In the absence of pairs of closely spaced detectors to collect speeds directly, speed is calculated on the basis of flow and occupancy:

$$\text{speed} = \text{flow}/(\text{occupancy} * g) \qquad (1)$$

where g is a constant to convert the units to their proper values and is related to mean vehicle length plus detector size.

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This procedure is used, for example, on some of the Los Angeles area freeways, where g is apparently calibrated during free-flow conditions when speeds can safely be assumed to be known (personal communications from California Department of Transportation, District 7, August 1987 and May 1988). Equivalent procedures are identified by Courage et al. (*1*) and by Mikhalkin et al. (*2*).

Given the data obtained from the QEW, it is possible to test the validity of this approach. The obvious way to do this is to compare the estimated speeds (found using Equation 1) with those actually obtained by the detector pairs. There are two possible flaws: (a) a consistent difference, suggesting the wrong g value had been used, and (b) a systematic change in the difference, suggesting that in fact g is not a constant. The first flaw is easily corrected, and therefore not of much interest. Mikhalkin et al. (*2*) note that Equation 1 gives a biased estimate, but the magnitude of the bias (0.6 mph or 1.0 km/hr) is small compared to the variation in the data. The second flaw is the more important one. If the purpose is to test whether g is indeed constant across the range of operations, this test can be done directly with values of g calculated from the data. Both speed and occupancy are indicators of traffic conditions, but because speed is the item at issue here, occupancy has been used as the variable against which to inspect whether in fact the "constant" g varies.

The "Constant" g as a Function of Occupancy

Station NB7 on the skyway, just before the beginning of the upgrade of the bridge, northbound, was selected for the detailed part of this analysis. The observed values of speed, flow, and occupancy were used to calculate g as shown in Equation 1 for data drawn from several days, including six incidents that caused congestion. The results, as calculated separately for each of the 30-sec intervals, are displayed in Figure 1. There is considerable scatter in the data, particularly for the extreme values of occupancy.

However, there is a trend in the results, and this trend is perhaps more easily seen by looking simply at the mean values of g at each occupancy value, as shown in Figure 2. No attempt was made to fit a regression line, largely because there is no theory to suggest what shape such a line should have. For occupancies from 1 to 37, most sample sizes were large enough to permit good estimation of the mean at each occupancy value. For occupancies above 37, means have been calculated for intervals of 2 or 3 percent because the number of observations at each occupancy is smaller; and for occupancies above 60 percent, for an interval of 5 percent. The figure also shows an approximation of the 95 percent confidence limits for the mean at each observation. (Because sample sizes at each occupancy varied considerably, rather than introduce a table of t-statistics into the calculation, the value for a sample size of 10 was used to simplify the estimation. This gives a conservative—i.e., wider than actual—confidence interval in most cases. The square root of the actual sample size was, however, used.)

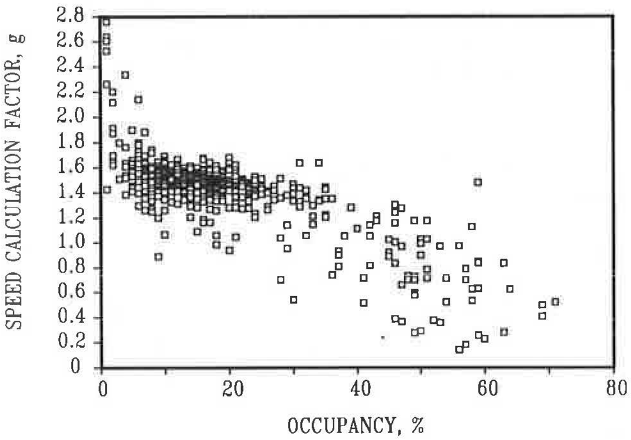

FIGURE 1 **Speed calculation factor, g, versus occupancy for skyway Station NB7, plotted for each 30-second observation.**

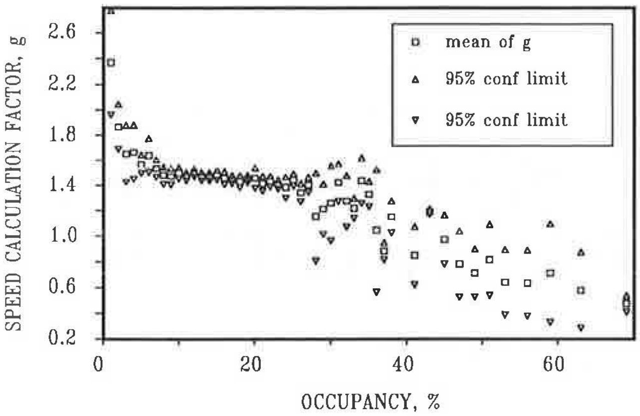

FIGURE 2 **The mean of g and its 95 percent confidence interval versus occupancy for skyway Station NB7 data.**

One of the two extreme points in Figure 2, that at 1 percent occupancy, may be spurious, in that at this low occupancy most of the flows will be based on a single observed vehicle. Thus round-off error in either occupancy or speed, or the discreteness of the volume counts, will contribute considerably to the calculation of g. At the other extreme, high occupancies, the confidence intervals are wider, in part because of the smaller sample sizes. However, the fact that there is a consistent trend over all of the observations for these higher occupancies overcomes those wider intervals and increases confidence in the result.

Despite the problems at the extremes, however, these results appear to support three important points: (a) for most of the range of uncongested occupancies (roughly the 8 to the mid-20 percent range), the variation in calculated g is minimal (Figure 1), and for most of this same range (8 to 20 percent) the mean value of g appears not to change appreciably with occupancy (Figure 2); (b) for higher occupancies, all of which are associated with congested operations, g is subject to considerably more scatter, and the mean value appears to decline with increasing occupancy; and (c) for very low occupancies, as occupancy decreases the range of g values increases and the mean value also increases. In short, the ratio of flow rates to the product of speed and occupancy is not constant, but decreases in a regular fashion as occupancy increases, through two portions of the range.

In an effort to confirm this result, data from three other locations were also analyzed. The first two are additional stations at the skyway FTMS; the third is one station at the Mississauga FTMS. The first is Station SB7, opposite Station

NB7 at the downhill end of the skyway grade. The results (Figure 3) show considerably less regularity than did the NB7 data, both in the presence of wider confidence limits (the total sample was only half the size) and in the absence of a region of roughly constant *g*. Nonetheless, the main conclusion from the NB7 analysis is clearly supported by these data as well: *g* is not constant over the range of occupancies; rather, it tends to decrease as occupancy increases. An earlier analysis also found that the mean value for the 8 to mid-20 percent range is a bit higher than at NB7 (*3*), which was attributed to the higher mean speeds found at the foot of an extended downgrade compared to those on a level roadway.

The second additional station is SB5 on the skyway, located two-thirds of the way up the grade (Figure 4). Here, the mean of *g* behaves in very similar fashion to that at NB7, in that there is a range over which the value seems to be fairly constant. (Note that in this range, it is lower than at either SB7 or NB7.) Station EB16 of the Mississauga FTMS (Figure 5) is a station upstream of the main bottlenecks for the commuting traffic, so is a reflection of the effects of recurrent congestion, rather than of incident-caused congestion. Nevertheless the pattern is the same as that originally found at NB7: as occupancy increases from very low values, *g* declines steeply, briefly; then levels off and remains constant until congestion begins; at which point *g* decreases again, although perhaps not so steeply.

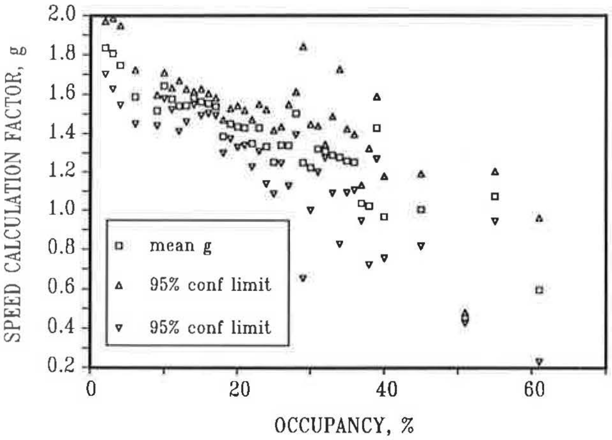

FIGURE 3 The mean of *g* and its 95 percent confidence interval versus occupancy for skyway Station SB7 data.

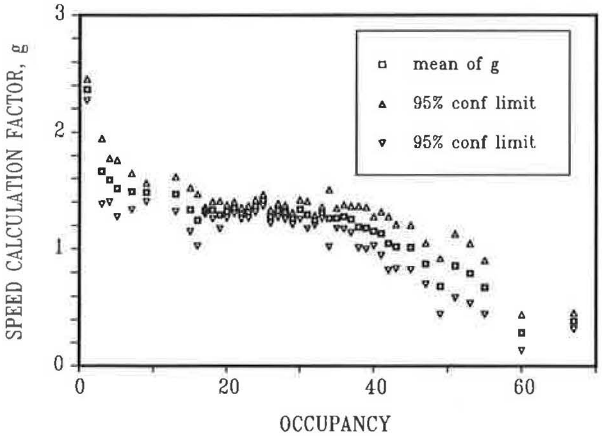

FIGURE 4 The mean of *g* and its 95 percent confidence interval versus occupancy for skyway Station SB5 data.

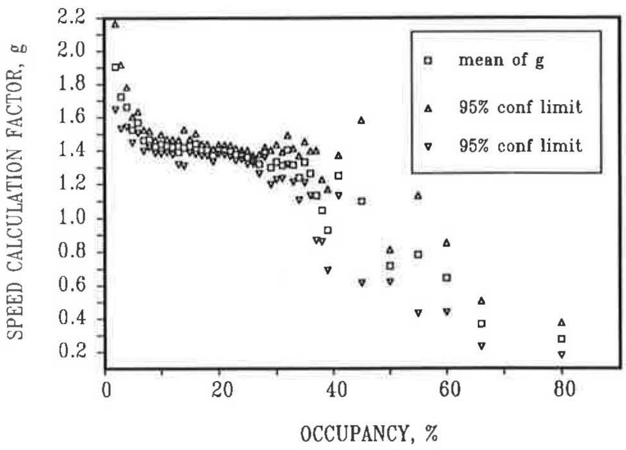

FIGURE 5 The mean of *g* and its 95 percent confidence interval versus occupancy for QEW Mississauga Station EB16.

DISCUSSION OF RESULTS

The conclusion from the preceding analyses is that the use of Equation 1 with a single value of *g* will not produce good estimates of speed. This conclusion is clearly the case from these results for any single station across a range of operating conditions. It is also the case, shown incidentally here and in more detail in an earlier paper (*3*), that a single value of *g* is not appropriate across several stations, at least if there are grade changes from station to station. The obvious next question is why. According to conventional traffic flow theory, such results should not arise. Three possible explanations are discussed here: the first looks simply at possible measurement errors; the second looks at some of the assumptions in conventional theory behind Equation 1 and the extent to which they are contradicted in practice; and the third is a summary of a new model of freeway traffic flow, based on the mathematical approach called catastrophe theory.

Measurement Error

The simplest possibility is that measurement errors in the data acquisition have caused these results. The problem with this explanation is that it needs to account for the changing nature of the error as traffic conditions change as well as for the changes across the different stations. Although this explanation can account relatively easily for changes across stations, it does not easily explain the variations at a single station. There would have to be a systematic error in the data acquisition that increases with decreasing speed (especially during congestion and at very low flows) to produce the results described above.

To investigate this possible source of error, we used the closed circuit television (CCTV), which is part of the skyway FTMS, to record travel across a known distance (roughly 110 m), just upstream of the NB7 detectors. Only a limited amount of timing of vehicles was done from the tape, covering a total of 317 vehicles over 27 30-sec intervals. There was a minor problem in matching the VCR times against the detector timing because the time recorded on the videotape was not precisely synchronized with the computer clock, but a close match was found.

Over the range of occupancies from 4 to 17 percent, all speed differences for the 30-sec intervals were less than 6 km/hr. For those occupancies with multiple observations, the averages of the differences were all less than 2 km/hr. Given the time offset, this seemed a very good match. At the lowest occupancies (4 to 7 percent), the match between VCR and detector speeds was so close that this result alone is enough to refute the hypothesis that there is a systematic error in detector-based speed measurement that would lead to underestimation of speeds and consequent inflation of the value of the "constant" g. At high (congested) occupancies, there were only two data points (at 34 and 57 percent occupancies). Although the detector-based speeds were higher than the VCR speeds in both cases, the difference was less than 10 km/hr, which is not high enough to account for the change in the value of g at higher occupancies. Further, the congested speeds would be most affected by the slight diffference in location of the VCR speed trap from that of the FTMS detectors. On the whole, then, measurement error does not seem to be able to account for the change in the mean value of g as occupancy changes.

Assumptions Behind Equation 1

To calculate speed from flow and occupancy information, Equation 1 relies on two major assumptions. The first is the so-called fundamental equation of traffic flow:

$$\text{flow} = \text{speed} * \text{density} \tag{2}$$

The second assumption is that occupancy and density are linearly related:

$$\text{occupancy} = c * \text{density} \tag{3}$$

As the following discussion shows, neither of these assumptions is met by actual traffic across the full range of operations.

The fundamental equation (Equation 2) assumes that traffic flow is uniform (i.e., that there are constant vehicle speeds and spacing), at least within substreams of the traffic (*4*). In congested conditions, this assumption clearly is not met. Individual vehicle speeds change frequently, with irregular acceleration and deceleration. The spacing between vehicles also changes rapidly, as queues alternately compress and relax. It is not clear whether Equation 2 should be expected to hold for very low flows. When there are only a few vehicles on a freeway, the notion of substreams with constant spacing makes no sense. Nor is the full traffic stream one of uniform flow. As the *Highway Capacity Manual* expresses it (*5*, pp. 1–3), "Individual users are virtually unaffected by the presence of others in the traffic stream. Freedom to select desired speeds and to maneuver within the traffic stream is extremely high."

As a result, not only are speeds of different vehicles unrelated, but at these low flow conditions the spacing between vehicles is random rather than regular. Hence the fundamental equation may not be valid for very light traffic and is clearly not valid for congested operations—the very conditions under which calculation of g does not behave as expected. Note, however, that conditions approximating uniform flow clearly do occur for high uncongested flows, such as say from 1,500 veh/hr in a lane up to capacity. Judging by Figures 1 to 5, it may in fact be a good approximation for operations down to perhaps 8 percent occupancy.

Likewise, the assumption that occupancy is a constant multiple of density is valid only under limited conditions, the most important of which are that vehicle lengths and speeds are constant. This dependence on the assumptions can be shown when these possibilities are introduced into Athol's original derivation (*6*) of the relationship between occupancy and density, as has been done earlier by one of the authors (*7*), as follows. Occupancy is the ratio of the sum of time taken by all vehicles to cross a detector (which includes not only the time to cross the detector, but also the time the vehicle covers the detector) to the total time of measurement. Let

k = density
u = space mean speed for vehicles passing in T
q = flow rate in vehicles/hour, expanded from time T
u_i = speed of vehicle i
x_i = length of vehicle i
d = effective detector length

Then

$$\begin{aligned}\text{occupancy} &= (\text{sum } (x_i + d)/u_i)/T \\ &= \text{sum } (x_i/u_i)/T + \text{sum } (d/u_i)/T \end{aligned}\tag{4}$$

Following Athol, it is helpful to multiply the second term by $n * (1/n)$:

$$\begin{aligned}\text{occupancy} &= \text{sum } (x_i/u_i)/T + d * (1/n)\text{sum}(1/u_i)*n/T \\ &= \text{sum } (x_i/u_i)/T + d * u^{-1} * q \end{aligned}\tag{5}$$

Assuming that the fundamental equation holds, this becomes

$$\text{occupancy} = \text{sum } (x_i/u_i)/T + d * k \tag{6}$$

Noting that T is simply the sum of the individual vehicle headways, h_i, and multiplying top and bottom by $1/n$ gives

$$\text{occupancy} = \text{mean } x_i/u_i)/\text{mean headway} + d * k \tag{7}$$

Athol assumed uniform vehicle length (x), which gives

$$\text{occupancy} = x * \text{mean}(1/u_i)/\text{mean headway} + d * k \tag{8}$$

but since the inverse of mean headway is the flow rate, this becomes

$$\text{occupancy} = x * u^{-1} * q + d * k = (x + d) * k \tag{9}$$

Thus for a uniform vehicle length (and at a single detector location), occupancy is a constant multiple of density. Likewise, for uniform vehicle speeds Equation 9 is still valid, if x is taken to be the mean of the vehicle lengths. However, if both vehicle lengths and speeds vary, then Equation 9 is not strictly correct.

The analyses in this paper were restricted to the median lane in part to limit the variation in both speeds and vehicle lengths. (Trucks are prohibited from that lane in both FTMS sections.) Nevertheless, there is obviously some variation in both, and this undoubtedly accounts for a large part of the scatter in the data. In addition, it is worth pointing out explicitly that the relationship in Equation 9 depends at several steps on the fundamental equation, which holds true over only a part of the range of occupancies.

As a result of the violation of these key assumptions under actual operating conditions, one should perhaps have expected Equation 1 to be correct only under limited conditions. This is in fact what has been found. The good news is that those conditions cover a wider range of occupancies than might have been expected.

An Alternative Model

The conventional understanding of traffic flow theory is, then, inadequate for explaining why *g* in Equation 1 varies. The fact that key assumptions are not met explains why the conventional understanding is not adequate, but leaves one looking for a better theoretical understanding. One recently proposed model (*8*,*9*), based on the mathematics of catastrophe theory, offers some promise in this context and is therefore worth a brief discussion here.

The first point to note about this new model is that, in contrast to the standard treatment of traffic flow theory, it uses occupancy rather than density. There are two reasons for using occupancy: first, occupancy is used in FTMS logic, so it makes sense to build occupancy into theory as well as practice; and second, density is difficult to obtain accurately. Three methods have been used, but all have their shortcomings. Density can be measured directly, but such measurement is much too expensive to do on a regular basis. Even when measurement is done, density must be measured over a large space whereas speed and flow are commonly point (or very short distance) measures, which leads to incommensurate data. (Occupancy on the other hand is relatively easily obtained and is commensurate with the speed and flow measures.) The previous section discussed the flaws in the other two methods: calculation from the fundamental equation and from the presumed constant relationship with occupancy.

Even with density replaced by occupancy, the standard depiction of relationships among the three key variables (*5*, Figure 1-1), when considered in a three-dimensional context, implies something like a horseshoe, located at an angle to the orientation of the three axes (speed, flow, occupancy). The catastrophe theory model on the other hand represents operations as taking place on a partly folded (or split) surface. The original derivation of this surface mathematically comes from work by Thom (*10*), explained subsequently by Zeeman (*11*) and Saunders (*12*) among others. This model has led to a new logic for incident detection with FTMS data, which has proven remarkably robust in preliminary trials (*9*).

Recent work by Gilchrist (*13*,*14*) has provided some very strong support for the model, including the feature that is a key one for explaining the failure of Equation 2 in congested data: that the congested and uncongested data lie on different planes, which meet at an angle and which do not both correspond to the surface described by the fundamental equation. Gilchrist has worked with the data in a three-dimensional graphical representation, for Station EB16 on the QEW in Mississauga, and then has rotated that representation to get a better picture of how the data actually occur. One consequence of this work has been to confirm the planar nature of the bulk of the uncongested data. It is clear from his work that all of the scatter within the uncongested data lies on a single plane, and that the congested data do not lie on that same plane. This observation is entirely consistent with the catastrophe theory model and is not accommodated by the conventional theory.

Summary

Three possible explanations have been discussed for the failure of Equation 1 to calculate speeds accurately across the full range of operations. It seems clear that measurement error is not the source of the problem. The speeds calculated from the detector data have been verified by CCTV videotaping. Hence the problem is in Equation 1. It turns out that two key assumptions underlying the equation are not in fact met by normal freeway operations. Because at least one of those assumptions is fundamental to conventional traffic flow theory, another possible model has been considered briefly. This model is consistent with the findings about speed estimation: uncongested data appear to lie in a different plane than do the congested data. Thus this discussion has shown clearly that the results of the analysis in this paper are not only reasonable but perhaps even to be expected.

IMPLICATIONS

Three practical implications follow from these results. The first two should be of concern to those responsible for FTMSs; the third is important for traffic flow theory.

Estimation of Speeds Using *g*

Many systems have only single-loop detectors, yet still wish to obtain estimates of speeds. The question in the past for such systems has been simply what value of *g* to use. One practice has apparently been to calibrate *g* when traffic approximates free-flow conditions on the grounds that speeds can be reliably estimated then, whereas they cannot be reliably estimated under other operating conditions. The results of the current analysis suggest that if this type of calibration is done for occupancies of around 10 percent, the resulting value of *g* is probably a reasonable one for most uncongested conditions. However, if the calibration is done for lower occupancies, there would appear to be a good chance that *g* has been overestimated. For example, Figures 2 through 5 suggest that the mean *g* for occupancies of 4 to 7 percent is 8 to 10 percent higher than the value for occupancies of 10 to 20 percent. Hence if *g* was calculated for the lower occupancies, speeds during those higher occupancies would tend to be underestimated by a similar 8 to 10 percent.

Even if g is calculated using data for occupancies of 10 to 20 percent, there will be a systematic bias in calculating speeds during congestion. In Figure 6, measured and estimated speeds for such value of g are compared. (The mean value of g for occupancies from 5 to 25 percent has been used to calculate speeds for the full range of data for skyway Station NB7.) On first glance, this figure suggests the estimates are not bad, but a closer look at high and low values of estimated speeds shows the problems. The magnitude of the error can be seen more easily in Figure 7. For low speeds (i.e., those during congestion), the negative errors show that the estimated speed is consistently lower than the observed speed. At high speeds, there is a consistent overestimation of speeds. If the value of g were taken from some other range of occupancies, the location of the points in Figure 7 would just be shifted up or down relative to zero error.

One unusual aspect of Figure 7 that merits comment is the vertical set of data at 81.4 km/hr, as well as the small ranges of excluded values of estimated speeds either side of these data. The vertical array at 81.4 km/hr arises because 120/1.475 is 81.4; 1.475 is the value of g used to calculate the estimated speeds, and 120 is the expansion factor used to obtain hourly flow rates from 30-sec volume counts, so all of these observations arise when occupancy is identical to the 30-sec volume count. The excluded ranges arise because flow and occupancy are in fact not independent variables. The pairs of values that would result in speeds in these ranges simply do not occur in the data.

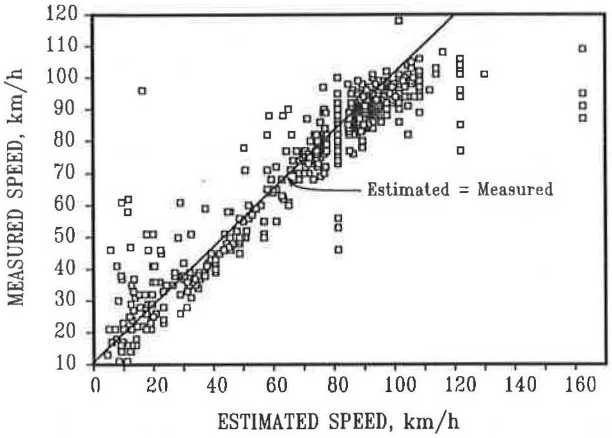

FIGURE 6 A comparison of estimated and measured speeds, using a constant value of g, for skyway Station NB7 data.

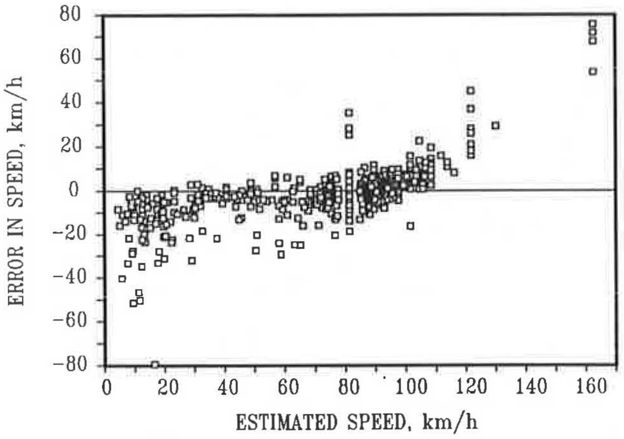

FIGURE 7 The error in speed calculations from using a constant g value versus estimated speed for skyway Station NB7 data.

Estimation of Vehicle Lengths

When speed, flow, occupancy, and detector length are all known, vehicle lengths are calculated by some FTMSs (*15*) as

$$x = (u * \text{occupancy})/q - d \qquad (10)$$

This equation, however, is derived from Equation 9 (i.e., the assertion of a linear relationship between occupancy and density). Because it has been shown that this relationship is approximately true over only part of the range of operations, calculation of vehicle lengths is likely to be reasonable only over that same range. In practice, the "constant" necessary to correct the units in this calculation will undoubtedly behave very much as g has in the above analyses.

Speed-Flow Diagrams

One intriguing question that these results raise, but to which we do not have a clear answer, is the extent to which earlier and ongoing work on speed-flow relationships was and is based on speed data calculated using Equation 1. Certainly if a value of g calculated from very low occupancies were used, the resulting calculated speeds would seem reasonable and would suggest a relationship that is more parabolic than the data presented in more recent papers.

An example of this is shown in Figures 8 and 9, using the Mississauga EB16 data. For these speed calculations, a value

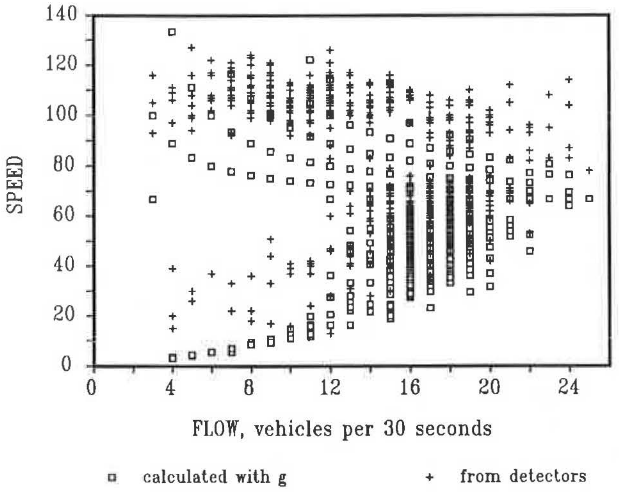

FIGURE 8 Speed-flow diagram, comparing scatter patterns resulting from the use of estimated and measured speeds, using QEW Mississauga Station EB16 data.

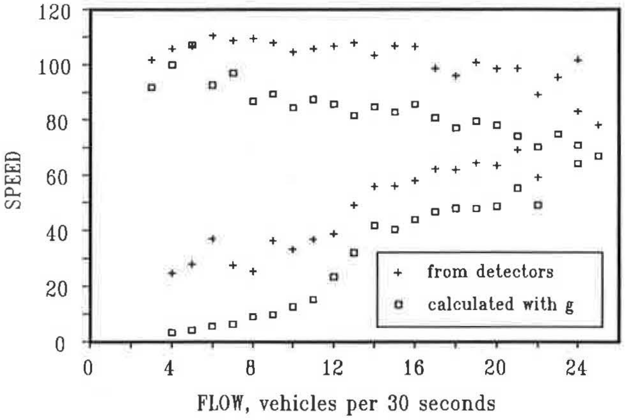

FIGURE 9 Mean values of speeds versus flows, resulting from the use of estimated and measured speeds, using QEW Mississauga Station EB16 data.

of *g* has been used from very low occupancies, such that the free-flow speed would be roughly the same for both curves. In the scatter plot (Figure 8), the detector-based speeds and the calculated speeds coincide mainly in the high-speed, low-flow area, and in the high-flow, low-speed portion of the curve. The areas of disagreement for uncongested flow are in the mid- to high-flow ranges, where calculated speeds are lower, suggesting the upper arm of a parabola, versus the much flatter line of the detector speeds. For congested flow, the calculated speeds at low flows describe a very neat parabola, whereas the detector speeds are higher and more scattered. In Figure 9, the averages, taken separately for the two regimes, are plotted, and a clearer picture of the differences is given, although smooth curves do not result.

It seems at least possible, then, that some of the conventional views of fundamental relationships have arisen from flawed data. Unfortunately, most publications do not go into sufficient detail about the source of the variables to allow one to verify this possibility. It is perhaps worth discussing with those involved in some of those early studies, where that is possible.

CONCLUSIONS

The most important conclusion from this paper is that calculating speed as

$$\text{speed} = \text{flow}/(\text{occupancy} * g)$$

gives biased results. The particular results describing the bias as a function of occupancy are based on limited data. More data are needed before specific proposals can be made for a way to modify that equation (or the value of *g*) to overcome this effect. The general conclusion, however, is supported not only by those data but also by the discussion of the reasons for these results. It is clear that one of the assumptions used to derive this particular equation is not valid in congested traffic, and that the other is not strictly correct when both vehicle lengths and speeds vary. Hence this important conclusion is stronger than the somewhat limited data used in the first instance to test it.

The safest procedure to follow for single-detector systems would appear to be to do without speed estimates. Although speeds are probably the clearest indicator of a breakdown in operations, flow and occupancy are equally important variables and are more reliably obtained. Incident management identification has worked quite well in the past using only these two, so there may be no need to calculate speeds.

On the other hand, speed estimates are valuable and are worth some effort to approximate well. If the constant for a given detector location can be estimated for occupancies of 10 to 20 percent, then the results in this paper suggest that the speed estimates for most uncongested flow will be quite reasonable on average. Figure 7 can provide an estimate of the correction that would need to be made for very high or low estimated speeds to bring them back to a more likely value. Alternatively, a variable value of *g* can be used for very low occupancies and for occupancies during congestion. In Figure 2, the general nature of the variation is suggested. With either approach, a larger sample from more locations would be necessary before definitive correction factors can be provided. It is important to note, however, that these estimates would not be good enough for incident detection or any other application requiring accurate short-duration speed estimates. The estimates would only be reasonable on average.

A better approach in the longer term is to develop a new relationship among the three variables. Our own work along these lines builds on the catastrophe theory model of traffic operations, but other approaches may also be productive. It is too early to offer any good answer to this issue.

The main conclusion has important implications for the design of new FTMSs. Unless a reliable set of sliding values for *g* or a new equation can be identified, single-detector data acquisition should not be used if knowledge of vehicle speeds is thought to be at all important. The apparent cost savings from single-detector versus paired-detector stations represent a false economy in that such systems probably cannot provide good indications of vehicle speeds. Particularly if speed is to be used in an incident-detection algorithm, reliable speed data are essential. The current approach using data from single-detector stations cannot provide reliable speed data.

ACKNOWLEDGMENT

The support of the Natural Sciences and Engineering Research Council of Canada is gratefully acknowledged, as is the assistance of Colin Rayman, Emanuel Morala, and others in the Freeway Traffic Management Section, Ministry of Transportation of Ontario, in making the data available to us. Special thanks to John Proctor and his crew at the Skyway FTMS Control Centre for their help with the videotaping to verify detector speeds and to Bongsoo Son for his work in extracting speed data from the videotapes. An earlier version of this paper was given at the 1988 Annual Meeting of the Institute of Transportation Engineers in Vancouver.

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Publication of this paper sponsored by Committee on Freeway Operations.

Real-Time Metering Algorithm for Centralized Control

LESLIE N. JACOBSON, KIM C. HENRY, AND OMAR MEHYAR

In response to growing freeway congestion problems in the Seattle area, the Washington State Department of Transportation (WSDOT) initiated a ramp-control program in 1981 as part of a regionwide transportation system management effort. The ramp-metering system is a computer-based, distributed intelligence system that consists of field-located microprocessors and a centralized computer system. It is an integrated, traffic-responsive metering system. The system uses an algorithm that calculates metering rates in real time based on systemwide traffic conditions. The algorithm is simple in its approach but very effective in its application. The system has proven to be effective in a series of ongoing evaluations. In this paper, the WSDOT real-time ramp-metering algorithm is described. First a brief description of the Seattle area freeway system and an overview of the development of the ramp metering system are provided. The components of the surveillance, control, and driver information system are then described, followed by a description of the physical elements of the ramp-metering system. After the real-time algorithm used, the limitations of the algorithm, and the advantages of the algorithm are described, the results of an ongoing evaluation effort are presented. Finally, further actions being planned are described.

In response to growing freeway congestion problems in the Seattle area, the Washington State Department of Transportation (WSDOT) initiated a ramp-control program in 1981. The ramp-control system is one element of a surveillance, control, and driver information (SC&DI) system that is part of a regionwide transportation system management effort called FLOW. Other FLOW system elements include park-and-ride lots, freeway flyer stops, high-occupancy vehicle (HOV) lanes, operation of an arterial control system, and operation of a reversible lane control system. The SC&DI system incorporates ramp control, closed circuit television (CCTV), electronic surveillance, a variable message sign system, a highway advisory radio system, a link to the computerized arterial control system, and a graphic display system to aid in driver information reports given to commercial radio stations.

The purpose of this paper is to describe the WSDOT real-time ramp-metering algorithm. First, a brief description of the Seattle area freeway system and an overview of the development of the ramp-metering system are provided. The components of the SC&DI system will then be described, followed by a description of the physical elements of the ramp-metering system. After the real-time algorithm used, the limitations of the algorithm, and the advantages of the algorithm are described, the results of an ongoing evaluation effort are presented. Finally, further actions being planned are described.

DESCRIPTION OF THE SEATTLE FREEWAY SYSTEM AND GEOGRAPHY

The combination of the Seattle area's population with its geography creates problems in providing mobility on the freeway system. The Seattle area contains roughly 2 million people, or about 47 percent of Washington State's population. Unfortunately, the physical characteristics of the area have resulted in very few parallel alternative routes that motorists can use to bypass congestion. Seattle is configured in a narrow hourglass through the downtown area (Figure 1). The length of the hourglass runs north-south, with Lake Washington to the east and Puget Sound to the west. Four major freeways serve the area: I-5 runs north-south through the Seattle area; I-405, a loop freeway that bypasses Seattle, also runs north-south through the suburbs east of Lake Washington; I-90 begins in downtown Seattle and runs east-west across Lake Washington; and finally, State Route 520 runs east-west and is the only other route across Lake Washington. While there are other routes in the area, these four present the toughest issues for traffic management. To further the challenge, the regional metropolitan planning organization, the Puget Sound Council of Governments, has adopted a transportation plan that includes no new highway segments through the year 2000. As a result, the Washington State Department of Transportation has spent a great deal of effort to operate its freeways most efficiently.

HISTORICAL DEVELOPMENT OF THE EXISTING SYSTEM

The Washington State Department of Transportation is now in its seventh year of operating a ramp-control system in the Seattle area. The metering system uses an on-line, centrally controlled algorithm that calculates metering rates based on systemwide traffic conditions.

The formulation of the Seattle area's ramp-control system began in 1968 with a preliminary planning effort. With the completion of the design report for the I-5 portion of the system in 1973, WSDOT developed a series of contracts, which led to the staged implementation of the existing system. The first of these contracts involved purchasing a computer and software to accumulate data from electronic surveillance sta-

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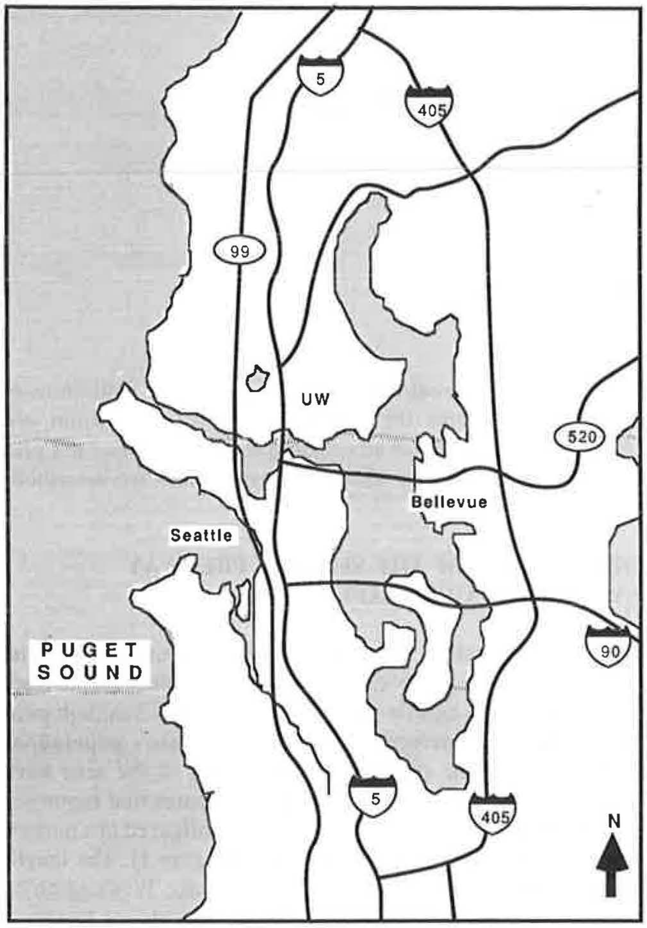

FIGURE 1 Seattle freeway system.

tions. (This computer also acts as the central master for an arterial signal control system.) Later contracts involved installing communication cable along the median of I-5, installing detector loops in the roadway, providing and installing data accumulators and cabinets, making geometric improvements to the roadway, providing and installing an improved closed circuit television system, and building an extension to the Traffic Systems Management Center (TSMC) to house the computers, peripheral equipment, and CCTV monitors.

In early 1979 WSDOT contracted to tie all these components together for an operational ramp-control system. The contract purchases included hardware and software for the central ramp-control computer, all central peripherals, and all field electronics for ramp control. The ramp-control system began operation on September 30, 1981. The initial system included 18 controlled ramps (*1*).

Since the initiation of the system, additional contracts have added six ramps to the system, updated and translated the ramp-controller software to Type 170 controllers, added data accumulation stations, and added cameras to and updated the CCTV system.

SYSTEM COMPONENTS

The Traffic Systems Management Center controls the SC&DI system, which is made up of the following eight components:

1. A closed circuit television system is used to verify incidents and report traffic conditions to local commercial radio stations. It comprises 34 color cameras, which cover 25 miles of freeway. It is controlled by a software switching system, which operates from a touch screen TV. Through the touch screen, the operator selects any combination of cameras and dwell time to appear on two sequencing monitors. All cameras have pan, tilt, and zoom functions. These functions are controlled through two additional monitors.
2. Induction loop detectors, embedded in the roadway, collect real-time volume and occupancy data. Currently just more than 900 loops are located on I-5, I-90, I-405, and SR 520. All mainline loops are 6 ft by 6 ft.
3. Seventy traffic data stations collect volume and occupancy data from the loop detectors and then transmit the data to the TSMC central computers.
4. Twenty-four ramp controllers perform the same data collection function as the traffic data stations, but they also meter ramps. Sixteen ramps are currently metered during the morning peak period, and seven ramps are metered during the afternoon peak. These include one dual-lane metering location and one freeway-to-freeway meter. Eleven of these 23 ramps have HOV bypass lanes.
5. A central computer system collects volume and occupancy data from the traffic data stations and the ramp controllers. The computer then uses this information to determine individual metering rates for each ramp based on local conditions and system capacity constraints.
6. Through color coding, a graphic display system shows various levels of congestion on I-5, I-90, I-405, and SR 520. This system is used extensively in ramp metering and also in reporting traffic conditions to the local radio stations. The information for the graphic display is obtained from the traffic data stations and ramp controllers, processed by the central computer, and output to color monitors.
7. Ten fixed-location variable message signs (VMSs), all electromagnetic flip disk, are controlled by a central system at the TSMC. Four of these signs are used on a 24-h basis to inform motorists approaching the north entrance to the I-5 express lanes of the lanes' status (open or closed). The other six signs warn motorists of downstream accidents, construction, or maintenance work. Four portable flip disk VMSs are also available to provide information on construction and maintenance projects and on major incidents.
8. The Highway Advisory Radio system consists of six low-powered radio transmitters. These also advise motorists of accidents, construction, or maintenance work.

RAMP-METERING SYSTEM

The ramp-metering system is a computer-based, distributed intelligence system that consists of field-located microprocessors and a centralized computer system.

Existing Field Equipment

The field-located equipment consists of both ramp controllers and traffic data stations. Both provide electronic surveillance through induction loop detectors embedded in each lane of the roadway. The loops are scanned by the microprocessors

60 times a second. Volume and occupancy data are then transferred to the central computer once every second.

Several validity checks are made in the field to determine the accuracy of the loop information. A loop actuation of less than 1/15 sec is ignored. Less than a 1/15-sec drop in presence is also ignored. The controller interprets this as a single actuation. Any volume count of more than two vehicles in a second is indicated by an error message sent back to the central computer. Although this check does not necessarily screen all bad data, it does cut down significantly on bad data transferred to and then used by the central computer.

Both the traffic data stations and ramp controllers provide the same traffic data accumulation functions. In metered sections, the ramp controllers and traffic data stations are spaced at ¼- to ½-mile intervals. In other freeway sections, spacings range from ½ to 1 mile. The ramp controllers are located at interchanges and are capable of sampling the larger number of loops often associated with an interchange. The ramp controllers also perform the ramp-metering functions and gather and transmit alarm and failure information. The data accumulators are located between interchanges and only gather and transmit volume and occupancy data to the central computer.

If communication between the central computer and the ramp controller is lost, the ramp controller is able to continue metering with an occupancy control algorithm based on local conditions or based on a time-of-day table. However, while metering at any individual location is not interrupted, the coordination of the system as a whole is lost.

The original hardware installed in the field included Safetran 1610 controllers for ramp metering. The data accumulators used hardware-modified Type 170 controllers and some specially built microprocessors. However, maintenance and replacement of this equipment have been extremely difficult. As a result, all new controllers are off-the-shelf Type 170.

Central System

The central computer system is made up of two Perkin-Elmer 7/32 minicomputers. A high-speed data link ties the two machines together. One of the 7/32s, the Central Traffic Control Master (CTCM), communicates with the data accumulators. The second 7/32, the Video Display System (VDS), communicates with the ramp controllers and controls the ramp-metering system. The VDS system also drives the color graphics system, which displays various levels of congestion using color coding and is based on 1-min averages of loop occupancies. All volume and occupancy data are shared between the two systems every 20 sec via the data link. The data link also keeps the clocks of the two systems synchronized.

Communication System

Half of the ramp controllers and data accumulators communicate on a state-owned twisted-pair cable that runs along 17 miles of I-5. All other data communications are over dedicated telephone circuits. Ramp controllers communicate at 1200 baud, and the data accumulators communicate at 300 baud. Frequency shift keying is used in all communications.

THE ALGORITHM

The unique aspect of the ramp-control system is its on-line metering algorithm. The most significant aspect of the algorithm is the system, or "bottleneck," metering rate calculation. The algorithm was developed in 1978 in a cooperative effort between WSDOT personnel and their consultant, H. W. Lochner. The description of the algorithm that follows will use terminology found in the 1985 FHWA *Traffic Control Systems Handbook* (*2*). This terminology will minimize any ambiguity in the description and flow diagrams used. Although this version of the handbook was not published at the time the algorithm was developed, the algorithm fits nicely into the framework described.

The algorithm used in the Seattle system is, in the terminology of the handbook, an integrated, traffic-responsive metering algorithm because metering rates are calculated in real time based on system as well as local capacity conditions. In addition, queuing conditions on the ramps are also considered in the final calculation of metering rates. In effect, the metering algorithm has three components: calculation of metering rates based on local conditions, calculation of metering rates based on system capacity constraints, and adjustment to the metering rates based on local ramp conditions. A generalized flow diagram of the algorithm is presented in Figure 2. In the Seattle system, metering rates are calculated for each ramp every 20 sec based on 1-min accumulations of volume and occupancy. All flow rates and metering rates are expressed in vehicles per minute (vpm), and occupancy is truncated to the nearest tenth of a percent.

Local Metering Rate

One method of calculating metering rates that are based on local conditions is traffic-responsive metering using occupancy control. According to the handbook, predetermined metering rates are selected on the basis of occupancy levels upstream of the given metered ramp. Historical data are collected from the given data station location. These data are used to determine approximate volume-occupancy relationships at capacity. Metering rates are then calculated from the volume-occupancy relationships to allow ramp volume to make up the difference between the estimated capacity and the estimated real-time upstream volume. The handbook implies that the metering rate is selected from a predetermined, finite set of discrete metering rates.

The handbook's outline of the process adequately describes the local metering rate calculation employed in the Seattle system. However, the metering rate is calculated from straight-line interpolation between discrete points on the occupancy-metering rate curve that is developed from the volume-occupancy curve for the upstream mainline station corresponding to the given metered ramp (see Figure 3). If the real-time measurement of occupancy is P_i, and $P_x < P_i \leq P_y$, where P_x and P_y correspond to adjacent discrete points on the occupancy-metering rate curve (P_x,A_x) and (P_y,A_y), where $P_x < P_y$ and $A_x > A_y$, then the metering rate is calculated as

$$A_i = A_x + \frac{(A_y - A_x)}{P_y - P_x}(P_i - P_x) \qquad (1)$$

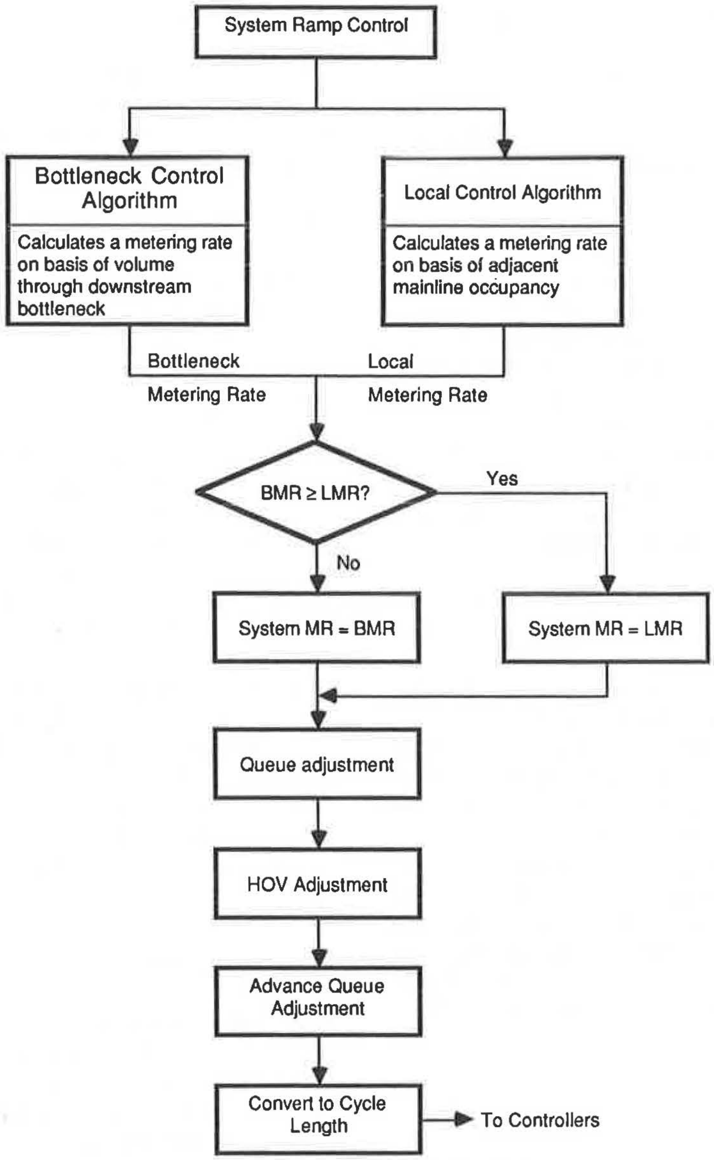

FIGURE 2 Generalized ramp-metering algorithm.

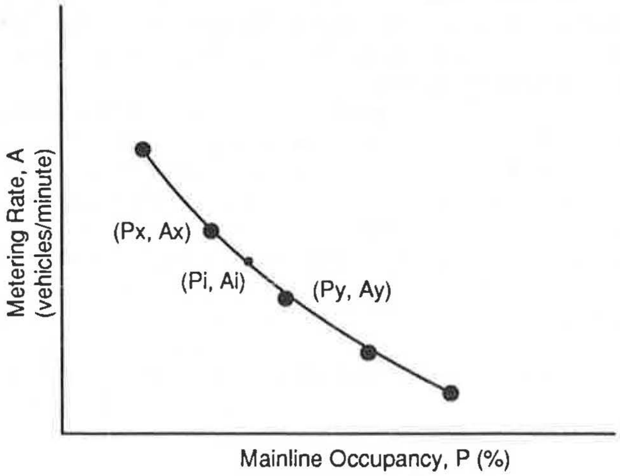

FIGURE 3 Occupancy-metering rate curve.

where

A_i = metering rate calculated,
A_x = metering rate associated with occupancy P_x (from the occupancy-metering rate curve),
A_y = metering rate associated with occupancy P_y (from the occupancy-metering rate curve),
P_i = mainline station occupancy at Station i, and
P_x and P_y = control points on the occupancy-metering rate curve.

The local metering rate calculation is not unique. Several systems around the country use this same occupancy control algorithm.

The System, or Bottleneck, Metering Rate

The unique aspect of this system is calculation of metering rates on the basis of system capacity constraints. The system, or bottleneck, metering rate calculation is what makes the ramp control system an integrated traffic-responsive metering system.

As described in the handbook, integrated ramp control is distinguished by the application of "ramp control to a series of entrance ramps where the interdependency of entrance ramp operations is taken into account" (*2*). System-wide conditions and capacity constraints drive the calculation of metering rates at all metered ramps in the system.

The handbook describes integrated traffic-responsive metering as "the application of traffic-responsive metering to a series of entrance ramps where the metering rates are selected in accordance with system, as well as local, demand-capacity constraints" (*2*). Volume, occupancy, and/or speed measurements, taken in real time, define demand-capacity conditions for each mainline data collection location in the system. The handbook states that the calculations of both an independent and an integrated metering rate are based on these conditions. The more restrictive of the two is selected as the metering rate to be implemented. The metering rate selected is then subject to adjustment on the basis of ramp queues, maximum red times (minimum metering rate), and, potentially, other conditions.

The WSDOT algorithm is basically structured in the same manner. The independent metering rate calculation is the same as the local metering rate calculation described above. The adjustments to the selected metering rate are described below. The integrated metering rate calculation will be described in this section as the system, or bottleneck, metering rate calculation.

The WSDOT bottleneck metering calculation differs from the calculation method described in the handbook. The handbook describes the integrated metering rate calculation as a linear programming problem. It implies that the linear programming model is run off-line to determine the metering rates to be implemented for the range of traffic conditions to be expected. The precalculated metering rates are then selected in real time according to systemwide conditions.

However, the WSDOT bottleneck algorithm calculates metering rates in real time. In essence, it determines demand-capacity relationships in real time by a straightforward, simplistic approach to calculating capacity on-line. The demand-capacity relationships are then used to determine metering rates throughout the facility being metered.

The capacity of a freeway section is calculated in real time by determining whether the section is near capacity, based on occupancy, and whether vehicles are being stored in the section. A freeway section is defined by two adjacent mainline detector stations. The detector stations consist of a 6-ft by 6-ft induction loop detector in each of the freeway main lanes. In the Seattle control areas, mainline detector stations are located at a maximum of approximately ½-mi spacings. If the downstream detector station detects occupancies above an operator-defined threshold (generally in the neighborhood of 18 percent), the section is said to be operating near capacity. If the section is operating near capacity and the total volume entering the section exceeds the total volume exiting the section, then the section is said to be storing vehicles. The total volume entering the section consists of the volume across the upstream station, the volume on any entrance ramps in the section, the volume from any HOV facilities within the section, and the volume from any other roadway (collector-distributor or center reversible roadway) within the section. The total volume exiting the section consists of the volume across the downstream station, the volume on any exit ramps in the section, the volume going to any HOV facilities within the section, or the volume going to any other roadway within the section. In a generalized freeway section, such as the one depicted in Figure 4, these conditions can be described as follows:

1. Capacity condition

$$P_{it} \geq P_{\mathrm{THRESH}_i} \qquad (2)$$

where

P_{it} = average occupancy across the downstream detector over the previous 1-min period, and
P_{THRESH_i} = the occupancy threshold for the downstream detector station that defines when section i is operating near capacity. (These thresholds are parameters that can be tuned from the operator's console for each freeway section.)

2. Vehicle storage condition

$$q_{\mathrm{IN}_{it}} + q_{\mathrm{ON}_{it}} \geq q_{\mathrm{OUT}_{it}} + q_{\mathrm{OFF}_{it}} \qquad (3)$$

where

$q_{\mathrm{IN}_{it}}$ = volume entering section i across the upstream detector station during the past minute,
$q_{\mathrm{ON}_{it}}$ = volume entering section i during the past minute from the entrance ramp,
$q_{\mathrm{OUT}_{it}}$ = volume exiting section i across the downstream detector station during the past minute, and
$q_{\mathrm{OFF}_{it}}$ = volume exiting section i during the past minute on the exit ramp.

If these two conditions are met, the system calculates the upstream ramp volume reduction as the number of vehicles

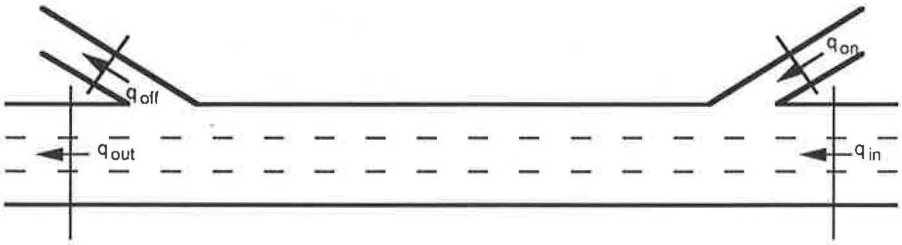

FIGURE 4 Generalized freeway section.

being stored in the freeway section during the past minute. This value becomes the total by which upstream ramp volumes must be reduced. The upstream ramp volume reduction is calculated as

$$U_{i(t+1)} = (q_{\mathrm{IN}_{it}} + q_{\mathrm{ON}_{it}}) - (q_{\mathrm{OUT}_{it}} + q_{\mathrm{OFF}_{it}}) \tag{4}$$

where $U_{i(t+1)}$ = upstream ramp volume reduction for section i to be acted on in the next metering interval $(t+1)$, and $q_{\mathrm{IN}_{it}}$, $q_{\mathrm{ON}_{it}}$, $q_{\mathrm{OUT}_{it}}$, and $q_{\mathrm{OFF}_{it}}$ are as stated for Equation 3 above.

Each freeway section has an area of influence assigned to it. Only upstream ramps within the section's area of influence are included in the volume reduction. The area of influence is defined by a tunable parameter that contains the number of upstream ramps that are affected by the bottleneck metering rate calculation for the given section. The parameters can be modified from the operator's console.

The total upstream ramp volume reduction is distributed to the upstream ramps on the basis of a set of weighting factors. Each metered ramp in the system is assigned a weighting factor according to how far downstream it is (how near it is to the bottleneck section) and the normal level of demand on the ramp. Ramps farther downstream (nearer the bottleneck) have larger weighting factors because vehicles using these ramps are most likely to pass through the bottleneck and reductions in metering rates nearer the bottleneck can have the quickest, most dramatic effect on the bottleneck. Ramps with higher demand tend to have higher volumes; therefore, ramps with higher demand can have a larger volume reduction in real terms.

The algorithm calculates the bottleneck metering rate reduction for each ramp within a given freeway section's area of influence by multiplying the total upstream ramp volume reduction by the given ramp's weighting factor, divided by the sum of the weighting factors for all the ramps within the section's area of influence. The calculation becomes

$$BMRR_{ji(t+1)} = U_{i(t+1)} \times \frac{WF_j}{\sum_{j}^{n} (WF_j)_i} \tag{5}$$

where

$BMRR_{ji(t+1)}$ = bottleneck metering rate reduction for ramp j based on section i for the next metering interval,
$U_{i(t+1)}$ = upstream ramp volume reduction for section i to be acted on in the next metering interval $(t+1)$,
WF_j = weighting factor for ramp j, and
$\sum_{j}^{n}(WF_j)_i$ = summation of weighting factors for all ramps within the area of influence for section i.

The system calculates the bottleneck metering rate for each ramp by subtracting the bottleneck metering rate reduction from the ramp's volume during the past minute. The calculation becomes

$$BMR_{ji(t+1)} = q_{\mathrm{ON}_{jt}} - BMRR_{ji(t+1)} \tag{6}$$

where

$BMR_{ji(t+1)}$ = bottleneck metering rate for ramp j based on section i for the next metering interval,
$q_{\mathrm{ON}_{jt}}$ = entrance volume on ramp j during the past minute, and
$BMRR_{ji(t+1)}$ = bottleneck metering rate reduction for ramp j based on section i for the next metering interval.

The system begins these calculations at the upstream end of the control area and works its way downstream for each section within the control area. Areas of influence for each freeway section overlap; therefore, any given ramp may have several bottleneck metering rates calculated for it. The most restrictive of these rates is selected as the final bottleneck metering rate for the ramp. (See Figure 5 for the flow diagram for the bottleneck metering calculation.)

Adjustments to the Calculated Metering Rate

As mentioned above, after both the local metering rate and the final bottleneck metering rate are calculated for a given ramp, the system selects the more restrictive of the two to be adjusted according to ramp conditions and subject to the maximum and minimum metering rates assigned to the ramp. There are a queue adjustment, a ramp volume adjustment, and an advance queue override.

The queue adjustment is implemented when the ramp queue has extended to the queue detector for a specified length of time. The queue detector is located upstream of the stop bar on the ramp, usually close to the intersection with the surface street and the ramp. When the occupancy level at the queue detector has exceeded a threshold value for a given length of time, the metering rate is increased by a small amount, usually one to three vehicles per minute, depending on the ramp and the length of time the queue condition has been in effect. The queue adjustment is essentially as described in the handbook.

The metering rates are calculated in real time to optimize the flow on the freeway. When the volume on the ramp differs from the assigned metering rate, either too many vehicles enter the freeway, which leads to breakdown conditions, or too few vehicles enter the freeway, which reduces the efficiency of freeway operations and exacerbates the ramp queuing problem. The system automatically adjusts the metering rate based on whether more or fewer vehicles entered the freeway at the ramp compared to the actual metering rate over the previous minute. If more vehicles entered than were supposed to, either due to violations or HOVs entering on the HOV bypass, the metering rate is reduced by the number of vehicles that entered in excess of the assigned metering rate. If fewer vehicles entered than were supposed to, usually due to inattention or inexperience on the part of the drivers, the metering rate is increased by the corresponding amount.

The final adjustment is the advance queue override. At selected ramps, a queue detector is located at the point of worst tolerable queue. If the ramp queue reaches this detector, then the metering rate is set relatively high. Depending on the ramp, this rate is in the range of 10 to 15 vehicles per minute. When the queue has cleared the advance queue detector, normal metering operation ensues. The reason for the override is one of equity. When the queue reaches the point

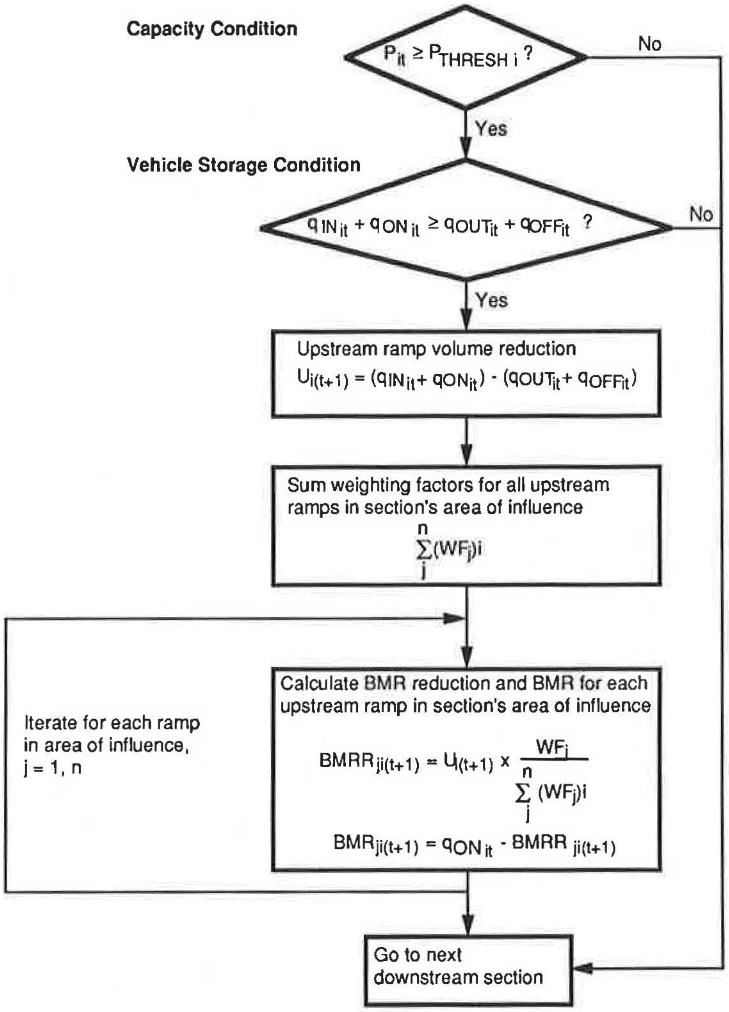

FIGURE 5 Bottleneck metering rate calculation flow diagram.

of worst tolerable queue, the system is starting to interfere with surface street operation and is affecting motorists not destined for the freeway. This is an undesirable situation, both politically and in terms of overall road network efficiency.

After all adjustment calculations are undertaken, the final metering rates are transmitted to the microprocessor-based controllers in the field for implementation. The entire algorithm is performed for all ramps and all freeway sections in all control areas every 20 sec, based on volumes and occupancies collected over the previous 1-min period.

Limitations of the Algorithm

There are some limitations apparent in the algorithm.

1. The bottleneck metering rate calculation does not include any estimation of origin-destination data. Therefore, the reduction of upstream ramp volumes calculated and then distributed over the bottleneck section's area of influence may meter vehicles off the freeway that are not destined for the bottleneck. Metering rates may be too restrictive under those conditions. However, the proper selection of areas of influence and weighting factors minimizes this problem. In the current system, there are no major exits from the system inside a given area of influence.

2. Because the bottleneck metering rate is calculated only when vehicles are being stored in a freeway section, a minor problem already exists in the section when the bottleneck calculation is put into effect. There also is a lag, equal to the travel time from the various upstream ramps to the bottleneck section, between the time the problem is detected and the time the actions taken can have a positive effect. Under severe circumstances, the system cannot catch up until the height of the peak is over. Under other circumstances, the system reduces ramp volumes significantly, severe queues form as the freeway clears, and then the advance queue override dumps traffic onto the freeway. Freeway conditions deteriorate as the queue clears and the system again reduces ramp volumes significantly while the queues build. This cycle tends to be dampened, and the system usually reaches equilibrium. (See "Future Direction," below, on ways to reduce these problems.)

3. The algorithm is very dependent on accurate volume information from the detectors in the field. In some areas of the country with severe weather conditions this may be a significant limitation. However, in the Seattle area, temper-

atures in both winter and summer are relatively mild and our experience with valid detector information in our control areas has been very good.

Advantages of the Algorithm

Despite these limitations, the metering system has been very successful. The advantages of the system are many.

1. The algorithm is well suited to real-time control. The calculations are very simple, but rely on many pieces of data and must be iterated many times quickly. These characteristics make it particularly suited to implementation in real time on minicomputers.
2. The system does not rely on origin-destination data. Although, as mentioned above, this may be viewed as a weak point theoretically, in practice, accurate origin-destination data are some of the most difficult and expensive data to gather. Origins and destinations change over time and from day to day. Having an effective system that does not require this information is advantageous.
3. Control strategies and metering plans do not have to be updated. Capacities do not have to be calculated off line. Therefore, the system requires little effort to keep operating effectively and there is no concern about metering plans aging.
4. The system automatically adjusts for incidents and weather conditions. When an incident occurs, the system operates under the same algorithm but reacts to the reduced capacity caused by the incident. The same situation applies when any condition, such as weather, reduces the operational capacity of the system.
5. Relatively few parameters need to be monitored. Only three parameters per ramp or freeway section need to be calibrated for the bottleneck algorithm—the number of upstream ramps in a section's area of influence, the occupancy threshold for a section to determine if it is operating near capacity, and the weighting factors for each metered ramp. These parameters rarely need to be modified. The minimum and maximum metering rates and the queue adjustment parameters are modified more often. Operators of the system modify these parameters as they are monitoring the system to respond to specific circumstances in the field. All parameters can be modified from the operator's console.

EVALUATION OF THE SYSTEM—METHODOLOGY AND RESULTS

To determine the effectiveness of the ramp control system, an evaluation has been ongoing since the system began operating (*3,4*). The performance of the corridor control system has been evaluated against its overall goal of more efficient movement of traffic within the corridor.

The principle of on-ramp control is to limit the number of vehicles entering the freeway so that the demand on the freeway does not exceed its capacity. The ramp meter should help maintain a stable flow in the freeway lanes. A stable flow minimizes congestion and its consequential shock waves, stop-and-go operation, and resultant loss in service.

Ramp metering has been an effective method of improving freeway operations in the Seattle metropolitan area. Ramp metering temporarily stores vehicles on the ramps to smooth out small peaks in freeway flows. The 22 meters on I-5 cause an average of less than 2 min delay per vehicle using the metered ramps during metering operation. The system has distributed demand among ramps in the system and discouraged short trips. In addition, the meters have encouraged the use of underutilized ramps and arterials.

Between 1981 and 1987, mainline peak period volumes increased about 86 percent northbound and 62 percent southbound. Violation rates at the ramp meters are low, ranging from 0.8 percent to 6.8 percent.

Ramp Delays

Delay is a critical performance measure for any traffic control system. For this evaluation, delay was defined as the difference between free-flow travel time and restricted-flow travel time. Delay was measured by comparing the time a car was in queue to its free-flow travel time from the beginning of the queue to the stop bar. The difference in these two measures was the delay. The Seattle metering system ramp delay study was conducted from April 14 to April 23, 1987.

The average delay at metered ramps was less than 2 minutes per vehicle during the morning and afternoon peak periods. During a one-half-hour period in the morning peak, average delays of 3.2 to 7.4 min occurred on 3 of the 13 ramps. The same ramps produced 5- to 8-min delays when measured in September 1983. Although these ramps produced up to 15-min delays during the first 6 months of operation, modifications in metering parameters and traffic patterns have subsequently reduced delays.

Signal Violations

Each violation of a ramp meter signal is registered by the ramp controller and transmitted to the central computer. The violation rate was found to vary from 0.8 to 6.8 percent for all ramps during 1986. Most violations occurred as the metering signal was first turned on and commuters were adjusting from free-flowing to metered conditions. Violations tended to diminish once a queue was formed.

Mainline Volumes

Mainline traffic volumes were calculated from the average volumes of detector stations spaced along I-5 during the months of September and October 1981 and March and October from 1982 to 1987. The results of the data analysis for the study section during the peak periods from September 1981 through March 1987 showed an 86 percent increase in volumes on northbound I-5 and a 62 percent increase in volumes on southbound I-5 (Table 1).

Not all of the reported volume increase can be attributed to the ramp metering system alone. There has been substantial growth in the urban, suburban, and exurban areas north of downtown Seattle since metering began, creating a much greater demand on I-5. In 1983, concurrent HOV lanes were added to both directions of I-5 in the metered corridor. The accident rate has decreased in the section since metering began. All of these factors have contributed to the increase in peak-period volumes on I-5. However, the contribution of metering to the volume increase cannot be overstated.

Mainline Travel Times

Travel time runs have been made over the years to determine whether any changes have occurred. Each run started at 7:30 a.m., the middle of the peak. Before metering was implemented, it took about 22 min to drive a specific 6.9-mile course from Lynnwood, a suburb of Seattle, to north Seattle. During the first 2 yr of metering, the travel times averaged between 12 and 13 min. In 1984, travel times for the year averaged 11.5 min. No travel time runs were made in 1985; and in 1986, they were made only in June, July, October, November, and December. The average of these travel times was 12.5 min. The only study conducted in 1987 was in September, and the average was 9.5 min (Table 2).

After metering was implemented, travel times showed an immediate and dramatic improvement. Since metering began, the travel times have remained fairly stable although mainline volumes during the morning peak have increased 49 percent. In other words, the mainline travel times have improved while traffic demands in the region have increased.

As with the increased mainline volumes, the improved travel times cannot be wholly attributed to metering. The initial travel time improvement was due primarily to metering. However, the addition of the HOV lanes and the reduced accident rates have contributed to maintaining the stable travel times.

Accident Data

Accident data were gathered for all accidents in the 12.4-mile section of I-5 (from 44th Avenue West to the Ship Canal Bridge, excluding the express lanes). The accident study was conducted during the period from October 1, 1976, to May 31, 1987. Data, matching peak-period flows, were collected on southbound I-5 between 6:00 a.m. and 9:00 a.m. and on northbound I-5 between 3:30 p.m. and 6:30 p.m.

From the premetering period (October 1976 through September 1981) to the latest evaluation period (March 1985 through May 1987), the northbound accident rate during the afternoon peak period dropped from 1.49 to 0.92 accidents per million vehicle-miles, a 38 percent decrease. The average northbound volume during the afternoon metering period increased 86 percent.

Southbound accident rates were lower than northbound rates. One possible reason for this is that southbound traffic consists mostly of commuters who are familiar with the system. Also, northbound traffic in the afternoon is a mix of many types of trips, including noncommuter trips, and the traffic volume on northbound I-5 is higher than that southbound, thereby increasing the drivers' chance of conflicts.

The southbound accident rate during the morning peak period dropped from 1.31 to 0.79, a 40 percent decrease, from the premetering period to the latest evaluation period. The average southbound volume during the morning metering period increased 62 percent. In Table 3, the northbound accident rates during the afternoon peak and the southbound accident rates during the morning peak are shown.

Relative Accident Rates

A comparison of accident experience on I-5 under ramp metering was made with a similar section of I-5 not under ramp control. The comparison section was a portion of I-5 south of downtown Seattle. Accident rates from March 1985 through May 1987 were compared to the 5-yr period just before the implementation of the metering system (1976–1981). The accident rates (accidents per million vehicle-miles of travel) were for the peak direction during peak hours.

For the afternoon peak, the accident rate in the ramp control section declined from 1.49 accidents per million vehicle-miles to 0.92 accidents per million vehicle-miles although there was virtually no change in the comparison section, which had 1.1 accidents per million vehicle miles during both periods (Figure 6).

For the morning peak, both the comparison section and the ramp control section showed a drop in accident rates. However, the ramp control sections showed considerably greater decline in accident rates, from 1.31 accidents per million vehicle-miles to 0.79 accidents per million vehicle-miles, than the comparison section, where accidents declined from 1.1 per

TABLE 1 PEAK PERIOD MAINLINE VOLUME

	Average Mainline Volumes	
Year	SB I-5 6:00 - 9:00 a.m.	NB I-5 3:30 - 6:30 p.m.
Sept. 81	10,685	11,491
81-82	11,550	12,330
82-83	12,210	15,413
83-85	13,038	17,673
85-87	17,267	21,332

TABLE 3 ACCIDENT RATES DURING PEAK PERIODS

	Accident rate per million vehicle miles traveled (MVMT)	
Study Period	NB I-5 3:30 - 6:30 p.m.	SB I-5 6:00 - 9:00 a.m.
10/1/76 - 9/29/81	1.49	1.31
9/30/81 - 3/31/82	1.10	0.93
4/1/82 - 8/28/83	1.08	0.92
8/29/83 - 2/28/85	1.15	1.44
3/1/85 - 5/31/87	0.92	0.79

TABLE 2 SOUTHBOUND TRAVEL TIMES (7:30 a.m.)

	Travel Times (minutes)					
Section Length (miles)	Sept. 1981	Oct. 1981 - Sept. 1982	Oct. 1982 - Sept. 1983	1984	1986	Sept. 1987
6.9	22.8	12.4	13.0	11.5	12.5	9.5

million vehicle-miles to 0.9 per million vehicle-miles (Figure 7).

Not all the reduction in accident rates can be attributed to the metering system. However, the accident rates during the peak periods in the peak direction in the ramp control section of I-5 decreased more than in the comparison section of I-5 south of downtown Seattle. Although there may be other factors contributing to the accident rate reduction, it appears that the metering system is a significant cause of the reduced accident rates.

FUTURE DIRECTION

The future of the SC&DI system holds some significant changes. Two major programs currently in progress will have major impacts on the system. The first is the reconstruction of I-90. This project will add 450 loops to the existing 900. It will also add 75 new CCTV cameras, 15 VMSs, 30 ramp meters, and 25 data accumulators. These additions to the system do not include 90 miles of SC&DI systems to be added on other area freeways. The existing computer system does not have the capacity to accommodate these additions. As a result, the I-90 reconstruction project will involve replacing the existing TSMC central control system, including both hardware and software.

New software is being redesigned in a modular format to allow as much flexibility as possible. The new software will provide a "slot" in the decision tree to allow easy implementation of any new algorithm. A new algorithm will be tested on-line and the new software will be capable of easily activating or deactivating this slot in the decision tree. This feature will allow the software to be debugged and adjusted without significant programming changes. This same software philosophy will be used throughout the new system, allowing for easy implementation and experimentation with other types of algorithms such as incident detection.

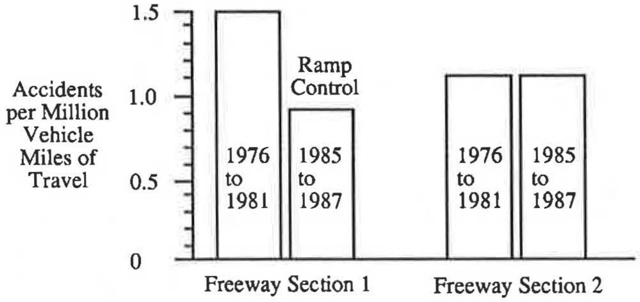

FIGURE 6 Relative accident rates—afternoon peak period.

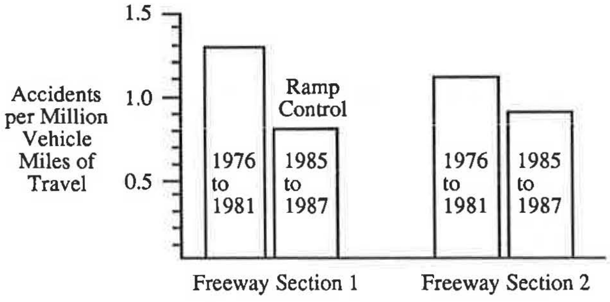

FIGURE 7 Relative accident rates—morning peak period.

In addition to the hardware and software upgrade described above, work is under way as part of the WSDOT's Freeway and Arterial Management Effort (FAME) research program to investigate ways to improve the existing metering algorithm. Researchers hope that by employing a predictive algorithm, they can overcome the time lag limitation mentioned above. By predicting traffic conditions 1 to 2 min in the future, the system could better anticipate conditions and reach an equilibrium state more quickly and smoothly.

Another modification to be investigated is the performance of the advance queue override check before any other metering rates for the ramps are calculated. Any ramps in the advance queue override will not undergo any other metering rate calculations and will be flagged to be dropped from consideration in the bottleneck metering rate calculation. This modification will allow the entire upstream ramp volume reduction to be distributed over only those ramps whose metering rates can be reduced, making the system more responsive to actual traffic conditions.

The TSMC redesign and the FAME project are not directly related. However, both programs are progressing with the goals of the other program in mind so that they can be easily integrated into a single final product.

SUMMARY

The existing real-time ramp-metering system in the Seattle area uses an integrated traffic-responsive metering algorithm. The algorithm is simple in its approach but very effective in its application. The system has proven to be effective in a series of ongoing evaluations.

WSDOT is expanding the system and upgrading hardware and software. Research efforts are under way to improve the efficiency of the algorithm employed.

The software for the new computer system will be structured to allow incorporation of newly developed metering algorithms. As new algorithms are developed, this new system will easily be able to use them and test their effectiveness. This system will prove to be a very valuable tool in the overall, nationwide effort to develop advanced freeway management systems.

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Publication of this paper sponsored by Committee on Freeway Operations.

Evaluation of Operational Effects of Freeway Reconstruction Activities

JIANFEI ZHANG, LANNON LEIMAN, AND ADOLF D. MAY

To better evaluate the operational effects of freeway maintenance/reconstruction activities, a new methodology has been developed. This methodology takes traffic demand, freeway geometry, and maintenance/reconstruction plans as input and uses the modified FREQ simulation model, FREQ10PC, to quantitatively predict freeway performance under different maintenance/reconstruction plans. Then a comprehensive evaluation of these plans can be carried out based on the predicted measures of performance. This paper describes the new methodology, the FREQ model, its modification and verification, and a literature search and survey of experts on freeway capacities through work zones. Descriptions of two major applications of the methodology, one for the San Francisco–Oakland Bay Bridge and the other for Interstate 80 (I-80) northeast of that bridge, are provided. The Bay Bridge application was designed to assess the operational effects of different maintenance plans, and the I-80 application was used to evaluate the traffic impacts of different nighttime lane closure alternatives during reconstruction activities. The results reveal that operational effects are extremely sensitive to lane closure schedules and plans and to freeway design elements. The results also show that the new methodology is effective in evaluating operational effects of freeway maintenance/reconstruction activities.

The traffic intensity on freeways, particularly in urban areas, continues to increase at a rapid rate, and near-capacity conditions occur for many hours of the day. At the same time, as the freeway system grows older, the need for and the extensiveness of maintenance activities and reconstruction work also have increased. The FHWA (*1*) reported that in 1983 less than 3 percent of the urban Interstate highways needed major reconstruction, but by the year 2000 more than 40 percent of Interstate highways will need such work. Thus, it will become more and more difficult to schedule and safely carry out freeway maintenance and reconstruction projects while at the same time providing a reasonable level of service to motorists.

Increasing traffic demand makes the freeway system more and more unstable. The public is becoming increasingly sensitive to traffic congestion. It is almost impossible to schedule a maintenance/reconstruction activity without causing at least some adverse impacts on traffic. It is therefore important to develop a quantitative method to estimate the traffic impact caused by freeway maintenance/reconstruction activities. With such a method, highway operation and construction engineers can compare traffic impacts of different maintenance/reconstruction plans and select the plan that will cause least traffic interruption and at the same time meet the requirements of the maintenance and reconstruction activities.

One of the disadvantages of current manual methods used to evaluate maintenance/reconstruction plans is that they do not have a comprehensive way to quantify the traffic impacts. A traditional plan is generated as follows: on the basis of current traffic data, traffic operation engineers generate several maintenance/reconstruction plans and estimate the queue length and delay caused by these plans. If the queue length caused by a plan is within tolerance, the plan will be regarded as a possible choice to construction engineers. This method has several shortcomings:

1. Only a short segment of the freeway section can be taken into consideration,
2. Only a few measures of performance can be estimated, and
3. Different plans cannot be easily compared.

This study has attempted to develop an improved methodology that will allow traffic operation engineers and construction engineers to quantitatively estimate measures of performance of a freeway under proposed maintenance/reconstruction plans through computer simulation, thereby overcoming some of the previously mentioned shortcomings. The objectives of this study were (a) to enhance the functions of the existing freeway simulation model FREQ so that it can be used in simulating temporary capacity changes caused by maintenance/reconstruction activities, (b) to verify the modified model predictions, (c) to determine reduced capacities in freeway work zones through a literature search and a survey of experts, and (d) to apply the methodology in evaluating freeway maintenance and reconstruction activities. This improved methodology has the following special features:

1. A more comprehensive and systematic approach,
2. Ability to include ramp control and diversion,
3. Ability to handle oversaturated and multibottleneck situations,
4. Ability to predict more measures of performance, and
5. Easy sensitivity analysis.

METHODOLOGY

Maintenance/reconstruction activities affect traffic mainly through capacity reductions in the work zones. The new methodology is a demand-and-supply analysis approach. In this analysis, the demand side is the origin-destination (O-D) demand pattern along the freeway section being analyzed, and the supply side comprises the freeway design features and

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related capacities. When there is work activity on the freeway section, supply diminishes because of reduced work-zone capacities and the demand side may change when a ramp control plan is implemented. A computer simulation model is employed to predict freeway performance resulting from such changes in supply. The supply (capacity) may be diminished only slightly, for example, by repair work on the shoulder, which requires minor narrowing of the adjacent traffic lane, or more drastically, as when one or more lanes are completely closed. The reduced-capacity effect is reported in the *Highway Capacity Manual* (*2*) and has been discussed in other literature (*3*). An additional consideration is when this supply reduction applies—the fairly exact period during which a lane is encroached upon or closed. In this report, only complete lane closures are dealt with, but the method applies equally to less-capacity-reduction situations.

In the evaluation of operational effects of work activities, usually a fairly long freeway section is analyzed. In addition to containing the site where the work activities are located, the freeway section must also include upstream potentially congested subsections as well as downstream affected subsections. The freeway section is then broken into homogeneous subsections. The traffic demand on every on-ramp and off ramp as well as on the main line at the first and last subsections are obtained from field studies. Then the capacity of each subsection is estimated. The capacity of a subsection without influence of work activity is regarded as the basic capacity of that subsection. When there is work activity on one or more subsections, the capacities on those subsections will vary during the day depending on the types of encroachments and, particularly, on the lane closure plans. A demand-and-supply analysis is then carried out by using a computer simulation model. The main output results of this analysis include (a) travel time, (b) travel distance, (c) average speed, (d) mainline delay, (e) ramp delay, (f) emissions, (g) fuel consumption, (h) optimum ramp metering plan, (i) short-trip and long-trip diversion, and (j) modal response.

FREQ SIMULATION MODEL—MODIFICATIONS AND VERIFICATION

The FREQ freeway simulation model (*4*) was selected because of its wide-scale use, the ease of modifying it for this study, and its familiarity to the research team and California Department of Transportation (CALTRANS), one of the research sponsors. In addition, the PC version of the model is user friendly and menu driven. It also has an interactive data processor.

The FREQ simulation model uses a macroscopic deterministic approach that assumes that freeway operations can be simulated by ignoring the actual randomness of traffic demand and the behavior of individual vehicles. The simulation model is structured based on the following assumptions:

- Time is broken into equal discrete time slices with demands and capacities remaining constant during each time slice.
- The freeway is divided into subsections that can be considered as discrete homogeneous segments in terms of demands and capacities.
- Traffic is modeled by analogy with a compressible fluid, ignoring the idiosyncrasies of individual drivers.
- Traffic demand propagates downstream instantaneously when it does not encounter bottlenecks.
- Merging and weaving analysis, when selected by the user, will follow the 1965 *Highway Capacity Manual* procedures.
- Freeway congestion can only begin and end at boundaries between time slices.

The FREQ simulation model can undertake three levels of analysis. The first level is the simulation, in which the user specifies input regarding time-slice traffic demands, subsection freeway geometric designs, subsection capacities, and ramp control plans. These inputs are then used to predict the traffic performance. This level of analysis can be used to evaluate an existing situation and provide a basis for later comparisons and/or for calibration with field-measured performance.

In the second level of analysis, the first level is used, and also a linear programming decision model is engaged to generate an optimum ramp metering plan. With this plan implemented, the simulation model is then again engaged and the traffic performance is predicted under controlled conditions. Differential performance tables and graphs are provided to evaluate the effect of the ramp metering plan without traveler response.

In the third level of analysis, the second level is used, and also a traveler response algorithm, which interacts with the simulation and the decision models to obtain equilibrium under controlled conditions, is employed. Differential performance tables and graphs are provided to evaluate the combined effects of control and traveler responses.

The modeling of operational effects of freeway work activities is a complex task. The most recent version of the FREQ simulation model before this study, the FREQ8PC model, can handle many of the required functions. For example, without modification, the FREQ8PC model can simulate the "before" situation, that is, simulate the existing situation without the freeway work activity. The FREQ8PC model also predicts many measures of effectiveness over time and space needed to evaluate the operational effects of work activities. These measures include (a) travel times, (b) speeds, (c) delay, (d) queue lengths, (e) queue duration, (f) fuel consumption, and (e) emissions of pollutants.

Thus the major modification task was to incorporate the temporary capacity reductions caused by work activity into the freeway model, essentially requiring that the capacity of subsections of the freeway be changed over time and space. The FREQ8PC model already permitted capacity to be changed over space, but not over time. Another required modification was to increase the number of time slices from 20 to 24. This requirement was due to the interest in nighttime freeway work scheduling and permits the analysis of complete 24-hr cycles. An additional major modification in the FREQ model provides the user greater flexibility in requesting specific output results for the application being considered. These modifications produced a new generation of FREQ—FREQ10PC, which can simulate temporary work-zone-capacity reductions as well as incidents.

Extensive testing has been carried out to verify the modified FREQ simulation model. Verifications were accomplished through previous model calculations and manual calculations. The results of these verifications show that the modified model works properly and gives similar results compared with earlier versions of the model and the manual calculations based on traffic theory.

LITERATURE SEARCH AND SURVEY OF EXPERTS FOR CAPACITIES THROUGH WORK ZONE

Determining the capacities through freeway work zones is a basic issue in estimating the operational effects of work activities. Such activities on freeways affect traffic mainly by reducing capacities at the work sites whether or not these activities involve lane closures. Some of the efforts of this study were devoted to estimating such capacity reductions via literature search and experts' assessment.

An on-line campus library computer search found that although there are many studies on freeway construction areas, there is very little research on the capacity through work zones. Chapter 6 of the 1985 *Highway Capacity Manual* (*2*) suggested capacity values through work zones. Dudek and Richards's study (*3*) is probably the most complete on this subject. Some of the results found in this paper are also reflected in the 1985 *Highway Capacity Manual*. Kermode and Myyra (*5*) attempted to correlate capacities with types of construction activities. A few other articles, such as the one by Eudash and Bullen (*6*), also discussed capacities through work zones.

Many factors affect capacities through work zones. At the microscopic level, factors such as alignment, grade, and percentage of trucks will affect the capacity (*3*). At the macroscopic level, the lane capacity of a freeway depends on the type of operations (*5*), the total number of lanes and the number of lanes open to traffic (*3*), and whether the work is being done during the day or at night. Experts at the Construction Division of CALTRANS District 4 report that nighttime operations have a greater impact on reducing capacity than daytime operations, due to strong lights and motorists' uncertainty about the construction site. Mathematically, the capacity through work zone can be expressed as

$$C_w = f(C_b T,\ N_{td},\ N_o,\ \text{Time})$$

where

C_w = capacity through work zone per lane per hour,
C_b = basic capacity,
T = type of work,
N_{td} = total number of lanes in the operation direction,
N_o = number of lanes opened to traffic, and
Time = day or night.

Different types of maintenance/reconstruction operations have different effects on capacity. Kermode and Myyra mentioned five maintenance-oriented types of operations:

- Median barrier or guardrail repair;
- Pavement repair, mudjacking, pavement grooving;
- Stripping, resurfacing, slide removal;
- Pavement markers; and
- Middle lanes—any reason.

Before Dudek and Richards's study, it was mentioned by experts that many operators used 1,500 vehicles per hour per lane (vphpl) as the freeway capacity through work zones. Dudek and Richards, through field studies, found that the capacities vary between 1,000 vphpl and 1,600 vphpl depending on the total number of lanes in the operating direction, the number of lanes open to traffic, and the types of work.

Kermode and Myyra in CALTRANS District 7 related the work-zone capacities to the type of maintenance/reconstruction operations.

After the literature search, a three-dimension capacity matrix was developed based on suggested work-zone capacities in the 1985 *Highway Capacity Manual* and the results of the studies by Dudek and Richards, Kermode and Myyra, and other researchers. Interpolation and extrapolation were used in developing certain aspects of this matrix. This matrix table was sent to members of the Committee on Freeway Operations of the Transportation Research Board and to 10 experts at CALTRANS for their assessments and comments. A significant number of responses were received. However, it should be noted that there were considerable differences in estimated capacity reductions among the respondents. Table 1 summarizes the best estimation of lane capacity values for different lane configurations and types of maintenance and reconstruction activity based on available literature and expert opinions. Because these values are only approximate, particularly considering varied expert opinions, and yet critical in predicting the effects of maintenance and reconstruction activity, further research is recommended as a high priority.

OAKLAND BAY BRIDGE APPLICATION

The San Francisco–Oakland Bay Bridge, the busiest bridge in the San Francisco Bay area, connects San Francisco with the East Bay area (Figure 1). The arrow in the figure shows the westbound direction. Figure 2 shows schematically the route and maintenance characteristics for the westbound deck. Both Origin 1 and Origin 2 are located in the toll plaza: Origin 1 is the entrance for high-occupancy vehicles, which have priority; Origin 2 is the entrance for nonpriority vehicles. During the morning peak period, Origin 2 is metered.

On the westbound deck, congestion normally begins at about 6:45 a.m. and ends at around 9:00 a.m. A secondary peak begins around 4:00 p.m. and ends at 6:00 p.m. The level of service is D or worse during much of the day. There is maintenance work on the bridge almost every day. Under such conditions an appropriate, carefully designed maintenance plan may save thousands of hours of motorists' travel time, whereas an inappropriate plan may cause massive congestion on or upstream of the bridge.

Westbound maintenance work usually begins after traffic flow in this direction diminishes to 6,600 vehicles per hour. According to experts at the bridge operation office, capacities throughout the bridge are reduced by 2,300 vehicles per hour during maintenance time. The maintenance work ends at 4:00 p.m., just before the afternoon peak traffic flow occurs. The bridge maintenance engineers, who are concerned with efficient use of time, prefer that the maintenance work start at 9 a.m. However, traffic operation engineers, who are concerned with the traffic flow, prefer that the maintenance work start at 10 a.m. Traffic engineers must also determine whether ramp control should be implemented.

The Bay Bridge application was designed to estimate the traffic impacts of different maintenance and ramp control

TABLE 1 SUGGESTED RESULTING LANE CAPACITIES FOR SOME TYPICAL MAINTENANCE AND RECONSTRUCTION ACTIVITIES

No. of Lanes		Types of Work*						Average
Normal	Open	1	2	3	4	5	6	
2	1	1400	1400	1250	1200	1200	1350	1300
	2***	1650	1650	1650	1650	1650	1650	1650
3	1	1300	1050	1050	1050	1100	1350	1150
	2	1550	1500	1400	1300	1200	1300	1350
	3***	1700	1700	1700	1700	1700	1700	1700
4	1	1300	1050	1050	1050	1100	1350	1150
	2	1550	1500	1400	1300	1200	1300	1350
	3	1550	1500	1300	1300	1200	1300	1350
	4***	1750	1750	1750	1750	1750	1750	1750
5	1	1300	1050	1050	1050	1100	1350	1150
	2	1550	1500	1400	1300	1200	1300	1350
	3**	1600	1550	1450	1400	1300	1400	1450
	4**	1700	1650	1550	1450	1350	1450	1500
	5***	1800	1800	1800	1800	1800	1800	1800

* Types of work are:

1. Median barrier/guardrail repair or installation
2. Pavement repair
3. Resurfacing, asphalt removal
4. Stripping, slide removal
5. Pavement markers
6. Bridge repair

** Data are not available. The capacity values are based on the values immediately above with a 6 percent increase.

*** Data are not available. The values are based on authors' judgment.

plans. Six situations were simulated: (a) existing conditions without ramp control, (b) maintenance activity beginning at 9 a.m. without ramp control, (c) maintenance activity beginning at 10 a.m. without ramp control, (d) existing conditions with ramp control, (e) maintenance activity beginning at 9 a.m. with ramp control, and (f) maintenance activity beginning at 10 a.m. with ramp control.

The results of this application are the measures of traffic performance under different control strategies and different maintenance plans. Total travel time, the most important of these measures of performance, is listed in Table 2 for each of the situations was studied. Table 2 shows that when there is no maintenance on the bridge and when the operational strategy is changed from no control (Situation A) to control with a metering plan generated by the FREQ model (Situation B), total travel time decreases considerably. Whenever there is maintenance activity on the bridge (Situations A1, A2, B1, and B2), total travel time increases significantly in comparison with total travel time under existing conditions (Situations A and B). When there is no ramp control and maintenance begins at 10 a.m. (Situation A2) instead of at 9 a.m. (Situation A1), 251 vehicle-hours are saved. When ramp control is implemented and the maintenance activity begins at 10 a.m. (Situation B2) instead of at 9 a.m. (Situation B1), 1,929 vehicle-hours are saved. Additional comparisons can be made between situations where maintenance activity begins at the same time but ramp control strategy is changed from no control to control (i.e., between Situations A1 and B1 and between Situations A2 and B2). Figure 3 graphically demonstrates the changes in total travel time between each of the different

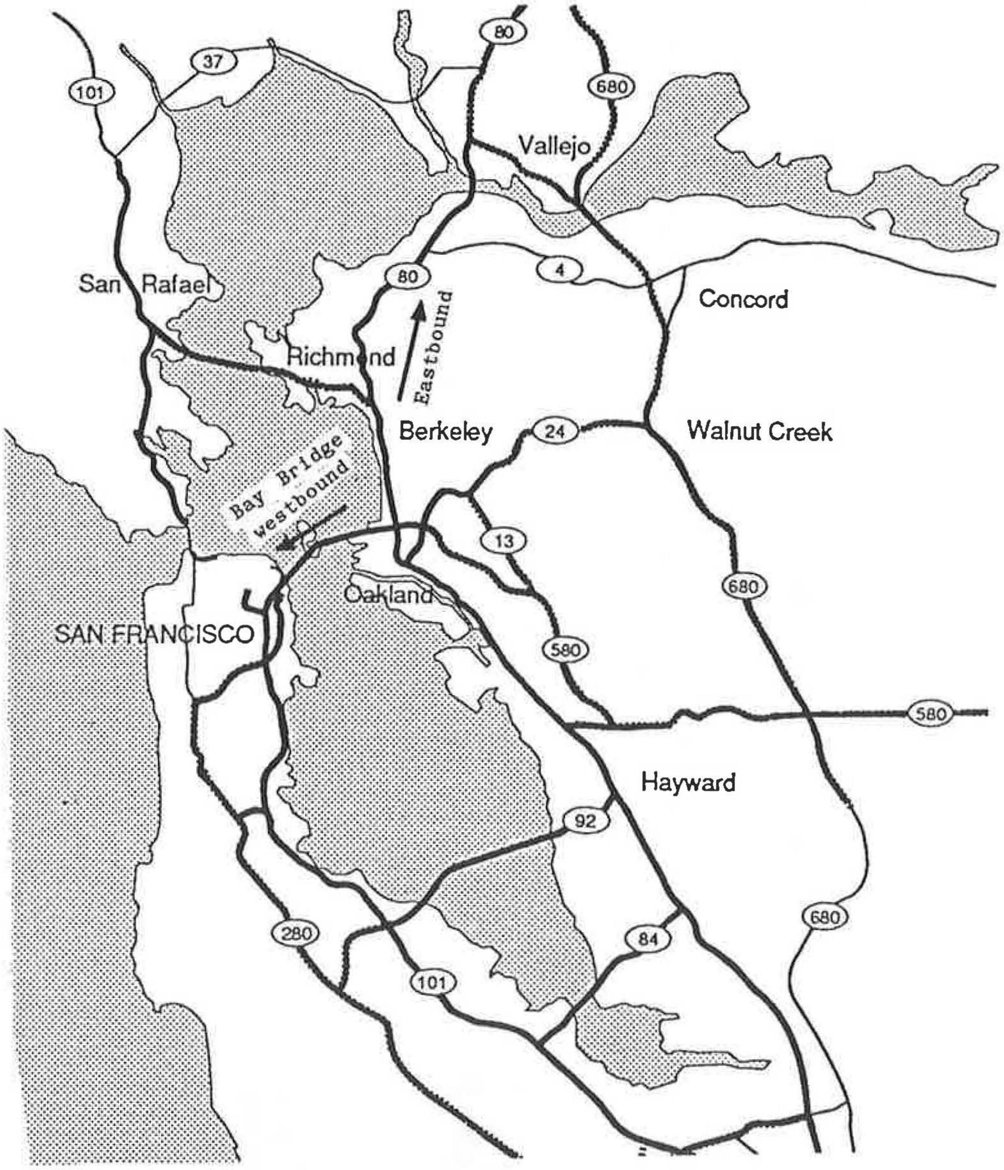


FIGURE 1 Location of application sites.

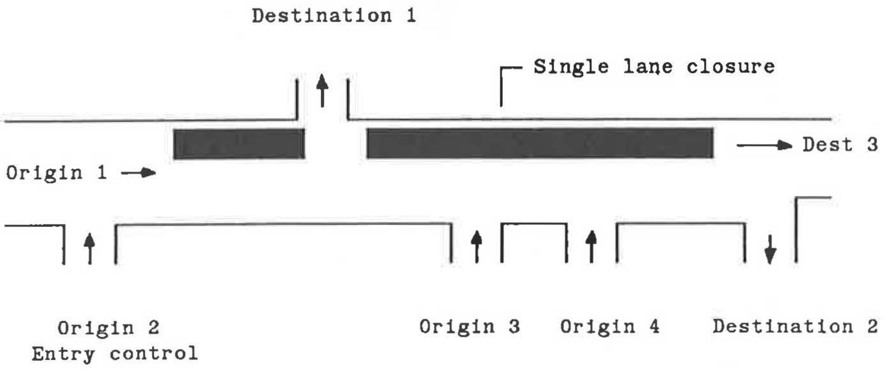


FIGURE 2 Route and maintenance characteristics for Bay Bridge.

TABLE 2 TOTAL TRAVEL TIME AND ITS CHANGES UNDER DIFFERENT CONTROLLING STRATEGIES AND DIFFERENT MAINTENANCE SCHEDULES

Measure of Performance	Situations			Changes		
	A	A1	A2	A1-A	A2-A	A2-A1
Total Travel Time	13951	18707	18456	4756	4505	-251
	B	B1	B2	B1-B	B2-B	B2-B1
Total Travel Time	13433	17299	15370	3866	1937	-1929

** Following situations were simulated:

- A - existing conditions without control
- A1 - maintenance activity from 0900 to 1600 without ramp control
- A2 - maintenance activity from 1000 to 1600 without ramp control
- B - existing conditions with ramp control (The ramp control plan was generated with FREQ model.)
- B1 - maintenance activity from 0900 to 1600 on the bridge with ramp control (The ramp control plan was generated with FREQ model.)
- B2 - maintenance activity from 1000 to 1600 on the bridge with ramp control (The ramp control plan was generated with FREQ model.)

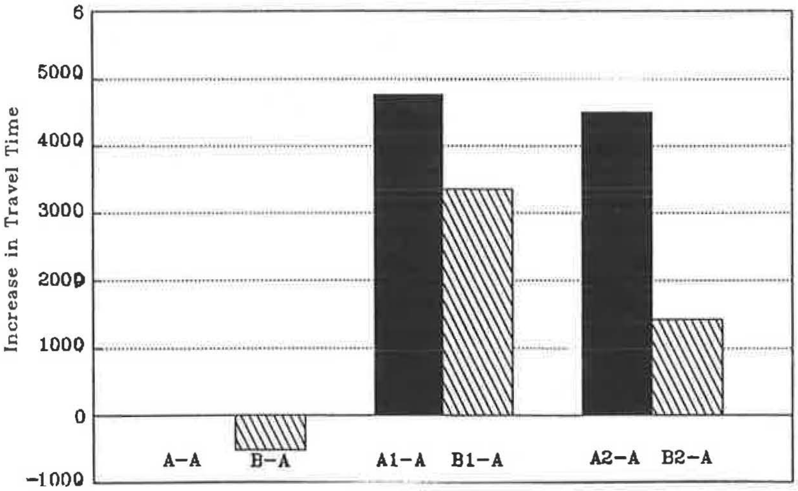


FIGURE 3 Changes in travel time under different maintenance and control plans.

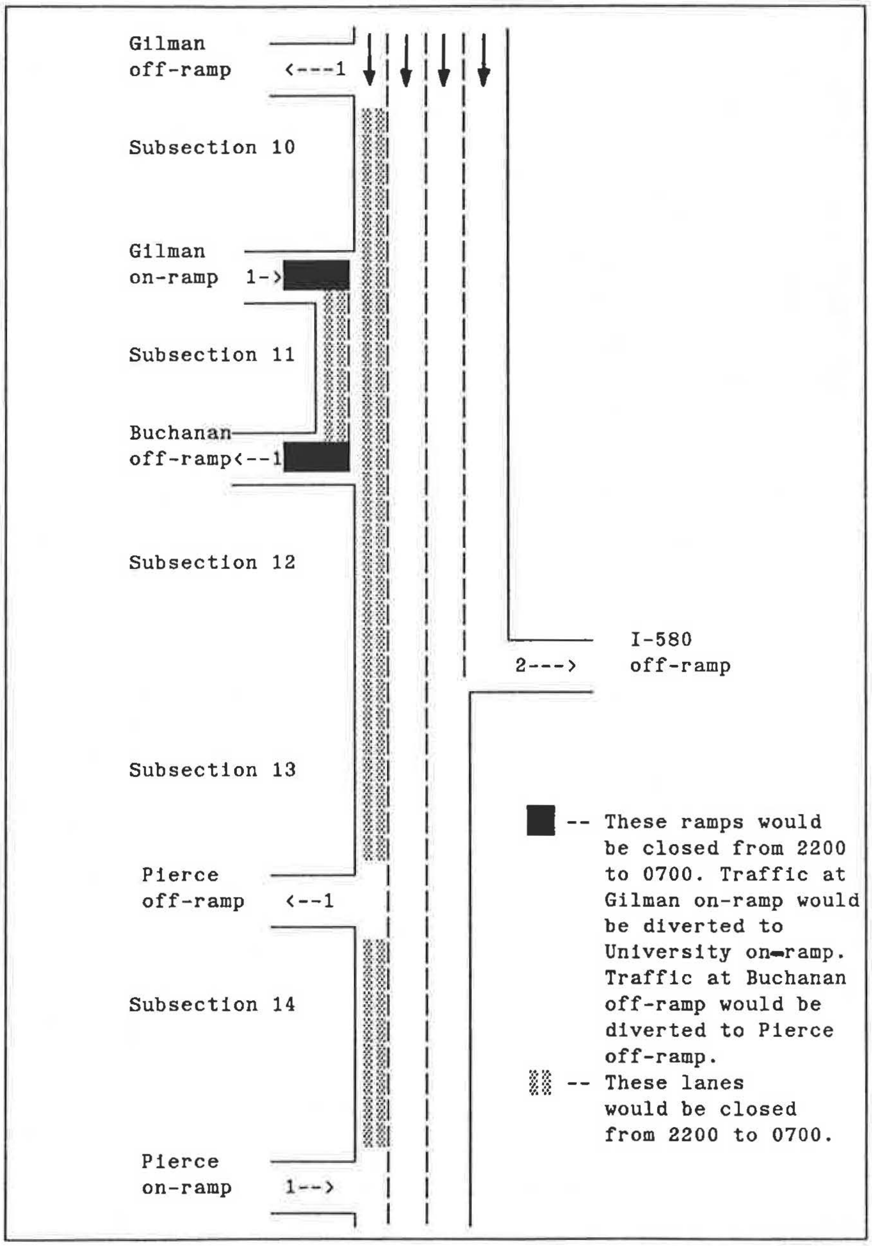
situations as compared to the total travel time under existing conditions without maintenance activities and without ramp control (Situation A). Using this measure of performance, the traffic and construction engineers can better evaluate these maintenance and control plans and select the best maintenance and control plan for the bridge.

INTERSTATE 80 APPLICATION

I-80 crosses the San Francisco Bay via the Bay Bridge, then passes by a series of suburban cities en route to the Carquinez Bridge and beyond (Figure 1). The study section starts at the Bay Bridge toll plaza and ends at the Willow off-ramp. The arrow line along I-80 in Figure 1 indicates the eastbound direction. In 1987, two-direction annual daily traffic between the Bay Bridge toll plaza and the Willow off-ramp was from 91,000 to 280,000 vehicles, depending on the location. Previous data and field studies show that on a typical weekday, there is no congestion eastbound during the morning peak period, but that the afternoon peak period congestion starts at 3:30 p.m. and lasts approximately 3 hours until 6:45 p.m.

Beginning in spring 1989, two major construction projects will be in progress on eastbound I-80: the construction of the I-80/I-580 interchange in Albany and construction of sections of a high occupancy vehicle lane from the Bay Bridge toll plaza to the Willow off-ramp. A serious concern about these two projects is their adverse impact on traffic.

The I-80 application was designed to estimate the eastbound traffic impact of the I-80/I-580 interchange construction. This construction site location is also illustrated in Figure 1. The entire analysis section (from the toll plaza to the Willow off-ramp) is 16.15 miles long and was divided into 40 subsections. During construction hours, some of the lanes in Subsections 10, 11, 12, 13, and 14 would be closed. Traffic and construction engineers at CALTRANS District 4 developed five different lane closure alternatives for the construction site as shown in Figures 4–8.



■ -- These ramps would be closed from 2200 to 0700. Traffic at Gilman on-ramp would be diverted to University on-ramp. Traffic at Buchanan off-ramp would be diverted to Pierce off-ramp.

▨ -- These lanes would be closed from 2200 to 0700.

FIGURE 4 Lane closure plan—Alternative 1.

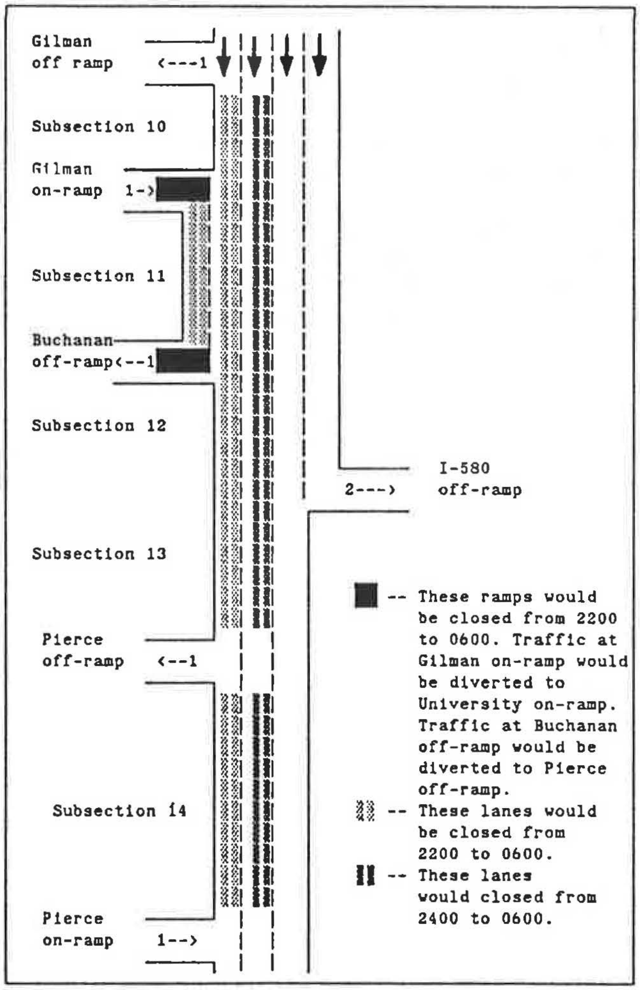


FIGURE 5 Lane closure plan—Alternative 2.

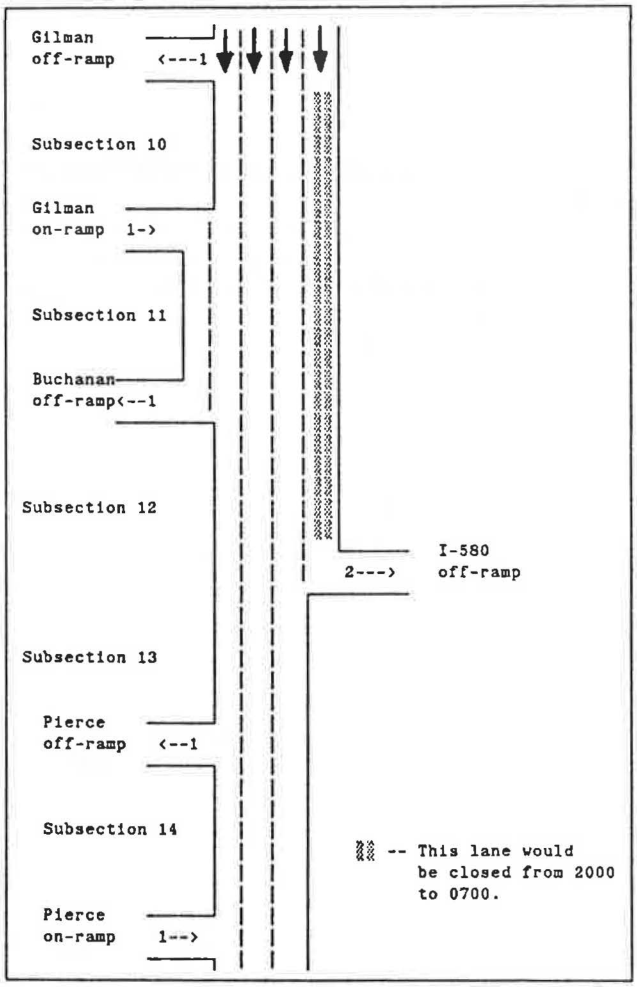


FIGURE 6 Lane closure plan—Alternative 3.

The traffic impact analysis of this construction project includes (a) simulations of the existing conditions and the lane closure alternatives, (b) a sensitivity study of capacity reduction values, and (c) evaluations of the lane closure alternatives. Five measures of performance and their changes were estimated in this analysis:

1. Queue status at, and upstream of, the construction site;
2. Changes in total travel time due to construction activities;
3. Changes in average speed due to construction activities;
4. Changes in fuel consumption due to construction activities; and
5. Changes in emissions due to construction activities.

A volume/capacity (V/C) ratio diagram was also predicted.

Table 3 illustrates the operational effects under different lane closure alternatives. Alternatives 1, 2, 4, and 5 will cause the formation of queues during the lane closures. The total travel time will increase while the average speed will decrease in comparison to the existing conditions in which no lane is closed. Alternative 3 will have only small adverse effects on traffic flow. The total travel time will increase slightly. The average speed will remain the same as the average speed under existing conditions. The fuel consumption will decrease slightly. Alternative 3 seems to be the best lane closure plan because it has the least traffic flow interruption.

Figure 9, the V/C ratio diagram under existing conditions, shows the V/C over time of day and over space. The horizontal axis represents the subsection location and the vertical axis represents time of day. Figure 9 is very useful because it also shows the system's excess capacity for given times and locations. Using this information, a lane closure contour map was generated (Figure 10). This lane closure contour map indicates the number of lanes that can be closed for given times and spaces without causing queue formation. Figure 10 demonstrates an alternative to the CALTRANS approach and should be treated separately.

Because there is uncertainty about the real capacities through the construction site, the question arises: What happens if the capacities are lower than those that have been used in the simulation of lane closure alternatives? To answer this ques-

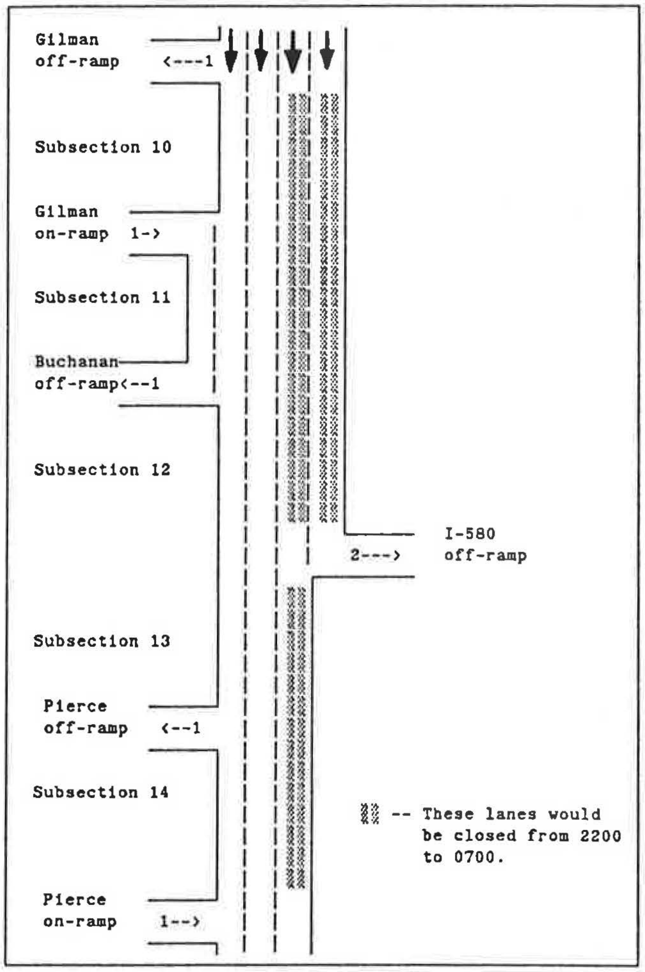


FIGURE 7 Lane closure plan—Alternative 4.

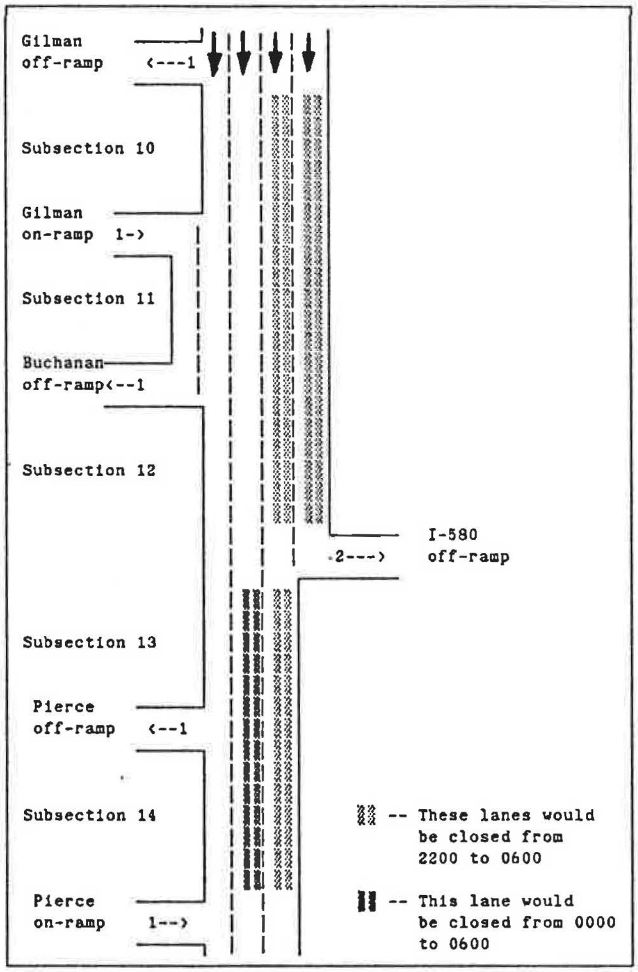


FIGURE 8 Lane closure plan—Alternative 5.

tion, a capacity reduction sensitivity study was carried out to test how the three major measures of performance—the queue length, queue duration, and total travel time—vary with changes in capacities through the work zone. In the sensitivity study, lane closure Alternative 3 was selected as a basic condition. Then five hypothetical work-zone capacity situations were tested. These hypothetical capacity situations were the capacities through work zone equal to 100, 90, 80, 75, and 70 percent of the work-zone capacities that were used in the simulation of lane closure Alternative 3.

Figures 11–13 show the results of the capacity reduction sensitivity study. If the capacities through the construction site decreased by 10 percent, there would be no obvious change in measures of performance. If the capacities decreased by 20 percent, there would be a big increase in total travel time. The average speed would decrease. Further decreases in capacity would worsen the traffic flow on the freeway. Hence, if the uncertainty of the capacity is within 10 percent, Alternative 3 is still a confident choice. Beyond 10 percent, there is a big risk of underestimating the adverse effects of the construction activities on traffic flow.

SUMMARY

This study has developed an improved methodology for the evaluation of operational effects of freeway maintenance/reconstruction activities. This improved methodology can quantitatively estimate the measures of freeway performance under different lane closure plans and thus provide a basis for traffic and construction engineers to evaluate various lane closure strategies. Two applications of this method have been demonstrated. The results of the applications show that operational effects are very sensitive to lane closure plans and freeway design elements. The results also reveal that this new method is effective in evaluating the operational effects of freeway maintenance/reconstruction activities.

Although this study has provided an improved methodology for evaluating operational effects of freeway maintenance/reconstruction activities, additional research in the following areas is still needed:

1. Further study of capacity reductions through work zones. As mentioned earlier, the capacity values through work zones

TABLE 3 MEASURES OF PERFORMANCE AND THEIR CHANGES UNDER DIFFERENT LANE CLOSURE ALTERNATIVES

Simulations**		Measures of Performance				
		Maximum Queue Length at Constr. Time (Mile)	Queue Duration (Hour)	24 Hour Total Travel Time (V-H)	24 hour Average Speed (MPH)	24 Hour Fuel Consump. (Gal)
0		0	0	25193	45.6	64571
1	Value	0.8	3	25321	45.4	64642
	Delta*	0.8	3	128	-0.2	71
2	Value	1.3	6	25808	44.6	64924
	Delta*	1.3	6	615	-1.0	353
3	Value	0.0	0	25206	45.6	64542
	Delta*	0.0	0	13	0.0	-29
4	Value	1.3	7	26514	43.2	65291
	Delta*	1.3	7	1321	-2.4	720
5	Value	1.3	5	26304	43.6	65078
	Delta*	1.3	5	1111	-2.0	507

* "Delta" denotes the changes in measures of performance in comparison to simulation 0

** Following simulations were made:

0 - existing condition
1 - lane closure alternative 1
2 - lane closure alternative 2
3 - lane closure alternative 3
4 - lane closure alternative 4
5 - lane closure alternative 5

are very critical to the operational effects and yet there are only a few studies dealing with this issue. Further research in this area should be a high priority.

2. Modification of the FREQ model to allow for a different set of speed V/C ratio curves through the work zone. In this study, only one set of speed V/C ratio curves was used for each application due to the limitations of the FREO model.

3. Field validation of the new methodology. This study, due to limited time and funding, was not able to validate the new methodology by field studies.

4. Generation of a maintenance/reconstruction plan using the FREQ model. This study demonstrated an alternative approach for scheduling maintenance/reconstruction activities by using a V/C contour map to generate lane closure plans.

5. Generation of entry control strategies by the FREQ model. The FREQ model can be used to generate ramp control plans during maintenance/construction time.

ACKNOWLEDGMENT

The authors would like to acknowledge the persons and institutions whose help has contributed to the completion of this paper. Financial assistance from the California Office of Traffic Safety via the California Department of Transportation has made this research project possible. The authors also would like to thank Linn Ferguson and Phil Jang at CALTRANS headquarters, James MaCrank, Albert Yee, James Siebe, and Hilmer Forsen at CALTRANS District 4, and Jeff Georgevich at the Metropolitan Transportation Commission for their interest and attendance at the advisory meetings. Especially, the authors would like to thank Wolfgang Homberger, Assistant Director of the Institute of Transportation Studies, University of California at Berkeley, who reviewed the draft of this paper and gave many valuable suggestions.

CONTOUR DIAGRAM OF
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BEFORE OPTIMIZATION

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THE DIGIT LEVELS DENOTE V/C IN VALUES FROM 0 TO 10 (CORRESPONDING TO 0.0 TO 1.0). THE ASTERISK DENOTES SATURATION.

FIGURE 9 The volume/capacity ratio diagram under existing conditions.

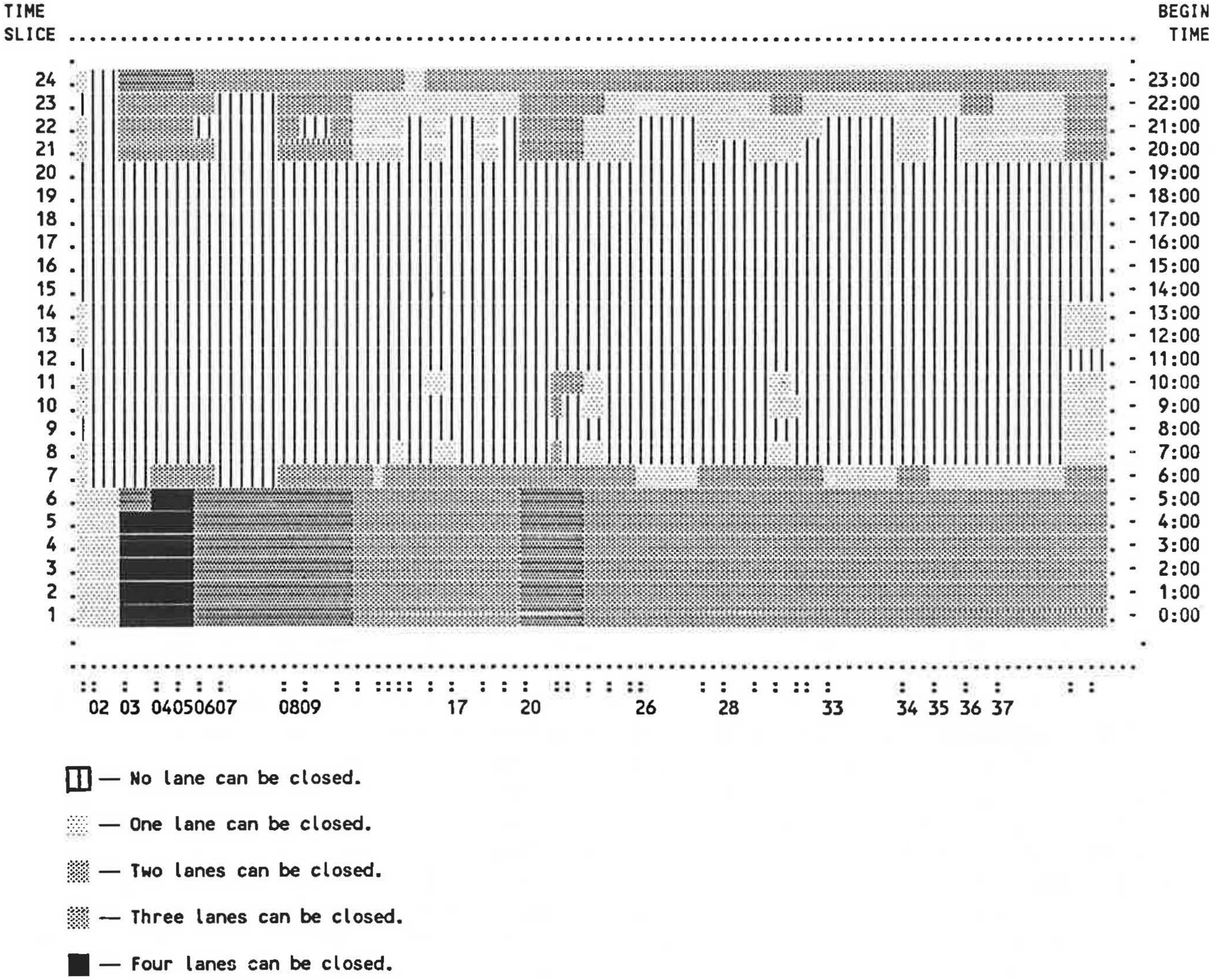

FIGURE 10 Lane closure contour map.

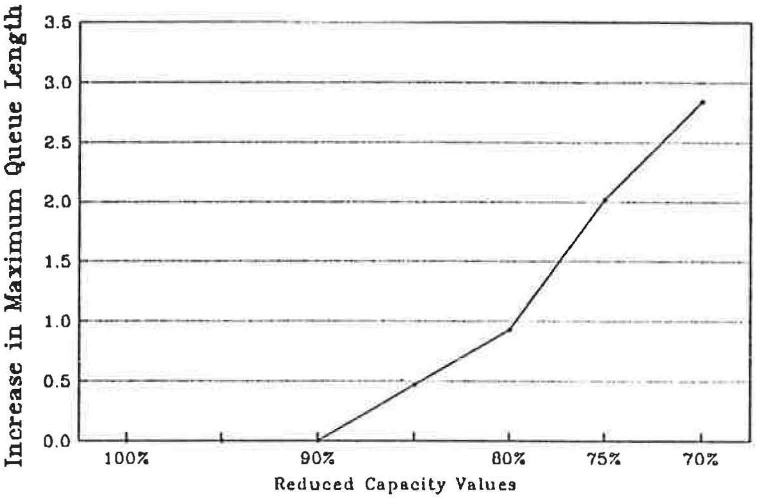

FIGURE 11 Increase in maximum queue length (miles).

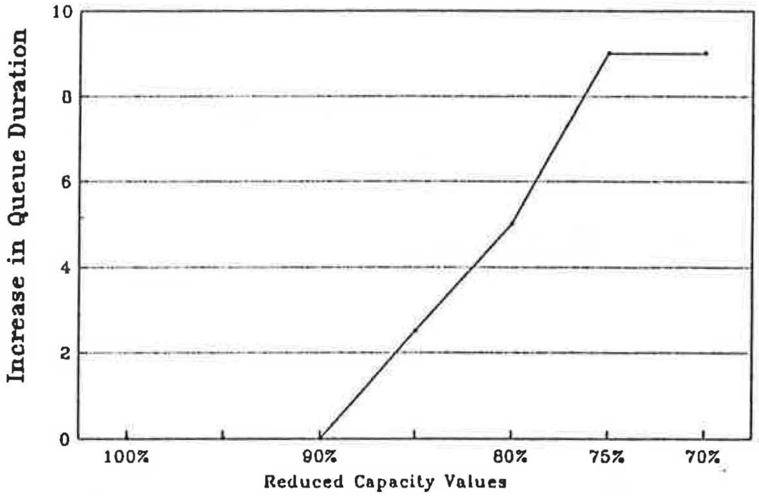

FIGURE 12 Increase in queue duration (hours).

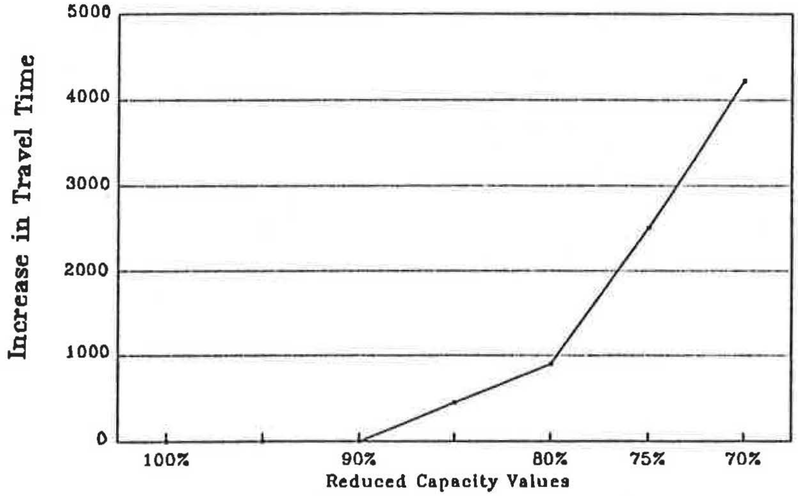

FIGURE 13 Increase in travel time (vehicle hours).

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Publication of this paper sponsored by Committee on Freeway Operations.

Synthesis of Traffic Management Strategies for Urban Freeway Reconstruction Projects

RAYMOND A. KRAMMES AND GERALD L. ULLMAN

Managing traffic during an urban freeway reconstruction project is a significant and complex problem. Fortunately, the planning efforts for future projects can benefit from the traffic management experiences from a number of successfully completed reconstruction projects. This paper compiles the corridor traffic management strategies employed at a sample of eight projects in Chicago, Pittsburgh, Houston, Syracuse, Boston, Philadelphia, Detroit, and Minneapolis. The paper also summarizes the observed effectiveness of the various strategies. Corridor traffic management plans are divided into three components: (a) a traffic-handling strategy for the highway being reconstructed, (b) impact-mitigation strategies for alternative routes and modes, and (c) a public information program. The three basic traffic-handling strategies are minor capacity reductions, lane closures, and total roadway closures on the highway being reconstructed. There have been successful applications of all three traffic-handling strategies. Keys to successful traffic management during reconstruction have been a coordinated, corridorwide perspective for managing traffic and an effective public information program for advising motorists about the project, prevailing traffic conditions, and travel alternatives.

Managing traffic during the reconstruction of heavily traveled urban freeways is a significant and complex problem being faced by an increasing number of cities in the United States. In many cases, the solution to the problem requires a corridorwide perspective that extends beyond the highway being reconstructed to alternative routes and modes. In recognition of the problem, the Federal Highway Administration (FHWA), in cooperation with the Transportation Research Board, sponsored a National Conference on Corridor Traffic Management for Major Highway Reconstruction in the fall of 1986. Conference participants made the following recommendation:

> The many successful corridor traffic management plans prepared to date and the excellent results obtained with them should be synthesized for reference by all state and metropolitan transportation and planning agencies likely to face rebuilding of major highway facilities (*1*).

This paper provides such a synthesis.

The paper compiles the traffic management strategies employed at a sample of urban freeway reconstruction projects and summarizes available data on the effectiveness of the strategies. The eight projects reviewed and the years they were conducted are as follows:

- Edens Expressway (I-94) in Chicago (1978–1980),
- Penn-Lincoln Parkway East (I-376) in Pittsburgh (1981–1982),
- Katy Freeway (I-10) in Houston (1983–1984),
- I-81 in Syracuse (1984),
- Southeast Expressway (I-93) in Boston (1984–1985),
- Schuylkill Expressway (I-76) in Philadelphia (1985–1989),
- John C. Lodge Freeway (US-10) in Detroit (1986–1987), and
- I-394 in Minneapolis (1985–1992).

SYNTHESIS OF TRAFFIC MANAGEMENT STRATEGIES

A corridorwide perspective for traffic management during reconstruction is implemented through a corridor traffic management plan. The three components of a corridor traffic management plan are as follows:

- A traffic-handling strategy for the highway being reconstructed,
- Impact-mitigation strategies for alternative routes and modes in the affected corridor, and
- A public information program.

The traffic-handling strategy addresses the accommodation of traffic in the reconstruction zone. Impact-mitigation strategies are transportation systems management actions to increase capacity and improve the level of service on alternative routes and modes. The public information program educates the public about the reconstruction project, prevailing traffic conditions, and travel alternatives. The three components are interrelated, but will be discussed in turn in the following sections.

Traffic-Handling Strategies

Traffic-handling strategies may be grouped into three general categories:

- Minor capacity reductions—the narrowing of lane and/or shoulder widths to maintain the same number of lanes on the highway being reconstructed, at least during peak periods;

Texas Transportation Institute, The Texas A&M University System, College Station, Tex. 77843.

- Lane closures—the closure of some, but not all, lanes in one or both directions of the highway being reconstructed; and
- Total roadway closures—the closure of all lanes in one or both directions of the highway being reconstructed.

Table 1 summarizes the basic traffic-handling strategy used at the reconstruction projects. The following sections provide a brief description of how the strategies were applied in each project.

Minor Capacity Reductions

The projects in Houston (I-10), Boston (I-93), and Minneapolis (I-394) involved only minor capacity reductions through the reconstruction zone. In each case, it was determined that adequate work space could be developed without reducing the number of lanes available to traffic and that the cost required to do so was justified because the alternative routes and modes did not have sufficient unused capacity to accommodate significant traffic diversion from the reconstruction zone. Consequently, project planners and engineers developed construction-phasing sequences and traffic control plans that maintained as much capacity as possible on the highway being reconstructed.

The Katy Freeway (I-10) is a major Interstate highway between downtown Houston and its western suburbs. A reconstruction project was conducted during 1983–1984 to retrofit the freeway with a median transitway and to rehabilitate the pavement structure (*2*). The freeway cross section varied from six lanes at the western end of the project to eight lanes at the eastern end, with 1982 average annual daily traffic (AADT) varying from 135,000 to 186,000 vehicles per day (vpd). The project contract required that the number of lanes on the freeway during peak periods be the same during reconstruction as before reconstruction. Lane closures were permitted only during off-peak periods. The existing cross section included 10-ft median and outside shoulders and 40 to 50-ft outer separations to one-way frontage roads. Work areas were created in the median and on the inside and outside edges of the main lane cross section with traffic routed around the work areas in narrow lanes (10 to 11 ft wide) with no shoulders on either side. Work areas and travel lanes were separated by portable concrete barriers. Because only minor capacity reductions were planned, no special impact mitigation or public information actions were taken.

TABLE 1 TRAFFIC HANDLING STRATEGY EMPLOYED AT A SAMPLE OF RECONSTRUCTION SITES

	Minor Capacity Reduction	Lane Closure	Total Roadway Closure
Houston	X		
Boston	X		
Minneapolis	X		
Chicago		X	
Pittsburgh		X	
Philadelphia		X	
Syracuse			X
Detroit			X

In Boston, the Southeast Expressway (I-93) is the only major highway facility connecting Boston with southeastern Massachusetts. The expressway is a six-lane freeway facility with a breakdown lane in each direction used as an additional travel lane during peak hours. It carried more than 160,000 vpd before reconstruction. An 8.5-mi section of the expressway was reconstructed during 1984 and 1985 (*3–5*). During reconstruction, the expressway was divided into four two-lane segments, and work was allowed on only one two-lane segment at a time. One two-lane segment was provided for each direction at all times, and the remaining segment was a reversible, express roadway for through traffic. Thus, four travel lanes were provided for peak direction traffic, the same number as before reconstruction, and two lanes for off-peak direction traffic. Because there was no previous experience with such a traffic-handling strategy, there was considerable uncertainty about how effective it would be. Therefore, an extensive package of impact mitigation and public information actions was implemented to provide motorists a wide variety of alternatives in the event that severe congestion developed during reconstruction. The package was implemented with the flexibility to discontinue actions that proved unnecessary.

I-394 is a new segment of Interstate highway being built along the alignment of existing US-12, the principal arterial highway linking the western suburbs with downtown Minneapolis (*6*). The western portion of the 11-mi segment being reconstructed was a four-lane divided highway with several at-grade intersections, and the eastern portion was a six-lane freeway. I-394 will be a six-lane freeway with two reversible, high-occupancy vehicle (HOV) lanes. The AADT on US-12 in 1984 ranged from 49,000 vpd near the western end to 99,000 vpd at the maximum load point. During reconstruction, two through lanes of mixed traffic were maintained in each direction. To accomplish this, the project was divided into eight major segments that will be completed over an 8-yr period (1985–1992). Temporary detours and bypasses, some of which required additional signalized intersections, were provided at several locations to maintain two lanes on US-12 as well as to minimize the disruption to cross-street traffic. Therefore, even though the same number of travel lanes was maintained, some reduction in capacity was expected. A number of impact-mitigation strategies were implemented as part of the during-reconstruction component of the long-range Transportation Systems Management Plan for the I-394 corridor. The key strategy was an interim HOV lane in the median of the existing facility (*7,8*).

Analyses of the projects suggest that traffic volumes through the reconstruction zones were maintained at nearly the same levels as before reconstruction with little or no effect on operating conditions. Average speeds in Houston decreased by less than 3 mph during the morning peak period and actually increased during the afternoon peak period (*2*). In Boston, the use of the express lanes in the peak direction allowed traffic to travel at slightly higher speeds than before reconstruction; it was also estimated that 5,000 to 9,000 vpd (3 to percent of before-reconstruction volumes) diverted from I-93 during the first year of reconstruction, but that volumes returned to before-reconstruction levels during the second year (*4*). In Minneapolis, preliminary indications are that traffic volumes on I-394 are only slightly lower than before reconstruction.

Lane Closures

As indicated in Table 1, several reconstruction projects—Edens Expressway (I-94) in Chicago, Parkway East (I-376) in Pittsburgh, and Schuylkill Expressway (I-76) in Philadelphia—have required long-term lane closures. Due in large part to careful planning and implementation by project officials, the required reconstruction work was accomplished without causing massive congestion through the affected corridor. In most instances, substantial improvements to alternative routes and modes were made to accommodate the traffic diverting from the reconstruction zone.

The Edens Expressway (I-94) is a six-lane freeway that serves the north shore suburbs of Chicago. The AADT before reconstruction ranged from 57,000 vpd at the Lake-Cook county line to 135,000 vpd at the southern terminus with the Kennedy Expressway (I-90). A 3-yr reconstruction project was conducted on a 15-mi segment of the Edens Expressway from 1978 through 1980 (*9–12*). During reconstruction, one directional roadway of the expressway was closed at a time and four-lane two-way traffic was maintained on the other directional roadway, resulting in approximately a 33-percent reduction in freeway capacity. A portable concrete barrier separated two-way traffic. A 35-mph speed limit was established due to the reduced lane widths, restricted lateral clearances to the concrete barrier, proximity of reconstruction operations, low-speed temporary ramp connections, and frequent changes in ramp closures. To accommodate the traffic that was expected to divert from the freeway, a limited package of improvements to alternative routes and modes was implemented through cooperation with affected agencies.

The Penn-Lincoln Parkway East (I-376) is the only major east-west freeway connecting downtown Pittsburgh with the Pennsylvania Turnpike (I-76) and eastern suburbs. The facility is a four-lane freeway, including the 0.8-mi double-bore Squirrel Hill Tunnel. It carried 132,000 vpd through the rehabilitated section, including 80,000 vpd through the tunnel. The Pennsylvania Department of Transportation undertook a reconstruction and safety update project on a 6.5-mi section of the parkway during 1981–1982 (*13–15*). The Parkway East project was the first in which FHWA authorized the use of Interstate funds to mitigate the off-system impacts of Interstate reconstruction. The traffic-handling strategy employed during most of the project was to close one directional roadway (inbound in 1981 and outbound in 1982) and to maintain two-lane, two-way traffic on the other roadway. The entrance ramps within the reconstruction zone were closed, and the entrance ramps nearest each end of the reconstruction zone were restricted to HOVs. The closure of one direction of the freeway reduced its capacity by approximately 50 percent, and the ramp closures reduced access. As a result, many motorists were forced to divert. Since the only alternative routes were arterial streets, many of which were already congested, a package of impact mitigation and public information actions was implemented to improve alternative routes and modes of travel.

The Schuylkill Expressway (I-76) is the major east-west freeway connecting downtown Philadelphia with the Pennsylvania Turnpike (I-76) and western suburbs. The 21-mi long freeway is predominantly four lane, although several segments near downtown have six or eight lanes. Traffic volumes before reconstruction ranged from 80,000 vpd near the turnpike to 143,000 vpd near downtown. Reconstruction of an 18-mi segment of the expressway began in 1985 and was scheduled for completion in 1989 (*16–18*). Two lanes of traffic are being reconstructed at a time. In the four-lane segments, two-lane, two-way traffic was maintained on one directional roadway while work was performed on the other roadway. The outside shoulders were upgraded to allow traffic to operate on the shoulder and the median lane with a buffer lane in between. The reduction in the typical cross section from four to two lanes translated into a 50 to 60 percent reduction in capacity. Since no major parallel alternative routes existed, the traffic management plan was designed to enable trucks, visitors, and long-distance travelers to remain on the expressway and to encourage short-distance, local drivers to divert from the expressway. A key to diverting traffic was the closure of most of the entrance ramps and some of the exit ramps within or leading to the reconstruction zone. Improvements were made to alternative routes and modes to accommodate the diverted local traffic, and an extensive public information program was implemented to educate motorists about the project and the travel alternatives.

Significant traffic volume reductions were observed at the Chicago, Pittsburgh, and Philadelphia reconstruction zones. In Chicago, the AADT was approximately 30 percent less during reconstruction, and peak period volumes decreased by nearly 35 percent. In Pittsburgh, a 60-percent reduction in daily traffic volumes was observed. The results in Philadelphia, although not yet fully documented, indicate a 50 to 60-percent reduction in AADTs through the reconstruction zone. The most common motorist response was diversion to an alternative route. Some shifting in departure times, which spread out the peak periods, was also observed. In Pittsburgh, for example, departure times during reconstruction averaged 20 min earlier than before reconstruction. The use of mass transit and ridesharing modes was heavily promoted but accounted for only a small portion of traffic diverted. In Chicago, no increase in mass transit was observed during reconstruction. In Pittsburgh, only 5 percent of the peak period traffic that diverted was traced to alternative modes. Officials in Philadelphia reported moderate increases in transit usage and ridesharing. An overall assessment of these reconstruction projects indicates that the reconstruction was accomplished within a reasonable period of time, that the impacts on motorists were minimized to the extent possible, and that the inconveniences and delays that did occur were well tolerated by the public.

Total Roadway Closure

Two recent freeway reconstruction projects have involved total roadway closures. The reconstruction projects on both

I-81 in Syracuse and the Lodge Freeway (US-10) in Detroit employed total closures of one direction of the freeway.

I-81 is the major north-south freeway running through Syracuse, New York. Traffic on the four-lane freeway had reached 70,000 vpd by the 1970s and was approaching capacity. Therefore, in the late 1970s the New York Department of Transportation initiated a reconstruction project to add two travel lanes on a 10-mi segment of the Interstate and to modernize three major interchanges (*19*, *20*). Throughout most of the project, the basic traffic-handling strategy was minor capacity reductions. However, in 1984, bridge deck rehabilitation and substructure repairs required the total closure of the 2.8-mi three-lane viaduct and adjacent structures carrying southbound traffic on I-81 through the I-690 interchange. It was also necessary to close one northbound lane and slow traffic on the remaining northbound lane to 30 mph to minimize damaging vibrations in the southbound structure. Improvements on alternative routes and modes and an extensive public information program were implemented to mitigate the impacts of the freeway closure.

The Lodge Freeway is a six-lane freeway connecting downtown Detroit and its northwestern suburbs. AADTs prior to reconstruction were approximately 125,000 vpd at the maximum load point. The Michigan Department of Transportation undertook a 2-yr project to reconstruct an 8.4-mi section of the freeway during 1986 and 1987 (*21*, *22*). Because considerable unused capacity existed on nearby parallel freeways and arterial streets, the traffic-handling strategy adopted was the total closure of one directional roadway at a time with traffic diverted to designated alternative routes. The traffic management plan involved staging the project over two construction seasons. In 1986, the work did not directly involve the travel lanes and therefore the freeway capacity reductions were minor. The traffic management plan for 1987 involved directional closures with one-way traffic maintained in the open direction. The northbound (outbound) lanes were closed from April through July 1987, and the southbound (inbound) lanes were closed from July through October 1987. Traffic in the closed direction was diverted to alternative routes and modes. An extensive public information program disseminated information on the travel alternatives during reconstruction.

At both projects, the most common motorist response was to use alternative routes in the corridor. The HOV measures that were initiated or expanded during reconstruction attracted little or no increase in ridership, due largely to the availability of unused capacity on the alternative routes and to the lack of a travel time advantage for HOV modes. The public information programs were considered vital to the success of the traffic management plans for both projects. Travel times in the corridor increased, but motorists were well aware of the project, why it was important, and what travel alternatives were available. As a result, the inconveniences were well tolerated and the overall public response was positive.

Techniques to Maximize the Capacity of the Reconstruction Zone

In conjunction with the basic traffic-handling strategy, a number of techniques have been employed to maximize the capacity of the reconstruction zone including the following:

- Using portable concrete barriers to separate the travel lanes from work areas or to separate opposing lanes of traffic;
- Widening and upgrading shoulders for use as temporary travel lanes;
- Using exclusive, reversible lanes for peak-period, peak-direction through or HOV traffic;
- Closing ramps or restricting ramps to HOVs; and
- Implementing incident management techniques to reduce incident detection and response time.

Table 2 summarizes the techniques used at each of the reconstruction projects reviewed. Limited data are available on the effectiveness of the individual strategies, because at most projects several techniques were used in combination and it is impossible to separate the impacts of each technique.

The combination of techniques used in Houston (portable concrete barriers, ramp closures, and temporary shoulder lanes)

TABLE 2 TECHNIQUES EMPLOYED AT A SAMPLE OF PROJECTS TO MAXIMIZE THE CAPACITY OF THE RECONSTRUCTION ZONE

	Portable Concrete Barriers	Ramp Closures/ Restrictions	Temporary Shoulder Lanes	Reversible Lanes	Incident Management Techniques
Houston	X	X	X		
Boston	X	X	X	X	X
Minneapolis	X			X	
Chicago	X	X	X		X
Pittsburgh	X	X	X		X
Philadelphia	X	X	X		X
Syracuse	X	X			
Detroit	X	X			X

allowed traffic to move through the reconstruction zone only slightly impeded (*2*). Peak period capacities averaged 1,750 vehicles per hour per lane (vphpl), which is higher than would be predicted by the 1985 *Highway Capacity Manual* (*23*) for a six-lane freeway with 10- to 11-ft lanes and no shoulders.

The impacts of utilizing shoulders as temporary travel lanes through the reconstruction zone have not been documented. However, the safety effects of shoulder removal to add travel lanes under normal urban freeway conditions have been investigated. Recent results suggest that converting the inside shoulder to a travel lane does not appreciably increase accident frequencies and may, in fact, decrease them significantly on high-volume facilities (*24–26*). Available data on converting an outside shoulder to a travel lane indicate a slight increase in accident rates. The results suggest that using the inside shoulder as a travel lane during reconstruction may be effective, but that outside shoulder removal, either alone or in conjunction with inside shoulder removal, may not be justified due to potential increases in accidents and delays during incidents.

Reversible express lanes for through traffic proved effective in Boston, where peak-period travel times on the freeway were the same or lower than before reconstruction even though little traffic diverted from the freeway. Separating through traffic from the merging and diverging maneuvers of local traffic streamlined traffic flow and was a key to the successful traffic management plan.

Ramp closures or restrictions to HOVs only reduce traffic demands on the freeway and may increase capacity by reducing merging conflicts. The costs of implementing ramp closures, which involve primarily signing and barricades, are minimal. The principal costs of ramp restrictions to HOV usage are for enforcement. During the Parkway East reconstruction in Pittsburgh, signing and enforcement of two HOV-only ramps cost $750 per day (in 1987 dollars) (*13*). The HOV ramps were located at the beginning of the reconstruction zone and enabled HOV users to bypass much of the congestion that developed upstream of the reconstruction zone. It was estimated that the ramps saved HOV users an average of 8 min per person-trip, which translated into a benefit-to-cost ratio of 31:1. Impacts on mixed flow traffic were reported to be minimal.

Incident management techniques during reconstruction have included additional police or courtesy patrols and free tow-truck service. Several projects have provided free tow-truck service to reduce incident response time and thereby minimize incident-related delays. Data regarding the costs and usage of the free tow-truck service in Boston and Detroit indicate that the cost per vehicle serviced was approximately $150 and $200, respectively. The number of calls handled per day is a function of both the amount of traffic on the freeway and the number of tow trucks provided. Unfortunately, data regarding the benefits of the service in terms of reduced motorist delay and accident potential have not been documented. However, the potential incident-related delays are considerable, particularly when lanes are narrowed and one or both shoulders are eliminated within the reconstruction zone.

Impact-Mitigation Strategies

Impact-mitigation strategies have consisted primarily of transportation systems management improvements to increase capacity or improve the level of service on alternative routes and modes of travel. The following sections summarize the actions that have been employed.

Improvements to Alternative Routes

In anticipation of large volumes of traffic diverting to alternative routes, impact-mitigation measures on arterial streets in the affected corridor have been implemented as part of several reconstruction projects. These improvements have included the following:

- Traffic signal improvements,
- Other intersection improvements, and
- Other roadway improvements.

Table 3 summarizes the types of improvements made at the eight projects reviewed in this paper. It is difficult to isolate the effectiveness of the individual strategies because at most projects a coordinated package of improvements was implemented.

Traffic signal improvements have included the following:

- Adjustments in signal phasing and timing;
- Improvements in signal equipment—installation of temporary traffic signals, traffic-actuated signals, time-based coordination, and computerized traffic signal control systems; and
- Deactivating signals.

The benefits of adjustments in signal timing in a reconstruction context have not been documented. However, these actions are likely to be cost-effective because the cost is low and the potential savings in travel time are significant. Although not in a reconstruction context, experiences from a recent signal retiming program in North Carolina provide an indication of the cost effectiveness of signal timing improvements. Signals were retimed at an average cost of $481 per intersection, and the benefit-to-cost ratio was 108:1 (*27*). Improvements in signal equipment are more costly, but their benefits extend beyond the reconstruction period, a fact that should be considered in cost-effectiveness evaluations. In Syracuse, signals at two intersections were deactivated during reconstruction to improve operations on an important alternative route (*20*).

Other intersection improvements have included the following:

- Temporary left-turn prohibitions;
- Parking restrictions;
- Improved signing, lighting, and pavement markings;
- Police officer control during peak periods;
- Intersection channelization; and
- Intersection widening.

Turn prohibitions, parking restrictions, and improvements in signing, lighting, and markings are relatively inexpensive but can yield valuable operational benefits. Police control is a flexible strategy that has been useful primarily at the beginning of projects while motorists are adjusting their travel patterns. However, the cost of police control is relatively high. In Pittsburgh, for example, police control of 17 signalized intersections during peak periods cost more than $17,600 per

TABLE 3 IMPROVEMENTS MADE ON ALTERNATIVE ROUTES AT A SAMPLE OF RECONSTRUCTION PROJECTS

	Traffic Signal Improvements	Other Intersection Improvements	Other Roadway Improvements
Houston			
Boston	X	X	X
Minneapolis	X	X	X
Chicago			
Pittsburgh	X	X	X
Philadelphia	X	X	X
Syracuse	X	X	X
Detroit	X	X	X

week (in 1987 dollars) for a total cost of $633,000 for the 2-yr project (*13*). In Boston, police control at key locations was budgeted at $438,000 (in 1987 dollars) for the 2-yr project (*5*). In both Pittsburgh and Boston, the number of locations at which police were used was reduced dramatically within 1 month after the beginning of the projects because most of the problems anticipated never materialized. Intersection channelization or widening to add turning lanes is more costly but can provide valuable, permanent increases in capacity.

Other roadway improvements have included the following:

- Reversible lane on an arterial street,
- Converting streets to one-way pairs,
- Pavement marking changes to add additional travel lanes,
- Midblock parking prohibitions,
- Pavement surface improvements, and
- Signing and lighting improvements.

These actions are relatively easy-to-implement operational improvements. Although no data isolating the benefits of these improvements are available, their cost is low enough that the probability of their being cost-effective is high.

Overall, improvements to alternative routes have been worthwhile impact-mitigation actions. For those projects where significant diversion occurred, most of the diverted traffic was traced to alternative routes in the corridor. The improvements implemented helped reduce the impact of these traffic increases on the alternative routes. Many of the improvements were permanent and continued to provide improved traffic operations after the reconstruction project was completed. In Pittsburgh and Detroit, alternative routes in the affected corridor were forced to handle large volumes of diverted traffic. Despite the significant increases in traffic, corridorwide travel times in Pittsburgh were only 16 percent longer during the morning peak and 57 percent longer during the evening peak (*14*). Motorists adjusted to these longer times by departing 20 min earlier during reconstruction (*13*). In Detroit, approximately 60,000 vpd were diverted to alternative routes; travel times increased approximately 33 percent on the alternative freeway route but did not change significantly on most of the alternative arterial routes, due in large part to the signal coordination efforts on those routes (*22*).

Improvements to Alternative Modes

At most of the reconstruction projects reviewed, improvements were made to alternative modes of travel in an attempt to reduce traffic volumes through the reconstruction zone by diverting motorists to mass transit or HOVs. Improvements in public transportation and other HOV modes have included the following:

- Expanded bus service—new express bus service, increasing feeder service to commuter rail or rapid transit stations, adding buses to maintain or increase prereconstruction headways, and placing backup buses on call in case of delays;
- New or expanded rail service—new commuter rail service, expanded rail rapid transit service, adding cars to existing trains, extending rail service beyond the existing terminus, and adding trains to increase service frequency;
- Expanded commuter boat service;
- New or expanded park-and-ride lots; and
- Expanded ridesharing programs.

Table 4 summarizes the improvements implemented at the projects reviewed. Expanded bus service, ridesharing programs, and park-and-ride lots were the most widely used strategies. Rail service improvements were made in Boston, Pittsburgh, and Philadelphia. In Boston, the commuter boat service was also expanded.

At most of the projects, the improvements did not produce substantial increases in transit ridership or ridesharing. Little or no increases were reported in Chicago, Syracuse, and Detroit. The limited documentation available from Philadelphia suggests that some increase in rail ridership (1,300 person-trips per day) and requests for ridesharing matches (3,200 during the first year) occurred during reconstruction.

The most detailed documentation is available for the projects in Pittsburgh and Boston. In Pittsburgh, the new com-

TABLE 4 IMPROVEMENTS MADE TO HOV AND PUBLIC TRANSPORTATION SERVICES AT SELECTED RECONSTRUCTION PROJECTS

	Expanded Bus Service	New or Expanded Rail Service	Expanded Boat Service	New or Expanded Park-and-Ride Lots	Expanded Ridesharing Programs
Houston					
Boston	X	X	X	X	X
Minneapolis	X			X	X
Chicago	X			X	X
Pittsburgh	X	X		X	X
Philadelphia	X	X		X	X
Syracuse	X			X	X
Detroit	X				X

muter rail service attracted 500 person-trips per day at a cost of $25 per trip (in 1987 dollars); the express bus service attracted 1,500 new person-trips per day at a cost of $5 per trip; and the expanded vanpool promotion efforts produced 750 new person-trips by vanpool at a cost of only $0.20 per trip. In Boston, the improvements to commuter rail service attracted 400 person-trips per day at a cost of $20 per trip; the rail rapid transit improvements attracted 850 person-trips per day at a cost of $2.50 per trip; the expanded commuter boat service attracted 200 person-trips per day at a cost of $12 per trip; and the expanded efforts to promote vanpooling attracted 140 person-trips per day at a cost of $3.00 per trip. Express bus ridership actually decreased in Boston in spite of a more than $1 million investment in expanded service.

In Minneapolis, the interim reversible HOV lane implemented during reconstruction of I-394 attracted 2,000 vpd, which represented about 5,400 person-trips per day. However, some of these HOVs were attracted from other routes due to travel time savings on the HOV lane. Hence, the cost of the interim HOV lane was approximately $1.30 per person-trip diverted from the mixed flow lanes in the reconstruction zone.

Public Information Programs

A critical factor in the success of the traffic management plans for the projects reviewed has been an extensive public information program. These programs helped create a positive, cooperative atmosphere in the affected communities by keeping motorists and public and private agencies apprised of conditions through the reconstruction zone and of travel alternatives.

Public information techniques have included the following:

- Traditional public relations tools—press conferences, media events, press tours, public meetings, press kits, news releases, interviews, paid advertising, and public service announcements;
- Special publications—posters, pamphlets, newsletters, maps, utility bill inserts, and other mailings;
- Toll-free hotlines;
- Special signing—changeable message signs, billboards;
- Highway advisory radio; and
- Ombudsman.

Table 5 summarizes the elements of the public information programs for the reconstruction projects reviewed in this paper. Although it is difficult to quantify its benefits, a public information program is vital to the success of a traffic management plan. Three important elements of the programs have been the efforts to (a) keep the public informed of the conditions through the reconstruction zone and of the availability of travel alternatives, (b) coordinate the actions of all public agencies involved in the project, and (c) maintain communications with public and private groups affected by the project. Perhaps the best indications of the effectiveness of the public information programs have been (a) the lack of congestion at the beginning of most projects because drivers heeded the responsible agency's advice to avoid the reconstruction zone and (b) the generally positive public attitude about the projects and the agencies involved.

SUMMARY OF EXPERIENCES AND OBSERVED STRATEGY EFFECTIVENESS

The experiences from the projects reviewed demonstrate that major urban freeway reconstruction can be conducted without intolerable disruptions in corridor traffic flow. The traffic management and impact-mitigation strategies deserve much of the credit for these successes. Latent capacity in the corridor and the ingenuity of motorists in selecting optimal routes also contributed to the fact that the regional transportation networks were able to accommodate the freeway capacity reductions with less congestion and delay than project planners had predicted.

TABLE 5 PUBLIC INFORMATION TECHNIQUES EMPLOYED AT SELECTED RECONSTRUCTION PROJECTS

	Traditional Public Relations Tools	Special Publications	Toll-Free Hotlines	Special Signing	Highway Advisory Radio	Ombudsman
Houston	X			X		
Boston	X	X	X	X	X	
Minneapolis	X	X	X	X		
Chicago	X			X	X	
Pittsburgh	X	X	X	X		
Philadelphia	X	X	X	X		
Syracuse	X	X		X		
Detroit	X	X	X	X		X

Motorists have five options for responding to the impacts of reconstruction projects:

- Cancellation of trips in the corridor;
- Spatial diversion (i.e., continue to travel in the corridor by the same mode but on a different route);
- Temporal diversion (i.e., continue to travel in the corridor by the same mode and route but at a different time);
- Modal diversion (i.e., continue to travel in the corridor but by a different mode); and
- Continuation of normal travel patterns.

Most motorists who changed their travel patterns continued to drive their automobiles in the corridor but either diverted to another route (spatial diversion) or changed their departure times (temporal diversion). Some motorists changed their mode of travel, but the numbers were not large. Few motorists canceled trips in the corridor.

Traffic diverted to many different routes. In Pittsburgh, where local traffic was forced to divert because entrance ramps were closed, diverting traffic was traced to many alternative routes but most was concentrated on the parallel arterial routes closest to the freeway. The experiences at the other projects were similar.

Motorists shifted back and forth between the freeway and alternative routes during the first several weeks of the projects, apparently experimenting with alternative routes before selecting their preferred route. In some cases, predictions of chaos by the press may have scared motorists away, but when the chaos failed to materialize the motorists returned to the freeway. After several weeks, an equilibrium was established. However, fluctuations continued. Throughout the projects, motorists shifted back and forth between the freeway and their alternative route as traffic conditions changed.

Temporal diversion was also observed. Motorists in Pittsburgh and Boston adjusted their departure times, especially in the morning, to compensate for the increased travel times in the corridor. In Pittsburgh, for example, morning departure times during reconstruction averaged 20 min earlier than before reconstruction.

Some modal diversion to HOV modes occurred, but the magnitude was much less than project planners had anticipated. In Pittsburgh, for example, only 5 percent of the peak-period traffic that diverted was traced to alternative modes. Officials in Chicago and Detroit reported little or no change in transit ridership. In both Detroit and Boston, much of the additional bus service provided initially was discontinued because it had not attracted sufficient ridership. It appears that the reconstruction projects reviewed did not cause significant enough changes in relative modal costs or travel times to change the long-held modal decisions of large numbers of commuters.

Importantly, at all of the projects reviewed there was little, if any, reduction in the total corridor daily traffic volumes. In Pittsburgh, for example, traffic volumes along a complete screenline through the affected corridor near the center of the reconstruction zone decreased by only 1.5 percent during the first construction season in spite of a 60-percent reduction in traffic on the Parkway East. Except for indications at the projects in Chicago and Boston that some discretionary, midday, nonwork trips were eliminated from the corridor, it appears that few vehicle trips were actually canceled.

In light of the motorist impacts observed, it is apparent that the improvements on alternative routes were the most cost-effective component of the impact-mitigation strategies. The improvements in HOV services were less cost-effective in terms of the cost per trip diverted. However, some investment in alternative modes was generally considered necessary to provide flexibility to the motorist and to allow for the margin of error in project planning analyses. The evidence suggests that improvements to existing services were more effective than the provision of new services, such as the new commuter train in Pittsburgh, which was discontinued near the end of the first year of reconstruction. The flexibility to discontinue lightly used services is desirable in implementing improvements in HOV services.

The public information programs were considered vital to the success of the projects. They helped prevent strong negative public reaction. More than that, they helped promote reasonably positive reactions that (a) the work was necessary for the long-term good and (b) the agencies involved were doing their best to complete the project with the least inconvenience possible.

Overall, past experiences suggest that a well-planned, -coordinated, -implemented, and -communicated traffic management plan can effectively limit the disruption in corridor traffic flow during urban freeway reconstruction projects. There have been successful applications of all three basic traffic-handling strategies (minor capacity reductions, lane closures, and total roadway closures) in conjunction with appropriate impact-mitigation strategies and public information programs. Good information and sound analysis are vital to the design of an effective strategy. Also vital are (a) the ability to evaluate unexpected impacts quickly and (b) the flexibility to alter strategies accordingly. The lessons that can be learned from successfully completed projects are valuable and merit careful study.

ACKNOWLEDGMENT

This paper was based primarily on the findings of research sponsored by the Federal Highway Administration. Joyce A. Curtis was FHWA's technical representative. The paper also incorporates data gathered as part of two studies sponsored by the Texas State Department of Highways and Public Transportation (SDHPT) in cooperation with FHWA. Mark A. Marek and B. Ray Derr of the SDHPT were the technical coordinators for these studies.

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Publication of this paper sponsored by Committee on Transportation System Management.

Husky Stadium Expansion Parking Plan and Transportation Management Program

MICHAEL E. WILLIAMS

In 1984 the University of Washington sought approval of the city of Seattle to increase the seating capacity of its 58,500-seat stadium to a total of 72,200 seats. Given the severe traffic and parking problems already associated with the existing stadium, the city required the university to develop a workable parking plan and transportation management program that would mitigate the impacts of the additional seating capacity. This paper presents the major elements of the Husky Stadium Expansion Parking Plan and Transportation Management Program and discusses its implementation during the 1987 football season. The major components of the program include incentives to use public transit through the issuance of free transit scrip good for use on all transit routes serving the stadium area; the creation of a park-and-ride system that provides direct service from outlying areas of the city and county to the stadium; a slight increase in on-campus parking supply and the leasing of off-campus parking spaces with free shuttle bus service to the stadium; implementation of a special-event, restricted parking zone in residential neighborhoods near the stadium; and a marketing program to promote increased use of nonautomobile modes. The implementation of the stadium transportation program in 1987 was a great success, far exceeding expectations. Much of that success can be attributed to the free transit scrip program and park-and-ride system.

Unlike other parking, special-event parking is usually generated by activities attracting large numbers of people. The attraction of people to special events depends largely on individuals' leisure time; as a result, events are usually held during nonworking hours, such as evenings and weekends.

By its very nature a special event can cause traffic and parking problems. Most special events attract crowds that arrive over a 60- to 90-min period. When the event concludes, the crowds typically leave at the same time. Even with special-purpose facilities designed to accommodate special events, the rapid accumulation of people and vehicles and their sudden departure create potential traffic and parking problems. When special events take place at locations not specifically designed for them, associated parking and traffic demands can become a severe problem (*1*).

The parking facilities, located adjacent to the University of Washington's Husky Stadium, are not specifically designed to handle the impacts associated with special event traffic and parking. The university currently has 12,300 parking spaces located in lots spread throughout the campus area that are designed to serve faculty, staff, and students during a typical weekday. The stadium is almost exclusively used for Husky home football games that occur only six to seven times per year during the 3-month period from mid-September to late November. The parking facilities located in the east campus adjacent to Husky Stadium have a maximum weekday capacity of only 4,875 automobiles.

Before the 1987 football season, Husky Stadium had a seating capacity of 58,500. In 1984 the university sought approval from the city of Seattle to increase the seating capacity by 13,700 to a total 72,200. Given the severe traffic and parking impacts already associated with the existing stadium, the city required the university to develop a workable parking plan and traffic management program for the proposed expansion that would mitigate the impacts of the additional seating capacity. In addition, the city required the university to produce an Environmental Impact Statement (EIS) and to solicit input from the surrounding neighborhoods during the development of the plan and EIS. On the basis of this requirement the university produced the Stadium Expansion Parking Plan and Transportation Management Program (hereafter referred to as the TMP) that was adopted by the Seattle City Council on April 21, 1986.

The purpose of this paper is to present the major elements of the TMP and to discuss the results of its implementation during the 1987 football season. Before the major elements of the TMP are presented, a description of the University of Washington and its setting is provided, along with a summary of the parking and transportation conditions that existed before the expansion of Husky Stadium.

BACKGROUND

University of Washington's Setting

The University of Washington is a major 4-yr instructional and research institution located in the city of Seattle (see Figure 1). In 1987, there were more than 33,000 students enrolled at the university, along with more than 17,000 faculty and support staff. The University District, or U-District as it is more commonly called, is the largest activity center in King County outside the Seattle central business district. It is characterized by a mixture of densely populated neighborhoods, commercial and retail activity, the university, and a major hospital.

Given the transportation and land-use impacts associated with the university, the city of Seattle and the University of Washington agreed in 1983 to require the university to prepare

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Transportation Office, University Facilities Building, FJ-05, Seattle, Wash. 98195.

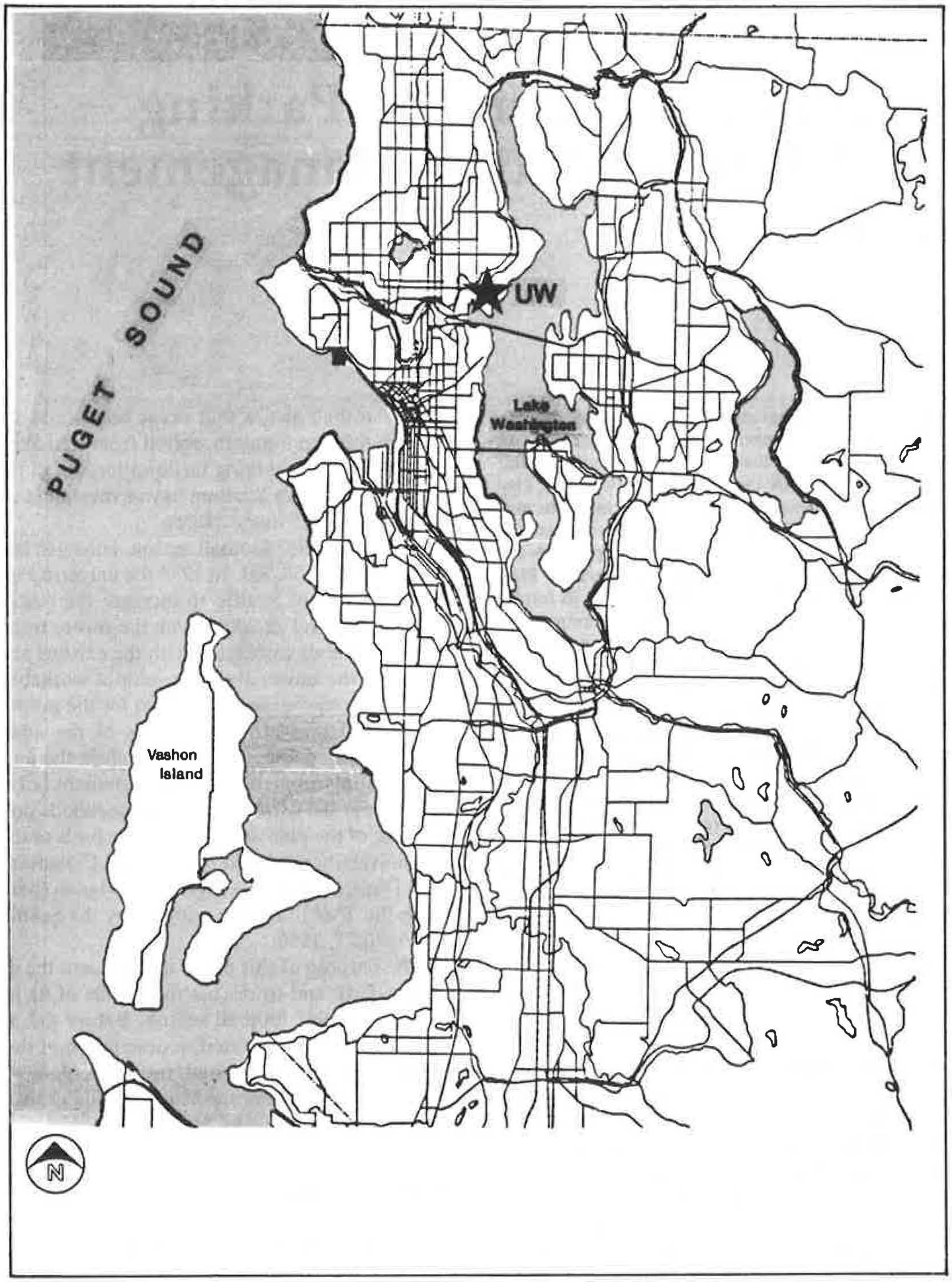

FIGURE 1 University of Washington location map.

a General Physical Development Master Plan (GPDP) that covered a 10-yr period and included measures to manage university-related traffic growth in the U-District.

The 1983 agreement also included a provision requiring the university to develop mitigating actions for traffic impacts associated with any expansion of Husky Stadium. These impacts were to be addressed through a workable parking plan and traffic management program.

Many access constraints limit the ability of Husky Stadium to accommodate special-event parking and traffic. These major access constraints are listed next.

- The stadium is bordered by water on two sides.
- Access to the site requires that vehicles operate a considerable distance over heavily traveled arteries to reach the stadium after they leave the freeway system.

- The four-lane arterial roadway in front of the stadium is the most heavily traveled in the state and includes a drawbridge just south of the campus.
- A major commercial and retail area is located west and northeast of the campus, with limited parking and street capacity for traffic.
- West of the stadium is the university hospital and health sciences complex serving a large population all year round, game day or not.
- High-income residential areas within walking distance of the stadium are affected by game-day parkers.

Conditions Before Stadium Expansion

Before 1987, there were 11,325 parking stalls, out of a total campus supply of 12,300, dedicated to football patrons for home games. Table 1 compares the number of parking spaces available at Husky Stadium, before stadium expansion, with that at other selected stadiums in the country (*1*). With 0.19 and 0.16 parking spaces per seat, Husky Stadium ranks in the middle of the range for stadiums shown in Table 1.

Table 2 shows the mode split for a sold-out Husky football game in 1984. The main transportation mode for football game attendees in 1984 was the private automobile, with more than 76 percent of the people arriving by that mode. Of the almost 20,500 vehicles used to access the game, more than 55 percent parked on campus and the remainder parked off campus in the U-District or on adjacent neighborhood streets (*2*).

Table 3 compares the percentage of persons who arrived by private vehicle for Husky football games before stadium expansion with that for other college football games played in major stadiums across the United States (*1*).

According to Table 3, the proportion of persons arriving by private automobile at college football games varies from a high of 95 percent at the Los Angeles Coliseum in California to a low of 68 percent at Memorial Stadium in Pennsylvania. The 76 percent preexpansion usage of private vehicles to access Husky football games makes it about average for other non-California stadiums.

The second most often used mode of transportation to Husky Stadium was walking (see Table 2). This fact makes Husky Stadium somewhat unusual compared with other stadiums in the country and is the result of its location in a residential area in close proximity to both on- and off-campus student housing. Almost 10 percent of all game attendees are walkers, motorcycle and bicycle riders, and those who are dropped off.

The remaining 14 percent of the people arrived at Husky Stadium in 1984 using public transit (4.2 percent), charter bus or boat (7.2 percent), or private boat (2.4 percent).

MAJOR PLAN ELEMENTS

The goal of the TMP for the expanded stadium was to accommodate a sellout crowd of 72,200 with less reliance on parking in the residential areas near campus than before expansion. The key to accomplishing this goal was to provide alternative modes of transportation other than the private automobile through such factors as increased transit service, preferential parking for charter buses, increased boat moorage, and so on, along with limited additional parking on campus. The university worked closely with the city of Seattle, Metro (the local transit agency), and the Washington State Department of Transportation (WSDOT) in development of the TMP (*3*). The successful implementation of the TMP required a continuing and cooperative effort between these agencies and the university. The main components of the program are as follows:

- Incentives to use public transit:
  - — Free transit scrip for all football game ticket purchasers that could be used on any Metro bus, and
  - — A new park-and-ride bus system that provided direct service from outlying areas of the city and county to the stadium;

TABLE 1 COMPARISON OF PARKING SPACES AT SELECTED STADIUMS (*1*)

Stadium	Seating Capacity	No. of Parking Spaces Provided by Stadium	Number of Parking Spaces per Seat
HUSKY STADIUM	58,500	11,325	0.19
Atlanta, GA	58,850	4,000	0.07
Shea Stadium, NY	55,000	7,400	0.13
Phila. Veterans, PA	65,300	11,000	0.17
Orchard Park, NY	80,000	15,000	0.19
Giants, NJ	76,000	20,800	0.27
Dodger, CA	56,000	16,000	0.28
R.F. Kennedy, D.C.	50,000	10,000	0.20

TABLE 2 MODE SPLIT, 1984 HUSKY FOOTBALL GAME

Mode	Persons	Vehicles/ Boats	ACO (a)	Percent of Persons
AUTOMOBILE MODE				
On Campus Parking				
Stadium Area	3,510	975	3.6	5.8
East Campus	12,260	4,900	2.5	20.3
Main Campus	6,750	3,070	2.2	11.2
South Campus	2,420	1,010	2.4	4.0
West Campus	2,740	1,370	2.0	4.5
Subtotal	27,680	11,325	2.4	45.8
Off Campus Parking				
U-District (b)	2,000	1,000	2.0	3.3
Neighborhoods (b)	16,340	8,170	2.0	27.2
Subtotal	18,340	9,170	2.0	30.5
Total Auto Mode	46,020	20,495	2.2	76.3
NONAUTO MODE				
Transit				
Regular Service	500			0.8
Husky Special	2,050			3.4
Charter Bus	3,280			5.4
Charter Boat	1,050			1.8
Private Boat	1,440			2.4
Drop Off/Walk/ Motorcycle/Bike (b)	5,960			9.9
Total Nonauto Mode	14,280			23.7
TOTAL	60,300 (c)			100.0

(a) ACO: Average Car Occupancy.
(b) Estimated number of persons and vehicles.
(c) Includes 1,800 unseated attendees (press, vendors, etc.)

TABLE 3 PROPORTION OF ATTENDEES ARRIVING AT COLLEGE FOOTBALL GAMES BY PRIVATE VEHICLE (*1*)

Stadium/Location	Percent of Persons Arriving by Private Vehicle
HUSKY STADIUM	76
Los Angeles Coliseum	95
Orange Bowl, Florida	78
Cotton Bowl, Florida	87
Ohio State University, Ohio	84
Weber State, Utah	75
Ware Memorial	73
Memorial Stadium, Penn.	68

- Reduced parking rates for carpools:
  - $6.00 for two or more occupants and
  - $9.00 for single occupants;
- A slight increase in on-campus parking supply and leasing of off-campus parking spaces with free shuttle bus service to and from the stadium;
- Implementation of a special-event, restricted parking zone in selected neighborhoods to discourage people from parking in residential areas;
- A marketing program to promote increased use of public transit, carpools, and other nonautomobile modes of transportation, such as charter buses and charter boats; and
- A monitoring program to ensure that the goals of the plan were met and to provide a means to revise the TMP if required.

The elements of the plan just outlined provide many incentives to encourage nonautomobile usage; however, the plan operates at a disadvantage given the policies of the university's Intercollegiate Athletic Department. All contributors to the athletic program who purchase football game tickets are provided with a free parking pass by the Athletic Department for the prime parking spaces closest to the stadium. The proximity to the stadium depends on the amount of the contribution. With expansion of the stadium, even more contributors have signed up. The incentive of a free parking pass makes it more difficult to convince people to use alternative modes.

Transit Scrip Program

The major goal of the transportation program is to encourage football game attendees to take public transportation to the stadium. In 1984, only 4.2 percent of the attendees arrived via public transit.

To achieve this goal all football game ticket purchasers are provided with transit scrip that allows them to ride free on any regular Metro service, "Husky Special" routes, and the new system of park-and-ride routes. The scrip is dated and valid on game day only and is mailed to all advance-sale ticket purchasers along with a description of the transportation program and information regarding transit routes to the stadium. Individual game ticket purchasers are either mailed transit scrip or given it when they pick up their game tickets on campus.

The Transportation Office is responsible for the printing and distribution of the transit scrip. Metro is responsible for counting the scrip after each game and billing the university according to the agreed reimbursement rate. Before 1987, game attendees using transit either took Metro's regular transit service to the U-District and walked to the game or used Husky Special service that delivered riders to within a block of the stadium.

Husky Special service is added by Metro on four existing routes to accommodate game attendees. All of the extra buses unload and load near the stadium, and arrival times are keyed to game time. Most of these extra buses are not needed elsewhere in the transit system, so they lay over on NE Pacific Street in front of the university hospital in position for loading after the game.

Park-and-Ride System

The university, in conjunction with Metro, developed a system of park-and-ride routes that provide service from outlying areas of the city and county. Figure 2 shows the location of the eight park-and-ride lots along with the parking capacity of each lot. There are three lots located in the north end with a total parking capacity of 1,185 vehicles, three lots located on the east side with capacity of 1,653 vehicles, and two lots located in the south end with capacity of 869 vehicles. Total parking capacity of the eight park and ride lots is 3,707. It should be noted that the Star Lake lot was not put into service until the third game of the 1987 season. The Houghton lot will be added during the 1988 season.

Reduced Parking Rates for Carpools

As shown previously in Table 2, the average car occupancy (ACO) rate for football game attendees parking on campus was 2.4 people per vehicle. This rate varies depending on the area of the campus; higher rates are achieved in areas closer to the stadium. The goal of the TMP was to increase the ACO for vehicles parking on campus from 2.4 persons per car to 2.7 persons per car. Vehicles arriving before 9:00 a.m. on game day pay the regular Saturday rate of $1.50 per vehicle. Faculty and staff with parking permits do not pay additional fees whether they are on campus to work or to attend the game. In 1987, the football parking fee was set at $9.00 for single-occupant vehicles and at $6.00 for vehicles with two or more persons.

Increase in Parking Supply

To accommodate more vehicles on game days, "stack-parking" was introduced to several parking lots on campus. With that change, the on-campus parking supply dedicated to football game parkers increased from 11,323 spaces in 1984 to 12,000 spaces in 1987. Figure 3 shows the general parking zones by campus area. The total number of parking spaces by zone, along with the number of spaces available for football parkers, is also shown in Figure 3 and summarized in Table 4.

In addition to the increase in on-campus parking supply, two off-campus parking facilities located in the U-District with a total of 706 spaces were leased by the university. The cost to park in the facilities is set at $4.00 and is competitive with that of other private parking lots in the area. As an incentive to use the university's leased off-campus parking facilities, a free shuttle bus with service to and from the stadium is provided to all parkers. All occupants of the vehicles that park in the garage are given a ticket for the shuttle bus. The ticket is shown to the driver and retained by the passenger for a ride to the game. After the game, the tickets are surrendered to the driver for a free return trip to the parking facilities.

Neighborhood Parking

Under the TMP, the impact on parking in the residential neighborhoods was to be mitigated through increased enforcement, multiticketing of vehicles, increased towing, and—if appropriate—increased parking fines. In addition, the TMP called for expanding the "no parking day of football game" zones in the Laurelhurst area northeast of the stadium and the Montlake community located south of the Montlake Bridge. Also, the residential parking zone that was in place in the Montlake community during weekdays was to be expanded on the weekends of football games via a special event residential parking zone.

Marketing Program

The TMP called for the university's Transportation Office and the Intercollegiate Athletic Department to work together on an aggressive marketing program to promote alternative modes of transportation. These marketing efforts were to include

- Promotional information mailed to season ticket holders,
- Public service announcements on local radio and television,

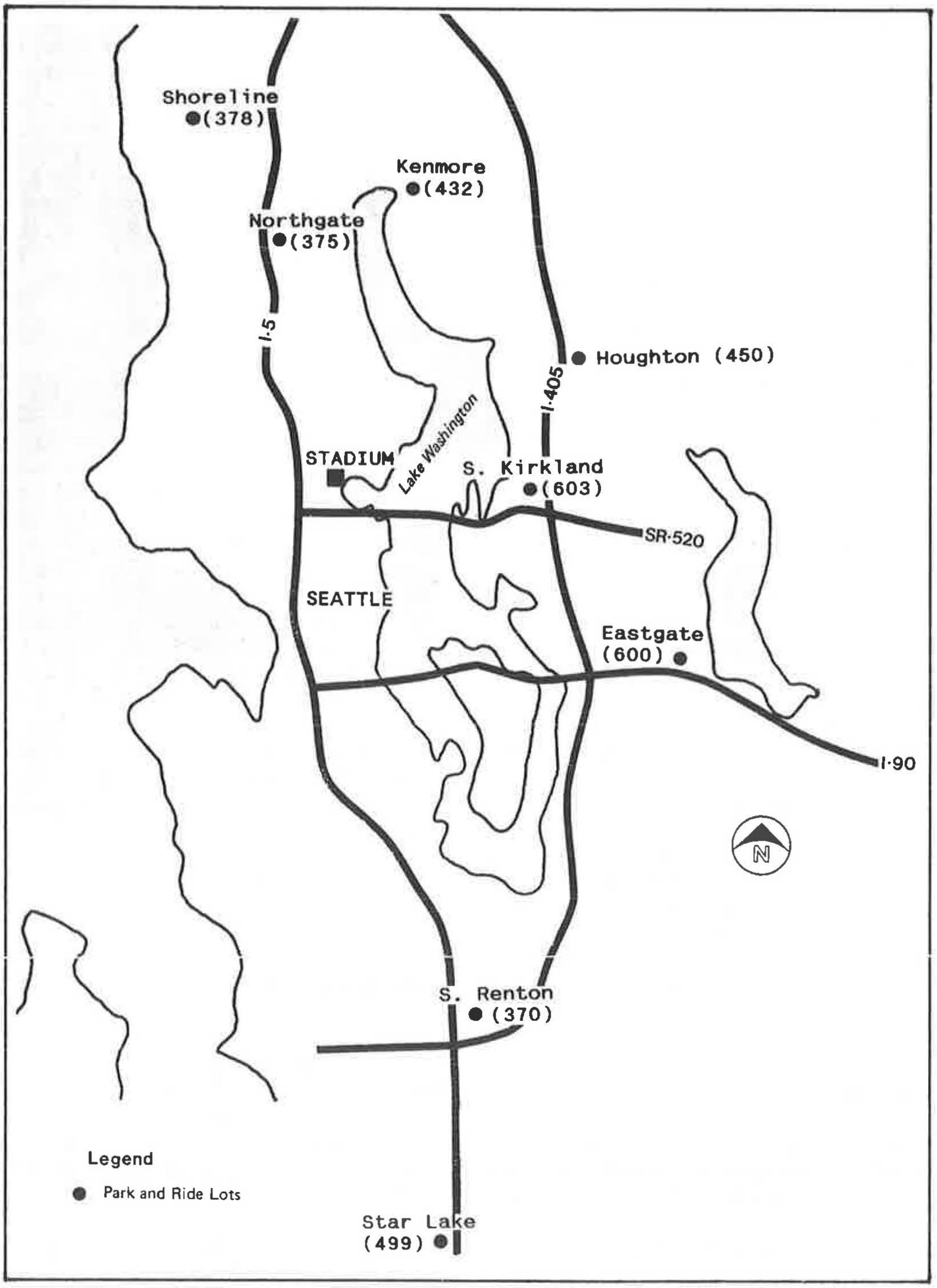

FIGURE 2 Husky Stadium park-and-ride lots.

- Public service messages on the stadium scoreboards and marquees,
- Special promotional events to publicize park-and-ride and transit services, and
- Other promotional activities developed by the Transportation Office and the Intercollegiate Athletic Department.

Monitoring Program

The monitoring program associated with the TMP is designed to provide information that will allow the university to make adjustments so that the desired goals are achieved. Information is to be gathered during each football season to determine the number of vehicles and the ACO for vehicles parking on campus and the numbers of people using public transit, charter buses, and boats. The data are to be reviewed to determine whether the goals of the TMP are being met and whether adjustments are needed.

An advisory group consisting of representatives from the university, the city of Seattle, Metro, WSDOT, and the community will meet each spring to review and assess the results of the monitoring program. In the event that the TMP needs adjustment to achieve the desired goals, the advisory group

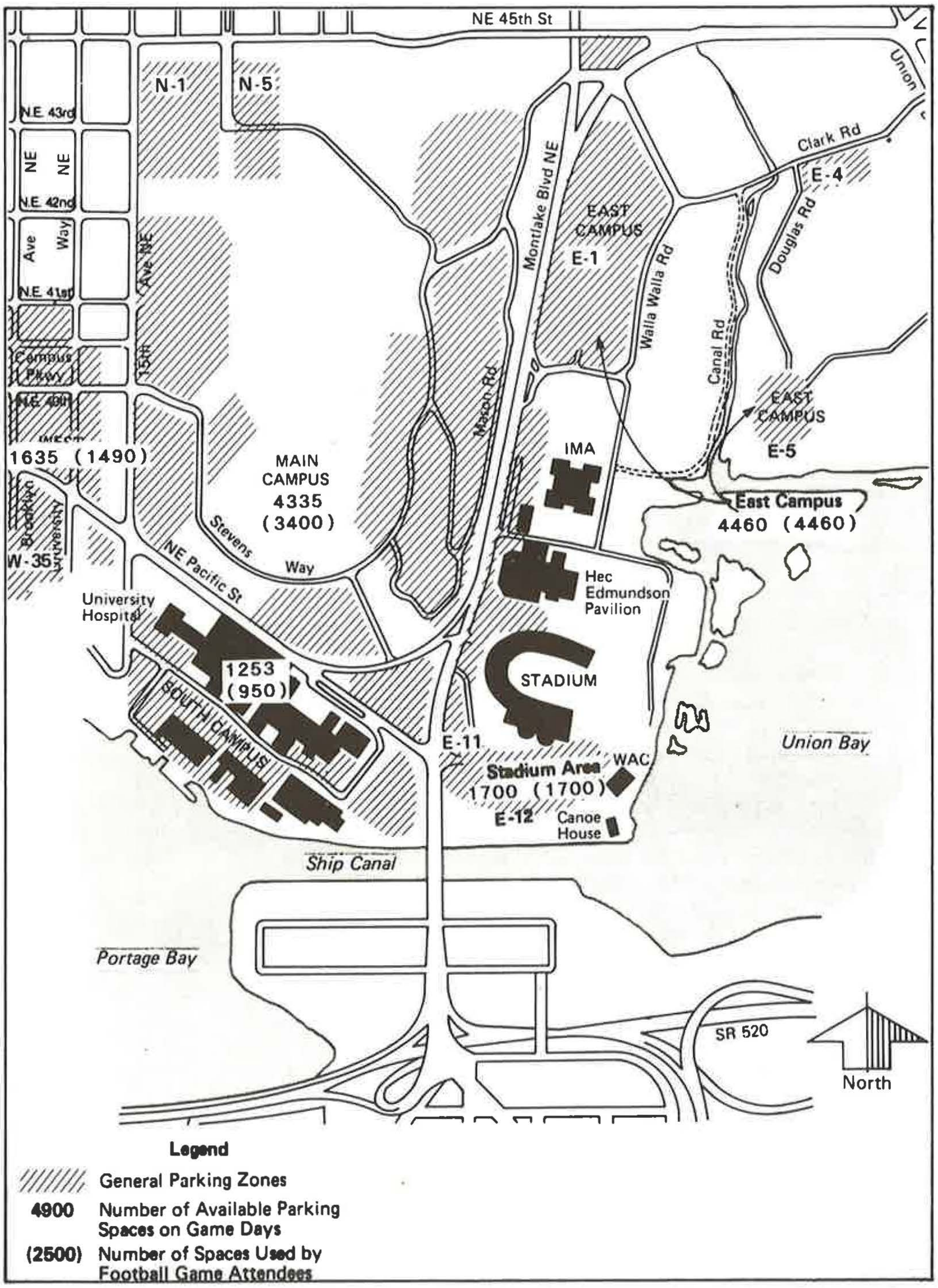

FIGURE 3 General parking zones by campus area.

will determine the appropriate action needed and responsible agencies involved. Any changes to the adopted TMP must be reviewed by the Department of Construction and Land Use, the Seattle Engineering Department, and approved by the city council.

RESULTS OF THE IMPLEMENTATION OF THE TMP

This section presents the results of implementing the TMP during the 1987 Husky football season. Particular emphasis is placed on discussing the development, operation, and results associated with the successful implementation of the free transit scrip program and park-and-ride system. The results of the neighborhood parking, marketing, and monitoring programs are also presented, along with a review of the program costs.

Transit Scrip Program

Working with Metro, the university developed scrip that came in a strip of seven tickets, with the date of the game printed on each ticket. Users were instructed to detach the ticket for

TABLE 4 ON-CAMPUS PARKING SPACES

Campus Area	Total Number of Parking Spaces	Spaces Available Game Attendees
Stadium Area	1,700	1,700
East Campus	4,460	4,460
Main Campus	4,335	3,400
South Campus	1,253	950
West Campus	1,635	1,490
Total	13,383	12,000

the day of the game and to use half the ticket for the trip to the stadium and the remainder for the trip from the stadium.

On the basis of preseason ridership estimates and associated coach needs, Metro determined that a one-way fare of $2.00 for the premium park-and-ride service would recover costs. It was decided that both Husky Special and regular transit service would be priced at the current one-zone Saturday rate of $0.55. It was estimated on the basis of these rates that the university would be required to pay Metro almost $190,000 for the 1987 subsidized transit service to Husky Stadium.

The Transportation Office developed and produced two brochures that were provided to all Husky game ticket purchasers. The *Husky Football Traffic and Transportation Guide* provided highlights of the new transportation and parking program for the 1987 season and included information on the transit program, parking rates, charter boats and buses, the Special Event Parking Zone created in the Montlake community, and postgame traffic routing. The second brochure, *Husky Football Transit Guide*, explained the transit scrip program and provided information on the Husky Special routes and park-and-ride system. The park-and-ride system description included information on bus schedules, pre- and postgame bus loading, and payment procedures, and a map with directions to the park-and-ride lots.

Because the Athletic Department had specific requirements for the type and size of envelopes used to mail football game tickets, the transportation brochures and transit scrip had to be mailed to season and individual ticket purchasers in a separate mailing, using labels provided by the Athletic Department.

Park-and-Ride System

As estimated in the TMP, when fully implemented, the eight-lot park-and-ride system would carry 2,740 riders to each game using 35 to 40 articulated buses. During the 1986 football season (before stadium expansion), limited park-and-ride service was introduced from the Northgate and South Kirkland park-and-ride lots (see Figure 2). Ridership on these two routes far exceeded expectations, averaging just beyond 3,000 passengers to each of the six home games.

On the basis of the experience of the 1986 season, estimates of park-and-ride ridership were increased to 6,000 riders per game. This expected increase in ridership caused major refinements of the operational aspects of the plan, including the number of required Metro supervisors, bus requirements, the routing of buses to the stadium, the staging of busing during the game, and, most important, the loading of passengers at the conclusion of the game.

A color coding system was established to assist passengers in finding their postgame loading area. Color-coded dash signs were placed in the front and side windows of the park-and-ride buses, corresponding to large, colored "bubble" signs held by park-and-ride attendants.

Once buses reach the loading area, Metro supervisors and additional park-and-ride attendants assist in loading the buses. To speed the loading process, both doors are used, and people pay with transit scrip as they leave the bus through the front door at the park-and-ride lot.

Using this postgame loading system, all buses were loaded and out of the area in less than 25 min after the conclusion of each game.

Data Collection Effort for 1987

During the 1987 season the following data were collected for each home game:

- Number of vehicles parked on campus by area,
- Number of vehicles and total persons using the Safeco parking facilities in the U-District,
- Number of passengers riding the Safeco shuttle both pre- and postgame,
- Husky Special and park-and-ride transit ridership,
- Number of charter buses/boats and passengers,
- Number of private boats moored and anchored, and
- Number of parking violations in the surrounding neighborhoods.

In addition to the individual game data collection efforts, a vehicle occupancy survey was conducted of all vehicles entering campus during the Oregon State game on October 31, 1987. The ACOs observed for that game were assumed to be representative of all games and therefore were used to estimate the ACO for all seven games. A survey of all park-and-ride system users was also conducted at the last game of the season (*4*).

Table 5 compares the 1987 football season average mode split with the 1984 preexpansion mode split. In 1984, 27,680 people, or 45.8 percent of all game attendees, parked on

TABLE 5 AVERAGE MODE SPLIT, 1987 AND 1984 HUSKY FOOTBALL GAMES

	1984		1987		Change
Mode	No. of Persons	Percent by Mode	No. of Persons	Percent by Mode	in Mode Split
AUTOMOBILE MODE					
On Campus Parking	27,680	45.8	26,269	36.8	-9.0
Off Campus Parking					
Safeco Garage	(a)	(a)	1,088	1.5	1.5
U-District (b)	2,000	3.3	2,300	3.3	-0.0
Neighborhoods (b)	16,340	27.2	17,300	24.2	-3.0
Subtotal	18,340	30.5	20,688	29.0	-1.5
Total Auto Mode	46,020	76.3	46,957	65.8	-10.5
NONAUTO MODE					
Transit					
Regular Service	500	0.8	1,428	2.0	1.2
Husky Special	2,050	3.4	1,818	2.5	-0.9
Park & Ride	(a)	(a)	7,131	10.0	10.0
Charter Bus	3,280	5.4	2,878	4.0	-1.4
Charter Boat	1,050	1.8	1,275	1.8	0.0
Private Boat	1,440	2.4	1,811	2.5	0.1
Drop Off/Walk/ Motorcycle/Bike (b)	5,960	9.9	8,097	11.4	1.5
Total Nonauto Mode	14,280	23.7	24,438	34.2	10.5
TOTAL	60,300	100.0	71,395	100.0	

(a) Not in use during the 1984 football season.

(b) Estimated number of persons and vehicles.

campus. During the 1987 season the average number of persons parking on campus was 26,269, which represented 36.8 percent of all game attendees. This was a decrease of 9.0 percent compared with 1984 figures. It was estimated that 700 vehicles, or 1,400 people, would park in the Safeco parking facilities. The season average was 1,088 persons arriving in 512 vehicles, for an ACO of 2.1. The Safeco shuttle average pregame ridership was 830, or 76.3 percent of the 1,088 people who parked in the facilities. Postgame ridership averaged 627 riders, or 58 percent of the total parkers.

The persons who parked in the neighborhoods and U-District were estimated at 19,600, or 27.2 percent of the total game attendees. The Seattle Police Department issued an average of 130 nonimpound citations and 112 requests for vehicle impound citations in the residential neighborhoods surrounding the stadium during the 1987 season. In 1986 (preexpansion) the average numbers of citations were 115 and 103, respectively. On this basis it does not appear that the stadium expansion had a major negative impact on the surrounding residential neighborhoods.

In all, only 65.8 percent of the game attendees came by automobile during the 1987 season, a 10.5 percent decrease from the 1984 season average of 76.3 percent.

The preseason estimates were for 29 percent of the game attendees to arrive at the stadium in a nonautomobile mode. The actual 1987 season average was 34.2 percent, or approximately 5 percent fewer automobile users than estimated. The greater percentage of nonautomobile users can be attributed to the tremendous increase in transit ridership over the preseason estimate. The park-and-ride system averaged 7,130 riders per game, which was an 18.8 percent increase over the 6,000 riders estimated in the preseason. Regular transit routes also experienced a much higher ridership than expected, with 1,428 riders, or 2 percent of the total game attendees. In 1984 only 2,550 people, 4.2 percent of game attendees, took transit to the game compared with 14.5 percent in 1987, an increase of more than 10 percent.

An on-board survey of park-and-ride lot users at the last home football game revealed that 78 percent of the users rated the service excellent, with another 20.3 percent rating it good, for an overall approval rating of 98.3 percent. The approval rating far exceeded the expectations of both the university and Metro and indicates that the system performed extremely well during its first full year of operation.

Revenue and Expenses in 1987

The Husky Stadium TMP is paid for through parking revenues collected at each game. The University of Washington Transportation Office, of which the Parking Division is a part, is a self-supporting operation both during the regular school year and for special events such as football. Therefore, the only source of income for the program is the revenue collected from the parking of autos, charter buses, and boats. Table 6 shows the estimated revenue and expenses associated with the TMP. It was estimated that revenues and expenses would total $353,000 during the 1987 season. Actual revenue was $331,000, with expenses totaling $336,000, for a net loss of $5,000. The loss had to be made up from other Parking Division revenue, such as that from the basketball parking program or other special event parking.

SUMMARY AND CONCLUSIONS

A summary of the paper is now provided.

1. The parking facilities associated with the University of Washington's Husky Stadium are not specifically designed to handle the impacts associated with special event traffic and parking.
2. Before the 1987 football season Husky Stadium had a seating capacity of 58,500. In 1984 the university sought approval from the Seattle City Council to increase the seating capacity by 13,700 to a total of 72,200 seats.
3. The main transportation mode for football game attendees in 1984 (preexpansion) was the private automobile, with more than 76 percent of the people arriving by that mode.
4. Of the 20,500 vehicles used to access a football game in 1984, more than 55 percent parked on campus and the remainder parked off campus in the U-District or on adjacent neighborhood streets.
5. In 1984, 10 percent of the game attendees either walked, rode their motorcycle or bicycle, or were dropped off at the stadium. The remaining 14 percent used public transit (4.2 percent), charter bus or boat (7.1 percent), or private boat (2.4 percent).
6. The goal of the TMP for the expanded stadium was to accommodate a sellout crowd of 72,200 with less reliance on parking in the residential areas near campus than before the stadium was expanded. To achieve the goal, a free transit scrip program was developed, a system of park-and-ride routes introduced, reduced carpool parking rates offered, on-campus parking increased, and marketing and monitoring programs developed.
7. For the 1987 season (after stadium expansion) the university's Transportation Office developed and produced free transit scrip along with two brochures explaining the transportation alternatives available to football game attendees.

TABLE 6 ESTIMATED AND ACTUAL REVENUES AND EXPENSES, 1987

	Pre-Season Estimate	Actual
REVENUES		
Parking	$ 325,000	$ 304,000
Charter Boats and Private Boats	20,000	21,000
Charter Buses	8,000	6,000
Total	$ 353,000	$ 331,000
EXPENSES		
Public Transit Recharges		
- Park and Ride Service	$ 168,000	$ 175,000
- Husky Special & Regular Service	20,000	14,000
Parking Operation & Administration	130,000	120,000
Off-Campus Leased Parking		
- Lease of Facilities	10,000	6,000
- Shuttle Bus Service	10,000	7,000
Publicity, Marketing, Printing & Mailing	15,000	14,000
Total	$ 353,000	$ 336,000
Over (Under)	-	$ (5,000)

8. The park-and-ride system put into operation in 1987 exceeded preseason ridership projections, averaging more than 7,100 riders per game.

9. The total cost of the program during the 1987 season was $336,000. The revenues for the season were $331,000, for a net loss of $5,000, or 1.5 percent of the total expenses.

In conclusion, the Husky Stadium TMP has been a tremendous success, far exceeding expectations for its first full year of operation. The primary goal of the plan, which was to accommodate a sellout crowd of 72,200 with less reliance on parking in the residential areas near campus, has largely been accomplished. The achievement of this goal is primarily attributed to the free transit scrip program that led to greater use of public transit than was anticipated.

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Publication of this paper sponsored by Committee on Parking and Terminals.

Parking Management and Traffic Mitigation in Six Cities: Implications for Local Policy

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Local jurisdictions are using parking management and traffic mitigation policies to discourage solo driving and encourage transit, ridesharing, cycling, and other alternatives to solo driving. This paper focuses on selected policies in six cities, including parking code requirements, encouragements for fringe or peripheral parking, preferential parking for carpoolers, and requirements on new office developments (e.g., through developer agreements) for owner-sponsored traffic mitigations. Included in the review is a synopsis of literature on peripheral parking as several of the cities surveyed are planning or implementing this strategy. The review examines the status of current parking management and traffic mitigation policies and issues of implementation and effectiveness; then it draws policy implications for localities.

The paper is organized in three sections. First is a summary of findings in six jurisdictions surveyed for this study. The jurisdictions are Portland, Oregon; Seattle, Washington; San Francisco and Los Angeles, California; Denver, Colorado; and Hartford, Connecticut. Second is a brief review of peripheral parking literature. Third is a summary with implications for localities.

REVIEW OF PARKING MANAGEMENT AND TRAFFIC MITIGATION IN SIX CITIES

Portland, Oregon

Background Information

Population Downtown employment is about 90,000; residential population is 380,000; standard metropolitan statistical area (SMSA) population is about 1.2 million.

Parking Supply There are 41,000 spaces in the central business district (CBD), with 8,100 publicly owned (5,500 are on-street meters); the balance are privately owned and operated with most open to the public.

Parking Rates Public rates off-street are $65.00 per month, but few monthlies are allowed; daily rate off-street rates range from $0.60 to $1.00 per hour. On-street meters average $0.50 per hour depending on the zone. Private off-street rates range from $87.50 to $35.00 per month. Some private commercial lots offer early bird specials, ranging from $3.50 to $5.50 per day.

Parking and Traffic Mitigation Policies

Parking Policy The city fixes the number of allowed off-street and on-street parking spaces with the intent of limiting automobile use. The current lid is set at 43,914. Hotel and residential parking is not counted in the controlled supply. The lid includes spaces in several approved projects that are not yet built. The parking code sets a maximum number of parking spaces allowed depending on proximity to transit, with no minimum except for residential uses. Requirements in most areas are 1.0 space per 1,000 sq ft of development but range to a low of 0.7 spaces per 1,000 sq ft. Parking is approved by conditional use permit only. It is allocated primarily to new development, major rehabilitation, and customer or visitor parking. Surface lots are also limited to selected purposes and sizes. The city manages several residential permit programs in neighborhoods adjacent to the CBD.

Traffic Mitigation Aside from maintaining a tight parking supply, Portland discourages solo driving through carpool and transit programs. The transit district promotes carpooling and matches carpool applicants by residential location. Reserved parking spaces for carpoolers are provided in city and state garages at $45.00 per month. The city also sells permits at $25.00 per month to allow carpools to park at long-term meters on-street. The city has conditioned some downtown developments to provide priority parking for carpoolers, bicycle racks, transit shelters, and other traffic mitigation strategies. However, the city does not have a trip reduction or transportation systems management ordinance.

The city is studying fringe parking among other new measures (staggered work hours, employer subsidies to transit) to maintain air quality and manage traffic but has not implemented a fringe parking system.

Key Findings

The city is generally satisfied with the parking lid and believes it has helped maintain high transit usage. As much as 48 percent of commuters into the downtown have used transit in past years, although the proportion has fallen to 43 percent

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K. T. Analytics, Inc., 885 Rosemount Road, Oakland, Calif. 94610.

in 1987. The carpool rate is 17 percent. City managers attribute the decline to falling gas prices and some reduction in transit service as a result of fiscal constraints.

The maximum parking requirement has brought both desirable and unexpected results. In accordance with the goals of the maximum policy, many developers have provided at or under the allowable level. However, several buildings have provided considerably less than the maximum, raising the issue of whether the maximum is perhaps set too high. Several developers provide 1 space per 1,200 sq ft where the maximum is 1 space per 1,000 sq ft. Close to transit, some large projects have provided 1 per 2,000 sq ft or less. Exceptions include small projects farther from transit, where developers provide exactly the maximum allowed.

Although the city has not instituted a fringe parking system, staff and consultants are concerned that a fringe system may not serve one important city objective—improved air quality. In Portland where apparently there is considerable demand for shopper parking downtown, shopper parking may replace employee parking as commuters park in the fringe lots. Shoppers generate cold starts (if parked longer than 1 hr) and short trips midday. Both occurrences can increase CO emissions.

Seattle, Washington

Background Information

Population Downtown employment is about 150,000; residential population is 461,000; SMSA population is about 2 million.

Parking Supply There are 72,000 spaces citywide; 12,000 are publicly owned (almost all are on-street metered or nonmetered—no public garages downtown); the balance are privately owned and operated, with most available to the public.

Parking Rates Public rates at parking meters range from $0.25 per hour to $0.50 per hour depending on the zone. Private off-street rates average about $90.00 per month. Average daily rates are $6.00.

Parking and Traffic Mitigation Policies

Parking Policy Various city policies are set with the intent of discouraging solo driving. The city imposes a maximum requirement of 1.0 space per 1,000 sq ft. Excess supply beyond this amount is allowed only through administrative review. Minimum requirements also are established by code and vary by proximity to transit. For example, the minimum for office is 0.54 spaces per 1,000 sq ft close to transit and 0.75 in areas with moderate access to transit. At least 20 percent of parking spaces provided to meet the minimum must be reserved for carpools.

Each carpool space provided (set aside for carpool use from 6:00 a.m. to 9:30 a.m.) in addition to the minimum gains a reduction in the parking requirement of 1.9 spaces. The same reduction in parking requirement may be obtained by subsidizing parking rates for carpoolers by at least 30 percent of monthly market rates. No more than 50 percent of long-term spaces can be set aside for carpools. Provision of free transit passes (for at least 5 yr) reduces the parking requirement by 15 percent. An in-lieu provision allows up to 100 percent of the long-term parking requirement to be waived for contributions to the Downtown Parking Fund. The fund may be used to construct parking anywhere in the downtown and on the periphery of downtown. New parking garages and long-term surface lots are not permitted except through administrative review.

Traffic Mitigation The zoning code establishes mitigation requirements applying to all nonresidential structures exceeding 10,000 sq ft. A transportation coordinator must be maintained on site to promote ridesharing, public transit, and flextime and to conduct an annual employee survey. The coordinator must work with Seattle Metro, the regional rideshare and transit agency, in traffic mitigation. A transportation information center must be established in the lobby or some other visible place. Also, bicycle parking is required at the rate of 1 space for every 20 parking spaces. Before traffic mitigation requirements were added to the zoning code, the city conditioned projects through a master use permit and review authority under the state Environmental Policy Act. The city does not have a trip reduction or transportation systems management ordinance.

The city takes other action to encourage ridesharing. It encourages carpooling by setting aside 700 discounted parking spaces in off- and on-street locations. The city is surrounded by several park-and-ride lots at some distance from the downtown but no peripheral lots.

Key Findings

The city parking management and mitigation program has met with mixed results. On the positive side, city staff who have been interviewed believe that parking and mitigation policies have helped maintain the high transit share for downtown commuters. About 45 percent of downtown employees use transit, although the proportion has been dropping in the past couple of years.

On the other hand, several policies have met with mixed results. First, an evaluation of 14 projects approved between 1979 and 1982 showed that few carpools occupied set-aside spaces provided in major office developments and that considerable developer opposition existed to set-aside policies (*1*). Second, very few developers have been opting to reduce minimum parking requirements for additional carpool stalls, transit pass sales, or contribution to the in-lieu fund. Without in-lieu funds, it is more difficult to proceed with any peripheral parking, as once envisioned. Third, the mitigation programs are working well at some buildings but not at others. According to city staff conducting recent evaluations of mitigation programs, much seems to depend on proximity to transit, the size of employers, types of employees (clerical versus professional), and parking availability nearby. Successes are found at First Interstate and Seafirst; failures at One Union Square and Weston. Fourth, enforcement of mitigation programs has proven difficult. Three or 4 of 16 buildings subject to mitigation requirements are not in compliance. The city is reluctant to enforce mitigation conditions by revoking occupancy permits as this action seems very drastic to all concerned. Fifth, city encouragement of carpooling through discount parking at some of its own facilities has met with problems. One evaluation showed that 40 percent of new poolers attracted to the lots were switching not from solo driving but from transit (*2*). Finally, recent observations and evaluations indicate that possibly as many as 25 percent of lot users may not be legitimate carpoolers.

San Francisco, California

Background Information

Population Downtown employment is about 250,000 (C-3 zone); the residential population for the city is about 740,000.

Parking Supply There are 38,000 spaces downtown, mostly off-street; 48,000 off-street spaces in the "greater downtown"; and about 13,000 off-street spaces publicly owned in the entire city, 11,000 of them in 13 public garages. Planners estimate that at least three-quarters of off-street parking in the downtown is privately owned and operated.

Parking Rates Public rates off-street range from about $60.00 to $260.00 per month, but few monthlies are allowed and provided through wait list and attrition. Hourly rates escalate to encourage short-term parking and discourage long-term parking (e.g., $0.65 for 1st hr, $4.25 for 4 hr, $12.50 for 7 hr; meter rates range from $0.50 to $1.50 per hour). Private off-street rates equal or exceed city rates. The city regulates rates charged at private off-street parking associated with new office development through conditioning requirements.

Parking and Traffic Mitigation Policies

Parking Policy The city "Transit First" policy influences both the supply and price of parking. The newest downtown plan aims at keeping an informal lid on parking supply and emphasizes short-term over long-term parking. There is no code-required parking in the downtown (C-3) area, and only up to 7 percent of a building's gross floor area can be devoted to parking. Under the downtown plan, new buildings must have an approved parking plan before receiving an occupancy permit. Requirements of the plan are a condition for development. In some cases, only short-term parking is approved; in another case, a mix of long, short, and carpool parking was approved. Parking rates are set by the newest parking code revisions. For example, the 4-hr rate cannot be greater than four times the first hour charge. The 8-hr rate cannot be less than 10 times the first hour charge. The city manages an extensive preferential parking program throughout the city.

Traffic Mitigation The city encourages traffic mitigation through a requirement for traffic mitigation plans (TMPs) from developers and annual progress reports. The plans must be developed and updated based on detailed guidelines issued by the city. Generally, the guidelines require designation of an on-site transportation coordinator, provision of transit and rideshare information, a biannual employee survey to track proportion of solo drivers, and implementation of various strategies such as the sale of transit passes.

The city has identified potential fringe parking lots (mostly now used by Caltrans, the state highway and transportation agency) for possible development. The city intends for private developers to develop the lots and implement shuttle systems as an alternative to providing parking on site.

Key Findings

City planners are generally satisfied that parking management strategies have helped maintain good transit use and kept automobile use to a minimum. There are no regular traffic trend or cordon count studies to support the assertion; however, planners indicate there has been no major increase in peak traffic during the past 10 yr in spite of considerable office growth. Local transit ridership is steady, although ridership on Golden Gate Transit into San Francisco has fallen in the past 2 yr. A 1983 survey of workers in the downtown (C-3) zone showed that 60 percent ride transit, 16 percent rideshare, and 17 percent drive alone (*3*).

For now, no developers have come forth with proposals to implement peripheral parking as a way to beat the high price of providing parking on-site, as planners believed might happen or might yet happen. Nor do developers or lenders object to the current limit on parking supplies on-site. Asked why some major companies, such as Bank of America, have removed some functions to suburban office centers, planners indicate that parking and mitigation policies are not the reason. They indicate that the cost of office space and land is the primary reason and point to continued growth in the city.

Developers do object to the regulation of parking pricing but not to requirements for TMP plans. The city is searching for ways to assist developers in preparing plans. The local rideshare agency, RIDES, cannot provide sufficient staff to help prepare plans. There are now about 60 buildings with TMP requirements.

Planners say developers and parking operators comply with the letter of the code on parking pricing rates but sidestep the main intent of requirement—discouraging long-term parking in favor of short-term parking. The city would not cite specific examples but did indicate the need to evaluate and possibly change the pricing regulations.

Los Angeles, California

Background Information

Population Downtown employment is about 200,000; SMSA population is now 3.3 million.

Parking Supply According to projections for 1990 in the CBD, there will be about 127,000 off-street spaces with 81,300 in facilities available to the public and 45,700 restricted to private use. Curb parking will make up about 5,000 spaces.

Parking Rates Public rates off-street range up to $0.50 per hour; on-street rates go up to $1.00 per hour, according to the Institutional and Municipal Parking Congress data.

Parking and Traffic Mitigation Policies

Parking Policy City parking policies are changing to encourage more use of transit and ridesharing. Parking requirements are a minimum of 2 per 1,000 sq ft of development, soon to be increased to 3 per 1,000. However, a lesser requirement is imposed in the "exception area," the downtown business district. There the minimum requirement is reduced to 1 space for each 1,000 sq ft. The city waives the requirement for property located adjacent to publicly owned parking lots.

The city also allows developers to provide up to 75 percent of required parking (in Zones C and M) at remote locations. In this case, shuttle or transit service must be provided between the lot and the destination; an annual report on the remote parking program must be filed with the city; and sufficient open space must be set aside to provide a parking structure to meet full requirements if the city finds it necessary. Another parking policy allows the parking requirement to be reduced by up to 40 percent for specific traffic mitigation programs. Again, sufficient open space must be set aside to meet full requirements if found necessary.

Within the area of Los Angeles regulated by the Community Redevelopment Agency (CRA), developers of projects exceeding 100,000 sq ft must provide no fewer than 25 and no more than 40 percent of code-required parking in peripheral locations. Shuttle service linking the project to the lot must be provided in peak periods and operate at least every 10 min.

The city has not yet initiated much preferential parking in the vicinity of downtown, but plans are under way to begin such programs.

Traffic Mitigation In addition to zoning code provisions aimed at reducing traffic in the central downtown, the city has adopted other traffic mitigation measures. The city rideshare ordinance requires that owners of work sites with more than 700 employees prepare and implement trip reduction plans. Plans must designate a transportation coordinator, list specific strategies that will be implemented to reduce solo driving, provide annual progress reports, and meet a goal of 1.75 average vehicle employee ridership (weekly employee population divided by weekly number of employee vehicles). Additionally, the CRA requires traffic mitigation strategies by agreement with developers in its area of jurisdiction.

Key Findings

The most significant finding from Los Angeles relates to peripheral parking. The CRA requirement for peripheral parking is too new to evaluate, but the city peripheral program has not succeeded. No developers have opted to provide off-site parking as allowed by code. Developers are discouraged by the possibility that additional on-site parking may be required by the city at a future date depending on the effect of the peripheral parking.

Similar problems beset the provision allowing reductions in parking for traffic mitigation measures. First, city requirements are considered minimal, so there is little incentive to reduce them for any reason. Second, developers do not like the possibility of providing more on-site parking if mitigation measures fail.

The city rideshare ordinance has been rescinded because the South Coast Air Quality Management District now requires all employers in the region to implement trip reduction plans. The effects of the ordinance were not evaluated, although city staff indicate that 45 plans were submitted to the city under the ordinance—some "very good but many very poor." CRA staff indicate that some of their longest-standing traffic mitigation agreements are not monitored well enough for their effects to be known. The staff believes the mitigation at City Corp Plaza is working well but could not provide specific evidence.

Overall, about 60 percent of employees drive alone to the downtown, 25 percent arrive by transit, and the balance arrive by carpool and other means.

Denver, Colorado

Background Information

Population Downtown employment is about 118,000; resident population is 491,000; SMSA population is about 1.6 million.

Parking Supply There are 71,000 spaces in the greater downtown area (153 blocks) and 37,000 in the core area (46 blocks). There are only 2,100 publicly owned off-street spaces; the great bulk of parking is privately owned and operated and open to the public.

Parking Rates Public off-street rates range from $60.00 to $80.00 per month; the daily off-street rate is $0.50 per half-hour. On-street meters range from $0.20 to $1.00 per hour. Private rates are somewhat above public rates. Early bird rates are offered in many facilities.

Parking and Traffic Mitigation Policies

Parking Policy Denver does not use parking policy as an explicit means for reducing solo driving or increasing transit use. Although the city offers price breaks for car and vanpools in certain city facilities, parking requirements are not set to encourage transit or ridesharing. Requirements for office development in the city are 2 spaces per 1,000 sq ft except in the downtown (Zone B-5), where there is no requirement, maximum or minimum.

In the downtown, parking policy encourages provision of parking, and at least one public parking policy encourages long-term parking. Concerned that developers were not providing enough parking in the downtown (0.5 space per 1,000 sq ft is not uncommon), the city adopted a "premium" policy in 1981. The policy provides developers an extra 500 sq ft of development for each parking space provided beyond 70 percent of what is required for the particular use outside the downtown (2 per 1,000 for office). Parking rates at publicly owned facilities lean toward catering to the long-term parker, as evidenced by some early bird specials (discount rates for parkers arriving before an early hour).

Another policy allows for the provision of peripheral parking. Part or all of required parking may be located off-site abutting the development or in the same zoning district, provided the developer can show a plan to ensure that the lot is devoted to parkers in the development. No shuttle service is required. Transit service may suffice as the connector, or a lot within acceptable walking distance may be approved.

In 1985 the city and regional transit set up a park-and-ride at Mile High Stadium, about 1 mile from the downtown. Shuttles ran every 20 min in the peak. Fares were $0.25, compared with $0.75 elsewhere.

The city has only two preferential parking zones. One is to protect neighborhoods from spillover parking around Mile High Stadium.

Traffic Mitigation Denver does not generally require buildings to have traffic mitigation strategies. No mitigation ordinance is envisioned. Occasionally, a planned unit development is allowed with reduced parking requirements on the basis of proximity to transit. A variances hearing is required. Very few such agreements are in place. Because Denver is suffering from high office vacancy (25 percent reported) and a slumping energy-dependent economy, city and transit district staff expressed more concern with stimulating economic activity than with mitigating traffic.

A voluntary program to reduce driving during times of poor air quality has been in place for 3 yr. The Better Air Campaign operated by the state Health Department is credited with reducing daily traffic by 3 to 5 percent in the region. Drivers are asked not to drive on certain days depending on their license plate number.

Key Findings

With the exception of a voluntary regional program aimed at better air quality, Denver policy has not been strongly directed at reducing automobile use. Mitigation policies have been limited to occasional agreements for reduced parking based primarily on proximity to transit. Parking policy is not aimed at reducing automobile use, although the absence of any minimum requirement in the downtown has tended to limit supply there. In some cases, developers provide as little as 0.25 space per 1,000 sq ft.

Even with this relatively tight supply of parking, transit ridership to the greater downtown is only a 13 percent share, with automobile drivers and passengers making up 87 percent, according to 1985 data. However, transit ridership to the core is about 28 percent of work trips, although this share may be declining according to transit officials.

Trends in transit ridership are attributed more to service levels and the state of the economy than to parking or mitigation policy. The city has implemented a transit mall in the downtown (no cars allowed on 16th Street except for cross traffic) with frequent shuttle service back and forth to transfer terminals at the ends of the mall. The terminals are destinations for express buses arriving and departing from outlying areas.

The Denver experience with peripheral parking has been mixed. Several developers have opted to provide off-site parking as allowed by code but have made no connections to their projects nor managed the lots to ensure that only project employees park there. City staff find it difficult to monitor and enforce the peripheral parking agreements. The park-and-ride at Mile High Stadium worked for a year or two but then was terminated. About 150 vehicles used the lot until the economy in Denver slumped and parking rates were lowered in downtown. Use of the lot declined, and shuttle service was halted. Today, only a few drivers park at the lot and ride regular, fixed-route service nearby. Transit planners say the park-and-ride may start again but only if and when the economy improves.

Hartford, Connecticut

Background Information

Population Downtown employment is about 90,000.

Parking Supply There are 21,000 spaces, with 2,700 publicly owned off-street; the balance is privately owned and operated, with about 10,000 spaces open to the public and the rest devoted to employees and patrons of businesses.

Parking Rates Private rates in garages range from $120.00 to $180.00 per month; in lots the range is $50.00 to $75.00 per month. Short-term rates are $1.60 per half-hour in some areas. Public rates escalate by duration to discourage long-term parking, beginning at $0.25 per half-hour. Meter rates are generally $0.25 per half-hour.

Parking and Traffic Mitigation Policies

Parking Policy Several policies in Hartford aim at encouraging transit, ridesharing, and traffic mitigation. The office parking requirement downtown is 1 space per 1,000 sq ft. Parking requirements can be reduced by up to 30 percent for discounted carpool parking, rideshare promotions, subsidized transit passes, and shuttle service from off-site parking. Additionally, through administrative review procedures rather than code, the city requires office developers to put new parking underground. The intent is to encourage off-site parking, shuttle service, transit, and ridesharing. At its own parking facilities, the city maximizes short-term parking and minimizes long-term parking.

Traffic Mitigation All developments in two downtown zones (B-1 and B-2) must prepare a Transportation Management Plan. TMP requirements encourage strategies for promoting ridesharing and transit and provision of off-site parking. Through negotiations on the plan, the city and developers agree to specific traffic mitigation strategies that are then secured by developer agreement. The state Transportation Commission also plays a role in mitigation. It requires special permits for downtown projects that will have an impact on state highways. The permit may require strategies to encourage transit and ridesharing or financial contributions in support of same. Finally, the Rideshare Company (a transportation management organization comprised of 14 large employers) promotes ridesharing downtown, encourages transit, and promotes policies supportive of ridesharing and transit—for example, reduction of employer parking subsidies for downtown employees.

The city has developed one fringe parking facility as part of mitigation efforts and plans now to start another operated by the state as a park-and-ride for state employees.

Key Findings

The Hartford incentive for reduced parking requirements has not been used. In particular, there have been no requests for reduced parking requirements since 1984 when reductions were offered for rideshare and transit encouragements. It seems that developers and lenders believe that parking is very short in Hartford and want to provide more than the minimum required. Thus, the possible relaxation in requirements is not a meaningful incentive.

City encouragements for developer provision of peripheral parking and shuttle systems also have not yet worked. City planners hoped that developers would provide peripheral parking and shuttles as a result of requirements for underground parking and development of TMPs. Instead, developers lease nearby surface parking where available and provide it to tenants. City planners hope that developers will provide peripheral lots and shuttles as new development takes away surface parking in the downtown. The one city-initiated peripheral lot (located at a sports facility to the north) has not attracted much use. Secure parking and shuttle service are offered at a cost of $50.00 per month. Much downtown commercial surface parking costs about the same rate, so the peripheral lot is not attractive.

Certain traffic mitigation policies are meeting with more success. The Rideshare Company claims success in reducing drive-alone commute trips by 12 to 15 percent at 16 companies it targets for services. The result is attributed to intensive, personalized rideshare services, including good support from company managers and fast carpooling matching. The company also indicates success in encouraging flextime to spread the traffic peak. The company has been working for 5 yr to reduce employer subsidies of employee parking. Estimates are that 70 percent of Hartford employees receive subsidies. So far, no employers have removed the subsidy. In spite of some successes, Rideshare Company estimates that solo driving shares are up by 7 or 8 percent over the past 5 yr, with transit ridership down by the same percent and overall ridesharing up just a couple of percent. Transit ridership share in Hartford was 20 percent in 1988; rideshare, 22 percent; and solo share, 55 percent. Finally, the effects of state-imposed mitigations are not yet known. The state has required street improvements and contributions to the state-operated transit system serving the city.

REVIEW OF PERIPHERAL PARKING LITERATURE

The review of parking and traffic mitigation policies in six cities reveals considerable interest in peripheral parking as one way to reduce downtown traffic and as an alternative to providing parking on valuable if not scarce downtown land. Peripheral parking is defined as parking within a mile or two of downtown, as contrasted with remote park-and-ride systems located many miles from downtown. A portion of the park-and-ride literature is devoted to peripheral parking. The literature provides some lessons about the effectiveness and operations of peripheral lots.

Effectiveness

The park-and-ride literature suggests cautions about peripheral lots. One careful study of park-and-ride systems in Seattle (*4*) suggested that lots located farther from downtown are generally more effective than those located closer to the CBD. Some close-in lots showed good use but drew a high proportion of their users away from local transit routes. The lots that attracted the highest proportions of people who previously drove alone were those more than 10 miles out in areas without previous transit service. The same result was found in a study of park-and-ride lots in Baltimore (*5*).

This is not to say that fringe parking cannot work, especially where coordinated with other policies. For several years, St. Paul operated a successful system of park-and-ride lots on the periphery of downtown. Low parking rates of $1.00 per day or $20.00 per month and frequent shuttle service (every 5 min) attracted good use of the lots (*6*). More recently, the city has abandoned the shuttle service because of growing expense. The system has been replaced by a program of low-fare public transit in a downtown zone ($0.10 compared with $0.75), dubbed the "dime zone," combined with inexpensive daily parking at the Civic Center garage (1,600 spaces) on the edge of the dime zone. According to city staff, many commuters drive to the Civic Center and other commercial parking facilities at the edge of the dime zone and ride transit to work. Parking in the downtown averages $50.00 per month and $4.00 per day, whereas Civic Center rates are about half these rates. No formal evaluation has been done of fringe parking demand, but the city believes the demand is considerable. Overall transit share for employees is about 38 percent into the downtown.

Operations

Park-and-ride facilities must be carefully planned and operated to succeed. The literature suggests conducting careful market research before initiating any park-and-ride lots. Research should include surveying commuters and employees regarding possible interest in park-and-ride, presuming certain bus frequencies, routes, fares, and parking fees, if any. The literature suggests there is no uniform way to estimate demand (*7*) but advises a combination of employee surveys and data analysis focused especially on the number of commuters passing near the proposed facility and their current mode shares. This work will define the probable market area and the maximum number of candidate drivers and transit users who might use the facility.

The literature suggests certain operational and design guidance. The facility must be visible and well marked. Transit must have access to the site. Walking distances within the lot to transit must not be more than 600 to 1,000 ft. Transit frequency should be no more than 5 to 10 min. Practical limits on overall size will be determined by the site, but experience suggests a maximum of 1,000 to 1,500 spaces per transit terminal. A daily demand of 250 is suggested as the minimum necessary to justify park-and-ride service. The literature also suggests using joint use lots (sports centers, churches, shopping centers), especially where there is uncertainty about demand or where low demand is probable. The literature offers other guidance regarding shelters for waiting, telephones, trash receptacles, security, liability, and lighting.

IMPLICATIONS FOR LOCALITIES

Parking Policy

The case studies and literature have several implications regarding parking policies. Certainly one lesson is that cities have a difficult time setting parking requirements in support of policy objectives. For example, Portland's maximum is set sufficiently high that many developers provide less than the maximum. Several cities have provided for optional relaxations in parking requirements for various purposes (support of peripheral parking, ridesharing and transit encouragements, in-lieu funds) only to find developers not taking advantage of relaxations. Los Angeles, Hartford, and Seattle all provide examples.

The difficulties of setting maximums, minimums, or relaxations to serve public purposes are understandable. Determining what developers and lenders prefer to provide in the way of parking supply and setting requirement policy accordingly are not simple tasks. Even if planners are able to determine the market demand and supply levels at any one time and place, the demand-supply equation is constantly varying because of everything from the state of the economy to the price of gasoline to the level of transit service. Policy implications for localities follow.

Local governments are best advised to be cautious with maximums, minimums, and flexible requirements. Cities and counties need to be especially careful in designing minimum requirements with relaxations in support of in-lieu funds or ridesharing and transit. It is very possible that such an approach will not be as attractive to developers as intended.

If support of ridesharing or transit is desired, it should be required directly rather than tied to optional reductions in requirements.

Likewise, any plans for fringe parking probably should not be tied to in-lieu financing, as anticipated funding may not develop.

Maximum or minimum requirements, if desired, should be set only after careful assessment of what developers and lenders perceive as the parking market. Even then, these limits may well miss the mark in some areas—if not immediately, then in the future—with changes in development, transit, and driving trends. It is probable that some developers will provide much less than the maximum or much more than the minimum, thereby raising questions about the rationale for the policies.

Another clear lesson from the case studies is that parking rate regulation also should be approached with caution. Not only is there virtually no experience with the strategy but in the one case where it is in effect (San Francisco), developers are finding ways to subvert the regulation. Perhaps in time San Francisco will find the formula that has the desired effect.

At this stage, the experience with rate regulation is simply too limited and problematic for localities to implement rate regulation.

Finally, it appears that employer subsidies of employee parking may be widespread, at least in some cities (Hartford). If so, this phenomenon will blunt the effects of any parking pricing policies aimed at raising rates and discouraging solo driving. Such policies include parking taxes, rate regulation, and requirements for priced permits in certain zones. Thus, if localities wish to analyze pricing options, the first step should be to assess the prevalence of employer parking subsidies.

Transit Use and Parking Policy

The case studies reveal an important lesson about transit use. In all the cities surveyed, transit use appears to be falling irrespective of parking policy. Transit use is falling where the most stringent policies are in effect (Portland, Seattle, San Francisco), as well as where little parking policy is in effect (Denver). Very probably the effect is due to such variables as declining gasoline prices or transit service or both. Although the declines are modest, they point up the fact that even the most aggressive parking policy cannot always boost transit ridership, especially in the face of counteracting variables.

Another conclusion is that limited and costly parking certainly appears to be associated with the highest transit shares. San Francisco, with the most expensive and least available parking downtown compared with the number of employees, shows the highest transit share (60 percent). Portland and Seattle come in next (43 percent and 45 percent, respectively), as do their average parking prices and relatively tight supplies. Denver is next (28 percent), with few stringent parking policies but a relatively tight supply provided by the market. The anomaly is Hartford, with tight and expensive parking but a relatively low transit share (20 percent). Perhaps the result can be explained by the relatively high rideshare rate in Hartford, 22 percent.

Policy implications for localities follow.

- Localities are advised to keep parking on the tight side compared with demand, presuming the goal of increased transit and ridesharing. Left on their own, local developers and lenders may prefer to provide limited parking, as in Denver. In such a case, local governments may decide not to intervene in the market. However, if the market provides ample parking, or if prices appear low, or if parking subsidies are common, then local governments may wish to intervene through maximum requirements or pricing policies.
- Given the experience of cities in regulating supply through code provisions, localities probably should proceed step by step and evaluate policies along the way. One approach to consider might be a maximum requirement in the immediate vicinity of transit corridors and major terminals. Again, the maximum must be set after careful market assessment and should periodically be reviewed.

Peripheral Parking

The case studies and literature suggest several lessons about peripheral or fringe parking. First, developers are not likely to develop fringe facilities and shuttle connections with only encouragements and incentives to do so. Hartford, San Francisco, and Los Angeles have encouraged developers to develop fringe park-and-ride systems through various direct and indirect means. However, no fringe parking has yet developed. In Los Angeles, it appears that the code provision attaches too many burdensome requirements to attract developers. Yet in Hartford, the fringe parking provisions are not a burden, and still no fringe parking has developed. Developers prefer simply to lease nearby surface lots for employees who then walk a block or two to work. In all these locations, the cost of providing on-site parking is substantial. In light of this situation, it is no wonder that the CRA in Los Angeles is now requiring peripheral parking instead of making it an option. In short, developers are not inclined to provide fringe facilities under the usual optional provisions found in codes.

Second, even if fringe parking is implemented by one means or another, it may not work well. Denver developers have provided some off-site parking in response to city code provisions but have not located or managed the parking in a way to ensure that tenant employees use it. Off-site parking is sometimes used by parkers not related to the project. And lots often are not on transit routes and are not linked to the development by shuttle. City staff find it hard to enforce provisions requiring better management and linkages. The Denver Mile High Stadium park-and-ride was modestly successful for a short time but very susceptible to changes in the economy and parking rates downtown. In Hartford, the city-initiated test lot is not yet working well. Finally, the park-and-ride literature suggests that close-in lots may take away ridership from local transit service or may not work as well as remote lots. In any case, fringe facilities must be carefully planned and coordinated with transit. One success in St. Paul seems to result from not only reduced parking charges at the lot but also frequent and inexpensive transit service to downtown.

Policy implications for localities follow.

- Localities should not attempt to encourage fringe parking through incentives in the parking code, such as reduced parking requirements. The experience suggests that cities have a difficult time developing fringe facilities in this way, as well as regulating and enforcing their use.
- Localities may wish to test fringe parking at a few facilities, perhaps starting through joint use arrangements to minimize cost and allow for easy termination. If experience is any guide, use may be limited or short-lived and in any case will be highly dependent on parking prices and policies downtown. Any such test should involve frequent shuttle service, low or no fares, and design considerations suggested by the literature.

Traffic Mitigation

The case studies suggest some pointers. First, the success of traffic mitigation strategies is heavily dependent on variables other than the strategies themselves. The size and makeup of the employment force, the availability of parking, the proximity to transit, and other variables are important. Consequently, it is no surprise that cities have very mixed results when requiring specific mitigation strategies, such as designated carpool stalls or transit pass sales. Seattle experience underscores this point. Second, mitigation programs require constant vigilance and enforcement complexities. The Seattle experience demonstrates the need to monitor developments for compliance with mitigation requirements constantly and the need to develop realistic sanctions (i.e., measures other than revoking occupancy permits). Monitoring preferential carpool treatments also is important. Clearly, staff and resources are needed to exert vigilance. Third, if mitigation plans are required from developers or employers, they too will require much review and interaction to ensure reasonable quality and follow-through, as suggested by the Los Angeles experience. Finally, voluntary and cooperative mitigation programs on the part of businesses and cities have brought some successes, as in Hartford, where ridesharing is up as a result of a concerted private sector effort. However, such efforts require strong commitment on the part of business leaders, good organization and staffing, and constant visibility. Policy implications for localities follow.

- Irrespective of what policy instrument localities use to encourage mitigation (ordinance, developer agreements, parking code provisions), cities and counties should not require many specific mitigation strategies, such as the set-aside of some proportion of parking for carpools. Instead, localities should require a designated coordinator, provision of transit and rideshare information to employees, and a plan that proposes strategies tailored to the site and types of employees at the site. Localities should be prepared to review and negotiate plans and develop staff accordingly.
- Local governments should investigate the potential of cooperative mitigation efforts with the private sector. The success of such efforts will be determined by the energy, commitment, resources and visibility given to the program.
- Localities should monitor the traffic mitigation plans and directions of the air quality management district for their areas and possible state legislation on air quality and mitigation. Evidence suggests that the role of regional and state actors and agencies in traffic mitigation and trip reduction is growing. In time, trip reduction may be preempted by other agencies.

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Publication of this paper sponsored by Committee on Parking and Terminals.

Air Quality Offsets for Parking

WILLIAM R. LOUDON, ELSA COLEMAN, AND JOHN H. SUHRBIER

As in many downtown areas in large metropolitan areas, air quality has been a serious concern in Portland, Oregon. Since the establishment of federal air quality standards in the early seventies, downtown Portland has been in violation of the 8-hr carbon monoxide standard. But unlike most major metropolitan areas, Portland has been willing to use parking management as a tool for improving air quality. As a central element of its transportation control plan, the city set a ceiling of roughly 40,000 parking spaces in the downtown and has maintained that ceiling for 13 yr. Although there is considerable optimism that the downtown will soon be in compliance with the carbon monoxide standard, there is also pressure to increase the parking ceiling to accommodate new growth in the downtown. This paper describes research conducted by Cambridge Systematics, Inc., and the city of Portland on alternative methods of reducing emissions in the downtown and on the "parking space equivalents" of these alternative measures. The 11 alternative measures that were considered have been referred to as "offsets" because they were viewed as potentially offsetting the air quality impacts of adding more parking downtown. The paper describes the 11 measures considered, the methodology used to evaluate the potential effectiveness of each in Portland, and the conclusions reached about each as a potential offset measure. The project involved considerable quantitative research and modeling to estimate the emissions impacts of different types of parking behavior and to estimate the emissions reduction potential of each measure. As a result, the paper provides new insights into the relationship between parking and air quality and can provide considerable guidance to other cities struggling to balance parking and emissions reduction needs.

Since 1975, the total supply of parking in downtown Portland has been constrained to a maximum of roughly 40,000 spaces as part of an overall transportation strategy to improve downtown air quality. In the 12-yr period since the parking lid was established, employment downtown has increased from roughly 65,000 to more than 80,000. Although much of the additional travel generated by this development has been accommodated through expansion of transit service, the growth has also begun to place pressure on the available parking supply. The desire to redevelop older parts of the downtown and to continue the overall economic growth downtown has prompted the city to explore the implementation of other measures that might meet the same air quality objectives that the parking lid was designed to fulfill. This paper describes research undertaken by the city of Portland (*1*) to identify a range of transportation measures that could help the city to accommodate additional parking while complying with the provisions of the federal Clean Air Act.

Eleven potential measures were examined in the research effort, each having been generated through a process of discussion and consensus building by city, regional, and state agency staff and through public input. The 11 measures were

1. Fringe parking (adjacent to downtown),
2. Alternative work hours (peak spreading),
3. Subsidy of ridesharing and transit,
4. Parking pricing and use management,
5. Park-and-ride remote lots,
6. Restrictions on parking for company fleets,
7. Alternative fuels,
8. Enhanced vehicle inspection and maintenance,
9. Increased transit capacity,
10. Signal timing and other traffic flow improvements, and
11. Improved bicycle access to transit.

These measures were called "offsets" because they were seen as potentially offsetting the emissions generated by additional parking spaces with an equivalent reduction in emissions. Each of the potential offset measures was evaluated in the specific context of downtown Portland, and an estimate of the potential reduction in carbon monoxide (CO) emissions was made for each.

This paper describes the 11 measures considered and presents the results of the research on their potential effectiveness. By describing the problem in Portland, the methodology used for the analysis, and the results of the research, the paper provides insights about the relationship between parking and environmental quality in a downtown area. The paper explores some of the intricacies of parking behavior and pollutant emissions and illustrates that attention to these intricacies is important to the prediction of the emissions impacts of transportation measures.

THE AIR QUALITY PROBLEM IN DOWNTOWN PORTLAND

Since federal air quality standards were established for metropolitan areas in 1970, the downtown area of Portland has exceeded the standard for 8-hr average concentrations of CO. The federal standard requires that the second-highest 8-hr average observed during a year be no more than 10 mg/m^3. Although the values recorded downtown have declined steadily since 1973, as illustrated in Figure 1, the recorded level in 1985 was still 10.1 mg/m^3.

There is optimism on the part of the city that the standard will be achieved by the new deadline imposed by the U.S. Environmental Protection Agency (EPA). There is also recognition, however, that the city's strict adherence to the parking supply ceiling set in 1973 and the concurrent increase in commuter trips on transit have been major factors in the reduction in emissions, particularly in CO concentrations.

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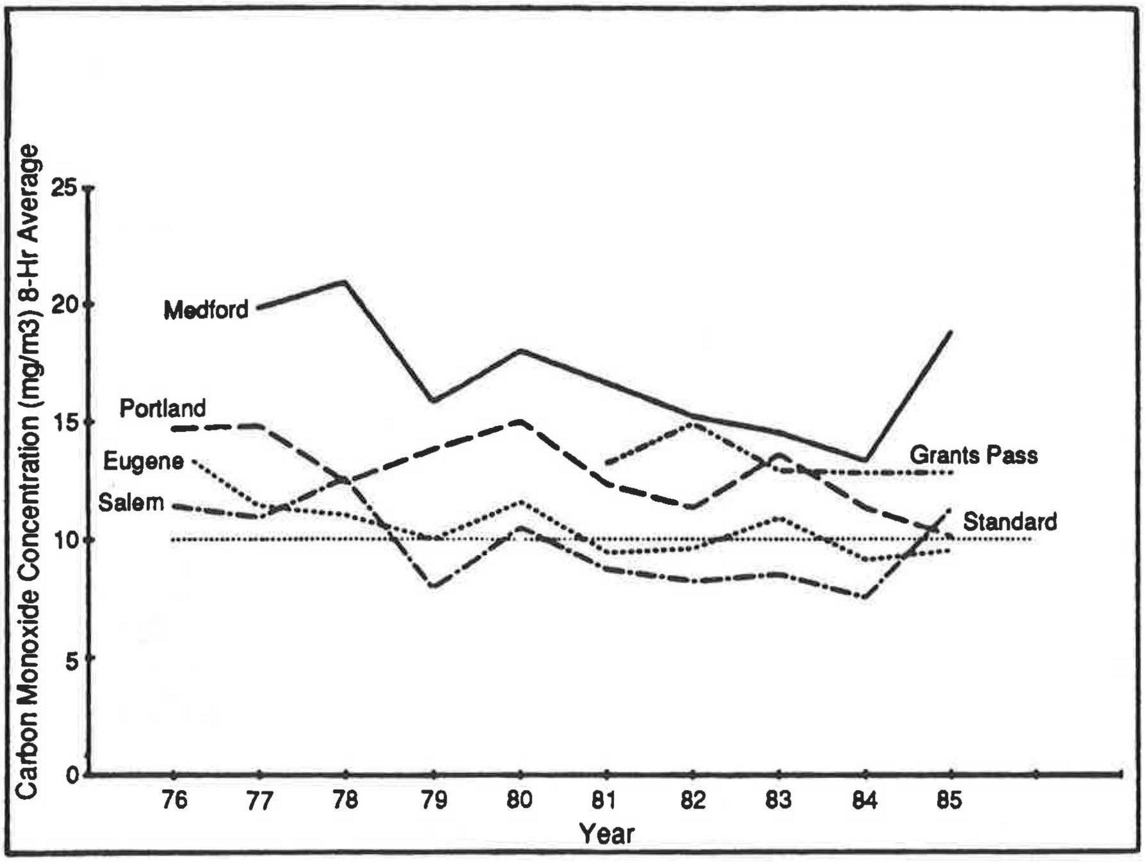


FIGURE 1 Ambient carbon monoxide trends in nonattainment areas, second highest day (*2*).

The inability to attain the 8-hr CO standard in the past has special implications for the types of offset measures that might be most effective or the types of parking that result in emissions most directly affecting the standard. Figure 2 illustrates the observed hourly concentrations for the permanent recording station located at the corner of Fourth Avenue and Alder Street in downtown Portland. The recording is for March 5, 1984, the day with the second-highest average for that year; it is the measurement by which compliance with the standard was judged.

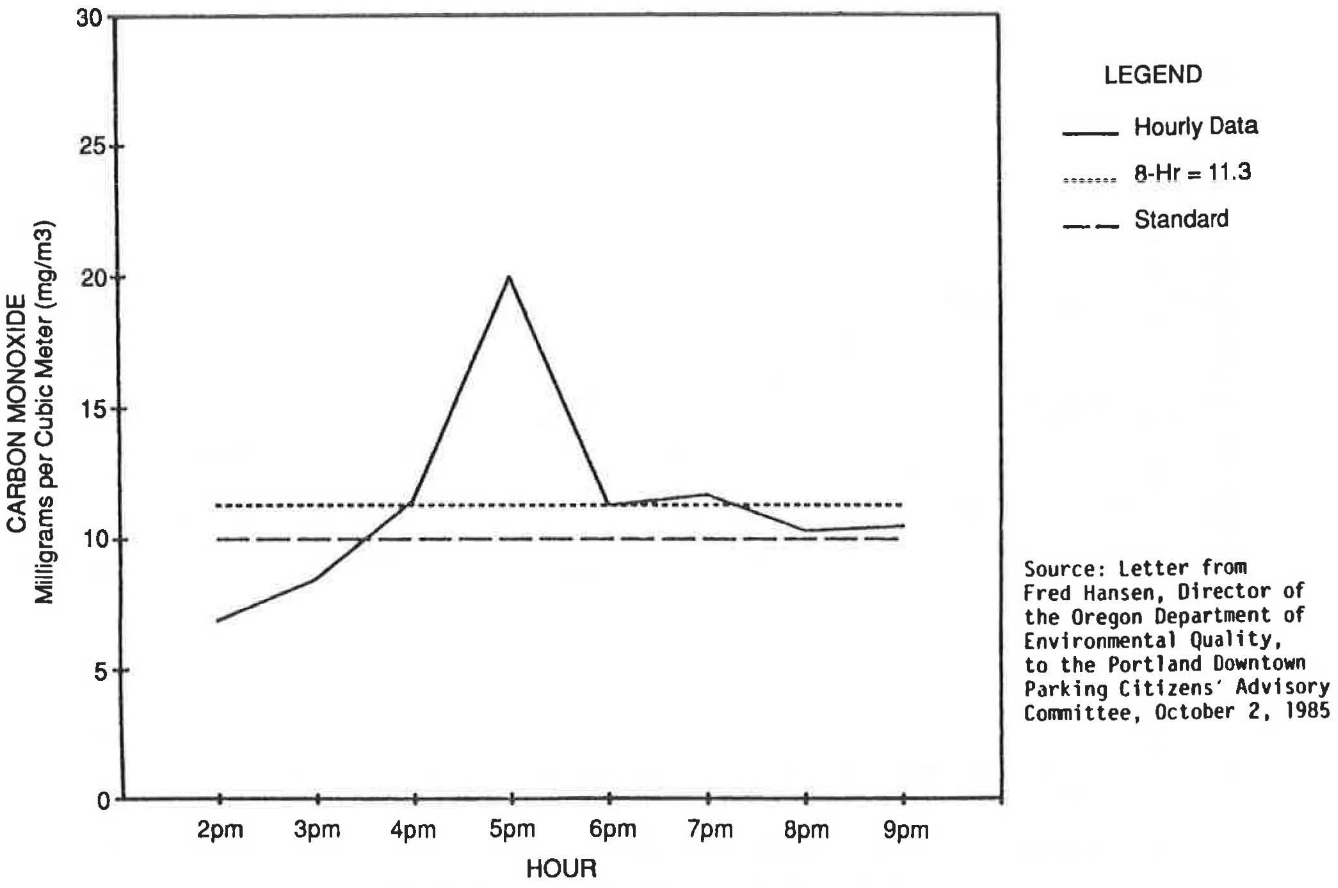
The most notable characteristic of the measurement is that the 8 highest hours of CO concentration were the hours between about 1:30 p.m. and 9:30 p.m. Although the timing of the highest 8-hr concentration varies from day to day and year to year, the period is almost always in the range from 10:00 a.m. to 10:00 p.m. The highest 1-hr concentrations almost always occur during the hour ending at 5:00 p.m.

A significant factor related to the timing of the peak 8-hr concentration is that it does not include the morning commute period, which in Portland is roughly 6:00 a.m. to 9:00 a.m., with the highest hour being from 7:30 to 8:30. Although it is possible that some of the emissions from this morning commute period affect the 8-hr period, the fraction would be quite small because most would have dissipated within 2 hr.

The dramatically higher hourly concentrations in the afternoon and evening reflect, in part, the significant difference between the rate of CO emissions (expressed in grams per mile traveled) from vehicles entering the downtown after their engines have had sufficient time to warm up and that from vehicles leaving the downtown. The vehicles leaving the downtown are most often being started cold after being off for a period of time, and emission rates immediately after a "cold start" are significantly higher than when the engine is started "warm." The average "cold start" emission rate for passenger vehicles in downtown Portland is estimated to be 114.3 g/mi compared with the "warm start" emission rate of 19.2 g/mi. Both rates are averages over the mix of vehicles, by age, in the downtown area.

Virtually all passenger vehicles are still "warm" if started within 1 hr of being turned off. For parking durations of 1 to 4 hr, only vehicles manufactured before 1975 would still be "warm" when restarted. Vehicles manufactured in 1975 and later have emission control equipment that causes a "cold start" to occur after only 1 hr (*3*, p. 47). Only about 9 percent of the passenger vehicles observed in downtown Portland during a recent survey were manufactured before 1975.

Because of the typical timing of the highest 8-hr concentration of CO and because of the difference between "cold start" and "warm start" emission rates, the parkers who have the most significant impact on the 8-hr CO levels downtown are those who arrive and leave during the peak 8-hr concentration period and who park for more than 1 hr. The level of emissions per trip for these parkers is roughly 123 g, based on an average trip length of 1.5 mi in the downtown area for a round trip to and from the parking location. This is 43 percent higher than the estimated emissions from a commuter (88.5 g) who arrives well before the 8-hr period during which the maximum CO concentration is measured, but who leaves



Source: Letter from Fred Hansen, Director of the Oregon Department of Environmental Quality, to the Portland Downtown Parking Citizens' Advisory Committee, October 2, 1985

FIGURE 2 Maximum 8-hr carbon monoxide at Fourth and Alder, March 5, 1984.

during the evening commute period after parking for more than 4 hr. The lowest emissions result from the short-term parker who parks for 1 hr or less. The emissions from such a trip are roughly 28.8 g. An estimation of the overall distribution of parkers by duration of stay based on available data is illustrated in Figure 3.

EVALUATION OF OFFSETS

The evaluation of each of the measures included a review of experience with the measure in other cities as well as any experience with the measure in downtown Portland. A computer-oriented model system was also constructed to aid in the quantitative assessment of the potential impacts of each of the measures (*4*). The Figure 3 model system provided predictions of the changes in parking by sector, by type of parking (garage, lot, on-street), by time of arrival, and by duration of stay. The estimates were based on observed sensitivities to changes in parking costs, the cost of other modes, the travel times by alternative modes, and the baseline level of parking demand and travel by mode as could best be constructed from available data. The sensitivities were based on a combination of model parameters from the regional models maintained by the Metropolitan Service District, Portland's regional planning organization, and sensitivities observed in other cities when similar measures were implemented.

The cornerstone of the parking analyses was a computer forecasting system that combines proven models of travel behavior into an integrated modeling approach that can be used to estimate the downtown emission impacts of potential changes in parking and other transportation policies. The overall structure of the resulting air quality offsets model system is illustrated in Figure 4.

The model provided the following analytic capabilities:

- A single, integrated data base oriented to the city's 11 defined parking sectors that combines existing information by type of parking facility, time-of-day occupancy, price, and duration of stay;
- Analysis of the characteristics of current or predicted future parking utilization by location, time of day, and type of facility;
- Examination of the impacts of changes in parking supply or cost, either on the level of parking demand downtown as a whole or by parking location, type, or time of day within the downtown;
- Translation of parking characteristics directly into CO emission impacts; and
- Consideration of the effect of changes in work trip mode choice in the demand for downtown parking by location and type.

The air quality offsets computer model was programmed as a series of interconnected Lotus 1-2-3 spreadsheets and operates on an IBM PC-compatible microcomputer. It was designed to allow city staff to evaluate additional candidate offsets and parking policies as the need arises. This could

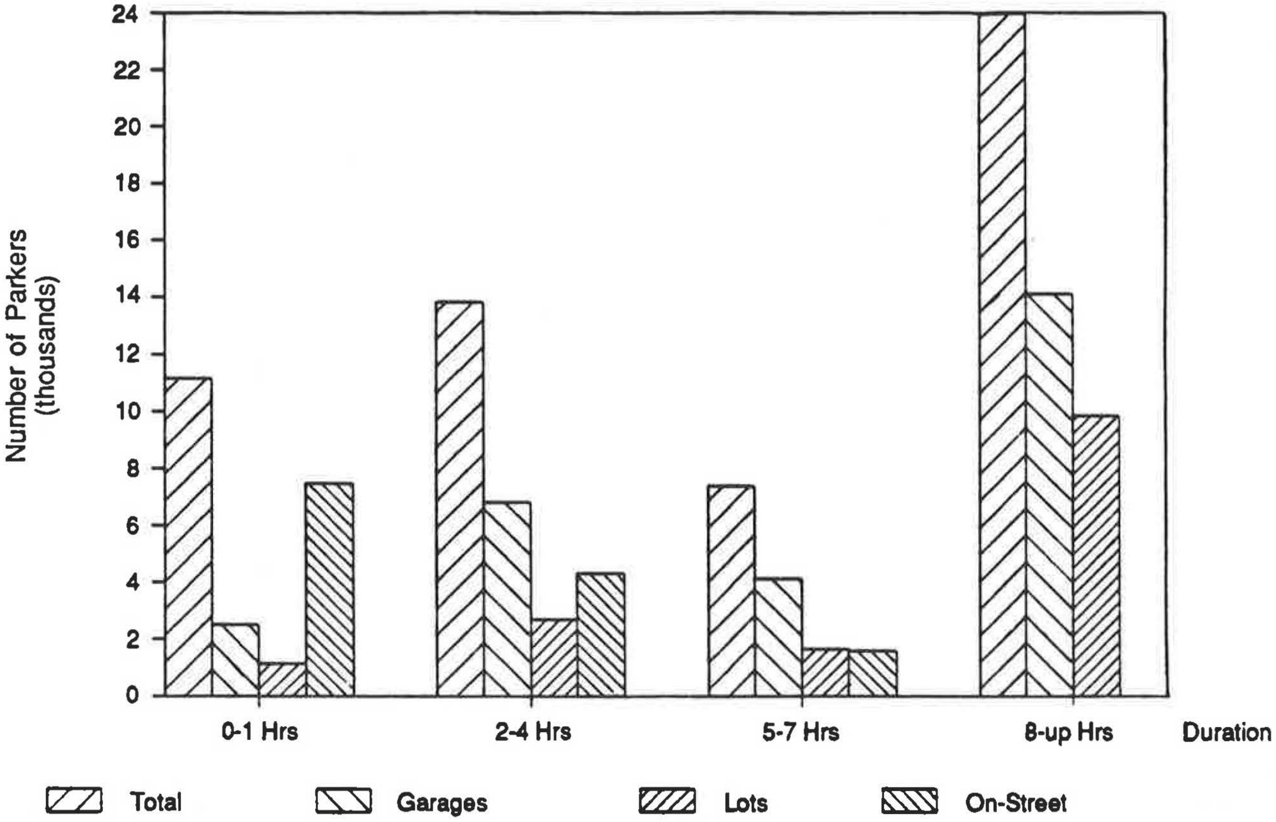


FIGURE 3 Distribution of parking by duration.

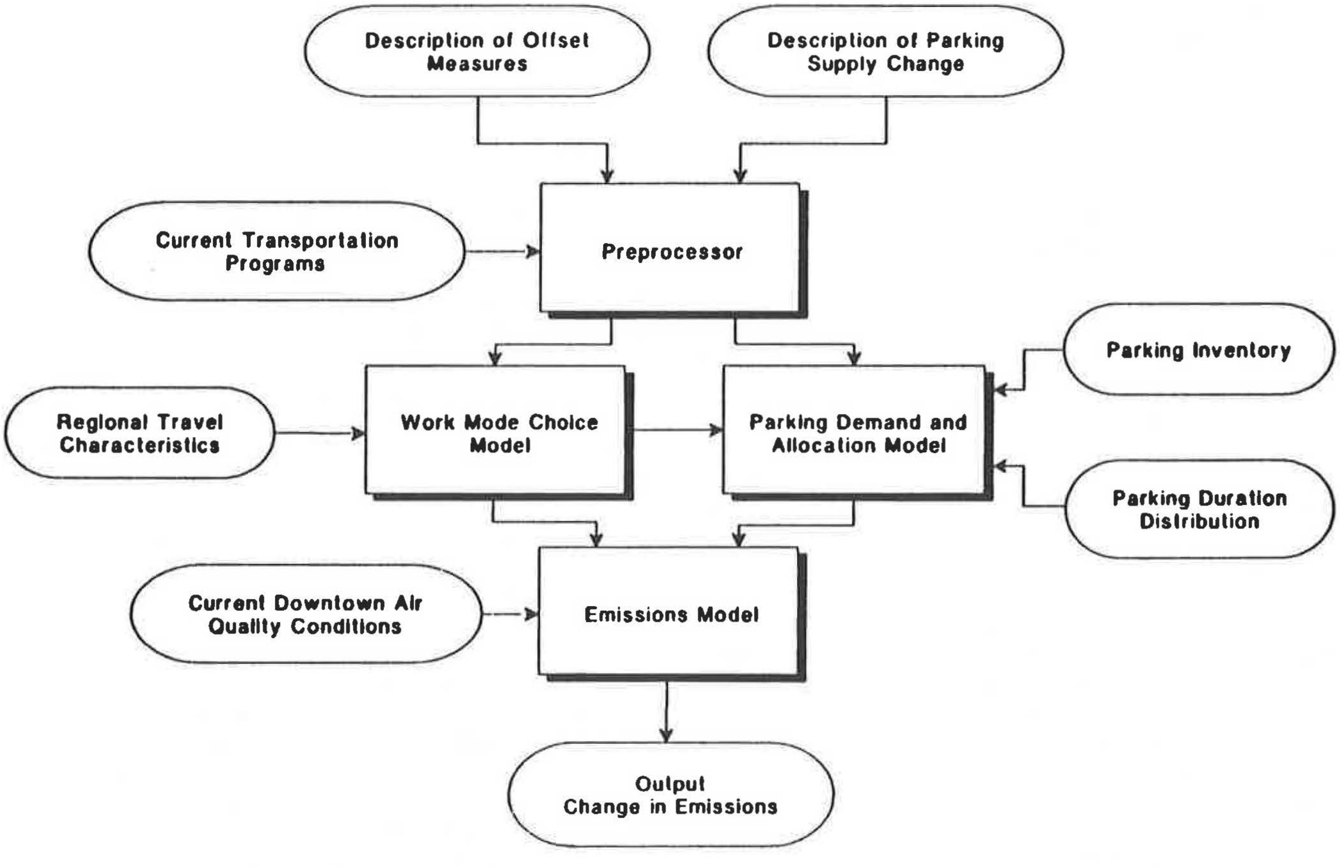


FIGURE 4 Air quality offsets model structure.

include other variations of parking pricing, supply, and hours of operation or variations in the price or level of service for alternative commute modes, such as transit or carpooling.

As illustrated in Figure 4, there are four basic components of the air quality offsets model system:

- A preprocessor,
- A work mode choice and vehicle occupancy model,
- A parking demand and allocation model, and
- A summary and emissions model.

In addition to the four basic components of the model system, there is also a large parking inventory and utilization data base, summarized by sector and type of facility, that forms a fifth component of the model.

The preprocessor prepares user-specified inputs for the parking demand and allocation model. An important part of the analysis conducted for each offset was an assessment of the level of participation that was expected to result from the measure and the extent to which the measure was likely to be implemented in downtown Portland. This could include, for example, estimation of the number of parking spaces that would be affected by a parking surcharge. The preprocessor allows a user to specify changes in parking costs (for example, increasing daily rates by some amount or raising all charges by 20 percent), restrictions on hours of operation (such as limiting availability of spaces in garages and lots to 80 percent of capacity until after 10:00 a.m.), or increases in supply by sector and type of parking facility.

The mode choice model calculates changes in work trip mode shares on the basis of specified changes in in-vehicle travel time, out-of-vehicle travel time, and out-of-pocket cost for each alternative mode. The modes considered in the model are drive alone, shared ride, and transit. The mode choice model is an incremental logit, pivot-point model that begins with current mode shares by market segment and "pivots" about these base shares using model coefficients that represent the sensitivity of mode choice to travel time and cost variables. The model structure and variable specification are based on model estimation work performed by METRO, and the actual coefficients used are taken from Portland's regional model system.

Within the total travel market, the mode choice and its associated vehicle occupancy model differentiate between 10 market segments defined by geographic divisions of the metropolitan area. This differentiation is designed to improve the accuracy with which changes in level of service are estimated. The model is designed to test the impact on each market segment of changes in in-vehicle time, out-of-vehicle time, and cost.

The output of the mode choice model is change in trips by mode, changes in vehicle occupancy for the shared-ride mode, and changes in demand for commute parking spaces downtown. When offsets are being considered for all work trips, the changes in parking demand are distributed to the sectors in proportion to the current estimated level of commuter parking demand. If an offset affects only certain locations, the effects on specific sectors are determined in the parking allocation model.

The parking demand and allocation model uses data from the sector summary of the detailed inventory of parking space supply and utilization and the preprocessor to predict changes in both total demand and the distribution of demand that would result from offset measures. Within the parking demand and allocation model, there are four main modules:

- An input and demand module that applies demand elasticities to estimate overall changes in demand resulting from changes in supply, price, and hours of operation;
- A distribution module that distributes changes in demand among the 11 sectors and among the different types of parking within each parking sector;
- A demand impact module that predicts changes in total demand for parking within the downtown; and
- A summary and emissions module that describes the overall impacts of the offset measures in terms of parking and travel characteristics by sector (e.g., total number of trips and total vehicle miles traveled) and by total change in CO emissions in grams per day attributable to those changes.

The four modules use empirically estimated elasticities with respect to supply and price from other cities where changes similar to the offsets being tested have been made. Some modifications of the elasticities, to reflect differences between Portland and the city where each elasticity was estimated, were made on the basis of professional judgment; no attempt was made to collect information to estimate new elasticities.

The fourth module predicts changes in CO emissions based on changes in

- Vehicle trips to and from the downtown (daily total),
- Vehicle miles traveled (daily total), and
- Daily mix of cold starts and hot starts in the downtown.

EPA's MOBILE3 computer program was used by the Oregon Department of Environmental Quality to calculate emission rates for various speeds, for different vehicle types, and for cold start emissions versus hot start emissions. These emissions rates were then incorporated into the emissions module, where they are used in conjunction with the estimated changes in travel and parking to calculate changes in total daily emissions for the downtown as a whole.

SUMMARY OF POTENTIAL EMISSION IMPACTS OF OFFSETS

The review of the 11 offset measures considered in the study suggested that each measure has some potential role in Portland, either as a parking offset or as a parking management tool. If additional growth is to be accommodated in the downtown in the future, a package of methods will be required, with some that decrease emissions per trip (thereby allowing some increase in the supply of parking) and some that make more efficient or appropriate use of the parking spaces available.

The evaluation of the 11 measures indicated that while the ultimate impact of each measure is not always obvious or predictable, some will clearly be useful as air quality offsets (reducing emissions per trip), whereas others appear more valuable as mechanisms for accommodating more parkers within the limits of capacity available. Successfully managing the supply of downtown parking while continuing to accommodate new development and achieving the federal air quality standards will most likely require a combination of these measures. The analysis conducted in this study should aid the city in selecting the appropriate balance of measures to pursue.

Table 1 presents a summary of the predicted emissions impacts of each of the 11 measures evaluated. The predicted impacts represent the direct impact of the measure and often do not include long-term adjustments that may occur as commuter parkers are shifted out of downtown and spaces are made available, or as travel speeds improve on downtown streets. In some cases, a reaction to these improved conditions (people returning to downtown by car) will result in a lessening of the predicted emissions reduction impact.

The estimated emissions reductions in Table 1 were developed by using the model system described earlier in combination with the review of experience in other cities to estimate a potential impact in downtown Portland. The model system was used to produce an estimate of the rate of change of emissions per unit of offset implementation. The review of national experience and the assessment of how each measure might be implemented in Portland were used to estimate the extent to which each measure would be implemented, or the level of participation that might be expected.

In interpreting the findings in Table 1, it is important to realize that the predicted impacts are based on the assumption that the measures would be implemented under the current conditions and do not represent forecasts of impacts under future conditions. The predictions are also based on the assumption that the system is currently in equilibrium; that is, the demand for parking is not constrained by the supply. The data available to this project do suggest that the parking demand is somewhat constrained by the supply in certain sectors, so the reduction in parking demand predicted for some measures may actually be partially or fully offset by new parkers filling the vacated spaces. Prediction of the full long-run impacts of some of the measures on downtown parking demand and emissions would require a more thorough analysis of current and future land use characteristics and the associated parking needs.

Four measures in Table 1 are significantly different from the others in their potential as offsets for additional downtown

TABLE 1 SUMMARY OF POTENTIAL EMISSIONS IMPACTS OF OFFSETS

Measure	Total Estimated Impact (1)	
	Potential Change	Potential CO Emissions Reduction
1. Fringe Parking	600 Downtown Parkers Diverted	60 kg
2. Alternative Work Schedules	1 MPH Increase in P.M. Speeds - 4,000 Employees	147 kg
3. Subsidy of Ridesharing	$.50/day Subsidy - 35,000 Employees	255 kg
4. Parking Management		
Increase Long-term Rates	$1 increase in All-Day Rate - 30,000 Parkers	129 kg
Increase All Parking Rates	20% Increase for All Parkers - 56,000 Parkers	187 kg
Reserve Off-Street Parking Before 10 A.M.	15% of Core Off-street Spaces Restricted - 2,000 Spaces	302 kg
Reserve Parking for Carpools	1,000 Additional Spaces Used	17 kg
5. Park-and-Ride Remote	335 Spaces Used	13 kg
6. Alternative Fuels	1,000 Light Vehicles Converted	51 kg
7. Reserved Parking	No Apparent Reduction	
8. Enhanced Inspection and and Maintenance	Annual Inspection for All Vehicles	462 kg
9. Increased Transit Capacity	6,000 Trips Diverted to Transit	364 kg
10. Traffic Flow Improvement	.5 MPH Increase in P.M. Peak Speeds	73 kg
11. Bicycle Access	50 to 100 Commuters Shifting	5-10 kg

(1) The change in parking and in emissions represents only the reduction in parking produced by the measure. As spaces become available, some additional parkers may be attracted to the downtown and the magnitude of the change is therefore likely to be less. Because of the limitations in the data available to the project, the response to the change in space availability could not be predicted.

parking. Alternative work schedules, alternative fuels, enhanced inspection and maintenance, and traffic flow improvement each affect the rate of emissions per parker rather than the number of parkers themselves. As a result, these measures are most clearly true offsets. Because virtually every space vacated by a parker shifting to another mode or to a parking space outside of downtown is likely to be filled by another parker, the other measures would represent useful offsets only if replacement parking produces lower emissions per space than current parking. Because all of the other measures are oriented toward commuters, the primary impact will be to replace long-term parking with short-term parking.

For the four offsets that produce reductions in emissions rates, the potential emission reduction was assessed in terms of the measure's equivalent in parking spaces—that is, the number of parking spaces for which current estimates of emissions are equal to the emissions reduction that would result from the offset measure. The parking space equivalents have been expressed in terms of four types of space:

- Downtown core, on-street;
- Downtown core, off-street;
- Downtown periphery, on-street; and
- Downtown periphery, off-street.

The parking space equivalents estimated for the four offset measures that would most clearly produce reductions in emissions per trip are presented in Table 2. The greatest potential from a single measure is from the change to an annual inspection and maintenance program. The Portland area currently has bi-annual inspection. This measure would produce a reduction in daily CO emissions of roughly 462 kg. The equivalent in parking spaces ranges from 2,030 spaces to 4,740 spaces depending on the type and location of spaces.

The second most effective measure would be an alternative work schedule program (or a corresponding traffic flow improvement program) that produced a 10 percent (or 1 mph) increase in the average speed in the p.m. peak hour. The total change in emissions would be roughly 147 kg per day. The parking equivalents would range from 650 to 1,500 spaces.

Other methods for improving traffic flow and increasing peak-hour speeds could also produce positive results. A 5 percent increase in p.m. peak-hour speed (.5 mph) would produce a reduction in daily emissions of roughly 73 kg. The range of parking space equivalents would be 320 to 750.

Finally, a fleet fuel conversion program that resulted in the conversion of 1,000 passenger vehicles or light trucks to methanol or compressed natural gas, from which there are only minimal CO emissions, would produce a reduction in CO emissions of roughly 51 kg. The corresponding range of parking equivalents would be from 222 to 520.

Each of the 11 offset measures reviewed in the study offers some potential improvements in air quality or a reduction in total demand for downtown parking. Some measures are clearly more appropriate as offset measures if more parking is to be added to the downtown supply, but others will be essential if the additional development is to be accommodated and air quality standards are to be maintained. Further analysis with more complete data on parking utilization and parking need will allow the city to refine the results presented in this report and develop a comprehensive parking policy for the downtown.

TRANSFERABILITY

Although many of the findings of this research effort are specific to Portland and would not be directly transferable to another city, the methodology could easily be adapted for a similar application in another setting. The potential effectiveness of the 11 measures analyzed for Portland is directly related to the current travel patterns there and the current level and nature of parking use. These characteristics include:

- Current parking occupancy level,
- Duration of stay by location,
- Time of arrival by location,
- Fleet mix by age of vehicle,
- Current work mode split, and
- Current emissions levels.

TABLE 2 PARKING SPACE EQUIVALENTS FOR FOUR OFFSET MEASURES

Measure	Potential Emissions Reductions	Parking Space Equivalents: Core Off-street	Core On-street	Non-Core Off-street	Non-Core On-street
Alternative Work Schedules	147 kg	1200	650	1360	1510
Alternative Fuels	51 kg	420	222	470	520
Enhanced Inspection and Maintenance	462 kg	3770	2030	4290	4740
Traffic Flow Improvement	73 kg	600	320	680	750

The estimated emissions per space in gr/day are: core off-street: 122.5; core on-street: 227.9; non-core off-street: 107.8; and non-core on-street: 97.5. core is Sectors C, E, F, and G.

Information on these characteristics, in addition to information about the current level of use of (or past history of trying) the 11 measures analyzed, was necessary to perform the analysis using the national review and the computer model system that was developed.

Some of the general conclusions about the relative effectiveness of the individual measures as offsets are also transferable. Among the 11 measures considered, 4 clearly achieved their effectiveness by reducing the amount of pollutant emissions per vehicle-mile traveled. These 4 measures are most clearly offsets. The effectiveness of each of the other measures depends to some extent on removing automobile trips from the downtown. Their effectiveness as offsets is therefore dependent on the response to the new availability of parking created by the reduction in automobile trips. If new drivers emerge to replace those diverted to other modes or parking locations outside the downtown, the value of the measure as an offset can be lost. If the shift is also accompanied by an increase in the turnover rate for the space vacated, the effect may even be an increase in the level of emissions.

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Publication of this paper sponsored by Committee on Parking and Terminals.

Implementation and Operation of Park-and-Ride Lots

ERROL C. NOEL

The implementation and operation of park-and-ride facilities must be carefully executed to optimize use of resources and to maximize the anticipated benefits. Implementation involves providing the necessary resources and the legal, administrative, and cooperative mechanisms for facilitating the construction and operation of park-and-ride facilities. There is a void of information in published literature on successful strategies for implementing and operating park-and-ride facilities. Although the *Guide for the Design of High Occupancy Vehicle and Transfer Facilities*, published by the American Association of State Highway and Transportation Officials, has been well recognized as a basic reference, the implementation and operation of parking elements need to be complemented. This paper discusses some of the frequently neglected aspects of implementation and operation and provides several ideas drawn from the author's experience and from the analysis of practices in several states. Liability, lease agreements, community involvement, funding and cost considerations, marketing, scheduling, fee structures, transit coordination, security, and enforcement are among the topics discussed.

The implementation and operation of park-and-ride facilities must be carefully executed to optimize use of resources and to maximize the anticipated benefits. Implementation involves providing the necessary resources and the legal, administrative, and cooperative mechanisms for facilitating the construction and operation of park-and-ride facilities. In the conduct of a national study (*1*) on the planning, design, operation, and implementation of park-and-ride lots, it was detected that formal planning of implementation and operation is still a capricious process, although a few states have good experiences that should be disseminated. Although the AASHTO Guide (*2*) has been well recognized as a basic reference for guidelines on planning and design of high-occupancy vehicle (HOV) facilities, implementation and operation of parking elements are given scant attention. This paper discusses some of the frequently neglected aspects of implementation and operation and provides several ideas drawn from the author's experience and from the analysis of practices in several states. The ideas presented in this paper can be viewed as supplementary to the national reference (*2*) on HOV facilities. Liability, lease agreements, community involvement, funding and cost considerations, marketing, and scheduling are some of the topics discussed under implementation. Items discussed under operation are fee structures, transit coordination, security and enforcement, maintenance, operations monitoring and evaluation, and overutilization.

IMPLEMENTATION

General Liability of Lot Program

A basic premise of American law is that government is immune from suits by citizens (*3*). According to Wright (*4*), a growing number of jurisdictions have, through court decisions, abolished municipal tort immunity. Wright notes that the idea that the sovereign can do no wrong is not in the spirit of current times. California, Michigan, Wisconsin, Alaska, Minnesota, and Washington are typical jurisdictions in which major progress toward partial or total waiving of tort immunity has been achieved at state or local governmental levels. California purchases liability insurance to protect landowners with whom lease agreements for carpool lots are made. Such insurance policies cover installation, maintenance, and use of the lot (*3*). Special insurance for park-and-ride facilities is another option. Michigan, a self-insured state, requires that landowners purchase insurance for joint-use lots. Landowners are subsequently reimbursed. Connecticut insures park-and-ride lots through its State Insurance Purchasing Board. As a lot is added to the system, it is also added to the insurance schedule (*3*). As a rule, a park-and-ride facilities program should be advised by the state's general counsel on legal and liability issues regarding the use of public/private property for park-and-ride facilities and on necessary arrangements for implementing their use.

Lease Agreement

A lease is a contract that conveys a facility or real estate with specific rent and conditions regarding its use. This type of agreement may be a formal document signed by the parties who agree to the terms. It is not unusual, however, to find parties engaged in informal lease agreements where no documents are signed. Whereas some jurisdictions prefer the specificity of a written formal lease, others prefer the casual nature of informal, unwritten leases. The formal lease assures parking privileges for a specific period, provided the terms are not violated. The informal lease provides no such assurance and spares all parties of obligations normally written into formal leases. Whether formal or informal, leases have become a popular way for making land available for park-and-ride facilities. Leases are applicable to undeveloped lands as well as existing parking facilities for park-and-ride operations. This type of formal leasing is practiced by many state and local governments as well as transit agencies. California, Maryland, Connecticut, and Minnesota are examples of jurisdictions where

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formal leasing is a standard practice. Figure 1 presents a typical lease agreement involving a transit agency and a church in Minnesota.

Transportation departments in states that have not sanctioned their involvement in park-and-ride facilities via legislation may not have the legal authority to enter formal lease agreements and, as a result, may use informal leasing as an interim procedure. Georgia feels bound by law not to enter formal agreements. It is the belief of some merchants in Atlanta, Georgia, that park-and-ride lots can boost profits of those businesses located near the facilities, thus putting remotely located merchants at an economic disadvantage. In Atlanta, some merchants had become jealous over the park-and-ride agreement of the Georgia Department of Transportation (DOT) with competing shopping malls. As a result of this situation the Georgia DOT adopted a hands-off stance on formal agreements with owners of private property.

Concerns about potential parking problems may make shopping center owners reluctant to allow joint-use parking. Studies of joint-use facilities in Houston (*5*) and Connecticut (*6,7*), as well as the *Park-and-Ride Planning Manual* (*8*), support the theory that merchants in shopping centers generally benefit from increased patronage resulting from the park-and-ride activity, except at peak shopping seasons when park-and-ride may deprive potential shoppers of parking spaces. The manual (*8*) recommends that the potential for increased business be advanced as an incentive to encourage owners of shopping centers to involve their facilities in park-and-ride.

The short-term nature—2 to 10 yr—of formal leases and the threat of parking disruption at informally leased lots would be a concern of transit agencies (*9*), particularly in planning park-and-ride facilities for rapid transit and commuter rail lines. Unlike bus routes, rail routes remain fixed for decades; thus, absolute ownership of associated parking lots should be the preferred option. The frailty of informal leases makes them unreliable elements in park-and-ride planning and, consequently, detrimental to a successful program.

The structure and contents of leases will vary among jurisdictions and transit agencies. There is no single model that is applicable to all lease situations. However, the following are the primary elements to be covered in leases for park-and-ride facilities.

1. *Purpose.* What the lot is to be used for.
2. *Premises.* A separate attachment detailing the lot or area of the lot to be used for park-and-ride.
3. *Access.* If only a certain area is to be used for park-and-ride, access must be guaranteed for those spaces.
4. *Term.* How long is the agreement for? What are the cancellation procedures? What is the status of any improvements made to the lot in case of cancellation?
5. *Improvement.* What type of improvements will be made to the lot? What is the notification procedure if the agency needs to go beyond the initial agreement? This could be a separate document detailing the improvements that will be effected. It could be a part of the maintenance agreement.
6. *Maintenance.* Who will perform specific duties? Such sections generally ask the owner of the lot to notify the agency of any maintenance that needs to be performed. For added flexibility, specific detailed maintenance responsibilities should be listed in a separate agreement.
7. *Liability insurance.* What types of insurance will be provided, if any? If none is to be furnished, it should first be ascertained that the agency is legally not responsible for liability claims, and this should be made clear in the agreement.
8. *Use of premises (nondiscrimination).* Some agreements stipulate that the lot shall be open for use by anyone without discrimination by the lot owner. In some cases this appears to be required by law when a government agency is involved.
9. *Examination of property.* Agreement attesting to the fact that the agency has examined the property and found it in good condition or that it accepts the property in its existing condition.
10. *Licensing.* In cases where only a license is granted by the lot owner, it must be made clear that no legal title or leasehold interest is created in the property.
11. *Governmental charges.* Finally, a clause stating that the agreement imposes no obligation on the sponsoring agency to pay the lot owner's taxes and the like.

These 11 elements may be addressed in all park-and-ride agreements. At the very least, the elements covering premises, term, improvements, maintenance, and liability insurance should be included.

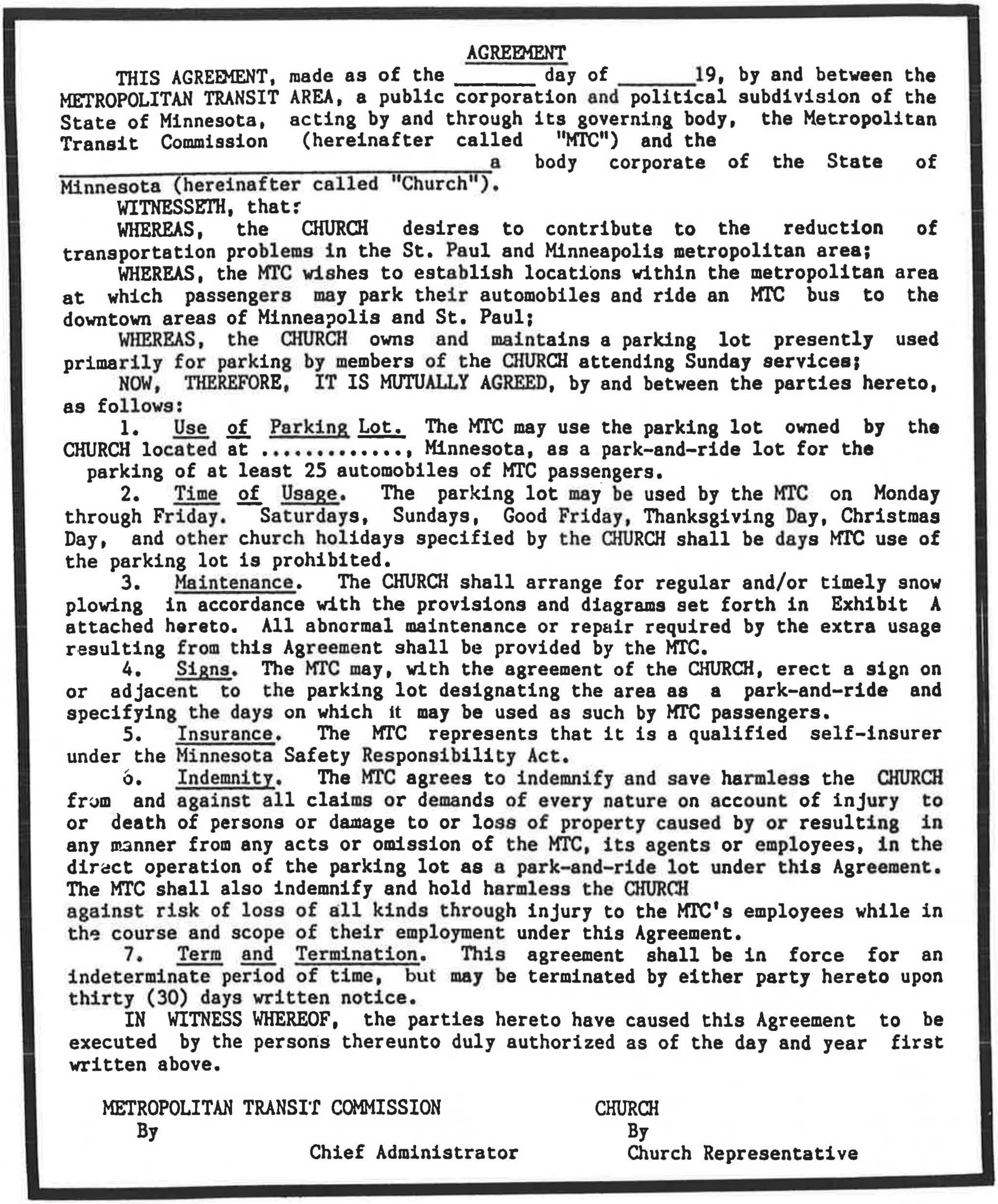
Community Involvement

The involvement of the local community in the facilities and service elements of park-and-ride starts at the conceptual planning stage and continues through implementation. The local community—merchants, employers, and residents—must feel assured that special efforts are being made to minimize the adverse effects of potential problems identified in the planning phase, that the solutions to those problems are being implemented, that reasonable and special features desired by the community are being installed, and that the implementing agency is complying with resolutions resulting from initial citizen participation. This continuity in community involvement establishes a cooperative mood, so that the implementing agency or the agency charged with future operation can expect a more positive response from the community on current and future matters pertaining to facility operations. It is not enough to build park-and-ride facilities; there must be a real perception among citizens that the facilities contribute to the common welfare of the communities they serve.

Community involvement is a proven strategy for blending local ideas into the planning, design, implementation, and operation of park-and-ride facilities. Radio, the press, and television; direct communication with citizen groups, employees, employers, and residents; and on-site notices are standard communication strategies. Very often, these strategies, used before the implementation phase, pave the way for a more positive marketing response that translates into higher utilization when the facilities are finally opened to the public.

Funding and Cost Considerations

The cost of implementing a park-and-ride program can be substantial, especially if a large number of parking spaces are to be built. Building the parking lots often requires coordination of several agencies that share different cost burdens



AGREEMENT

THIS AGREEMENT, made as of the _______ day of _______19, by and between the METROPOLITAN TRANSIT AREA, a public corporation and political subdivision of the State of Minnesota, acting by and through its governing body, the Metropolitan Transit Commission (hereinafter called "MTC") and the ________________________________ a body corporate of the State of Minnesota (hereinafter called "Church").

WITNESSETH, that:

WHEREAS, the CHURCH desires to contribute to the reduction of transportation problems in the St. Paul and Minneapolis metropolitan area;

WHEREAS, the MTC wishes to establish locations within the metropolitan area at which passengers may park their automobiles and ride an MTC bus to the downtown areas of Minneapolis and St. Paul;

WHEREAS, the CHURCH owns and maintains a parking lot presently used primarily for parking by members of the CHURCH attending Sunday services;

NOW, THEREFORE, IT IS MUTUALLY AGREED, by and between the parties hereto, as follows:

1. Use of Parking Lot. The MTC may use the parking lot owned by the CHURCH located at ...., Minnesota, as a park-and-ride lot for the parking of at least 25 automobiles of MTC passengers.
2. Time of Usage. The parking lot may be used by the MTC on Monday through Friday. Saturdays, Sundays, Good Friday, Thanksgiving Day, Christmas Day, and other church holidays specified by the CHURCH shall be days MTC use of the parking lot is prohibited.
3. Maintenance. The CHURCH shall arrange for regular and/or timely snow plowing in accordance with the provisions and diagrams set forth in Exhibit A attached hereto. All abnormal maintenance or repair required by the extra usage resulting from this Agreement shall be provided by the MTC.
4. Signs. The MTC may, with the agreement of the CHURCH, erect a sign on or adjacent to the parking lot designating the area as a park-and-ride and specifying the days on which it may be used as such by MTC passengers.
5. Insurance. The MTC represents that it is a qualified self-insurer under the Minnesota Safety Responsibility Act.
6. Indemnity. The MTC agrees to indemnify and save harmless the CHURCH from and against all claims or demands of every nature on account of injury to or death of persons or damage to or loss of property caused by or resulting in any manner from any acts or omission of the MTC, its agents or employees, in the direct operation of the parking lot as a park-and-ride lot under this Agreement. The MTC shall also indemnify and hold harmless the CHURCH against risk of loss of all kinds through injury to the MTC's employees while in the course and scope of their employment under this Agreement.
7. Term and Termination. This agreement shall be in force for an indeterminate period of time, but may be terminated by either party hereto upon thirty (30) days written notice.

IN WITNESS WHEREOF, the parties hereto have caused this Agreement to be executed by the persons thereunto duly authorized as of the day and year first written above.

METROPOLITAN TRANSIT COMMISSION	CHURCH
By	By
Chief Administrator	Church Representative

FIGURE 1 Sample lease agreement involving private property.

for implementation and operation. It is not uncommon to find local or state transportation departments providing the funds for constructing park-and-ride lots, with another private or public agency having the authority to operate them. This situation draws attention to the need for accurate cost accounting by the operating agency, so that the real capital costs can be identified. Of course, many agencies build and operate their own lots. Transit agencies have been doing this for decades.

Funds for implementing park-and-ride facilities are available from the federal government. Federal law (Title 23, U.S. Code) provides for categorical funding for park-and-ride through the federal-aid highway program administered by the Federal Highway Administration (FHWA), depending on the purpose and location of the facilities.

The federal share of the costs of qualifying projects depends on the applicable federal-aid highway programs—Federal-Aid Primary, Federal-Aid Secondary, Federal-Aid Interstate, Interstate 4R, Federal-Aid Urban. The Surface Transportation Act of 1982 provides a local-federal matching formula for distributing federal-aid highway funds (contact the FHWA division Office). For highway construction, the federal share is normally 75 percent, although states may request up to 100 percent federal support for commuter carpool and vanpool facilities. Section 3, discretionary funds; Sections 9 and 18, formula grant; and Section 8, planning grant, programs administered by the Urban Mass Transportation Administration (UMTA) provide funding for park-and-ride facilities associated with transit and certain funds for rideshare activities. Department of Energy (DOE) funds are also available for park-and-ride activities when they are included in the State Energy Plan.

The acquisition of federal funds for park-and-ride programs requires an understanding of the budgetary process of the state and local governments and metropolitan planning organizations, as well as of the federal criteria for selecting projects and administering the funds. Generally federal-aid highway funds administered by the states are cost reimbursable. Thus, agencies must first use their own funds and then ask for the federal government to contribute its share. Projects that receive federal-aid highway funds must also be in the budget of state governments. Thus, park-and-ride development must have projects registered in the local and state budgets if federal-aid highway funds are to be committed. This is particularly important because most jurisdictions normally exclude nonbudgetary items from their spending programs. The transition of a project idea to a budget item requires deliberate actions. Selective use of the political channels and strong factual justification based on evidence of potential savings in highway construction, improved highway capacity, and increased patronage of regional transit are essential for project recognition in the budget process.

It is not always possible for agencies to satisfy the criteria for federal funds for park-and-ride lots. In addition, federal funds for such facilities are anticipated to decline in future years, while the demand for park-and-ride will be increased. Thus agencies may have to rely on nonfederal funding sources and use innovative approaches to minimize the cost of new capital investments in park-and-ride lots. Many agencies are already funding 100 percent of the capital cost for park-and-ride lots through special taxes or general revenues. Giving developers the option of providing fewer on-site parking spaces while contributing the associated cost savings to a local fund for promoting park-and-ride is a feasible fund-raising strategy. Another parking management tactic (*10*) that reduces the cost to local government involves the use of zoning regulations that shift part of the cost of park-and-ride lots from government to developers and large employers. The Los Angeles Planning Commission allows developers the option of substituting off-site park-and-ride spaces for on-site spaces (*9*). Preferential parking rates for HOVs using standard facilities is another interim measure for reducing total space demand and for deferring capital investment on new facilities. Seattle, Washington; Montgomery County, Maryland; and San Francisco, California, are some of the jurisdictions that have had success in using preferential rates.

Staged development of park-and-ride lots is a viable strategy that could be combined with 100 percent local funding. Staging allows an agency to upgrade facilities when the demand warrants. In spite of potential administrative problems, joint-use lots are good interim measures for postponing the need for major capital investments. In urban areas where major restructuring of transit routes is anticipated because of the introduction of rapid rail systems or changes in land use, the delay in capital investment could accommodate the possibility of a shift in demand that must stabilize before permanent facilities can be effectively located. For example, the Soldiers Home lot and Carter Barron joint-use park-and-ride lots in Washington, D.C., are no longer effective urban-fringe facilities. Major shifts in demand as a result of improved service provided by the regional rail rapid transit system and parking facilities have been responsible for declining use of those once-busy parking facilities.

Jurisdictions faced with rapidly increasing land development and severe limitations on their ability to expand existing highway facilities require new methods for diverting a significant proportion of new trips to HOVs. Faced with this need, the Montgomery County (Maryland) Planning Board has been experimenting with the involvement of developers in ridesharing programs as a partial condition for approval of building permits for large office and residential subdivisions (*11*). Such development-related ridesharing programs must be reviewed and approved by the county, although they are to be planned and executed by developers at their own expense over a stipulated number of years. As a precaution against default, developers are required to post a substantial annual bond for the duration of the stipulated period. The county plans to assume control of the developer's ridesharing program after the expiration of the agreed term of operation. Although the cost of ridesharing programs may be high—$45,000 annually for 10 years in one case—developers of large projects seem willing to comply rather than face the possible rejection of subdivision development plans. Developers and government agencies are also becoming aware of the benefits of reduced congestion in making development sites more attractive to employers. This approach may become an accepted alternative strategy for funding ridesharing programs.

Marketing Program

Marketing involves the use of promotional techniques to inform motorists about park-and-ride services. The marketing effort for new park-and-ride programs must be deliberate, and it must be geared toward achieving the objective of increasing the use of HOVs. Effective marketing can both increase the level of park-and-ride facility usage and hasten the rate of user growth (*12*). Both outcomes are particularly beneficial to paid facilities that require immediate revenue to cover operating expenses. In the long run, park-and-ride facilities that are properly implemented could become the focus of promotional campaigns for increasing ridership on all associated high-occupancy modes.

Two important aspects of a marketing program are identifying the target audience and determining the most effective mechanism for communicating the desired information. Communication techniques for familiarizing potential travelers with rideshare and park-and-ride services include informational signs strategically placed along roadways and in parking facilities, news releases, brochures distributed directly to residents of the service area, public service announcements on radio and television, newspaper advertisements, posters, bumper stickers, billboards, brochures distributed to large employers, employer-coordinated activities, and maps showing the location of lots, transit routes, and schedules.

In some cases, rideshare and park-and-ride marketing can be coordinated with other public service messages to provide more efficient use of public facilities, as in the case of the Southeast Expressway reconstruction in the Boston area. The target audience usually consists of motorists who travel alone and have either an origin or a destination in the service area. Carpoolers and vanpoolers for whom a diversion to rapid transit is feasible can also be a target audience. In San Francisco, California, parking is more conveniently located for vanpoolers and carpoolers who use the rapid transit system.

As a general rule, the strategy for reaching target audiences depends on their travel characteristics. Work-related travel characteristics are the principal information category for park-and-ride studies. State and local departments of transportation, transit agencies, metropolitan planning organizations, and rideshare agencies can play a leading role in coordinating the marketing effort. The services of professional advertising firms may also be used in designing and/or implementing promotional advertisements for share-a-ride and park-and-ride, especially when a large market is anticipated and information on the characteristics of potential users is unavailable. It is also important to note that promotional efforts must cover both the facilities and the transportation connection; they go together as hand and glove. Many jurisdictions have active campaigns for disseminating information on the location of park-and-ride facilities: it should not be assumed that motorists know where they are.

The marketing program must be of the same scale as the park-and-ride service. For isolated carpool and vanpool lots located on a major commuter route, it may be sufficient to use public service announcements to advertise the initiation of such facilities and to use roadside information signs as a continuing long-term advertising strategy. Regional park-and-ride programs involving multiple facilities could require a combination of marketing techniques coordinated by a ridesharing agency, the state DOT, or a regional government group.

Implementation Plan

A detailed implementation plan should be developed to define implementation details and agreements. The magnitude of the plan must be equivalent in scope to the park-and-ride program. Programs involving the expenditure of tens of thousands of dollars for many facilities, the coordination of several jurisdictions or agencies, and staged development over several years should receive a more detailed implementation plan than isolated lots where a less sophisticated system is appropriate. The implementation plan may also serve as a future reference on park-and-ride actions. The implementation plan should include the size and location of facilities, engineering design information, construction cost, advertisement strategy, facility usage options, traffic control features, vehicle acquisitions for HOV service, coordination with planned or existing transit service, funding sources, operating framework, and major tasks and milestones. The implementation plan may also be adopted, in whole or in part, into larger regional or sector development plans and may serve as the basis for budgetary discussion within the implementing agency.

OPERATION

The operation of an HOV program is a dynamic process aimed at sustaining a desired level of service through use of its various elements. Typical program elements include marketing, amenities, security, connecting HOV user service, traffic control, and parking lot pavement and drainage. These elements cannot sustain themselves and require continuous attention. Each operating agency must develop an operating program with procedures for providing operating resources, monitoring systems status, and providing the resources needed to maintain or improve service. It must be understood that the quality of service provided by any one element can affect utilization. For example, neglect in the area of security can lead to low utilization of park-and-ride lots, and unpredictable transit schedules will surely cause motorists to stay in their automobiles for the work trip. In spite of good planning, there is no guarantee that these elements will function as planned. Hence, the operating process must be able to respond to conditions that adversely affect the park-and-ride program. Some of the basic considerations to be addressed in lot operations are fee structure policies, security and enforcement, transit service coordination, maintenance, marketing, and monitoring of facility operations.

Fee Structure Policies

The fee structure established for a park-and-ride facility is the subject of an important policy decision. Parking fees are a potential means of facility financial support and can be used to control demand in heavily used lots.

Parking is most commonly free in park-and-ride lots. The provision of free parking is a policy that is used to encourage park-and-ride by providing a free transfer point. Most lots are publicly developed or located on private property where the landowner (e.g., a shopping center) provides the space as a public service. The primary rationale for providing free parking is to encourage ridesharing, but in many locations competing free spaces are readily available. Fees may be charged for only the most heavily used lots, and these are most commonly associated with heavy demand at rail rapid transit stations.

Parking at reduced fees in some public garages not exclusively constructed for HOVs can be provided for carpools and vanpools as an incentive for their use. These reduced fees are also usually associated with reserved spaces as an added incentive. How to collect fees should also be taken into consideration when a fee is charged. It would obviously be cost-ineffective to attempt to charge fees at small remote lots. In large lots where fees will be levied, the use of meters or exit payment must be compared for their operational convenience and cost-effectiveness. The alternatives analysis must compare the capital and operating costs, including costs and manpower requirements, and the effectiveness of the fee collection method (e.g., without effective meter-limit enforcement, much revenue will be lost). Fee collection provisions are also a factor in design requirements. Exit payment booths, for example, require environmental provisions for staff and gates, with their added construction and maintenance costs.

The decision to charge fees is based on whether the lot must be financially self-supporting or whether it must remain free to attract HOV users. If a fee is charged, it should be related to the overall trip cost with and without the park-and-ride opportunity. The cost of parking and a high-occupancy mode trip should not exceed the cost of driving and parking at the destination end. The fee is set at or below that rate level if it is to provide an incentive for park-and-ride lot use.

Security Provisions

Security issues are normally treated in the location and design stages of park-and-ride facility development. It is only during the operation stage, however, that the effectiveness of planned security measures can be determined. Arrangements must be made to ensure that supplementary security measures—closed circuit television, police patrols, guards, and the like—are in place and working. There is a need to coordinate the security at publicly owned facilities with the activities of the police department having statutory or designated jurisdiction. Park-and-ride lots for promoting transit usage are usually under the security jurisdiction of transit authorities. It should be noted that police departments will not automatically assume the responsibility for security surveillance of such facilities. There must be a clear understanding at the time of facility development of who will be responsible for security measures and the degree of surveillance required. The Connecticut DOT conducted a study (*13*) of theft and vandalism problems at lots throughout the state. Among the recommendations for providing better security at park-and-ride lots are

1. Establishment of law enforcement responsibilities,
2. Frequent police patrol of lots,
3. Lot location and design for high visibility,
4. Lighting and fencing of facilities,
5. Encouragement of all-day lot traffic by providing amenities such as phones and newspaper vending machines, and
6. Better crime recording and monitoring procedures to permit problem recognition and analysis.

Maintenance Operations

Maintenance of the physical elements of park-and-ride facilities must be a planned, deliberate activity that includes an appropriate budget, designated responsibility for maintenance requirements, and an established program of maintenance that provides for normal and special needs (e.g., snow removal). Priorities should be established for normal and special requirements so that conflicts between park-and-ride maintenance and other maintenance responsibilities are easily resolved. Negligence in maintaining a park-and-ride facility has an adverse impact on perceived and real personal security, as well as the physical condition of the facility.

Transit Service Operations

Transit service is often the main reason for using a park-and-ride facility. It is important to provide sufficient information on service availability, both at the lot and throughout the lot market area. It is equally important to monitor transit use to maintain adequate levels of service and to determine the need for different services. Where possible, new services should be routed to serve park-and-ride lots.

Monitoring Park-and-Ride Lots

Monitoring the operation of park-and-ride lots is a necessary part of the planning process. Monitoring involves the development and execution of a strategy for collecting and analyzing specific information that can be used in the operation and improvement of park-and-ride lots and the planning of future facilities. Monitoring could involve a detailed study to determine whether the target goals are being met. Such a detailed study would involve the collection and analysis of data to determine if planned objectives were accomplished on the basis of a set of predetermined measures of effectiveness. Monitoring may also focus on the collection and analysis of information that can be used to identify potentially adverse situations that affect park-and-ride. Traffic congestion and overutilization of lots are examples of adverse situations that may be identified through monitoring.

Factors to Be Monitored

Comprehensive monitoring of lot operations is a costly and labor-intensive process. It is primarily because of cost that many operators of park-and-ride lots monitor only selected data. Utilization is the most commonly observed factor. Although utilization is a good indicator of space usage, it does not reflect the success of design elements, traffic operation and control, environmental precautions, needed personal safety measures, and aesthetics. A good monitoring process must also determine whether each lot continues to be conducive to park-and-ride activities. Elements that should be monitored include utilization, access traffic operation, economics of operation, traffic-generated air and noise pollution, energy conservation, transit service, user satisfaction, access modes, effectiveness of park-and-ride information, user characteristics, physical condition of lot, and degree of achievement of specific goals.

Utilization

This involves a periodic parking inventory based on standard traffic engineering practice. Utilization surveys for determining average usage should be conducted between 9:00 a.m. and 3:00 p.m. on Tuesdays, Wednesdays, and Thursdays to avoid the effects of weekend variations on lot usage. The primary product of this inventory is the percentage of spaces in use at the time of the inventory. Over time, this result can be evaluated to develop future trends. This statistic does not address use of spaces. However, it is a good general measure involving data that can be collected by technicians. Evaluation of the observed trend in utilization may suggest needed actions. For example, high utilization—greater than 85 percent—suggests the need for facility expansion or for parking management strategies to distribute users among a set of lots. Low utilization—less than 30 percent—may be a result of one or more factors that require reevaluation and correction. Thus, utilization is a minimum factor to be monitored. When it takes on values at the extreme ends of the percentage scale, there is a need to evaluate other factors in making decisions. Utilization data should be correlated with other pertinent information about a park-and-ride lot.

Access Traffic Operation

Standard traffic engineering techniques must be used in planning the access to park-and-ride lots. Once implemented, however, the traffic operations design must be periodically monitored, because changing land use, user characteristics, and demand for parking and roadway capacity will generate the need for access improvement. Monitoring access traffic operations may involve one or more typical traffic engineering studies—volume studies, capacity analysis, traffic control evaluations, accident studies, and so on—that must be executed by experienced traffic or transportation engineers.

Economics

In planning a system of park-and-ride lots, it is often necessary to use estimates to determine the potential costs of capital investment, operation, maintenance, and the monetary value of benefits and disbenefits. A more accurate picture of the relationship between benefits and costs can be determined only after implementation. The benefit/cost analysis is a suitable technique for monitoring cost-effectiveness. Typical benefits include direct user-cost savings, fuel savings, reduction in hydrocarbon and carbon monoxide pollution, and reduced formation of nitrogen oxide pollutants. A benefit/cost analysis should be performed at least once after the implementation of a park-and-ride program. Although it is possible to conduct such analyses for individual lots, the aggregate cost-effectiveness of a system of park-and-ride lots should be the target of a benefit/cost analysis. Monitoring provides the opportunity to acquire more realistic data for computing the monetary value associated with user and community benefits. Several available publications (*14–19*) present good information on the theory and practice of benefit/cost analysis and may be reviewed for further information.

Traffic-Generated Noise and Air Pollutants

The monitoring of traffic-generated noise and air pollutants should be done on a regional basis, preferably by agencies such as metropolitan planning organizations and states whose domain transcends local jurisdictional boundaries. At least once a year, air pollutants should be sampled. However, seasonal variations in atmospheric conditions and travel can be more appropriately monitored by a continuous sampling process. All pollution monitoring must be executed by individuals with training in that technical area.

Energy Conservation

Monitoring this factor normally involves obtaining factual data on reductions in vehicle miles of travel, as opposed to crude estimates developed in the planning stage. Where energy conservation is an important goal, it can be assessed only with the collection of travel data.

Transit Service

The availability, quality, and scheduled frequency of transit service must be evaluated periodically. This is particularly important in routing transit to existing park-and-ride lots and in identifying those lots that have been adversely affected by the elimination of connecting bus service or the introduction of regional rapid rail systems. Some jurisdictions tend to ignore those park-and-ride lots whose usefulness is significantly reduced or eliminated. Such lots could be rededicated to other uses. Deterioration in the quality of transit service is a concern for users who are motivated by the convenience of such services.

User Satisfaction

In spite of efforts to incorporate user needs in planning park-and-ride lots, there is no assurance that all concerns will be satisfied and that new concerns will be identified automatically. To be effective, park-and-ride lots must meet minimum user standards. It is the duty of park-and-ride lot operators to strive to seek continuous feedback on users' experience and perceptions about park-and-ride lots. Information from monitoring user satisfaction should be collected via brief surveys that provide users with the opportunity to comment. These surveys may be part of a larger information-gathering exercise or may be dedicated to assessing user satisfaction. All such surveys must be formal, properly prepared, and executed with the explicit authorization of the agency in charge.

Access Modes

The modes used to access park-and-ride lots are not fixed. Users make decisions on modal choice that could affect lot usage and traffic operations. Increased use of small cars, motorcycles, bicycles, and recreational vehicles could affect the distribution of parking spaces. Operators must be aware of changing modes so that they can plan to accommodate and/or control the parking of vehicles that were not specifically considered in the planning process. The need for motorcycle parking is often detected by monitoring lot usage.

Effectiveness of Park-and-Ride Information

A park-and-ride program often involves several strategies for disseminating information. These strategies may include signing and special marketing efforts to reach users at home and at work. Lot usage correlates with the effectiveness of the information and its dissemination method. It is important for operators to know which techniques yield the best results. Here, too, information for assessing the effectiveness of promotional activities may be part of a larger survey.

User Characteristics

User information is particularly useful in estimating demand for park-and-ride program expansion. Information on user characteristics must be gathered for the specific region where the facilities will be located. Planners must be aware that user characteristics vary across the nation and that there is no substitute for collecting information on actual and potential users in a region. User characteristic surveys are usually very broad in coverage and may involve sensitive data on age, sex, income, education, and so on. Therefore, they should be conducted infrequently or less than once in 2 yr.

Physical Condition

Deterioration of park-and-ride lots reduces use and must be prevented. Periodic surveys should be done of the pavement conditions, drainage structures, trash facilities, illumination, amenities, traffic control, and informational signs and markings. Neglect in the upkeep of some physical elements could contribute to unsafe conditions. Utilization and physical condition surveys may be executed using the same techniques when the lots are visited.

Management of Overutilization

Overutilization of park-and-ride lots is characterized by unsatisfied demand, with many potential users being turned away as a result of unavailable spaces, illegal parking on the overutilized lot and on adjacent private facilities and nearby roadways, and illegal vehicle maneuvers by frustrated motorists. Premature overutilization could reflect a weakness in the planning process. Underestimation of demand is clearly a defect in the planning process. There are also situations, however, where the facility must be scaled down at the implementation phase as a result of funding limitations. Unforeseen circumstances, such as energy shortages, user preference for certain lots, and accelerated land development, could cause a premature surge in demand for some parking facilities. Whatever the cause of overutilization, it is clearly a condition that requires immediate attention to eliminate those characteristics that discourage park-and-ride usage and contribute to unsafe traffic flow.

Treatments for overutilization may involve facility expansion to increase the space supply by reducing the size of some of the parking spaces to small-car dimensions, provision of alternative overflow facilities, pricing tactics that make other lots more attractive from a cost standpoint, use of periodic lotteries to distribute the parking opportunity, preferential parking spaces for HOVs, a facility served by transit, flexible working hours, selective use of compressed workweeks, pricing tactics favoring carpoolers and vanpoolers, and shuttle bus service from satellite parking facilities. Pricing has been used experimentally to manage overutilization of some of the park-and-ride lots on the regional rapid rail system serving the Washington, D.C., metropolitan area. New Jersey has used a lottery for distributing the opportunity to use one of its largest park-and-ride lots. The Bay Area Rapid Transit used preferential parking for carpoolers and vanpoolers. Flexible work hours, although not aimed specifically at park-and-ride facilities, are used by the federal government in Washington, D.C.; this has significantly moderated commuter traffic surges and partially transferred the use of parking facilities to nontraditional working hours. Prince George's County, Maryland, operated a public shuttle bus from a park-and-ride lot to the central business district of its county seat, Upper Marlboro. A number of additional transportation system management tools and parking management tactics (*6,9,10*) may also ensure compliance with traffic control measures. Each case of overutilization must receive careful study to determine the appropriate management strategy. As a general rule, the chosen strategy must be simple, fair, supported with resources for implementation and maintenance, and perceived to be just by facility users.

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Publication of this paper sponsored by Committee on Parking and Terminals.

Comprehensive Approach to In-Vehicle Route Guidance Using Q-Route

YUVAL BLUM AND MICHEL VAN AERDE

The Q-Route route guidance concept was developed with the objective of providing drivers with comprehensive and traffic-responsive route guidance to address-specific network destinations within a large urban area. The traffic-responsive aspect of Q-Route is implemented using a macro level routing, which can consider historic and/or real-time traffic volume and capacity estimates on all roads in the control area. In the autonomous mode, macro routings, which reflect recurring congestion, are implemented on a time-of-day basis. However, a communication link is required to have real-time routings that respond to nonrecurring congestion. The driver is delivered to address-specific network destinations using a micro level routing, which considers only the local streets within the immediate vicinity of the driver's final destination and is invoked automatically once the driver's destination zone is reached. The combined macro/micro routing procedure is transparent to the user/driver. The prime objective of this paper is to describe the Q-Route route guidance concept and to indicate how the system can be integrated with traffic control models to provide consistent routing information through several compatible driver information subsystems. In addition, the paper illustrates the prototype implementation of the in-vehicle subsystem of the Q-Route prototype, which was tested in Kingston, Ontario, Canada.

For the design of Q-Route, it was considered that drivers within most urban traffic networks belong to one of three subsets of drivers, each of which could benefit significantly from improved route guidance (*1*).

The first group consists of those drivers who are unfamiliar with the city's road network structure and are unaware of either the exact location of their destination or the optimum route toward that destination. Second, there are drivers who have a general awareness of the road network structure, as indicated on a standard city map, but who are unfamiliar with the relative amounts of traffic congestion on alternative routes at various times of the day. Finally, there are drivers who are familiar with both the network structure and recurring traffic congestion patterns, but who are unaware of any nonrecurring traffic congestion that is unique to that particular time or day.

The ultimate objective of Q-Route is simultaneously to provide improved routing information that can satisfy the needs of drivers belonging to any of the aforementioned subgroups. Such a system would reduce excess travel distance/time, decrease the extent of recurring congestion, and minimize the impact of nonrecurring traffic congestion. Consequently, the emphasis of the Q-Route system is on determining the optimum traffic routings within a traffic network and on effectively communicating this routing information to the drivers. This focus is distinctly different from that of similar systems that attempt to establish/trace accurately a vehicle's location and only passively display the amount of traffic congestion on various links throughout the network. Within this paper, the former Q-Route activity is referred to as routing, and the latter is referred to as navigation. It is the opinion of the authors that although navigation may prevent drivers from getting lost, only routing can achieve the aforementioned travel distance and time savings.

Whereas some of the attributes of Q-Route are similar to those of ALI-SCOUT (*2*), AUTOGUIDE (*3*), and CACS (*4*), as all of these systems are ultimately attempting to provide a similar type of service to the driver, the Q-Route concept is seen to be unique for three main reasons. First, Q-Route is intended to disseminate routing information that can be generated using a variety of different traffic control and simulation models. Second, the in-vehicle component of Q-Route is intended to be functional in either an autonomous mode—using historical traffic flow patterns—or in a nonautonomous, quasi-real-time mode—using real-time traffic flow data that are periodically downloaded to the in-vehicle unit to update the default historical routings.

Finally, the Q-Route concept is intended to be comprehensive in that it can immediately provide networkwide routing coverage in an urban area and can provide consistent routing information using either its In-Vehicle, Changeable Message Sign (CMS) or Pre-Trip Planner subsystem. Because overviews of Q-Route's CMS and Pre-Trip Planner subsystems were presented earlier, however, this paper focuses in detail on primarily the core structure of Q-Route's in-vehicle aspect.

Q-ROUTE: A COMPREHENSIVE DRIVER INFORMATION SYSTEM

The Q-Route Driver Information System was first described by Van Aerde and Blum (*5*) as a single system that could address the route guidance needs of an urban area. This is accomplished through the joint control of three compatible subsystems:

1. Pre-Trip Route Planners,
2. Changeable Message Signs, and
3. On-Board Route Guidance Systems.

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These three subsystems are all designed to be simple variations of the same basic Driver Information System, as shown in Figure 1. This is true both conceptually and physically, as consistent route guidance information needs to be assembled and disseminated, and as the same algorithms, hardware, routing vectors, and data base structures can be relied upon.

Routing Vector Concept

The entire Q-Route route guidance concept is developed around the use and sharing of a central set of route guidance vectors (*5,6*) by all routing subsystems. These vectors are also standardized with respect to the central traffic control models, which are used to generate the traffic-responsive routings. As illustrated in Figure 2, the routing vectors indicate the shortest or quickest route from any point in the network (origin node) to any specific network destination (destination node). Specifically, the vectors indicate, for any network node, the next street to follow to get closer to one's destination. At the end of this street, one can iteratively reuse the vector to proceed incrementally toward the desired ultimate destination.

The routing vectors are stored for use in Q-Route in a standard tabular format, which allows the use of a variety of different procedures to generate these vectors and allows each of the three Q-Route subsystems to derive its "optimum" routings using these same routing vectors. For example, as illustrated in Figure 3 (for the sample network in Figure 2a), the Pre-Trip Planner can trace all the links along the intended path and can list both the turning movements and the distances to them. Similarly, the in-vehicle unit can display "bird's eye view" maps of each intersection en route and indicate the optimum turning movement as indicated by the corresponding routing vector entry. Even the CMS Controller can use them to select the appropriate freeway exit for a given destination. This shared use of a common routing data base is intended to provide more consistent and less expensive routing services within an urban area.

Quality of Routing Services

The quality of the route guidance information depends not only on the quality of the traffic model that determines the actual routing vectors but also on the extent to which this routing vector generator has considered the feedback impact of driver responses to the recommended routings or reroutings. Therefore, Q-Route was designed to be compatible with a variety of different traffic models, including the INTEGRATION (*7–11*) model. This traffic model determines traffic-responsive routings through congested traffic networks in response to any incidents, queuing, and changes in the prevailing network controls. In addition, the model can consider the feedback impact on the city's traffic pattern of different percentages of drivers who use in-vehicle route guidance units.

Prototype Testing in Kingston

A typical Q-Route application involves the sequential or concurrent execution of the routing vector generator and a Q-Route routing information dissemination subsystem.

Fully autonomous route guidance is provided by pregenerating sets of routing vectors off-line and preprogramming these data into the in-vehicle unit. An appropriate set can be selected from this library on a time-of-day or day-of-the-week basis. This type of preprogrammed routing is very similar to fixed-time control of traffic signals, with a similar economy of operation and level of effectiveness.

If a communication link exists, routing vectors can be disseminated on request in real time using approaches parallel to those taken to provide real-time traffic signal control. When the routing vectors are calculated on-line, fully traffic-responsive routing can be implemented. At a lower cost, this same objective can be achieved through a dynamic selection of routings from a library of precalculated routing patterns. In either case, the operation of the Q-Route in-vehicle control logic is virtually identical.

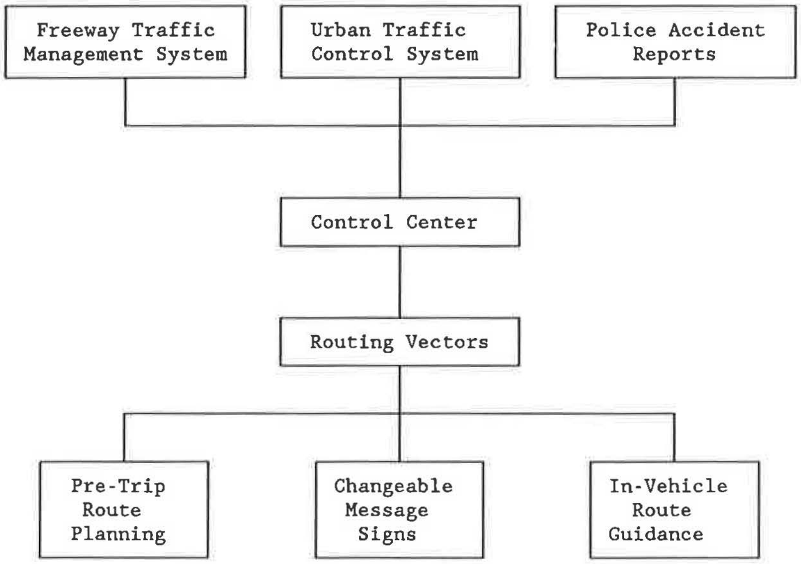
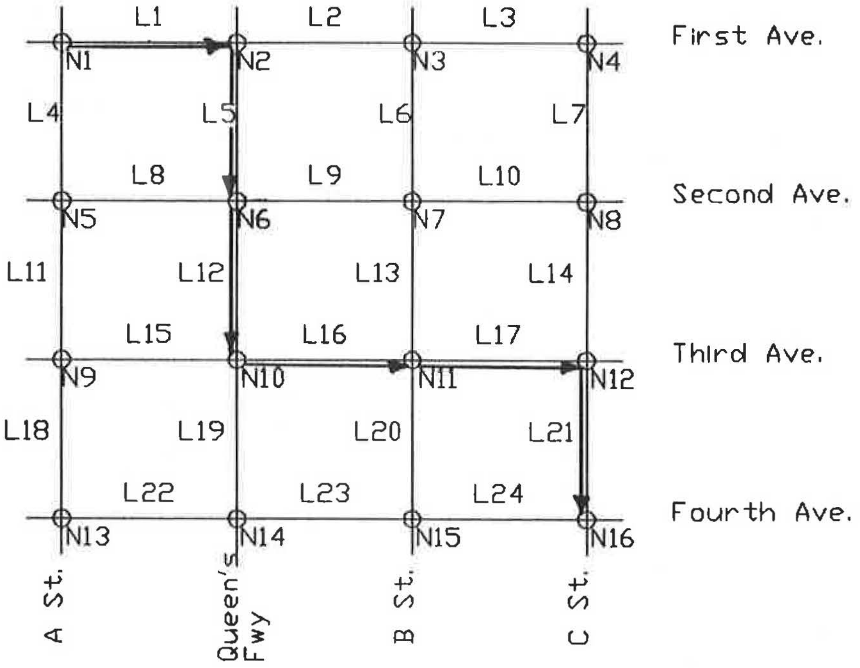


FIGURE 1 Overview of Q-Route route guidance subsystems.

(a)



(b)

Routing Vector Corresponding to Dest. N16

Node From	Number of Next Link	Start/End Node of Next Link
N1	L1	N1 -> N2
N2	L5	N2 -> N6
N3	Lx	
N4	Lx	
N5	Lx	
N6	L12	N6 -> N10
N7	Lx	
N8	Lx	
N9	Lx	
N10	L16	N10 -> N11
N11	L17	N11 -> N12
N12	L21	N12 -> N16
N13	Lx	
N14	Lx	
N15	Lx	
N16	0	Destination

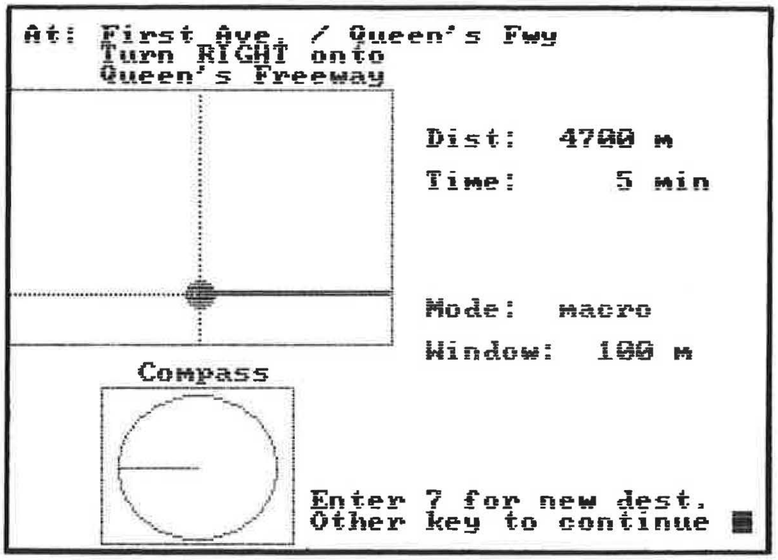
Lx - other link number, not relevant to this route.

FIGURE 2 Minimum path route of hypothetical network: a, sample; b, routing vector representation.

(a)

```
                    Queen's Route Planner

Current Location:   A St. /First Ave.  (N1)

Destination:        C St. /Fourth Ave. (N16)


Take First Ave. (L1)
     at  1000 meters  Turn RIGHT onto      Queen's Fwy (L5)

Queen's Fwy
     at  1900 meters  Go STRAIGHT through  Queen's Fwy /Second Ave. (N6)
     at  2800 meters  Turn LEFT onto       Third Ave. (L16)

Third Ave.
     at  3800 meters  Go STRAIGHT through  B St. /Third Ave. (N11)
     at  4800 meters  Turn RIGHT onto      C St. (L21)

      drive another  900 meters to your destination.

Total Trip Length:  5700 meters.
Estimated Time:     5.9 min.
```

(b)



```
At: First Ave. / Queen's Fwy
    Turn RIGHT onto
    Queen's Freeway

                    Dist:   4700 m
                    Time:      5 min

                    Mode:   macro
                    Window:   100 m

              Enter 7 for new dest.
              Other key to continue
```

(c)

CMS Located at Node N6:

```
Dest. N16:  USE EXIT N10
```

FIGURE 3 Q-Route use of routing vectors: a, Pre-Trip Planner Subsystem; b, In-Vehicle Subsystem; c, CMS Subsystem.

During the 1988 Q-Route prototype testing in Kingston, the autonomous mode was evaluated most extensively. The use of a communication link, based on a cellular car telephone, was also tested. The configuration of the Q-Route prototype during this testing is illustrated in Figures 4a and 4b, which show the linkages to the computer voice routines (TEXT TALKER) and the trip origin-destination selection menu (NODEID), as well as to the main data inputs.

MACRO/MICRO ROUTING CONCEPT

The data management problems associated with providing the "best" traffic-responsive routing within large metropolitan areas are addressed in Q-Route by selecting a driver's trip path based on a sequential macro/micro routing process.

Combined Macro/Micro Routing

The macro routing considers only major freeways, arteries, and collectors and provides the driver with a traffic-responsive routing to the edge of the zone of the intended destination. Usually, only the freeways and major streets are considered, as interzonal trip makers should be discouraged from traveling along local streets. In addition, these macro network links are likely the only ones to be sufficiently detectorized to support traffic-responsive routing. Furthermore, by limiting the initial macro destination choices and restricting the routing choice set to only those links that represent major streets, the macro routing calculation is significantly simplified.

Prototype Testing in Kingston

Figure 5a illustrates the macro network that was used during the Kingston route guidance experiment, whereas Figure 5b illustrates the micro network that was employed to provide a sample micro routing within Macro Zone 39, which contains the Queen's University campus. During the tests, micro routings to various macro destination zones within the downtown area were also tested. Typically, each of the micro networks contained approximately the same number of links/nodes as the initial macro network for the entire study area.

Once Q-Route detects that the driver has reached the periphery of the macro destination zone, a second micro routing is automatically invoked. It guides the driver from the zone's periphery to the final micro destination by finding the quickest path from the macro/micro transition node to a specific landmark. The micro routing is necessary because the macro network usually contains neither the local destination street nor the local streets that lead to the final micro destination. A lack of guidance to the exact destination would limit the system's potential usefulness to drivers who are unfamiliar with the ultimate trip destination.

As the local street links contained within the micro network are usually not detectorized, the final micro routing is usually performed using preprogrammed link speeds and link lengths. Only when the final micro network is for a congested downtown area would the routing vectors be generated on the basis of a more detailed local analysis.

Switching Between Modes

Within the current version of the Q-Route system, the routing starts with the macro mode and switches automatically to the micro mode if a micro network is available. The actual macro/micro switch is performed at one of many possible destination-specific transition nodes, which indicate to the macro routing system that the micro routing network has been reached and that the micro routing can take over. As there are a number of different transition nodes designated along each macro zone boundary, the transition can take place at a number of different locations, depending upon which direction the driver arrives from. In any case, the macro-to-micro transition is transparent to the user.

Super Macro Mode

It is anticipated that a super macro mode will later be added that will contain all the major roads within a province or state. In this fashion, a super macro routing would first guide the driver to the metropolitan area of interest. Subsequently, the normal macro mode would guide the driver from the boundary of the metropolitan area to the neighborhood of interest, before the micro routing would guide the driver to the ultimate street address within the desired neighborhood.

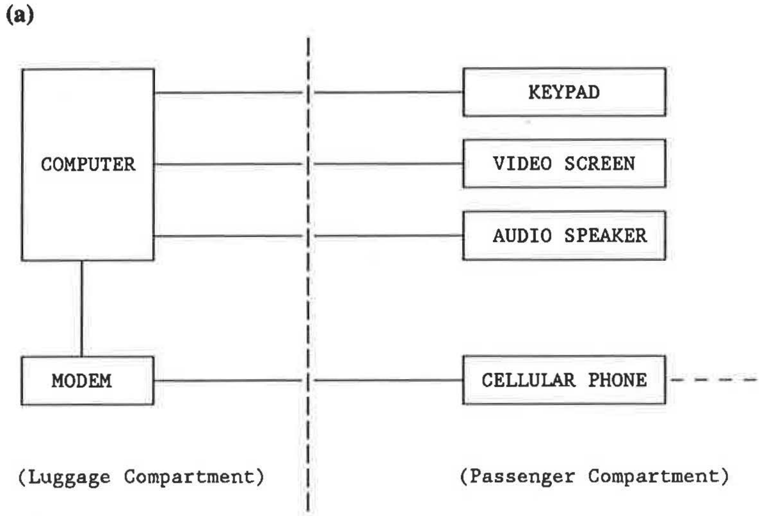
Advantages of Mixed Macro/Micro Routing

The main advantage of the mixed routing approach arises from the fact that a data base containing all macro network links within a city remains relatively small. A concurrent, rather than sequential, analysis of both the macro and micro networks would likely cause several problems in terms of memory space requirements and execution time for both the on-board unit and the central routing control facility. The macro/micro network partitioning also allows the system operator to provide only macro routing coverage at the outset, whereas micro networks for critical destination zones can be added as resources permit. Alternatively, even the ultimate configuration may provide strictly macro level coverage in the suburbs and may concentrate the micro routing services in the downtown areas.

The use of a macro network en route avoids the cumbersome reference to local street details during cross-city trips on main freeways or arteries. The reduced information load along the route will allow the drivers to concentrate better on the display when they reach their destination zone and the micro routing is invoked.

GENERATION OF ROUTING VECTORS

In contrast to the micro routing, which is usually derived from strictly static travel time estimates, the macro routing vectors can be made traffic-responsive if an appropriate data input source is available. Of course, if the more sophisticated, real-time, traffic-responsive data are not available, or if the vehicle is not equipped with a communication link, the macro routing mode can always default to the use of static routings. The traffic-responsive potential of Q-Route's macro routing derives from its compatibility in structure and concept with different



COMPUTER - IBM compatible Personal Computer, 640 Kbytes memory

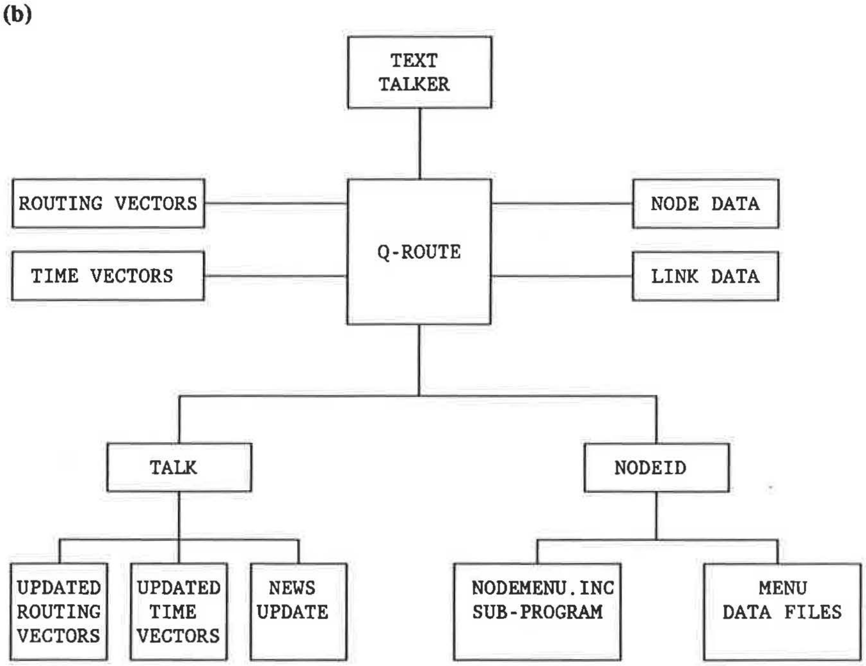
KEYPAD - 6.5 X 5 inch, 23 keys

VIDEO SCREEN - 8 inch monochrome graphics screen, 23 rows X 40 col.

AUDIO SPEAKER - with volume control

CELLULAR PHONE - standard portable cellular phone

MODEM - 1200 baud



Q-ROUTE - Route Guidance Program

TEXT TALKER - Synthetic Speech Software

TALK - Communications Software (used with cellular phone + modem)

NODEID - Menu Program (for easy selection of origin/destination)

FIGURE 4 Q-Route prototype during field tests in Kingston: a, hardware; b, software.

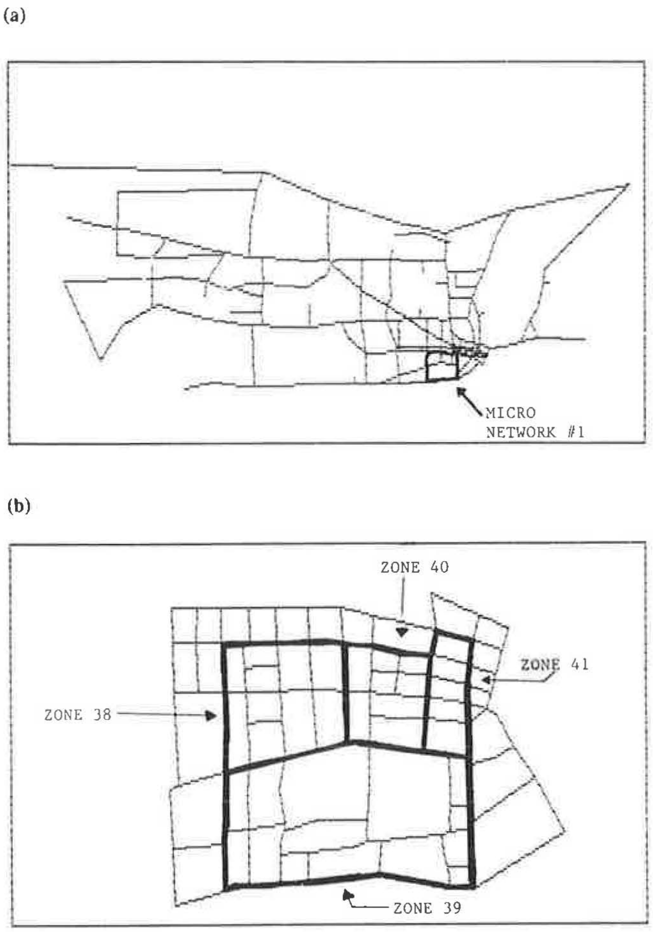


FIGURE 5 Typical network representations: a, greater Kingston area; b, Micro Network # 1.

types of related traffic models. This compatibility includes common link and node files that describe the network topography and common routing vectors that are the key to the exchange of traffic-responsive routing information, as described next.

Generation of Routing Vectors Using an Off-Line Model

The simplest way of generating Q-Route's macro routing vectors involves the use of an off-line transportation planning model or a freeway corridor control model. Relatively large networks can be handled in this fashion, and often such networks have already been coded for other traffic studies of the same area. In addition, these models can easily be used off-line to pretest different routing scenarios, and routing vectors for different traffic flow scenarios can be simulated using different origin-destination (O-D) demands for different times of the day. In each case, the routings can be pregenerated, checked, and stored in the form of a library, using either disks, tapes, or EPROMS, from which they can be selected on a time-of-day or day-of-the-week basis. This approach can deal only with recurring or predictable congestion, however.

Hybrid traffic operations/transportation planning models, such as CONTRAM (*12*), SATURN (*13*), or INTEGRATION (*7–11*), may be of assistance in preparing these off-line routings, as they provide a traffic assignment capability in a traffic management context that reflects local congestion, queuing, and signal timings. They may be used in conjunction with either a part of the macro network or for an entire micro network that includes a troublesome traffic generator.

Generation of Routing Vectors Using On-Line Data

The ideal operation of the Q-Route system would provide routings that respond to nonrecurring as well as recurring congestion in real time. The initial step toward traffic-responsive route guidance would involve the use of on-line traffic flow measurements and incident data to compute the optimum routings through the network in real time. At this time, the main obstacle to this type of on-line generation of routing data is the difficulty of pooling the traffic data for an entire urban area from the numerous traffic authorities that may be responsible for different parts of the traffic network.

The ultimate objective of an on-line Route Guidance System would involve the use of real-time O-D counts, rather than simple real-time link counts (*10,11*). These data, in conjunction with an on-line control model, could predetermine the expected diversion impact for a given rerouting instruction and establish whether the impact of the re-routing could be accommodated by the system. Not only could these vectors be purely reactive in the sense that they respond to existing traffic problems, but they could also become preemptive by responding to expected traffic problems before they actually occur (*1*).

Prototype Testing in Kingston

The initial Q-Route prototype was tested using preprogrammed routing vectors that were based on a transportation planning type of analysis of peak and off-peak traffic conditions during a typical day. These routings were then selected in the autonomous mode based on the time of day. All routings for a given O-D were all or nothing, on the basis of travel times and a traffic assignment for a network that was already in equilibrium. Because the number of routing participants initially is relatively small, these all-or-nothing routings are not likely to disturb the existing equilibrium assignment.

As no computerized traffic control center is now in operation in Kingston, it was impossible to test properly the online capabilities of Q-Route. The general capability, however, was tested by uploading to the mainframe a series of different routing vectors, which were downloaded to the in-vehicle unit through the cellular car phone and a modem. This allowed the testing of both the communication software and the automated data-manipulation procedures. It was found that even when no on-line traffic source is available, the communication link may advise drivers of road conditions and reroute them around construction. Although a separate cellular phone number may need to be set up for approximately every 100 participants in the traffic-responsive mode, this cost should be compared with that of installing beacons throughout an entire urban area.

ROUTING INFORMATION DISSEMINATION

Q-Route's initial field testing identified a number of issues related to the dissemination of real-time route guidance data.

On the basis of an analysis of these issues, the two main types of communication hierarchies, which are illustrated in Figures 6a or 6b, appeared to provide feasible implementation approaches.

Alternative Communication Hierarchies

Figure 6a shows the first hierarchy in which the Q-Route central control facility could process the traffic and routing information and produce the macro routing vectors for each macro destination. In addition, any descriptive messages regarding significant traffic incidents within the system would be generated. These vectors would then be downloaded to the roadside units at each major intersection at prespecified time intervals. Any vehicle that then passes the roadside unit would be provided with the routing vector for the driver's specific destination on request. As the roadside unit could also communicate its location ID, this roadside-to-vehicle link would therefore also support a form of vehicle navigation.

Within the second Q-Route hierarchy, which is shown in Figure 6b, a central control facility could communicate directly with the in-vehicle units through a cellular telephone or another type of radio communication. With this type of communication system, new routings and descriptive messages could be downloaded to the vehicle, but the unit would need to identify its current network location without any external assistance. This is not a problem if the driver follows the recommended route but may cause problems if an incorrect turning movement is made. In this case, navigation techniques, such as dead reckoning plus a ground- or satellite-based radio frequency method, may be required to reestablish the vehicle's

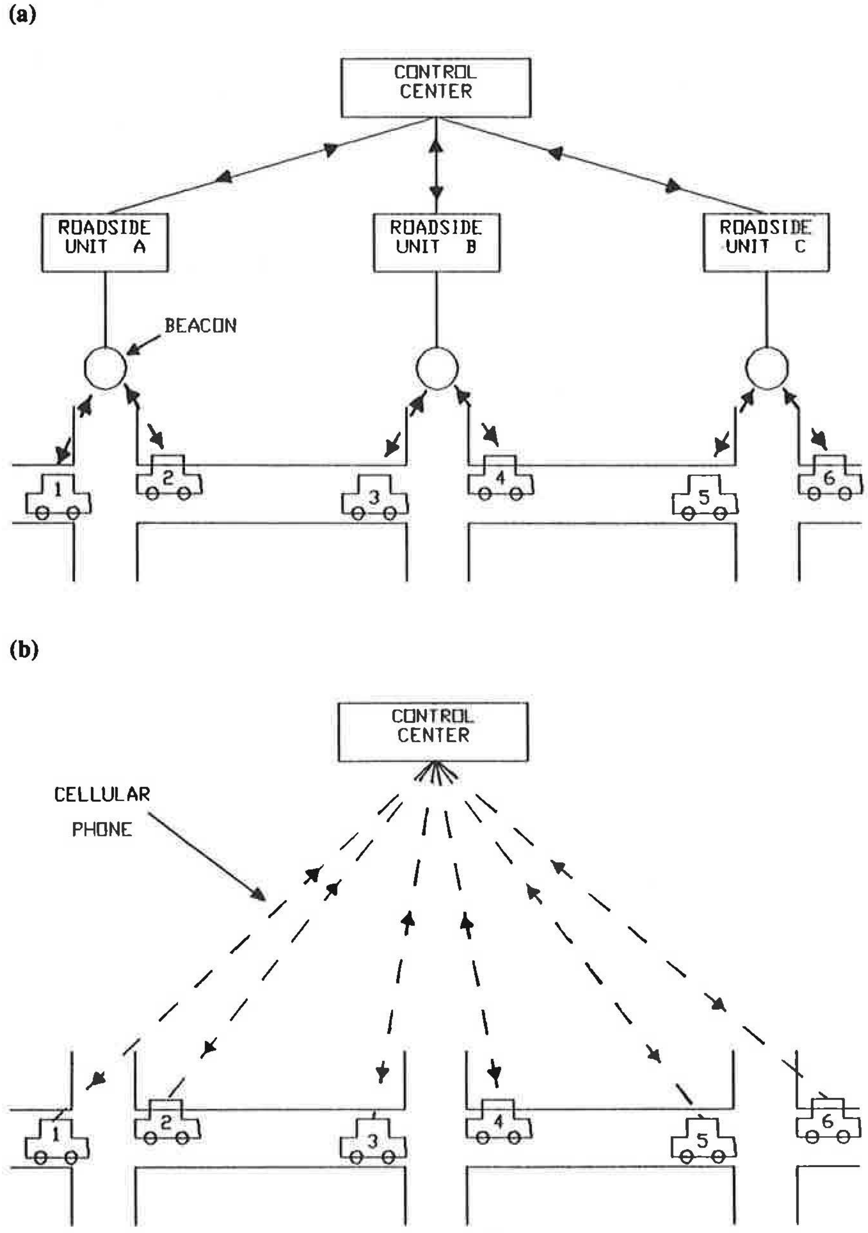


FIGURE 6 Communication hierarchies: a, Version I; b, Version II.

network position so that Q-Route can provide a new routing from the new network location onward.

Communication Links

For the system configuration in Figure 6a, two major communication links must be present. The first link primarily supports the downloading of the routing vectors from the control center to each roadside unit. Reverse communications from the roadside unit to the central computer would allow the roadside unit to send statistics on the number of user queries back to the control center. These statistics on the number and types of destinations queried by the users could provide a real-time update of the prevailing O-D patterns. This communication would likely share existing traffic control communication links to each intersection.

The second link is a two-way communication link between the roadside unit and the in-vehicle computer. It allows the driver to request and receive the routing vector for his or her specific destination and to perform emergency calls and incident reports. In addition, the roadside unit's ID allows the vehicle to reestablish its network location if the driver has not followed the recommended route. Q-Route could be implemented using either infrared beacons or inductive loops to support this two-way exchange of data.

DISTRIBUTION OF DATA AND INTELLIGENCE

The type and extent of communications that need to be provided within a Route Guidance System are intimately related to the distribution of data and intelligence within the system and to the level of routing sophistication that is desired. For a given level of sophistication, increased communications can often be substituted for decreased intelligence, and vice versa, as shown next.

Extremes in Data/Intelligence Distribution

On one extreme, the central computer could only download updates of link travel times and therefore required the on-board unit to compute the new routings on its own. This would demand considerable on-board computational power and require that the on-board unit store internally the entire network data base. The amount of data to be transmitted to the drivers would be proportional to the number of links in the network, however, and this data stream would be common to all drivers, regardless of their origin or destination. Consequently, a general citywide broadcast system would be sufficient, and no communication link from the driver to the central computer would be required.

On the other hand, the central computer could perform all computations and only forward information about the next turning movement to the on-board unit for display. The reduction in computations and data storage would allow for a less expensive on-board unit. This would require more extensive deployment of roadside hardware, however, as dedicated communication services would need to be provided at each intersection. In addition, two-way communications would be required for the roadside unit to send the appropriate routing instructions.

Prototype Testing in Kingston

Q-Route experiments to date have compromised by computing routings centrally and by storing the network data base on-board. At the start of the trip, the user can either retrieve a routing from the on-board library or request a new vector for the destination through the cellular phone link. In the latter case, the routing vector for the intended destination is downloaded by phone to the on-board unit, and both systems operate identically from this point on.

During long trips, the routing vector can be updated by request, so that the best new route from the vehicle's current location onward will be selected. Any diversion options that have already been passed, however, will obviously no longer be considered. This flexibility in downloading frequency allows one to trade off the communication costs involved in each update against the expected benefits.

DESIGN OF USER INTERFACE

Critical to the success of any Route Guidance System are the details of the final user interface design. This section provides the types of user interface formats that have been considered for use with Q-Route, and discusses the consequent tradeoffs involved.

Alternative Modes for Presenting the Routing Data

In the ideal Q-Route system configuration, the user would have a color graphics screen display available for presenting the routing information. This represents the user interface that has been used in laboratory experiments to date; virtually all other types of interface are subsets of this ideal.

At the start of the trip, Q-Route provides the driver with a plot of the entire network, with the recommended route highlighted in a different color. This allows verification of the trip's origin and destination and provides a general indication of the intended routing for the trip. Upon the start of the trip, a sequence of timed intersection map snapshots and turning movement instructions are shown for each major intersection along the route. Each such snapshot screen includes

1. A graphics representation of the turns at each intersection,
2. A supporting verbal description of the recommended turn movement,
3. A positive identification of the name of the intersection,
4. The name of the street or road to be taken or followed,
5. The remaining distance to the ultimate destination,
6. The estimated time to the ultimate destination, and
7. Warning messages dealing with incidents or weather conditions.

In more economical system configurations, the in-vehicle units consist only of simple LED/LCD character displays of the required turning movement messages at each intersection. Alternatively, a directional turning movement indicator can replace the turning messages and can be used in conjunction with another message that identifies the intersection. Each of these alternatives requires a lower cost to the in-vehicle unit but also only provides a more limited route guidance message.

Prototype Testing in Kingston

During the Q-Route in-vehicle field tests in Kingston, a monochrome composite video monitor in 40-column mode was used to display graphics and text simultaneously. In addition, a synthetic voice was included to provide an audio equivalent of the messages provided on the screen. This option was found useful during heavy traffic conditions, but problems remained in terms of the quality of the computer voice and its ability to pronounce irregular street names. Before commencing the trip, the aforementioned video screen and computer voice were also used to provide the driver with a series of hierarchical menus to assist in the selection of his trip destination. This menu program could be accessed by street name or number, by street intersection, by city landmark, or through a directory of services, such as hotels, restaurants, banks, shops, and tourist attractions.

Selecting the Appropriate Display Medium

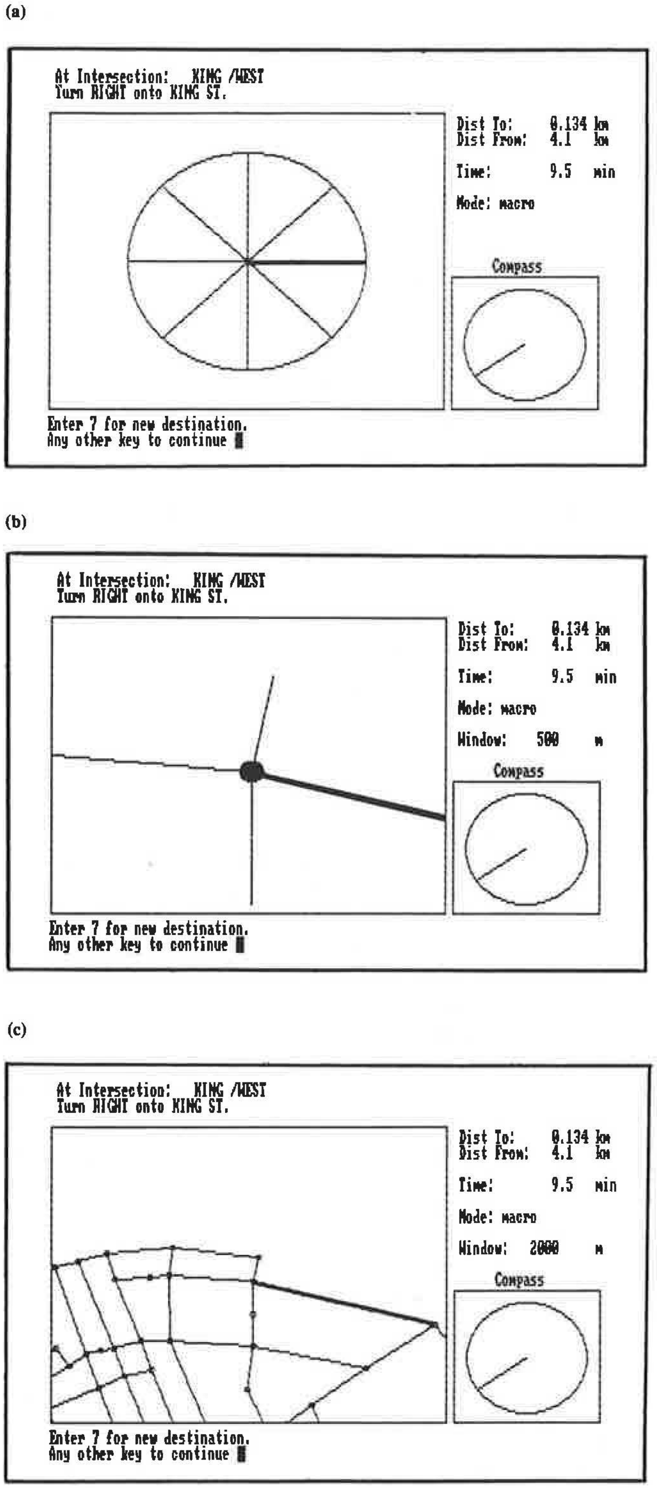
Even for the ultimate user interface, which included a color graphics screen, finding the right balance between sufficient and excessive information proves to be no simple task. On one hand, there is a tendency to provide the driver with all the information that is known to the central system and that could be of possible interest to the most sophisticated user. On the other hand, however, this ideal amount of information for the sophisticated driver also turns out to be too much information for the less sophisticated driver. Such a driver either becomes lost in the wealth of information provided or becomes distracted enough to present a safety hazard to others as well as to himself.

The cost of the display is intimately related to its resolution and quality. Experiments to date have shown that multicolor displays are clearly the most attractive and interesting but that, in routine application of the unit, those benefits may not warrant their extra cost. Even for a given display hardware configuration, considerable flexibility remains in the actual format of the display. Consequently, three types of display formats are undergoing user testing. All of these directional displays conspicuously indicate to the user the recommended turning movement at each intersection.

Alternative Screen Messages

The simplest version of the display is illustrated in Figure 7a and consists of a directional arrow on the screen. This is a very simple display as it illuminates one out of eight arrows, which indicates the recommended turning movement to within a 22.5-degree angle. This display can also be implemented without a video screen, but then additional hardware is needed for the accompanying messages to be displayed.

Improved routing information is provided using an intersection display that provides an abstract bird's eye view of all the streets that meet at the current intersection, as illustrated in Figure 7b. In this case, the turning movement direction is superimposed on the shape of the intersection, which provides the driver with the relative angle of the recommended road relative to the other roads at the intersection. This mode requires either a low- or medium-resolution graphics display, and it was used most extensively during the Kingston experiments.



(a)

```
At Intersection:   KING /WEST
Turn RIGHT onto KING ST.
                                  Dist To:     0.134 km
                                  Dist From:   4.1   km

                                  Time:        9.5   min

                                  Mode: macro

Enter 7 for new destination.
Any other key to continue
```

(b)

```
At Intersection:   KING /WEST
Turn RIGHT onto KING ST.
                                  Dist To:     0.134 km
                                  Dist From:   4.1   km

                                  Time:        9.5   min

                                  Mode: macro

                                  Window:   500     m

Enter 7 for new destination.
Any other key to continue
```

(c)

```
At Intersection:   KING /WEST
Turn RIGHT onto KING ST.
                                  Dist To:     0.134 km
                                  Dist From:   4.1   km

                                  Time:        9.5   min

                                  Mode: macro

                                  Window:   2000    m

Enter 7 for new destination.
Any other key to continue
```

FIGURE 7 Alternative user interface display formats: a, arrow display; b, intersection display; c, graphics display.

The highest-quality message is produced using a full graphics display, as shown in Figure 7c. In this case, the driver is presented with a localized electronic map that is centered at the next intersection and is rotated to show the crossing roads and any nearby streets in the same orientation as they are seen from the car. A zoom capability has been added to provide both small- and large-scale views of the area on the graphics screen. The computations involved in this display are much more complex than in either of the preceding displays and, while useful in the lab, this display was found impractical in the vehicle.

Drivers interact with the aforementioned display using a simple keypad. The arrow keys are used during the O-D selection process, and the function keys can retrieve special weather and news information.

SUMMARY AND CONCLUSIONS

This paper discusses the development and prototype testing in Kingston of the Q-Route route guidance approach to collecting, processing, distributing, and presenting traffic-responsive route guidance information.

At this stage, the routing vectors provide all-or-nothing assignments to the Q-Route users, and it is assumed that their routings do not influence the network's traffic assignment equilibrium. As a larger fraction of the drivers become Q-Route users, however, it will be necessary to provide multipath routings that explicitly take into account the impact of the Q-Route routing vectors on network equilibrium. Ultimately, the routing vectors may be generated in such a fashion as to permit preemptive routing strategies, which prevent anticipated traffic congestion rather than strictly respond or react to traffic congestion that has already materialized.

The combined macro/micro routing concept permits fully traffic-responsive route guidance within large urban areas using a macro network of all freeways and major arteries and collectors. Ultimately, a super macro network may be available for the entire province, state, or country, which automatically switches to the available macro and micro networks for each city as the vehicle is detected on the periphery of the latter networks.

Critical to the successful implementation of a driver information system such as Q-Route is the availability of comprehensive traffic data for all parts of an urban area, regardless of who has legal jurisdiction in each subnetwork. In addition to the administrative obstacles, the technical aspects of such data integration in an off-line or on-line mode may impose some other difficulties. These technical and administrative difficulties are by no means unique to Q-Route.

In addition, standards need to be established for the development of route guidance data bases, communication protocols, and hardware and software. Without such standards, it appears unlikely that drivers would purchase systems that they could not use in other cities, towns, or states/provinces within the same country. As in any emerging technology, however, standards may negatively affect the application of new technology as it becomes available and may result in standardization based on an obsolete technology.

Q-Route's current prototype implementation only assists in selecting the most efficient route from a known location to either a known or unknown destination, and it assumes that drivers follow this route at all times. Before a more comprehensive experiment can take place, an affiliated navigation system may need to be incorporated to deal with drivers who fail to follow the recommended route and get lost. At this time, the system is capable of providing new routings when a driver gets lost, but it is unable to establish on its own that the driver has drifted from the recommended path.

At present, current route guidance research is concentrated on more extensive field testing of Q-Route in the Greater Toronto Area, on the evaluation of the benefits of route guidance during different types of recurring and nonrecurring traffic congestion, and on the opportunities for providing micro route guidance on freeways with core and collector lanes, such as Highway 401 in Toronto, Ontario (*9–11*).

ACKNOWLEDGMENTS

During the development of the Q-Route concept useful suggestions were provided by other researchers from the Department of Civil Engineering at Queen's University and by E. R. Case and A. Ugge of the Research and Development Branch of the Ministry of Transportation, Ontario. The research reported in this paper was sponsored in part by Queen's University, the R&D Branch of the Ministry of Transportation, Ontario, and the Natural Sciences and Engineering Research Council of Canada.

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Publication of this paper sponsored by Committee on Communications.

Effectiveness of Traffic Restraint for a Congested Urban Network: A Simulation Study

AJAY K. RATHI AND EDWARD B. LIEBERMAN

Restricting ("metering") traffic flow on the approaches to an urban street network ("control area") can be considered an application of the concept of freeway ramp metering to surface street systems. In this application, local demand is reduced by metering traffic at the periphery of the control area during peak traffic demand periods. The purpose of this strategy is to maintain a level of traffic density within the control area to avoid congested flow conditions. It is postulated that if this objective is achieved, the performance of traffic will improve significantly within the control area and this improvement will more than offset the disbenefit associated with the possible delay of some traffic at the periphery. That is, the performance of the affected traffic, overall, will be improved. This paper presents the results of a simulation study that evaluated this hypothesis. On the basis of the results obtained in this study, it appears that the peripheral ("external") metering control strategies have the potential to improve the overall performance of traffic in a highly congested control area. The results indicate that it is virtually essential to apply a metering control along the periphery of a control area that is congested to the extent that the ensuing traffic demand cannot be serviced because of overflow queues causing extensive intersection spillback. It has also been shown that the optimal metering control policy to be enacted depends on the traffic condition before the implementation of such control (i.e., base condition) as well as the selected measure of effectiveness.

Traffic restraint consists of measures that are aimed at restricting vehicle use to achieve a significant modification in mode, time, route, or destination of vehicle trips. Restraint measures differ widely in the form and level of restriction they impose. One extreme of traffic restraint is the macroscopic measures that affect demand, such as techniques to reduce trip generation, trip distribution, or mode split, both spatially and temporally. This type of restraint is implemented primarily through fiscal or regulatory measures. The other extreme of traffic restraint is the direct control of demand at the micro level (e.g., individual intersections, approaches to a grid network). This form of traffic restraint is imposed by measures such as physical restrictions (e.g., street closure) or delay-based restrictions (e.g., signal control) and is primarily intended to reduce temporarily the demand for congestion control. One such traffic restraint-based control strategy is the focus of this paper.

BACKGROUND

The problem of urban congestion has received considerable attention recently and for good reason. Traffic congestion is no longer a characteristic only of big cities. Medium-sized cities, such as Charlotte and San Antonio, and even smaller urban areas experience levels of congestion rivaling that in many major metropolitan areas. On the other hand, urban congestion in big cities is reaching such proportions that it is no longer merely a nuisance; it is becoming a critical liability that adversely affects the economic growth of urban areas. The policymakers and administrators of transportation agencies throughout the United States and elsewhere have recognized urban traffic congestion as one of the critical problems facing urban areas. The Executive Committee of TRB has identified congestion of traffic facilities as one of the ten critical issues in transportation (*1*).

Traffic engineering techniques designed to reduce the adverse impacts of urban congestion fall into three general categories:

- Measures designed to increase capacity of the road system,
- Measures designed to maximize use of the available capacity, and
- Measures designed to reduce demand.

Measures designed to increase the capacity of the road system include building additional facilities or physically altering existing facilities to provide additional capacity in the road network. Measures designed to maximize available capacity include traffic engineering techniques aimed at minimizing the capacity-reducing factors (e.g., parking, standing, and stopping control or turn regulations) or at maximizing the use of existing capacity (e.g., improved signal control).

After all possible measures for increasing capacity have been implemented, and the available capacity is optimally utilized, congestion may still occur if traffic demand exceeds system capacity. Under these conditions, congestion is unavoidable unless demand can be reduced through traffic restraints.

TRAFFIC RESTRAINTS

The necessity for traffic restraint was recognized a long time ago. Nearly 25 years ago, in the preface to the book *Traffic in Towns* (*2*) Lord Crowther wrote, "Distasteful though we

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find the whole idea, we think some deliberate limitation of the volume of motor traffic in our cities is quite unavoidable." Some macroscopic forms of traffic restraints implemented through fiscal or regulatory measures have been tried successfully in some older cities in Europe and are becoming increasingly popular in the large metropolitan areas of developing countries (*3*,*4*).

However, with one or two exceptions (*5*), policymakers and administrators in the United States and elsewhere have avoided direct control of demand on a micro level (i.e., restricting traffic flow on individual approaches or to a small cohesive area). The reasons for rejection or abandonment of such restraints are many. The major objections are that such measures will be unworkable and ineffective and will have an adverse impact on business in the affected area (*6*). Some minor objections, such as that restraints are unfair to certain groups in society or that they are hard to enforce, are also raised.

Although some of these arguments have their strength and political clout, the arguments in favor of traffic restraints (e.g., efficiency, resource conservation, environmental improvement) have in the past rested on largely unsubstantiated ("intuitive") claims of solving severe traffic problems. That is, these arguments have suffered from a lack of credibility and in many cases there has been no sound technical basis for justification of such restraints. At a minimum, policymakers, administrators, and the public will want to know the resulting transportation effects.

This limitation can now be overcome because sophisticated models are available that can simulate traffic operations in a large urban grid network with the desired degree of detail and precision. Simulation models such as Traf-Netsim (*7*) or TRAFLO (*8*) can be used to predict, with reasonable accuracy, the transportation as well as environmental impacts of traffic restraints in urban areas before their real-life implementation. This paper presents the result of a simulation study that evaluated the effects of applying a traffic restraint at the periphery (hereafter referred to as "external metering control") of a congested area in the New York central business district (CBD).

OBJECTIVE

The policy of external metering consists of applying controls on the periphery of a congested control area to limit the rate of traffic inflow to the area during a period of traffic accumulation (i.e., during the a.m. peak period). The purpose of this strategy is to maintain a level of traffic density within the control area that will avoid congested flow conditions. It is postulated that if this objective is achieved, the performance of traffic will improve significantly within the control area, with a concomitant reduction in vehicle emissions and energy consumption. It is further postulated that the improvement of traffic performance within the control area will more than offset the disbenefits associated with delaying the traffic at the periphery.

As part of a project to examine ways to improve air quality and reduce congestion in the high-density sectors (i.e., highly congested areas) of the New York CBD (*9*), a simulation study was undertaken to assess the feasibility of an external metering-based control strategy. The objective of this study was to evaluate the potential impacts of applying an external metering control during peak traffic demand periods for a congested area in the New York CBD.

SELECTED CONTROL AREA AND METERING LOCATIONS

The control area selected for analysis, as shown in Figure 1, extends from 63rd Street to 54th Street and from First Avenue to Lexington Avenue in mid-Manhattan. Table 1 lists the possible metering locations within this control area. This control area was selected because it is part of one of the high traffic density areas of mid-Manhattan (*10*). This grid area experiences excessive delays for a relatively long time frame during the a.m. peak period and hence offers a potential for reducing aggregate trip travel time during the metering period. Furthermore, the traffic can be metered at almost every entry point by suitably adjusting the signal timing.

PROCEDURE

The Traf-Netsim simulation model (*7*) was used to evaluate the impact of external metering on traffic operations in the control area. The performance of traffic under existing conditions (i.e., without any metering control) was compared with that when different rates of metering were implemented for traffic entering the control area. The analyses were performed for the a.m. peak period.

To use the Traf-Netsim simulation model, the street system within the control area was represented as a network of links and nodes, shown in Figure 2. Data were collected in the field to prepare the input data for the simulation model. The data collected include geometrics, channelization, traffic volumes, turn counts, signal timing, and bus data specific to one control area. Some of these data were obtained directly from the New York City Department of Transportation.

Computer runs were then made to simulate traffic operations under existing conditions as well as for a number of external metering control scenarios. Both restrictive and permissive metering rates were implemented in these experiments. That is, the impacts of restricting the entry of traffic at the periphery of the control area and the impacts of permitting additional traffic to enter the control area were analyzed. Metering was implemented directly by modifying the input traffic volumes at all entry points of the control area to the desired inflow rate. This metering control was implemented in this preliminary study in accord with the following rationale.

1. The same level of metering is implemented throughout the periphery of the control area, so that all entering traffic streams are affected to the same extent.
2. The impact of the metering is uniformly distributed throughout the control area. It is therefore reasonable to assume that no substantive changes in traffic control within the control area are required and that such control measures will have an insignificant or very little impact on traffic assignment.
3. In a congested environment a desired level of metering may not be obtainable through peripheral signal control alone, because the number of vehicles that can enter the control area depends on the traffic conditions within the control area. That

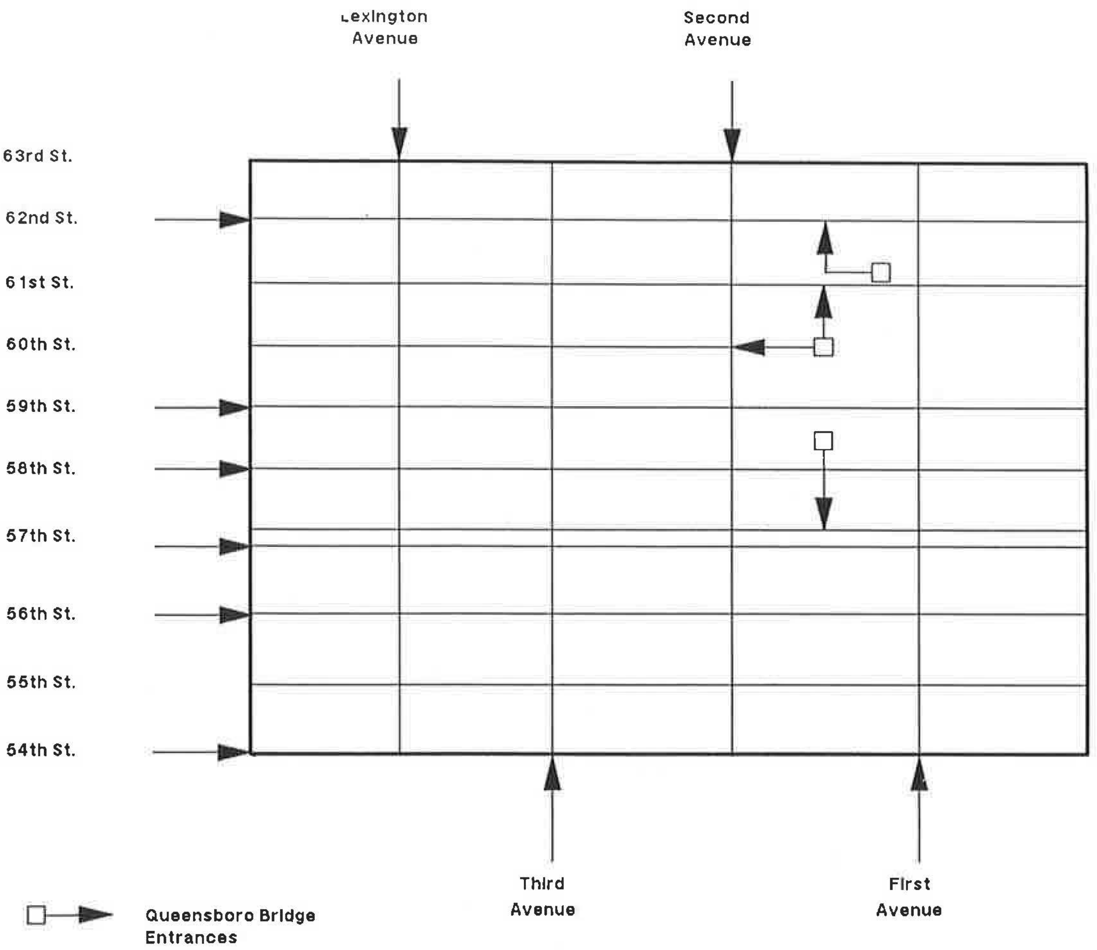

FIGURE 1 Control area.

TABLE 1 POSSIBLE METERING LOCATIONS IN THE SELECTED CONTROL AREA

1. Southbound Second Avenue and Lexington Avenue at 63rd Street.
2. Northbound First Avenue and Third Avenue at 54th Street.
3. Eastbound 62nd, 59th, 58th, 57th, 56th, and 54th Streets at Lexington Avenue.
4. Westbound 63rd, 61st, 59th, 57th and 55th Streets at First Avenue.
5. Queensboro Bridge exits at 62nd, 60th and 58th Streets.

is, signal control can specify only the maximum possible inflow rate; the actual inflow rate also depends on traffic conditions within the control area. Specifically, congested conditions within the control area can produce queues that limit the rate of traffic inflow below that permitted by the metering policy.

Simulation studies were undertaken for the following scenarios:

- Scenario 1. Present conditions,
- Scenario 2. A 10 percent reduction in inbound traffic at all entry points in the control area,
- Scenario 3. A 20 percent reduction in inbound traffic at all entry points in the control area,
- Scenario 4. A 40 percent reduction in inbound traffic at all entry points in the control area,
- Scenario 5. A 10 percent increase in inbound traffic at all entry points in the control area,
- Scenario 6. A 20 percent increase in inbound traffic at all entry points in the control area,
- Scenario 7. A 30 percent increase in inbound traffic at all entry points in the control area, and
- Scenario 8. A 35 percent increase in inbound traffic at all entry points in the control area.

SIMULATION RESULTS

The comparisons of traffic performance under the existing control policy versus the metering control scenarios are based on the following networkwide aggregate measures of effectiveness (MOEs): mean speed, production (vehicle trips), delay,

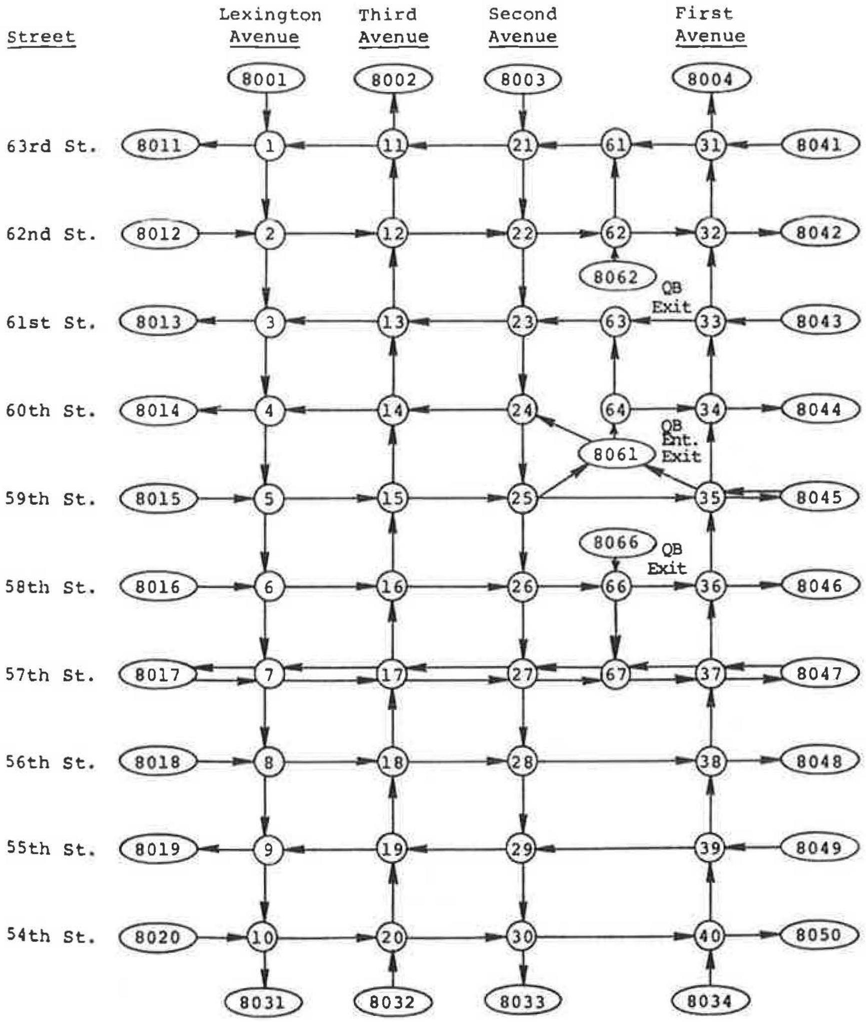

FIGURE 2 Link-node representation of the control area.

total travel time (vehicle hours), and saturation (vehicle content). Throughput, computed as the product of mean speed and vehicle trips, is also considered in analyzing the result.

Table 2 presents the simulation results for Scenarios 1 through 8. It contains the simulated values of the MOEs based on a simulation time period of 12 min following an initialization period of 9 min for each scenario. Scenario 1 represents existing conditions for the control area, and Scenarios 2 through 8 represent the conditions under different levels of metering implemented at the periphery of the control area but with the same signal control policy within the area. For Scenarios 2 through 8, the percent differences—relative to Scenario 1—are also shown (in parentheses) in Table 2 for each MOE. An examination of these simulation results leads to the observations that follow.

Vehicle Trips

When traffic demand attempting to enter the control area is restricted relative to the base condition (Scenarios 2, 3, and 4), the number of vehicle trips serviced on the control area is reduced in almost direct proportion to the implemented metering rates. The results, however, are quite different when a permissive metering allows more traffic to enter the control area than at present. Scenario 6, where a 20 percent permissive metering is implemented, the vehicle trips completed within the control area increased by only 5.5 percent. A further relaxation of the metering rate to permit a 30 percent increase in entering traffic volume produces no additional vehicle trips. When the metering rate is further increased to 35 percent (Scenario 8) relative to the base condition, the number of vehicle trips through the control area actually decreases relative to the 30 percent increase in the metering rate of Scenario 7 (see Table 2).

The changes in completed vehicle trips for individual entry links to the control area indicated that the percent decreases in vehicle trips serviced on entry links along the periphery of the control area for Scenarios 2, 3, and 4 are nearly the same as the percent decreases in metering rate. These results imply that because there is nearly a direct linear relationship between traffic volume entering the control area and traffic volume serviced within the control area, the network is undersaturated at these lower metering rates. There is also some indication that the base condition is, to some extent, reflective of an undersaturated network.

When the metering rate is increased uniformly for all entry links, however, the intrinsic heterogeneity of the network

TABLE 2 SIMULATED TRAFFIC PERFORMANCE—SCENARIOS 1 THROUGH 8

Measure of Effectiveness	Scenario (Metering Rate, Pct.)							
	2 (-10)	3 (-20)	4 (-40)	1 (0)	5 (+10)	6 (+20)	7 (+30)	8 (+35)
Vehicle Trips (veh)	3056.0 (-8.2)	2770.0 (-16.8)	2118.0 (-36.4)	3330.0	3475.0 (+4.3)	3515.0 (+5.5)	3518.0 (+5.6)	3405.0 (+2.3)
Travel Time (veh-hrs)	150.7 (-15.3)	113.6 (-36.2)	77.0 (-56.7)	178.0	208.7 (+17.2)	232.1 (+30.4)	254.5 (+43.0)	279.5 (+57.0)
Total Travel Time (veh-hrs)	226.8 (+9.1)	239.3 (+15.1)	360.4 (+73.3)	207.9	215.4 (+3.6)	232.6 (+11.8)	254.5 (+22.4)	300.4 (+44.5)
Mean Speed (miles/hr)	7.5 (+10.3)	9.1 (+33.8)	10.3 (+51.5)	6.8	5.9 (-13.2)	5.3 (-22.1)	4.9 (-27.9)	4.3 (-36.7)
Delay (veh-hrs)	110.0 (-18.5)	76.5 (-43.3)	48.3 (-64.2)	134.9	164.8 (+22.2)	187.7 (+31.9)	210.3 (+55.9)	236.7 (+75.5)
Content (veh)	761.4 (-15.4)	574.5 (-36.2)	389.5 (-56.7)	899.8	1054.0 (+17.1)	1171.8 (+30.2)	1285.4 (+42.8)	1410.7 (+56.8)
Throughput (veh-miles/hr)	22920.0 (+1.2)	25207.0 (+11.3)	21815.4 (-3.6)	22644.0	20502.5 (-9.5)	18629.5 (-17.7)	17238.2 (-23.9)	14641.5 (-35.3)

Notes: 1) The numbers in parentheses are the percent change relative to Scenario 1.

2) Metering is (restrictive, permissive) if (negative, positive).

3) Total travel time is the sum of Travel Time (within the control area) and the additional travel time outside the control area due to metering relative to Scenario 7.

response becomes apparent. That is, some roadways within the control area exhibit the ability to accommodate additional demand in the control area over the entire range of metering whereas others do not (i.e., they exhibit saturated conditions with small changes in entering traffic volumes). The detailed results are presented elsewhere (*11*).

The inability of some entry points to accommodate additional entering demand, even when metering rates are relaxed to accommodate higher levels of entering traffic, reflects the de facto metering imposed by congested conditions within the control area. That is, the queues formed within the control area preempt, to some extent, the ability of entering traffic on some links approaching the entry points from fully using the available green time provided by the metering policy. Consequently, these queues override the metering policy.

It is seen, for this case study, that there is a strong "asymmetry" in the response of aggregate vehicle trips serviced within the control area to changes in nominal metering rates, M, relative to the base condition, M_o:

- Decreasing metering rates in a restrictive policy (i.e., $M < M_o$), by some percent, p, acts to decrease vehicle trips by approximately the same percentage, p.
- Increasing metering rates (i.e., $M > M^* > M_o$) by some percent, $p \leq p^*$, will increase vehicle trips by a substantially smaller percentage. The percentage, p^*, with the associated metering rate, M^*, is that point beyond which further increase in metering rates, $M > M^*$, does not provide an increase in vehicles serviced and could actually decrease vehicle trips somewhat.

The preceding conclusions apply when $M_o \leq M^*$. Under that condition, application of either restrictive or permissive external metering will change vehicle trips. If, on the other hand, $M_o > M^*$, then restrictive external metering will unconditionally improve traffic operations. It is therefore essential to establish the status of an existing condition, in the sense just discussed, to determine the potential of external metering to provide important benefits in improving traffic operations.

Mean Speed

The previous discussion addressed the quantity of traffic flow serviced. It is also essential to discuss the influence of external metering on the quality of traffic flow. A prominent measure of the quality of flow is mean speed.

Table 2 reveals that mean speed responds in a sensitive way to changes in metering rates. In the cases of restrictive metering (Scenarios 2, 3, and 4), the percent increases in mean speed are greater than the associated percent decreases in metering rate, and they are also greater than the associated percent decreases in vehicle trips. When the entering traffic volume at the periphery is increased (Scenarios 5, 6, 7, and 8), the percent decreases in mean speed are about the same as the percent increases in metering rate. Note that mean speed percentages decrease much more sharply than the corresponding small increases in vehicle trips under permissive changes in metering rates. In fact, both the mean speed and the vehicle trips decrease in Scenario 8 relative to Scenario 7, indicating that, past some point, increasing the metering rates is counterproductive for both vehicle trips serviced and for traffic performance.

It should be mentioned here that because of microcomputer memory limitations, the Traf-Netsim model could not be used to simulate the conditions when entering traffic volume at the periphery is specified at 40 percent above the base condition. For that scenario, the simulation run ended after 8 min of simulation past initialization. On the basis of intermediate output for the first 6 min of simulation, a sharp decrease in vehicle trips completed and in mean speed was observed. These results indicated a pronounced deterioration in operational performance within the control area with high delays and spillbacks throughout the network. Thus, permitting more vehicles to enter the control area at this level (i.e., if $M >> M^*$) sharply exacerbates congestion in every respect. This condition must be avoided.

Delay

The delay within the control area decreases significantly when the entering traffic volume is reduced by restrictive external metering. On the other hand, delay increases as the traffic volume entering the control area increases as a result of permissive metering. As expected, the delay increases sharply at higher traffic volumes as in Scenario 8.

Vehicle Content

Under a restrictive metering policy, relative to the base condition of Scenario 1, the vehicle content of the network decreases (in percent) about 50 percent more than do the associated percent decreases in vehicle trips. Under a permissive metering policy, however, vehicle content increases markedly while the number of trips remains essentially unchanged. This relationship reflects the adverse impact of congestion that increases traffic density but not the service rate.

Throughput

Throughput, p, is a measure that combines two measures, traffic volume and speed, to form a single performance measure:

$$p = \int_{o}^{T} v(t)q(t)dt$$

where

p = throughput (vehicle miles per hour),
v = speed (mph),
q = volume serviced (vph),
t = time (hr), and
T = analysis period (hr).

The Traf-Netsim simulation model provides the value of p directly as the product of networkwide aggregate mean speed and total vehicle trips. This measure, which is comprised of measures describing both the quality and quantity of traffic flow, can therefore serve as an optimizing parameter.

As discussed previously, a permissive metering policy acts to increase slightly vehicle trips (i.e., the number of vehicles serviced) but at higher levels of congestion (delay and vehicle content) and at lower speeds. A restrictive metering policy sharply increases speed and reduces delay but at somewhat lower levels of vehicles serviced. The throughput measure represents a trade-off between the conflicting objectives of increasing the number of vehicles serviced while increasing speed and reducing travel time.

Under permissive external metering (Scenarios 5, 6, 7, and 8) relative to the base condition (Scenario 1), the throughput within the control area is significantly reduced. Under a restrictive metering policy (Scenarios 2 and 3), throughput is increased relative to Scenario 1. Specifically, restricting traffic inflow by 20 percent increases throughput by 11.3 percent in the control area. More restrictive metering of traffic demand, however, is counterproductive because the resulting increase in speed is more than counterbalanced by the decrease in vehicle trips, thereby reducing throughput (Scenario 4).

Travel Time

Travel time is expressed as vehicle hours of travel and is strongly correlated (inversely) with speed. Its value as an optimizing parameter lies in the ability to calculate this measure for traffic operations within the control area and for the effect of metering on the travel time of traffic approaching the control area from outside.

To provide a consistent comparison, it is assumed that the aggregate demand for service over the 12-min simulation analysis period is that associated with Scenario 7—3,518 vehicles. Thus, this demand is serviced over a longer (than 12 min) period for all other scenarios.

For this case study, total travel time is increased for both restrictive and permissive metering policies relative to Scenario 1 (Table 2).

SOME REAL-WORLD CONSIDERATIONS

The discussion of simulation results so far has

- Addressed a single "base condition" (i.e., the existing condition in the control area during an average weekday a.m. peak period); and
- Considered several different measures of effectiveness (e.g., vehicle trips, travel time).

Because traffic volume varies from one peak hour to the next and from one weekday to another, however, it is reasonable to assume that Scenario 1 does not cover the entire spectrum of traffic operations in the control area. That is, Scenario 1 merely represents average weekday a.m. peak period traffic conditions within the control area; at times the system's operational status can be better or worse than that of Scenario 1. At times, the state of traffic operations in the control area can be similar to the conditions represented by Scenarios 2 through 8. It is therefore appropriate to assess the impact of metering control implemented during these conditions—that is, to explore the base condition where traffic in the control area is represented by these scenarios.

Similarly, it is seen that the impact of different metering strategies is not consistent across different MOEs. That is, one metering strategy is better than others for one MOE, but it may not be desirable for other MOEs. For example, Scenario 3 is the best strategy when the selected MOE (or objective) is throughput. It is not the best strategy, however, if the objective is to maximize the vehicle trips. The consequence of this inconsistency is that the optimal metering policy will differ depending on the MOE selected. This relation implies that the optimal metering strategy for a given control area depends on the base condition as well as the selected objective. A simple analysis will illustrate this point.

Consider three base conditions: Scenario 1, Scenario 3, and Scenario 7. For each base condition, we will identify the best metering strategy for each of several specified objectives. The results of this analysis are presented in Table 3. As indicated therein, the optimal external metering policy to be enacted depends on the base condition and the selected objective.

As indicated in Table 3, the objective of maximizing trips would yield a permissive metering policy. This policy would produce a congested environment that just avoids systemwide breakdown within the control area. For the case studied, selecting this objective implies the acceptance of significant penalties in total travel time and throughput.

The objective of minimizing total travel time is intrinsically appealing, particularly when, as in this case, the policy's production (i.e., vehicle trips) is about 95 percent of that provided by the policy that maximizes production. For this policy, the traffic environment is still congested, albeit less so than for the previous policy.

The objective of maximizing throughput produces a traffic environment that is appealing to the motorist within the control area (i.e., moderate density, acceptable speed) but penalizes the motorist on the approaches to the control area. This policy, which produces a stable traffic environment within the control area, may be attractive to policymakers who wish to provide improved service within a control area and are less concerned about delays of traffic attempting to enter the area. That is, although the total travel time for this policy exceeds that for the previous policy, the apportionment of travel time here is such that those inside the control area benefit, while those on the approaches are penalized, relative to the situation attendant to the previous policy.

In summary, with Scenario 1, which minimizes total travel time, as base condition, a metering policy that maximizes trips increases trips by 5 percent, but increases total travel time by 17 percent and decreases throughput by 21 percent. A metering policy that maximizes throughput increases throughput by 11 percent but decreases trips serviced by 17 percent and increases total travel time by 15 percent.

With Scenario 3, which maximizes throughput, as base condition, a metering policy that maximizes trips increases trips by 27 percent but increases total travel time by 2 percent and decrease throughput by 29 percent. A metering policy that minimizes total travel time decreases total travel time by 9 percent and increases vehicle trips by 20 percent but decreases throughput by 10 percent.

With Scenario 7, which maximizes trips, as base condition, a metering policy that minimizes total travel time decreases total travel time by 18 percent and increases throughput by 31 percent but decreases vehicle trips by 5 percent. A metering policy that maximizes throughput increases throughput by 46 percent and decreases total travel time by 6 percent but decreases vehicle trips by 21 percent.

On the basis of the results obtained in this study it appears that a policy designed to maximize trips offers very limited benefits in that respect and penalizes traffic operations to a far greater extent. It appears from this study, then, that the most permissive external policy should be what minimizes total travel time and the most restrictive policy should be what maximizes throughput.

CONCLUSIONS

The objective of this study was to evaluate the potential impacts and feasibility of an external metering control strategy for a congested urban network. According to the results obtained in this study, it appears that the external metering control strategies have the potential to improve traffic operations within and on the approaches to a congested control area. The simulation results for this case study suggest that it is virtually essential to apply an external metering policy along the periphery of a control area that is presently congested to the extent that production (vehicle trips serviced) is reduced because of extensive queue spillback. It has been shown that the optimal external metering policy depends on the base condition as well as the specified objective (i.e., MOE). Thus, an external metering policy can potentially benefit any con-

TABLE 3 EXTERNAL METERING POLICIES FOR THE TEST NETWORK UNDER SEVERAL BASE CONDITIONS

Base condition	Objective	External Metering		Vehicle Trips		Total Travel Time (veh-hrs)		Throughput (veh-mi/hr) x 1000	
		Policy	Pct. Change*	Base	With Metering	Base	With Metering	Base	With Metering
Scenario 1	Maximize Trips	Permissive	+25	3330	3517	207.9	243.6	22.64	17.93
	Minimize Travel Time	-	0	3330	-	207.9	-	22.64	-
	Maximize Throughput	Restrictive	-20	3330	2770	207.9	239.3	22.64	25.21
Scenario 2	Maximize Trips	Permissive	+56	2770	3517	239.3	243.6	25.21	17.93
	Minimize Travel Time	Permissive	+25	2770	3330	239.3	207.9	25.21	22.64
	Maximize Throughput	-	0	2770	-	239.3	-	25.21	-
Scenario 3	Maximize Trips	-	0	3518	-	254.5	-	17.24	-
	Minimize Travel Time	Restrictive	-23	3518	3330	254.5	207.9	17.24	22.64
	Maximize Throughput	Restrictive	-38	3518	2770	254.5	239.3	17.24	25.21

*Percent change in metering rate relative to the specified base condition. Note that interpolation in Table 2 was employed to estimate the optimum policy.

gested area and, furthermore, can be responsive to traffic management policies formulated by the decision makers.

FUTURE WORK

The study discussed in this paper presents an interesting evaluation of the external metering-based control concept. It appears from this preliminary study that such metering control has the potential to improve traffic operations in the affected control area and that this improvement exceeds the disbenefit associated with metering traffic at the periphery of the control area. That is, metering control can lead to an improvement in overall traffic performance. It would therefore be desirable to perform a detailed study identifying optimal metering policies; economic, social, and environmental impacts of such metering controls; behavioral and locational response of the metered vehicles and distributional effects of such restraints; and detection and implementation criteria and procedures for real-life implementation.

In the interests of limiting the extent of the present study and of presenting results in a clear format without introducing confounding factors, only scenarios with a uniform rate of metering at all approaches to the control area were considered. Scenarios with nonuniform metering rates should also be evaluated, however, because a metering control policy should be designed in recognition of the heterogeneity of the traffic environment in the control area. That is, different metering rates should be applied to different approaches to the control area so as to "tailor" the metering rate to the maximum use of available street capacity in the immediate vicinity of the approach.

ACKNOWLEDGMENTS

This paper is based on research funded by the U.S. Department of Transportation in cooperation with the New York Metropolitan Transportation Council and the New York City Department of Transportation. The contributions of Lee L. Home of Signals and Communications for New York City Department of Transportation and of his staff to the success of this study are gratefully acknowledged.

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Publication of this paper sponsored by Committee on Traffic Signal Systems.

Operational Considerations in HOV Facility Implementations: Making Sense of It All

FRANK CECHINI

This report analyzes data collected from selected existing freeway high-occupancy vehicle (HOV) facilities. On the basis of the experience drawn, several criteria are suggested for HOV lanes to be effective in increasing person throughput. In addition, general conclusions are drawn from existing operational data about design and enforcement issues. The many aspects of HOV facility design are not addressed in detail, nor are specific geometric guidelines established. Presented are regional objectives of urban mobility, lessons learned from the various HOV facilities, design and enforcement issues, and principal operational issues centered on systems planning, access eligibility, occupancy, marketing, and time of operations. Facility development and implementation have reached the stage at which some operational guidelines can now be developed. These guidelines, however, should be flexible to allow for local variations. Suggested thresholds are more appropriate. The interaction of "technical" criteria with "public perception" criteria dictates this flexibility. Several issues are identified as needing further analysis. For example, HOV modeling-based analytical tools do not exist, and carpooler behavior is not fully known. Other issues need stronger consideration for implementation, such as the interface between HOV facilities (interchange and end treatments) and greater attention to local feeder interface and local street HOV facilities.

This report analyzes data collected from selected existing, exclusive (within freeway right-of-way), and concurrent-flow lane facilities of an extended length, and develops a consensus on several operational issues. Figure 1 provides a physical description of the operating facilities discussed.

Facility development and implementation have reached the stage at which we can now develop some guidelines. These guidelines, however, should be flexible to allow for local variations. Today's system operators are uncomfortable with the idea of "warrants" being established. Suggested thresholds are more appropriate. The interaction of "technical" criteria with "public perception" criteria dictates this flexibility; public attitudes toward underutilization often have a strong influence in the decision-making process.

LESSONS LEARNED

Surveys of current operations suggest a growing consensus among planners and engineers about high-occupancy vehicle (HOV) project implementation. Current thinking based on this experience is that HOV mainline priority lanes are effective in increasing person throughput when:

- The non-HOV lanes are operating in a congested mode at least during the peak hour (see Figure 2);
- The HOV facility expedites the flow of HOVs without adversely affecting the flow of mixed-flow traffic;
- The facility appears adequately utilized—the HOV lane carries at least 800 to 1,000 vehicles in the peak hour (see Figure 3);
- The time savings to HOVs exceeds 1 min per mile with a total time savings of at least 5 to 10 min per trip (see Figure 4);
- Development policy and operations management are closely coordinated from a regional and multiagency perspective;
- The HOV lane is separated from mixed-flow lanes by either an actual barrier or a buffer area;
- Enforcement is integrated into the design of the project; and
- The HOV lane is implemented in conjunction with (and enhanced by) other strategies to increase vehicle toccupancy, such as park-and-ride lots, transit/carpool transfer centers, new bus services ("Freeway Flyer"), ramp treatments, carpool matching services, vanpool programs, and so forth.

DESIGN AND ENFORCEMENT

Design and Enforcement Considerations

For this discussion, the typical sections for exclusive (within freeway right-of-way) and concurrent-flow facilities are depicted in Figures 5, 6, and 7.

In the past, within the same urban area, different HOV facilities have been designed and operated differently. More recently, however, there appears to be a growing consensus favoring a particular system design and operation of exclusive and concurrent-flow lanes. This paper does not address in detail the many aspects of HOV facility design or attempt to establish specific geometric guidelines. At this stage in HOV facility development, however, general conclusions can be drawn from existing operational data for facility type.

Enforcement is critical to effective operations. The violation rate (percent of the total number of vehicles using the HOV lane that fail to meet eligibility criteria) appears to be

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Federal Highway Administration, P.O. Box 1915, Sacramento, Calif. 95812-1915.

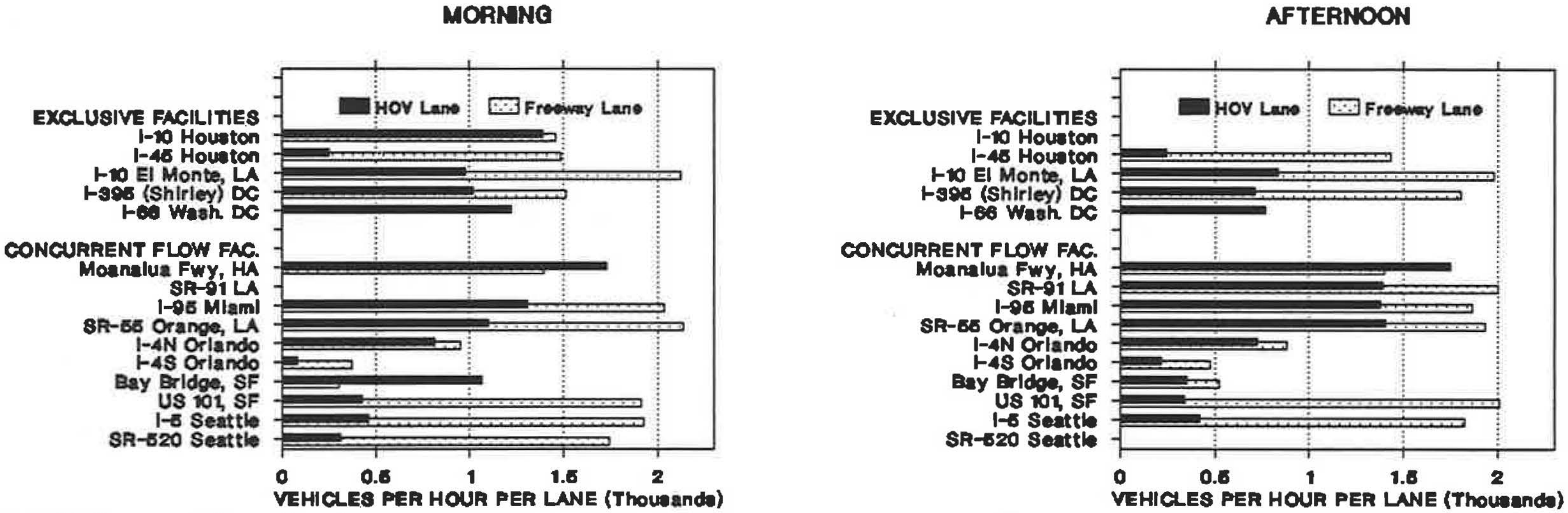
FACILITIES	No. of HOV Lanes	Frwy lanes	Length (mi)	Eligible Veh.	Hrs. of Service	Pk Period Length AM/PM	Separation from Non-HOV	Signing & Marking **	Comments
EXCLUSIVE									
I-10 Houston	1(reverse)	3	6.2	2+	AM/PM	3/3	Barrier	a,b,c,d,e	
I-45 Houston	1(reverse)	3	9.6*	Bus,Van	AM/PM	3/3	Barrier	a,b,c,d,e	Elig by Permit
I-10 El Monte	1/direction	4	11.0	3+	24	4/4	Barr(4 mi); 13' shldr(7mi)	a,d	
I-395 (Shirley)	2(reverse)	4	11.0	4+	AM/PM	2.5/3	Barrier	a,b,d,e	
I-66 Wash. DC	2/direction	NA	9.6	3+	AM/PM	2/2	NA	a,b,d,e	High Violation
CONCURRENT FLOW									
Moanalua Fwy,HA	1/direction	3	2.3	3+	AM/PM	---	Paint Stripe	a,d	High Violation
SR-91 LA	1 (EB only)	4	8.0	2+	PM	NA/4	1'-2' Paint Stripe	a,b,c	
I-95 Miami	1/direction	3	7.5	2+	AM/PM	2/2	Paint Stripe	a,d	High Violation
SR-55 Orange,LA	1/direction	3	11.0	2+	24	3/3	1' Paint Stripe	a,e	
I-4 Orlando	1/direction	2	6.2N,14.5S	2+	AM/PM	2/2	Paint Stripe	a,d	Not Enforced
Bay Bridge, SF	3 (WB only)	16	0.9	3+	AM/PM	3/3	Pylons/Striping	a,b,d	Br Toll Bypass
SR 101, SF	1/direction	3	3.7	3+	AM/PM	3/3	Paint Stripe	a,d	Looks not used
I-5 Seattle	1/direction	4	4.0N, 5.6S	3+	24	---	Skip Stripe/Ln Markrs	a,d	Looks not used
SR-520 Seattle	1 (WB only)	2	3.0	3+	VARY	NA/2	8" White Stripe	a,b	Outer Frwy Ln
I-15 San Diego	2(reverse)	2	9.8	2+	AM/PM	3/3	Barrier	a,c,d	Opens 10/19/88
I-10 Phoenix	1/direction	3	3.0	3+	24	---	4' Paint Stripe	a,d	Partial open

* In AM, 3.2 mi concurrent flow + 9.6 = 12.8 mi.

** a = static, b = variable message, c = lane assign arrow, d = pvt markings, e = bus or HOV only, f = portable signs

ITE, 1986 Survey of Operating Transitways

FIGURE 1 Description of operating HOV facilities.



ITE, 1985 Survey of Operating Transitways

FIGURE 2 Freeway and HOV lane volumes—peak-hour comparisons.

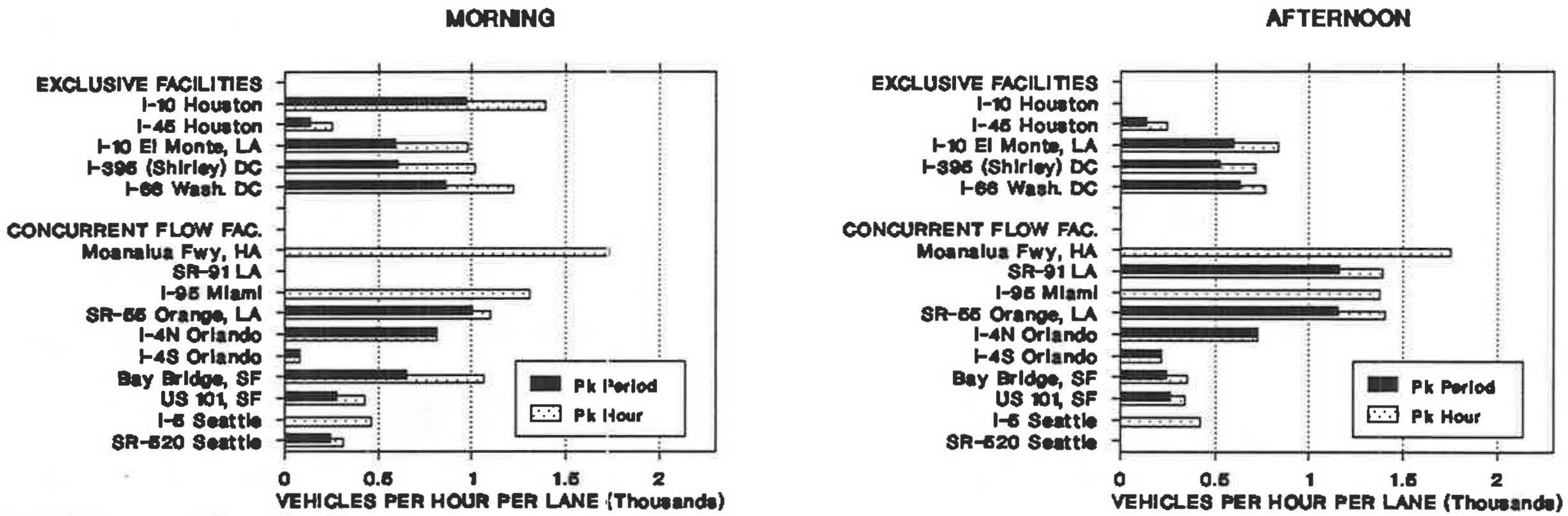


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FIGURE 3 Volume per HOV lane, peak hour and peak period.

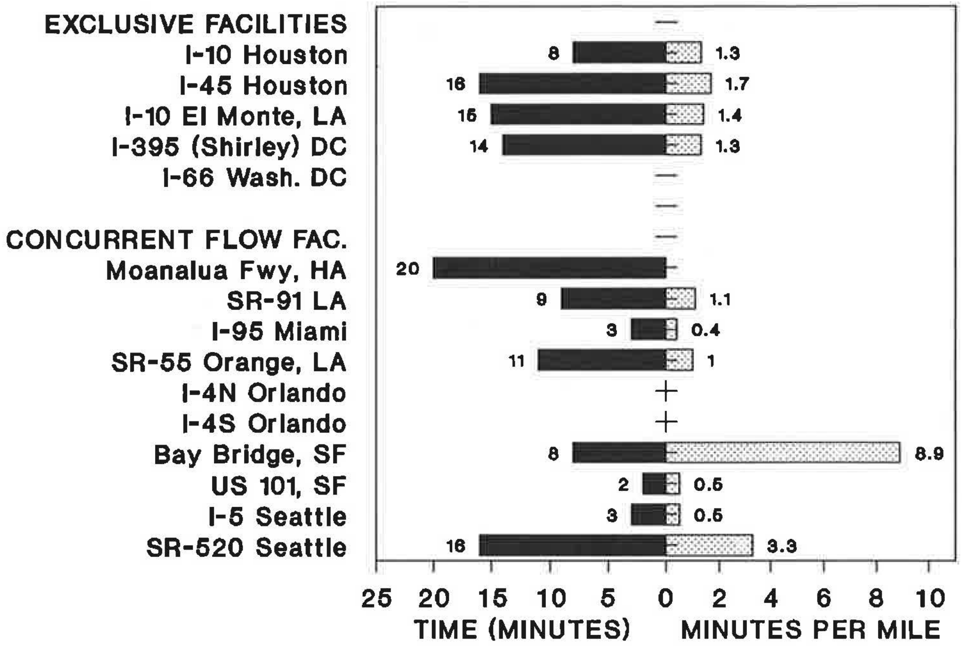


FIGURE 4 Average peak hour travel time savings for HOV lanes.

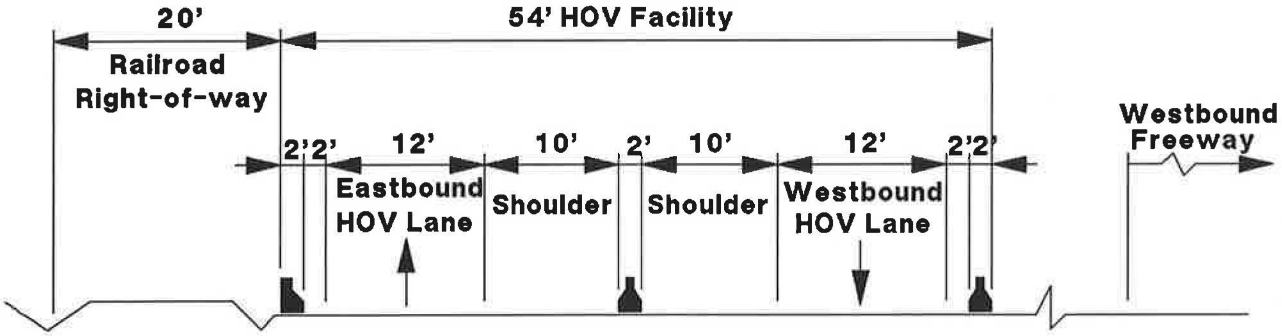


FIGURE 5 Barrier-separated freeway HOV facility cross section (I-10, Los Angeles).

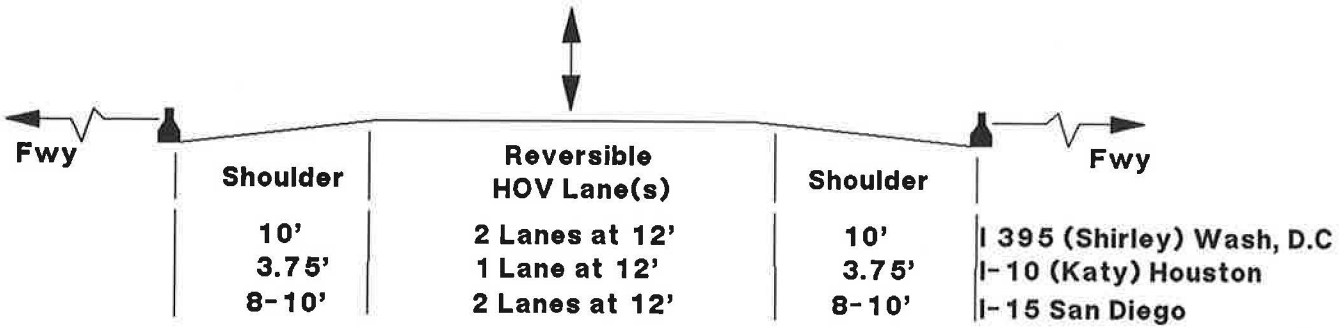
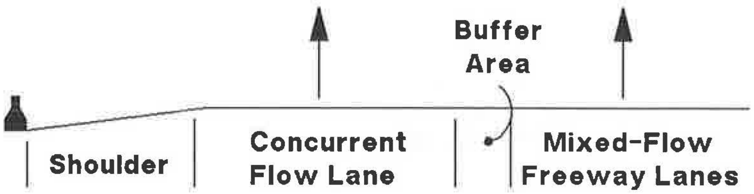


FIGURE 6 Typical cross sections for reversible HOV facilities in freeway medians.



Shoulder	Concurrent Flow Lane	Buffer Area	Mixed-Flow Freeway Lanes	
7'	12'	0'	2 at 12'	Moanalua, Hawaii
3'	11'	2'	4 at 11.75	Rte. 91, L.A.
2'	12'	0'	3 at 12'	I-95, Miami
3'	11'	* 1'	3 at 11'	Rte. 55, Orange Co.
3' to 6'	11' to 12'	0'	3 at 11' to 12'	US 101, San Francisco
3'	12'	0'	4 at 12'	I-5, Seattle
10'	12'	0'	2 at 12'	I-4, Orlando
2' to 10'	12'	4'	4 at 12'	I-405, Orange Co.
12'	12'	4'	3 at 12'	I-10, Phoenix

* Proposed for change to 4'.

FIGURE 7 Typical cross sections of concurrent-flow lane projects.

more a result of public acceptance and level of enforcement effort than of how large a fine is levied or of particular designs. For these reasons, the violation rates are varied, whether on physically separated or concurrent facilities (see Figure 8). Experience generally suggests that enforcement is easier and violation rates are lower on physically separated facilities.

Design and Enforcement Conclusions

The following conclusions and recommendations are offered.

- Physically separated lane and access designs will, in general, provide optimum operation. Where feasible, these are preferable.
- Where physically separated facilities are not feasible but long sections are required with intermediate access provided, traversable buffer-separated designs with adequate acceleration or deceleration lanes at appropriate access points are preferred.
- Direct intermediate access to HOV facilities is preferable, because encouraging large numbers of vehicles to cross all mixed-flow lanes to reach a slip ramp is marginal design practice and can reduce mixed-flow capacity.
- From an enforcement standpoint, any buffer of suitable size for a refuge area is unacceptable because of the potential hazard of high-speed traffic on both sides of the officer and the public. Therefore, a buffer measuring more than 4 ft is undesirable.
- Experience does not point conclusively to a specific width for buffers between HOV and mixed-flow lanes. Until further analysis is made, 4 ft is a preferred buffer width. If additional space is available, it should be used on the left side of the HOV lane.
- Where a continuous full-width left shoulder is not available, specially designated enforcement areas are desirable. Safety should be the predominant consideration in the design of enforcement areas.
- To overcome some of these enforcement design difficulties, "innovative" enforcement techniques should be used.

OPERATIONAL CONSIDERATIONS

System Planning—"The Bigger Picture"

Experience to date suggests that HOV lanes are successful in bypassing adjacent facility congestion. These lanes have been implemented predominantly for such "special case" facilities, satisfying the needs and constraints of the particular facility and incorporating the lessons of prior successes and failures. However, the continuity of HOV lanes along a given corridor and connecting with other corridors are significant factors contributing to the effectiveness of an HOV lane system.

Regional issues must be addressed in many large urban complexes in developing an HOV program. These issues are determinations of how HOV facilities fit into regional transportation plans and what type of facility should be used (i.e., exclusive or concurrent flow). Will rail transit be an ultimate corridor need? Following these questions are assessments of designs for HOV lane connectors between freeways; the connectivity (or ingress/egress) with arterial streets; provision for on-facility transfer stations; the need for dedicated HOV ramps, implemented either through or between interchanges; and operational control flexibility, now recognized as needed with facility demand approaching capacity in some cases (see Figure 9).

Implementation must be more carefully planned and local and regional agencies must be involved, giving special attention to public and political relations. More often, projects have interagency sponsorship, and their strategic development is shared. A "systems" orientation thus evolves. To have a measurable impact on regional congestion, a coordinated and comprehensive HOV system plan is necessary. As the concept of HOV facilities has been demonstrated successfully in urban corridors around the country, inclusion of a system of HOV routes in the regional transportation plans (RTPs) formulated by metropolitan planning organizations (MPOs) is a natural progression. Alternative mixes of different system management and development recommendations, including the proposed HOV facilities, must be evaluated extensively in developing the final RTP mobility plan. Until the RTP

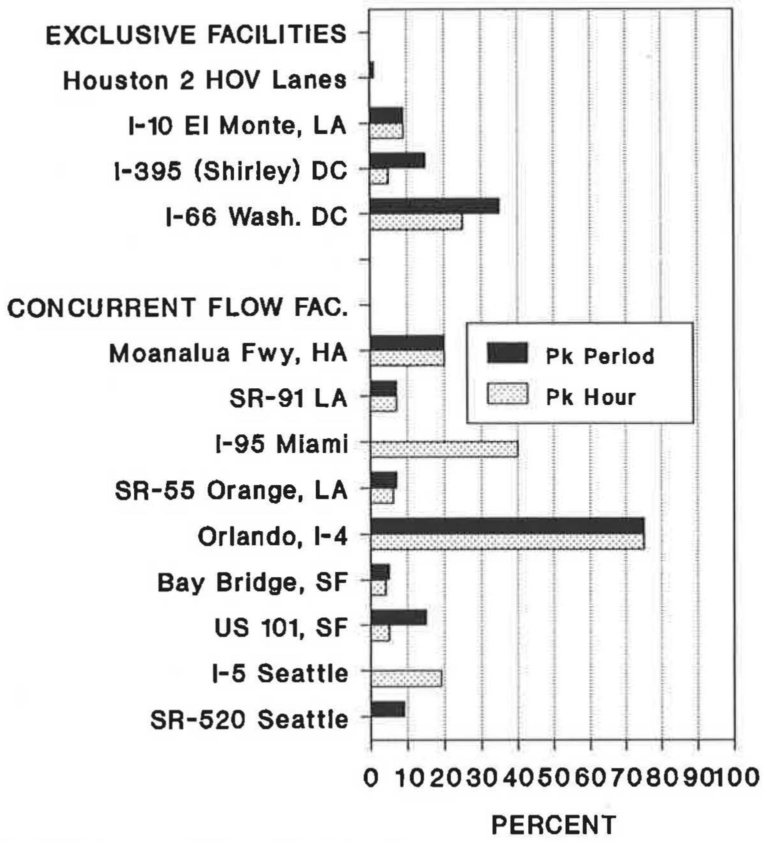


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FIGURE 8 HOV facilities violation rates.

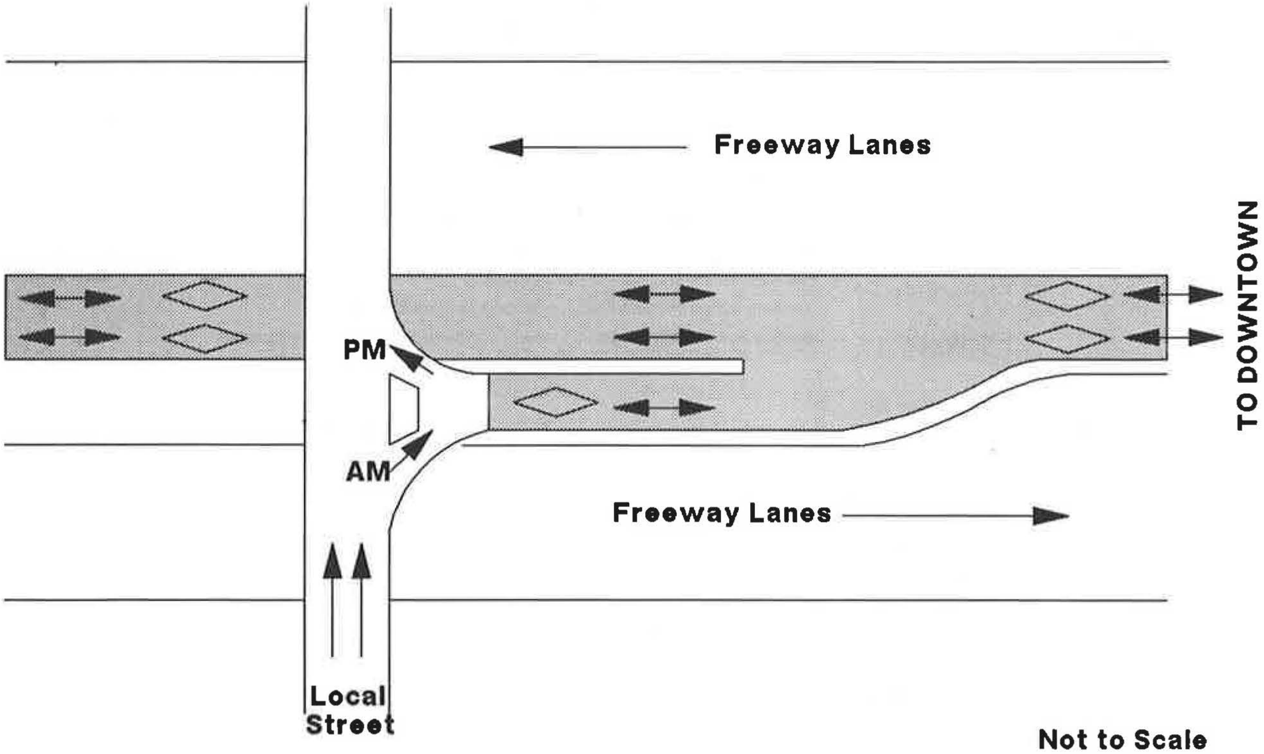


FIGURE 9 Elevated access ramp at intermediate location.

process is completed, the facility and policy recommendations of an HOV facilities plan can serve as direction for short-term project decisions.

Unfortunately, the standard transportation modeling-based analytical tools are not now fully developed for evaluating the effectiveness of HOV facilities. Only the general contours of HOV impacts are currently known with certainty, and this knowledge is insufficient to drive a model-based assessment. HOV experience has not yet been subjected to precise enough observation. Accordingly, off-model methodologies are being developed by individual MPOs to perform the desired impact assessment. Further research is needed in this area. In California, the Southern California Association of Governments and the Orange County Transportation Commission are developing a model for forecasting travel demand, with emphasis on how many of the potential trips would be carpools, how many transit, and how many recreation or other special attractor trips.

The orientation of HOV facilities in some urban areas is shifting from serving primarily the traditional downtown market to serving new and emerging activity centers in the suburbs. Suburb to suburb carpool trips, not bus transit, stand to benefit most from this growth pattern. Attention to date has predominantly been toward freeway facilities in both HOV planning and implementation. To obtain ultimate regional success, though, the integration must include other arteries, particularly reaching out to activity centers. Many of these centers have sprung up in low-density environments with minimal transportation facilities. Congestion recurs daily on these facilities from the freeway access point to the workplace. The opportunities are just as ripe to improve person-movement on these arterial/expressway feeders as on the adjacent congested freeways.

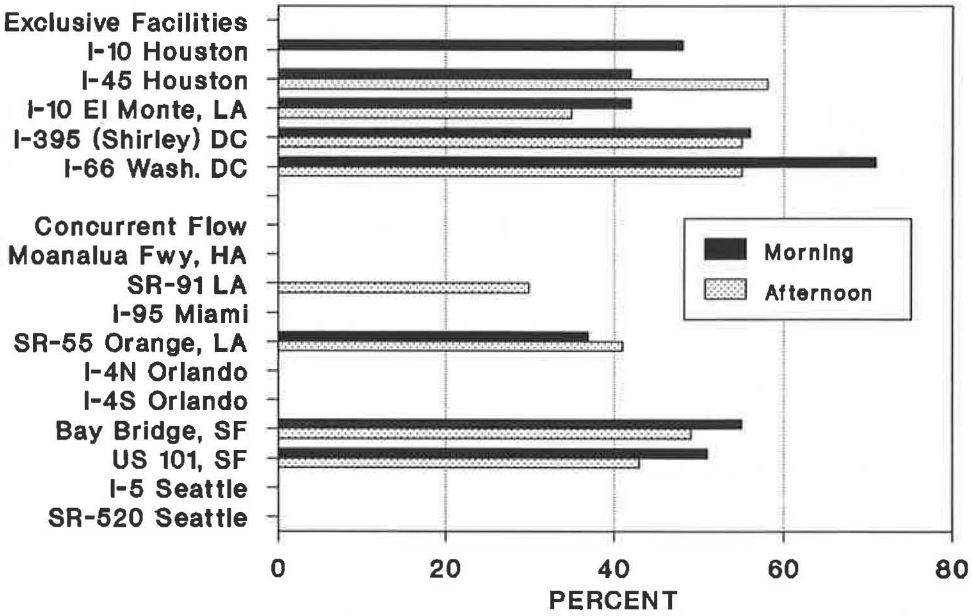
HOV Volume/Capacity

There appears to be a consensus that the capacity of an HOV lane on a freeway facility is in excess of 1,000 vehicles per hour (vph). This assumes that adequate capacity exists at the HOV ingress/egress locations. Once volumes begin to exceed 1,200 to 1,500 vph, operating speeds begin to drop below 55 mph. An added dimension results from public perception of HOV facility use. Exceeding the threshold of 1,000 vph appears to mitigate this concern. Part of this concern is a result of the high peaking characteristics associated with HOV facilities. Peak-hour volumes are typically 40 to 60 percent of peak-period volumes (see Figure 10).

Figure 11 illustrates the speed-volume relationship for exclusive HOV lanes. It shows "capacity" conditions represented at an hourly volume of 1,500 vph. These data, calculated using Katy Transitway (Houston) 5-min flow rate data, may be representative of exclusive facilities elsewhere in the United States. Flow for these facilities will always be constrained by the slowest-moving vehicles (usually buses) in the traffic stream.

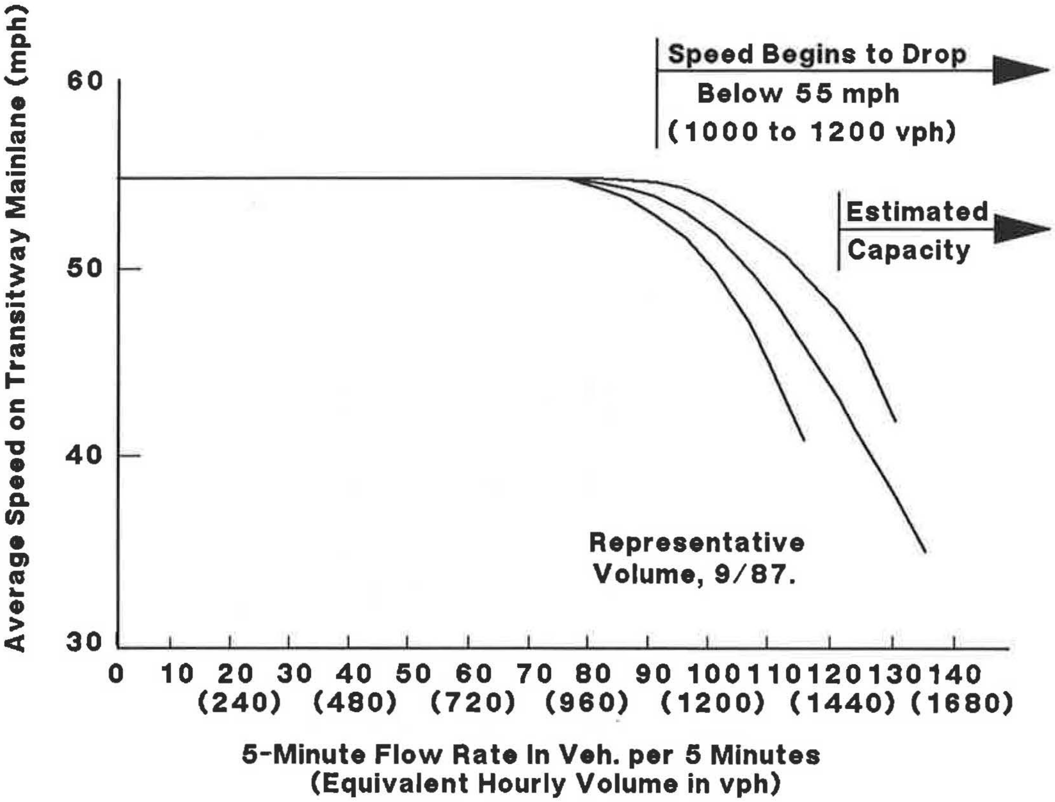
The conditions might be quite different for HOV facilities with only a paint stripe buffer between them and the adjacent mixed-flow lanes. On buffer-separated HOV facilities, with the adjacent mixed flow quite often reaching levels greater than 2,000 vph, flow will go higher than the 1,500 vph shown for exclusive facilities because of direct association with the adjacent flow. This occurs probably because there is no positive movement restriction. Slow-moving vehicles become less of a restriction as passing can occur at points along the facility. Capacity for concurrent-flow facilities may best be represented at 1,700–1,800 vehicles/hour/lane (vphpl), as has been demonstrated in California. There are instances of stoppages at flow rates of 1,500 to 1,700 vphpl, probably caused by merging or diverging movements downstream of the stoppage or associated with slow-moving vehicles.

Travel time surveys indicate that very few HOV facilities have had a significant long-term effect on adjacent mixed-flow lane traffic volumes. Freeway conditions are certainly no worse than before the projects were implemented. Carpools in the HOV lane continue to grow. The displacement of large buses from mixed-flow lanes will certainly have a



ITE, 1986 Survey of Operating Transitways

FIGURE 10 HOV lane volumes—ratio of peak hour to peak period.



TTI, Options for Managing Traffic Volumes and Speeds on the Katy Transitway, 9/87.

FIGURE 11 Speed-volume relationship for exclusive HOV facility.

positive effect on the capacity of the general highway facility. Several hundred vehicles are initially removed from the mixed-flow traffic stream, yet the large reduction in mixed-flow travel times that sometimes occurs during the first 9 to 12 months will nearly dissipate.

Experience has shown that the freeway will soon approach congestion again from the latent demand in the already congested corridor. This demand comes from commuters who switch from surface streets to take advantage of improved freeway operation and from trips not previously made that now materialize. Others who traveled during the fringe of the morning and evening peak, thus spreading the peak periods, readjust their travel schedules to take advantage of improved operation during the mid-peak period. The result is that the spaces made available become filled and very little time is saved for mixed-flow freeway users.

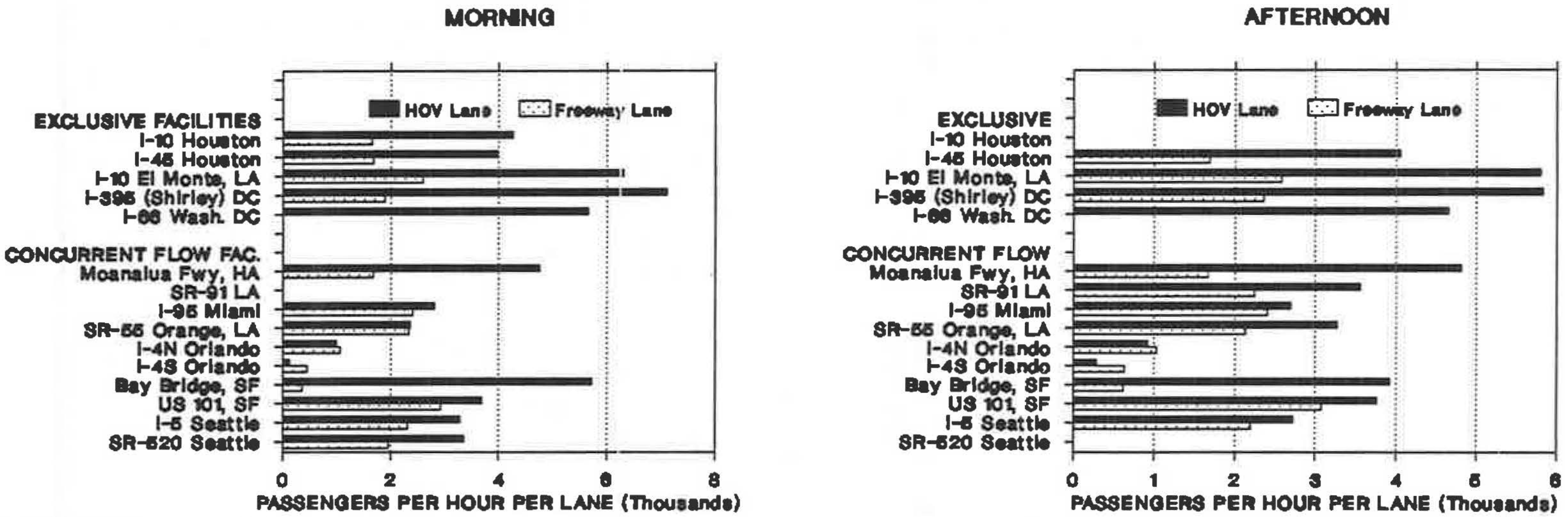
HOV Facility Eligibility

Most HOV lanes are carrying at least 50 percent more peak-hour person trips than an adjacent freeway lane (see Figure 12). Yet the perception of drivers of the adjacent mixed-flow lanes continually puts the HOV facility operators on trial. Implementation is jeopardized most often over this aspect of operation.

Initial minimum carpool requirements must be selected carefully to optimize the efficiency of the facility. The selection must allow for growth as more commuters switch to carpooling and take advantage of the time and fuel savings. Retaining the potential to carry more people over time offers important operational flexibility. At the same time, however, public perception must also be addressed. Traffic volumes of at least 800 to 1,000 vphpl appear to mitigate this concern. Flexibility is desirable to accommodate local conditions and level-of-service requirements. The positive aspect of a 2+ eligibility (two or more occupants) is that a staged resource of commitment to ridesharing is being groomed. Less work is involved in forming a carpool. There may eventually be less resistance to adding a third passenger than to forming a 3+ carpool in the beginning.

If we are optimistic and a carpool lane initially restricted to vehicles with three or more people is underused, it is not difficult to redefine the restriction to vehicles with two or more. The converse, however, is not true. If a carpool lane restricted to cars with two or more people is overused, redefining the lane to cars with three or more people can be fraught with potential problems. To date, only in Houston on the Katy Transitway has the use of a carpool lane been made more restrictive after inception. This change was recently initiated during a portion of the morning peak period. The idea of casting two-occupant vehicles back into the mixed-flow lanes conflicts directly with one of the basic objectives of HOV effectiveness or success—expediting HOV flow without adversely affecting mixed-flow traffic.

Subsequent changes in occupancy threshold need to be weighed with projected future demand. To go to 3+ by rejecting 2+ carpools may reduce demand by 75 to 80 percent. This may be severe if only a 10 to 20 percent reduction in demand is necessary for the near future. The problem is that



ITE, 1985 Survey of Operating Transitways

FIGURE 12 Comparison of freeway and HOV lane person movement during peak hour.

an HOV 3+ lane typically carries only 400 to 500 peak-hour vehicles at 55 mph while an adjacent freeway lane carries 1,500 to 2,000 peak-hour vehicles under stop-and-go conditions. The HOV lane may be carrying at least 50 percent more peak-hour person trips than an adjacent freeway lane, but to the driving public the lane appears to be seriously underused. Compounding this is the fact that peak-hour HOV lane volumes are typically 40 to 60 percent of peak-period volumes. To move to 3+ from 2+ would then antagonize the regular motorists on the freeway mainlanes as well as the carpoolers no longer eligible to use the HOV lane.

Changing the number of carpool riders to three or more will constitute a significant behavioral shift for commuters. There are no easy solutions, and agencies are struggling to find answers. Such a change will necessitate an extensive marketing and education campaign designed to allow sufficient time for restructuring of carpools from two to three or more persons per vehicle and for the change to become publicly and politically acceptable. Ridesharing agencies and employer carpool coordinators should increase promotional activities. Also, capital improvement projects, such as fringe parking facilities, improved access to HOV lanes, and extensions to the street system, could be introduced at the time of change.

For facilities already in operation, and long before this 2+ demand approaches capacity, other commute management techniques could be marketed with the existing captive demand. With the high peak-hour to peak-period volume difference, shifting the work hours of the HOVs can ease the situation. In Houston, a flyer mailing asked for voluntary spreading of the peak hour, pointing out the substantive restrictive measures that may be necessary. Impact was projected to be minimal, however. As volumes exceed capacity, it is unlikely that the problem will be solved through voluntary actions alone. Another option, where design allows, is to close or meter exclusive entrance ramps to the HOV facility. Ramp metering is a proven effective measure for balancing mainline flow at freeway ramp locations. There is unfortunately no sign that any of these measures will actually alleviate the problem.

The ultimate answer may rest with early design development of HOV lane facilities. Computer traffic surveillance and control technology are operating or being implemented in most of the urban centers of the United States. The driver is being informed of road conditions ahead by changeable message signs, highway advisory radio, and radio traffic reports. Lane-use control signals have been effective in several urban areas, either for contraflow operations or special-event traffic handling. Maximizing use of an HOV lane with these same techniques to vary the occupancy requirement by time of day, specifically during the peak period, may be a logical extension of the technology.

As pointed out earlier, HOV facilities have high peaking characteristics. HOV lanes restricted to 3+ carpools, in particular, have a pronounced temporal peakedness. Maximum use of the HOV facility would thus result from an occupancy requirement that varied by time of day: restricting access to 3+ carpools during the shorter period of peak carpool demand, then allowing access by 2+ carpools during the remaining hours of HOV operation. In effect, the Katy Transitway is now operating with variable access during the morning commute. To be completely effective, however, such a time-of-day system must incorporate existing technology in surveillance, system control, lane-use control, and communication systems. The temporal distribution strongly suggests that it is technically advisable to investigate the viability of an HOV occupancy requirement that varies by time of day. Implementation (real-time or defined hours) and enforcement are issues that need close scrutiny.

This discussion of changing to a more restrictive user eligibility applies to the present-day implementation of HOV lanes as "special case" facilities. There is no knowledge of long-term operational effects when facilities are implemented regionwide. For those HOV facilities now experiencing peak-hour volumes approaching capacity, the volume impact may not ultimately be as significant. A systems-level analysis may indicate that upon implementation of an areawide HOV system plan, specific facility volumes may stay below the 2+ HOV lane capacity and a balance will result.

Where such systems-level analysis shows that the problem will not be alleviated by regionwide implementation or by these other operational improvements, the addition of another HOV lane would be considered. This decision is made with the understanding that improved person throughput is a primary objective—a corridor-oriented objective rather than the facility-oriented objective of improved traffic flow. The addition of mixed-flow lanes to increase freeway capacity generally alleviates congestion temporarily. Experience has shown that the productivity of the freeway will level off in the short term. When demand exceeds capacity (2,000+ vphpl), vehicle throughput will decrease to as low as 1,400 to 1,500 vphpl as congestion worsens. On the other hand, vehicle throughput on HOV lanes may take years to reach capacity and does result in a 50 percent or more increase in person movement. This approach has led one FHWA division office to amend planning guidelines to concentrate on the corridor-oriented objectives. Future plans to add lane capacity to existing freeway corridors will have to include HOV facilities if demand numbers show that an HOV facility will exceed the person-moving use of a comparable, general-purpose freeway lane within a 5-yr period. To date, most projects around the country achieved this objective in a short time.

Occupancy

The localized (corridor) effect of HOV lanes has been to obtain higher facility occupancy rates overall by stimulating a continual formation of carpools and vanpools. Precise information on the rates at which increased carpool formation will occur and on the ultimate extent of that growth is not available. Although we do not know when carpool generation ends, we sense that with 2+ a base of future HOV riders of the highway system is being built.

Only recently has project information been gathered to establish the exact extent of new carpool formation, as opposed to previously existing carpools that have diverted from other routes. Figure 13 shows the results of before and after surveys that were conducted on HOV facilities in Houston, Texas, and Orange, California. Significant changes appear to have occurred in each of the corridors, with more than 50 percent of the HOV lane users indicating that they drove alone before the lanes were opened. Data collected recently in Minneapolis (I-394) are in general agreement with these figures. Caution is needed in interpretation because of the large natural turnover in carpools that seems to be evidenced around the coun-

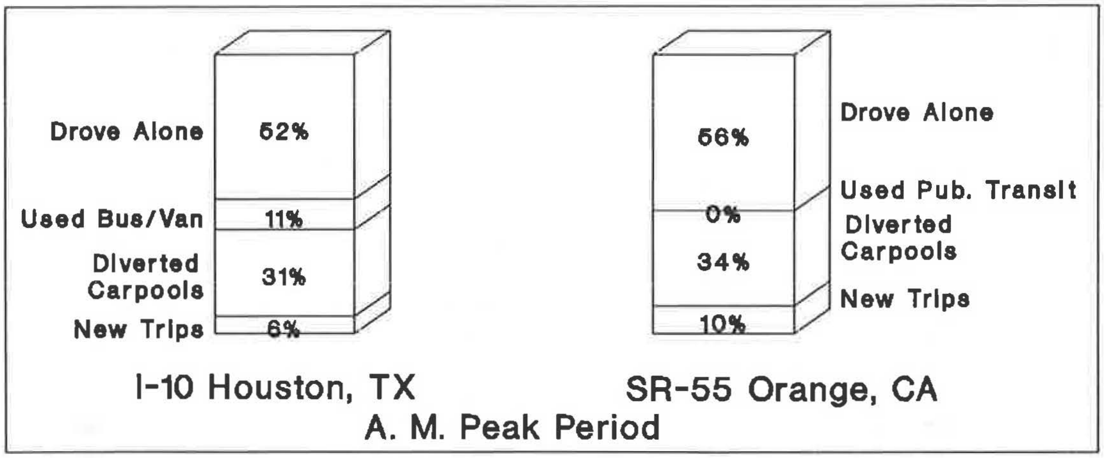


FIGURE 13 Survey of previous mode used by HOV lane users.

try. Full corridorwide occupancy count studies are needed from several projects around the country, so that carpool formation can be measured accurately.

In general, the carpool data base is lacking. Driver and passenger behavior under various carpool occupancy requirements is not fully known. There is a need to format a consistent data base structure that all agencies can use; then a further need to share data as they develop, thus building an empirical record. The newly formed TRB Task Force on HOV Systems is promoting the development of this data base.

Marketing

Public education is clearly a key to successful implementation of travel demand management techniques. As pointed out here and elsewhere, many examples now exist of HOV lanes that are carrying more person trips than are adjacent freeway lanes. Technical measures of effectiveness support the potential benefits of HOV facilities. Acceptance of what constitutes a successful HOV facility is still unresolved. The public perception of success apparently does not fully acknowledge the relationship of person trips on HOVs to person trips on regular freeways or arteries. It is focused more on whether or not the facility appears to be fully used (i.e., vehicular flow rate).

A concentrated marketing effort on HOV facilities and other commute management techniques cannot start too early. Traditional highway department approaches to marketing have focused only on "project" advertisement needs. Concept marketing is needed, and the most successful work is done by marketing professionals. For the larger departments of transportation, full-time employment of marketing professionals should be considered. At a minimum, marketing plans with long-term program objectives are needed for metropolitan planning organizations and transportation departments.

A resource of commitment to ridesharing has been established with the 2+ HOV facility. A concerted effort should be directed at this group to encourage rideshare improvements. To date, this group is given attention only after the demand for HOV facilities has developed into a problem.

Public awareness is also essential to any enforcement program. If the public is made to understand the HOV operating strategy and its restrictions, the tendency to violate may be reduced.

Hours of Operation

There is some difference of opinion about whether an HOV facility should be operated only during peak periods or for 24 hr. From the facilities analyzed in this report emerges the following breakdown of current practice:

Period of Operation	*Facility*
24-hr HOV	I-10 El Monte, SR-55 Orange, I-5 Seattle
Peak period only (closed off peak)	I-10 Houston, I-45 Houston
Peak period only (mixed-flow use off-peak)	I-395 D.C., I-66 D.C., Moanalua, I-95 Miami, I-4 Orlando, Bay Bridge US-101 San Francisco
Peak period only (shoulder off-peak)	SR-91 Los Angeles (future proposal—24-hr operation)
All-day HOV (shoulder nighttime)	SR-520 Seattle

On HOV facilities operating during peak periods only, off-peak use is predominantly by mixed-flow traffic. A large amount of data have been gathered indicating that, for a given average daily traffic, the greater the number of lanes (thus lower densities), the lower the accident rate. This is true even where there generally is no recurring congestion. Therefore, opening HOV lanes to mixed-flow traffic during off-peak periods (including weekends) can reduce accident rates.

Exclusive facility designs do not always provide maximum efficiency of off-peak use by mixed-flow traffic. Yet the two suburban Washington, D.C., facilities allow mixed-flow traffic with no problem. There is no apparent pattern of increased violations on facilities that allow mixed-flow use during off-peak periods, whether they are exclusive lanes or concurrent-flow facilities. Although exclusive and buffer-separated facilities are more suited to 24-hr HOV use from a design standpoint, mixed-flow use during off-peak times cannot be precluded.

On both of the aforementioned facilities that currently adapt to shoulder use during non-HOV operation, the operating agencies are considering changes to 24-hr HOV operation. Neither of the facilities had accident rates or specific problem areas that gave the agencies great concern. Signing was a perplexing issue on the SR-91 facility. Originally all signing relative to hours and occupancy requirements was fixed. Later most signing relative to shoulder or HOV use of the shoulder was made "real time" and operated manually. To add to the difficulties, the striping pattern on this facility is not typical for left shoulders. In general, traffic control applications have been complicated and unusual in these instances of off-peak shoulder use.

For facilities that are open for continuous use 24 hr a day, traffic control (signing and marking) is simplified. Benefits to HOVs will be assured during nonrecurring events (e.g., special events, freeway incidents, and heavy holiday and weekend traffic). The prevailing philosophy for 24-hr operation is that HOVs should be given preferential treatment during congested periods at any time; if speeds can be maintained at 55 mph without mixed-flow use of the HOV lane, then there is no reason to open it to mixed-flow use. The fact remains, however, that at locations where HOV facilities operate 24 hr a day, there is quite often no significant speed differential and no significant congestion in any of the lanes during the off-peak period.

More efficient use of the HOV lane during off-peak hours may be achieved with lane-use control technology, as pointed out earlier in the section headed HOV Facility Eligibility. The lane would be available to mixed-flow traffic when congestion did not exist. Experiments of this sort should not be ruled out.

Operational Conclusions

From the previous discussions of the systems planning and operational issues of the effectiveness of HOV facilities, certain conclusions and recommendations can be made.

- HOV lanes must be part of an overall regional transportation plan.
- The interface between freeway HOV facilities (interchange and end treatments), and between HOV facilities and arterial feeders, needs more consideration.
- HOV modeling-based analytical tools do not exist.
- Arterial and city-street HOV facilities are not getting enough attention.
- The threshold levels of congestion on HOV lanes are dependent on facility type. Typically, 1,500 vphpl represents capacity condition for exclusive facilities and 1,700 to 1,800 vphpl for concurrent-flow facilities.
- Implementation must balance the flexibility of HOV growth and public perception of facility use.
- A 2+ eligibility for HOV lanes grooms a broad resource of commitment to ridesharing; a base of future HOV riders is being built.
- Changing user eligibility necessitates an extensive marketing and education campaign.
- Use of HOV facilities can be maximized by varying occupancy eligibility by time of day. Existing lane-use control technology can support this practice.
- Plans to add lane capacity to existing freeway corridors should include HOV facilities if demand numbers show that use of an HOV facility will exceed the person-moving use of a comparable, general purpose freeway lane within a 5-yr period.
- New carpool formation appears significant compared with the situation before the HOV facility.
- Carpooler behavior is not fully known. A consistent data base structure that all agencies can use is needed.
- Concept marketing is needed; full-time employment of marketing professionals should be considered.
- Opening HOV lanes to mixed-flow traffic during off-peak periods (including weekends) can reduce accident rates.
- There is no apparent pattern of increased violations for facilities that allow mixed-flow use during off-peak periods, whether they are exclusive lanes or concurrent-flow facilities.
- In general, traffic control applications have been complicated and unusual in instances of off-peak shoulder use. Conversely, when facilities are open for continuous use 24 hr a day, operation (signing) and enforcement are simplified.
- More efficient use of the HOV lane in off-peak hours may be achieved through lane-use control technology, allowing mixed-flow traffic when congestion does not exist.

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