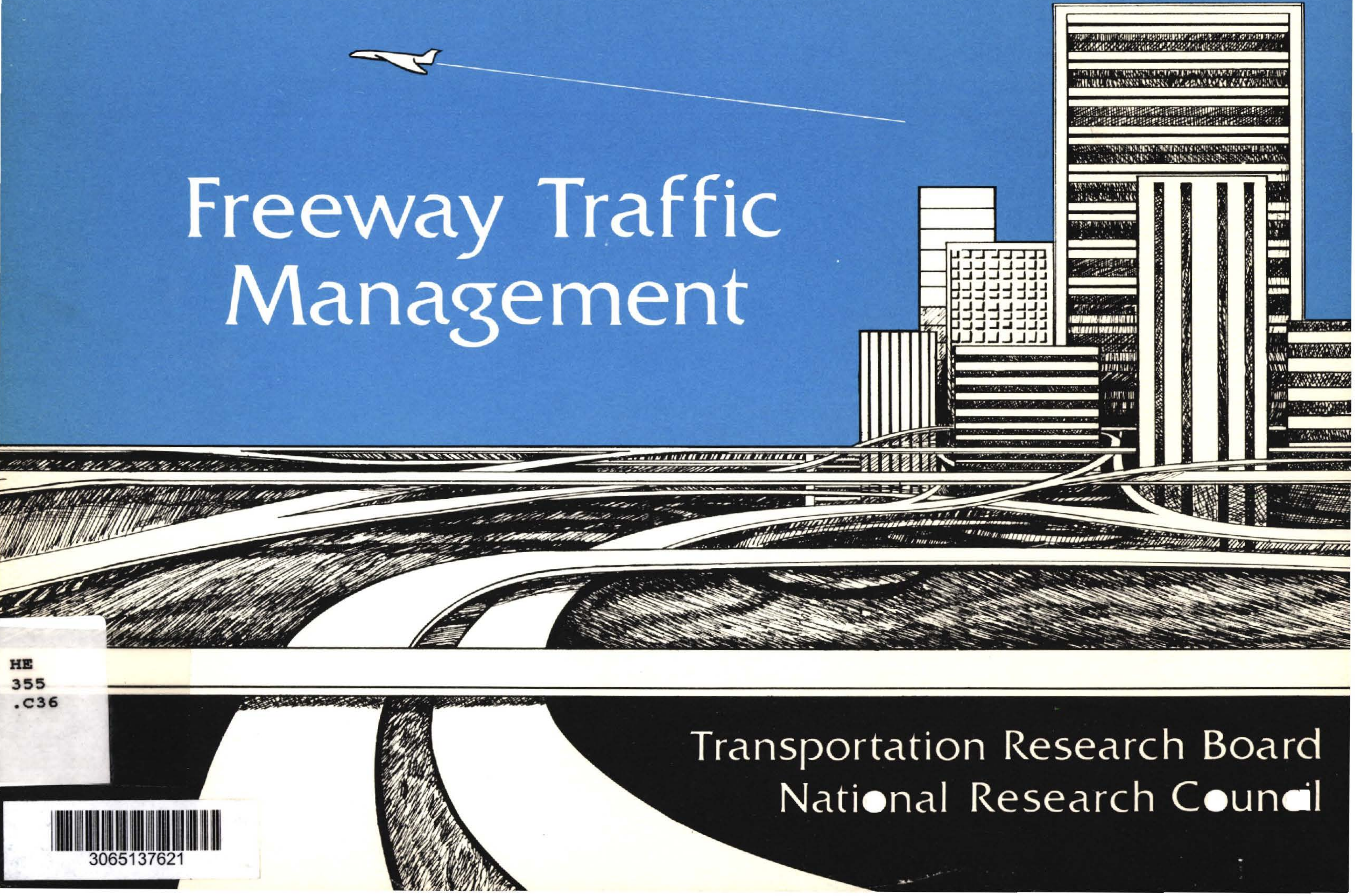
National Cooperative Highway Research Program

Freeway Traffic Management



Transportation Research Board
National Research Council

This report of the National Cooperative Highway Research Program summarizes the alternative measures that are being used effectively in various cities to deal with the compounded problem of ever-increasing traffic demand on existing freeways and deemphasis on providing new facilities. Contrary to the customarily-used format for NCHRP reports, unique treatment has been employed in this instance because of the broad audience of highway administrators, legislators, and other public officials who should find useful to their management and operation of freeway systems the overview of proven traffic control and improving operations.

Freeway Traffic Management

Donald G. Capelle
Alan M. Voorhees & Associates

Areas of Interest:
Administration
Planning
Operations and Traffic Control
(Highways)

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Preface

This publication results from growing concern about increasing congestion on urban freeways. It provides an overview of proven traffic control techniques for reducing congestion and improving operations that will be of interest to highway administrators, legislators, and other public officials concerned with the management and operation of freeway systems.

The ever-increasing traffic demand being placed on existing freeways, coupled with the current deemphasis on providing new facilities, confronts the highway administrator with the need and the challenge to develop and employ innovative traffic control techniques. This summary of alternative measures that are being effectively used in various cities should prove useful in helping meet this challenge.

This synthesis of past and present practices describes operational and safety problems typical to an urban freeway corridor, a range of options for dealing with these problems, and guidelines for implementing and operating freeway control systems. The report is based on previous research, actual experience from operating freeway control systems in various parts of the United States, and numerous interviews with individuals having responsibility for those systems.

General guidance is provided for the planning and implementation of freeway control projects at the executive and administrative levels. Thus, this is not a technical evaluation of the various types of freeway control systems in operation but instead is a narrative of how freeway control techniques can be effectively used to improve traffic flow, reduce delays and accidents, increase capacity, and create a better traffic environment.

The research reported herein was the fifth and final phase of NCHRP Project 20-3. Previous research under this project evaluated various traffic surveillance, communication, and control techniques using the John C. Lodge Freeway in Detroit as a test facility. The earlier work also provided a summary of all research conducted on the Lodge Freeway by the NCHRP and others. This summary is available from University Microfilms International, 300 North Zeeb Road, Ann Arbor, Michigan 48106.

Special acknowledgment and appreciation are extended to all the members of the NCHRP Project Panel for their guidance in the development of this publication and for their extensive review of the various draft manuscripts. Appreciation is also extended to my colleagues, too many to name, for providing an opportunity for numerous discussions and for providing information and photographs for use in this publication.

Donald G. Capelle
September 1979

Chapter One

Introduction

A vast network of highways has been constructed during the past few decades in an effort to meet the nation's need for increased mobility. While one result is that Americans today are history's most mobile society, the total effort has not been completely successful. Traffic congestion, still a chronic problem in most densely populated areas, has been compounded by environmental pollution and limited fuel supplies. Although it is generally agreed that the automobile will continue to be the most common form of transportation, the "more highways" approach is not the ultimate solution to improving urban transportation. How, then, can this be accomplished?

Increased use of both traditional and modern forms of transit will help, as will techniques such as carpooling, staggered work hours or four-day weeks. Another promising way to reduce congestion is through more intensive management and control of traffic—especially in urban freeway corridors.

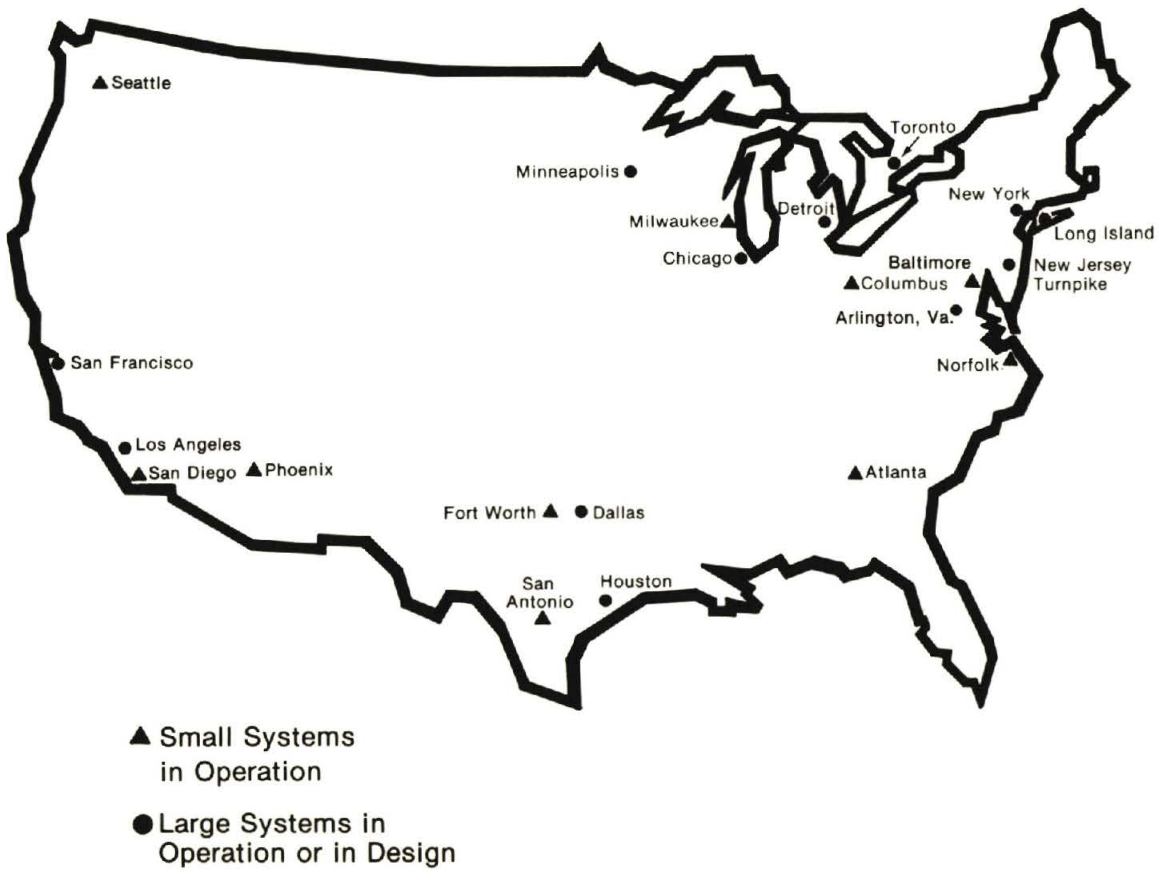
The growing need for better management of freeways to provide increased levels of capacity, service, and safety is becoming more and more apparent. Experience has shown that freeway traffic management systems can significantly improve the movement of people by:

- Detecting and responding to accidents, disabled vehicles and other incidents that affect the flow of traffic.
- Restraining traffic flow at certain points to prevent congestion at more crucial points, which helps traffic move through critical bottlenecks.
- Giving priority treatment to higher-occupancy vehicles (such as buses and carpools), which increases the person-moving capacity of the freeway.
- Diverting traffic from congested sections of a freeway to under-used roadways serving the same corridor.
- Providing real-time information to the motorists, aiding them in efficient utilization of the freeway system.

◀ *Houston, Texas.* (Texas State Department of Highways and Public Transportation.)

Programs to improve the capacity and efficiency of urban freeways are not new. As early as 1955, the City of Detroit implemented a project on the John Lodge Expressway that used closed-circuit television for freeway surveillance. Chicago, Detroit, Houston, Los Angeles, and Dallas pioneered the application of freeway surveillance and control in the early 1960s. New York applied the technology to increase the flow of traffic through the Hudson River tunnels. Based on the success and experience of these early experiments, freeway surveillance and control systems are now being developed and placed in operation in a number of urban areas throughout the world. Figure 1 shows those areas in the U.S. where some form of freeway management and control is currently being used.

Figure 1. Location of Freeway Traffic Management Systems



Initially, projects focused primarily on the hardware aspects of surveillance and control, but experience soon showed that other elements were equally important: development of good relations with the public, the press, and concerned political jurisdictions; participation of police, fire, and maintenance organizations; development of operating procedures and control logic; and staff considerations. It was also found that freeway traffic management need not involve major commitments of staff and money. Installations of automated traffic control systems can often provide significant benefits for a relatively small investment. This is particularly true where limited installations are required for controls, such as ramp metering devices.

Freeway surveillance and control can be a highly reliable and valuable management tool. Research conducted during the past 20 years has demonstrated that improved operations will provide tangible benefits to freeway users. However, relatively few freeway management systems are in operation today. One reason is that many highway administrators anticipate that the design, implementation, and operation of a freeway control system is too complex an undertaking. For this reason, it is important that every highway administrator become familiar with the concepts and benefits of freeway management systems so that they can promote the application of techniques for improving safety and mobility for people in urban areas.

Chapter Two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A Look at the Problems

The 1956 Federal-Aid Highway Act resulted in construction of a large network of freeways. These freeways, a vital element of the total transportation system, serve approximately 20 percent of motor vehicle travel in the United States although they comprise only about 1.1 percent of the total road system. While increased mobility and greater levels of safety have resulted, the mere building of these freeways has not been sufficient. Experience has shown that these facilities must continue to provide a high level of operational service if they are to provide the safety, comfort, and convenience expected by the motoring public. This level of service has been maintained on rural freeways; however, the demand from an ever-increasing number of commuters and other travelers in urban areas has led to conditions that prevent many urban freeways from providing the intended level of service. The resulting impact on these freeways has been congestion—the predominant problem.

Congestion is typified by slower-than-desired travel speeds, erratic stop-and-go driving, unpredictable travel times, increased operating costs, higher accident frequencies, energy waste, air pollution and many other frustrating conditions. It is attributed to overloaded facilities when traffic demand exceeds capacity; in other words, when too much traffic is attempting to use the same facility. Undesired delay, increased pollutants, and a waste of scarce resources are the resulting impacts.

The term "recurring problem" is used to describe congestion when it routinely occurs at certain locations and during specific time periods. The term "non-recurring problem" is used to describe congestion when it is due to random events such as accidents or other extraordinary events. While numerous factors contribute to the congestion problem, most of the problems can be classified in one of the following general categories:

- Recurring excessive demand
- Recurring geometric deficiencies
- Non-recurring temporary hazards (incidents)

RECURRING PROBLEMS

The most common cause of recurring congestion is excessive demand, the basic overloading of a facility that results in traffic

◀ *Golden Gate Bridge, San Francisco, California.* (San Francisco Regional Office - Alan M. Voorhees & Associates.)

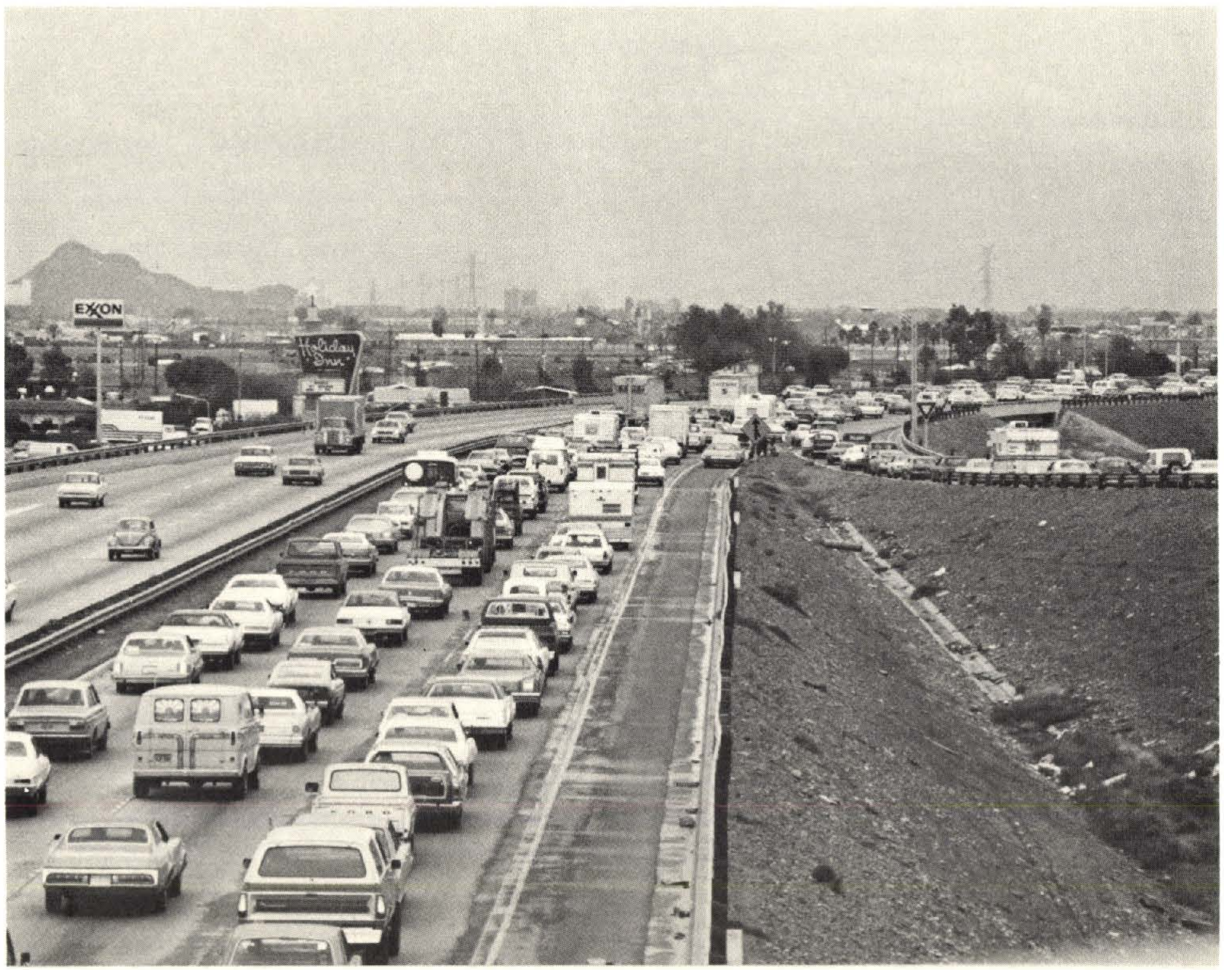
stream turbulence. Under ideal conditions, the capacity of a freeway is approximately 2,000 passenger cars per lane per hour. When the travel demand exceeds this number, an "operational bottleneck" will develop.

Excessive demand is illustrated by Figure 2, which represents cars passing a point in the road as a function of time. The solid line represents the capacity of a point on a section of freeway at a particular time; i.e., the number of vehicles passing the point under the prevailing roadway conditions. As long as the traffic demand (dashed line) is less than or equal to the capacity of that section of freeway, there is no congestion. However, once the arrival rate begins to exceed the capacity at time t_a, a bottleneck is formed and vehicles begin to accumulate upstream of the bottleneck until time t_b when the demand once again is equal to the capacity of that section of freeway. The amount of delay, represented by the shaded area between the demand and supply curves, cannot be changed unless either demand or capacity is altered.

An example is congestion associated with unrestrained ramp access. If the combined volume of a freeway on-ramp and the main freeway lanes creates a demand that exceeds the capacity of a section of freeway downstream from the ramp entrance, congestion will develop on the main lanes of the freeway, which will result in queuing upstream of the bottleneck. The time and location of this type of congestion can be predicted fairly accurately.

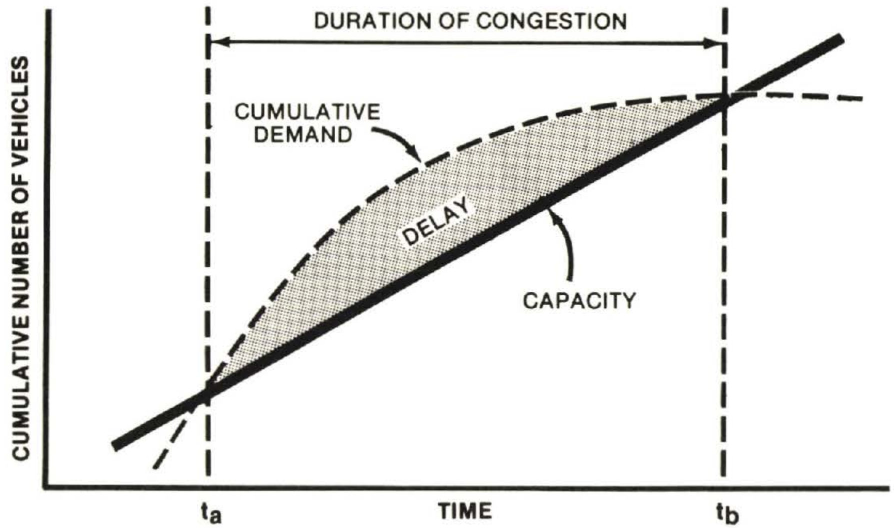
Another cause of recurring congestion is the reduced capacity created by a geometric deficiency such as a lane drop, difficult weaving section, or narrow cross-section. The capacity of these isolated sections, called "geometric bottlenecks," is lower than that of adjacent sections along the freeway. When the demand upstream of the bottleneck exceeds the capacity of the bottleneck, congestion develops and queuing occurs on the upstream freeway lanes. The bottlenecks exhibit some of the same characteristics as the "excessive demand" bottlenecks. Likewise, the resulting congestion can also be predicted fairly accurately.

Lane drops, short weaving sections, narrow cross-sections, inadequate signing, sight restrictions, and non-standard interchanges are the most common causes of geometric bottlenecks. An active program of redesign and reconstruction of existing facilities could eliminate many of these geometric deficiencies. However, since these improvements tend to be very expensive, this type of problem will continue to be a source of congestion on many urban freeway facilities.



◀ *Recurring congestion associated with unrestrained ramp access. The time and location of this type of congestion can be predicted fairly accurately.* (Arizona Department of Transportation.)

Figure 2. Relationship Between Demand, Capacity and Congestion



When traffic demand exceeds the service rate of a section of freeway a bottleneck is formed and vehicles will accumulate upstream of the bottleneck. The amount of delay is represented by the shaded area.

NON-RECURRING PROBLEMS

Delay and hazards caused by random events constitute another, and sometimes equally serious, freeway congestion problem. Referred to as temporary hazards or freeway incidents, they can vary significantly in character. Included in this category is any unusual event that causes congestion and delay. Usually the effect of non-recurring problems is the reduction of traffic flow either by blocking a lane or lanes, or by causing some other impediment to traffic flow that has the effect of reducing the capacity of a section of freeway. The most common types encountered on urban freeways include:

- Traffic accidents
- Disabled vehicles
- Spilled loads
- Adverse weather conditions
- Gawking

Because neither the location nor time of these random events is predictable, the resulting congestion cannot readily be dealt with by routinely controlling demand or increasing capacity—strategies typically used to alleviate the recurring type of congestion problem. Experience has shown that these non-recurring problems happen frequently in day-to-day freeway operation and can create considerable congestion, especially if they occur early in peak demand periods.

SEVERITY OF IMPACT

Different freeway congestion problems have different impact severities; however, the severity of a particular problem is generally dependent on time of day, place of occurrence, and duration. Severity also depends on whether the different types of problems occur simultaneously or independently of one another. For example, a temporary hazard such as a disabled vehicle on the shoulder of a freeway may have only negligible impact during off-peak conditions. But the same incident during a peak period, when freeway traffic is approaching capacity, may result in severe congestion.

Many studies have been conducted to determine the extent and magnitude of freeway problems. Although it is difficult to generalize the results because of the variety of problems encountered, it is possible to use statistics from a few of the studies to exemplify the magnitude of the overall freeway congestion problem.

During a recent traffic-responsive ramp control experiment in Los Angeles, it was found that freeway volumes increased by 3 percent, waiting times at ramps decreased by 20 percent, and average speed on the freeway increased 100 percent (from 25 to 52 mph). It was estimated that the freeway management system contributes to annual savings of more than 220,000 vehicle-hours with an annual net benefit of nearly $675,000. In Detroit, where ramp metering was installed to combat recurring congestion problems, it was estimated that 225,000 annual vehicle-hours were saved as a result of this control. A similar savings in travel time has been reported for the outbound lanes of the Eisenhower Expressway in Chicago.

Delays due to incidents may be as great or greater than those caused by recurring congestion. One study reports that at least one lane in a typical urban freeway network is likely to be blocked 7.2 percent of the time due to accidents and 6.7 percent of the time because of stalled vehicles or breakdowns. Such blockage of freeway lanes has severe impact. Recent research has shown that a one-lane blockage caused by a minor accident actually reduced the capacity of a freeway section by 50 percent even though the physical reduction was only loss of one lane (a 33 percent reduction in capacity).

In an analysis of incidents using data from the Detroit study, it was calculated that delay-causing incidents on a 10-mile freeway segment would produce 550,000 annual vehicle-hours of delay, resulting in excessive hydrocarbon pollutants and a waste of more than 360,000 gallons of gasoline. The Los Angeles program of early detection and rapid removal of unusual incidents reported similar results and noted that non-recurring congestion could be reduced by as much as 65 percent with an incident-management program. There are no national figures indicating the total costs associated with freeway congestion, but it has been estimated that these costs constitute a multimillion dollar annual burden—one that need not be tolerated.

Non-recurring incidents constitute a major source of congestion on urban freeways. A program of early detection and rapid removal is necessary to effectively deal with these problems. (California Department of Transportation.) ▶

Chapter Three

Possible Solutions

A wide range of options is available to minimize congestion and control the level of service provided motorists on urban freeways. These options deal with both recurring and non-recurring problems.

MANAGEMENT OF RECURRING PROBLEMS

Although management of recurring problems can take a variety of forms, the following are usually involved: managing vehicular demand, managing person demand, or increasing capacity through geometric improvements.

Management of Vehicular Demand

Vehicular demand is managed by various freeway operation control techniques—control of traffic at entrance ramps, control of traffic on the freeway mainline, and priority control.

Entrance Ramp Controls—Entrance ramp control is the most widely used method of managing vehicular demand. Its basic objective is to reduce the number of vehicles entering the freeway so that freeway traffic can move in the most efficient range of speeds and densities—i.e., the optimum speed to achieve the maximum flow. This type of control provides for a higher and more predictable level of service on the freeway and, at the same time, improves the overall safety of operation, reduces air pollution, and conserves energy.

Ramp closure and ramp metering are the most frequently used forms of entrance ramp controls. Ramp closure consists of physically closing the ramp to traffic on either a permanent or a short-term basis. Because this is a very restrictive type of control, it is normally used only at selected locations. Such locations include facilities with inadequate storage at the entrance ramp (to prevent disruption to surface street traffic due to vehicles waiting to enter the freeway), facilities where the freeway is running at capacity on the section before the entrance ramp, and facilities where the ramp (even when controlled) does not allow traffic to merge into the freeway traffic stream without considerable hazard or disruption.

Signs, manually placed barriers, and automated barriers are commonly used to

◀*Highway monitoring.* (The Port Authority of New York and New Jersey.)

effect ramp closure. Automated barriers are the most effective because the gates can be opened and closed automatically, giving more flexibility in responding to fluctuating changes in traffic conditions. Signing tends to be ineffective since a high number of violations normally occur. Although effective, manually placed barriers are highly labor intensive and normally used only under experimental conditions.

Ramp metering, the most common technique for controlling vehicular demand, limits the rate at which traffic can enter the freeway, thus allowing the freeway to operate at a higher level of service. A standard traffic signal that operates in the same manner as a signal at any intersection is used on the ramp.

The ramp metering rate generally depends on whether the metering is being used to minimize congestion on the freeway or to improve safety at the merging area. If the intent of the system is to minimize congestion, the metering rate is set to equal the difference between upstream freeway demand and downstream freeway capacity. If the metering is used only to improve safety, the metering rate is set to ensure that each vehicle has time to merge before the following vehicle approaches the merge area. The intent of single-vehicle entry is to reduce the incidence of collision (mainly rear-end) created by vehicles on the ramp competing for gaps in the freeway stream. In either case, the metering rates are selected on the basis of historical traffic data on both the freeway and the ramp. Three basic types of metering are used in ramp control systems—pretimed metering, traffic-responsive metering, and merge control. Pretimed metering consists of fixing the metering rate in accordance with some selected time period (i.e., time of day). In this technique, the ramp signal operates at a fixed cycle length in accordance with a metering rate selected for a particular control period.

Pretimed metering has proven to be an extremely cost-effective ramp control technique. Its simplicity of design and the fact that the largest net gain in benefits is achieved in going from no control to some simple form of control make pretimed metering very appealing. The greatest dis-

▲*Entrance ramp control is used to reduce the number of vehicles entering the freeway, thus allowing the freeway to move in the most efficient range of speeds and densities. Ramp control is the most widely used method for managing vehicular demand.* (Arizona Department of Transportation.)

advantage is that the system cannot adjust to fluctuating changes in demand and therefore cannot be responsive to non-recurring problems such as incidents or special events. Furthermore, the system may meter when unnecessary, which results in loss of credibility and compliance.

Traffic-responsive metering is based on the same principle as pretimed metering; however, the strategy of selecting a metering rate differs. Pretimed metering rates are determined from historical measures of traffic conditions; traffic-responsive metering rates are determined from actual measurements of traffic conditions, which allows response to current rather than historical conditions. The basic strategy of traffic-responsive metering is to obtain real-time traffic measurements of conditions on the freeway, examine how the freeway is operating with respect to capacity, and from this information determine the number of ramp vehicles that can be released without causing congestion on the freeway. Thus, traffic-responsive metering is an effective means of control because it can react to fluctuating traffic flows and minimize the adverse effects caused by short-term variations in traffic demand. The added surveillance required for traffic-responsive metering can also be used for incident detection and route diversions.

Merge control is used to achieve optimum use of freeway gaps. The system is basically a method of merging a maximum number of entrance ramp vehicles into available gaps on the freeway without causing significant disruption to the flow of traffic on the freeway. A series of detectors, installed in the right-hand lane of a freeway in advance of an entrance ramp, monitor the flow in that lane. Once a gap of a predetermined length occurs, a vehicle is allowed to leave the ramp and enter the freeway. This type of control is most effective on ramps where considerable turbulence is generated by vehicles trying to enter the main stream of traffic. This situation is most predominant on older freeways that have poor merging operations because of inadequate design standards. Where ramp designs are of high standard, merge control strategies are unnecessary, and a pretimed or traffic-responsive metering system is more effective.

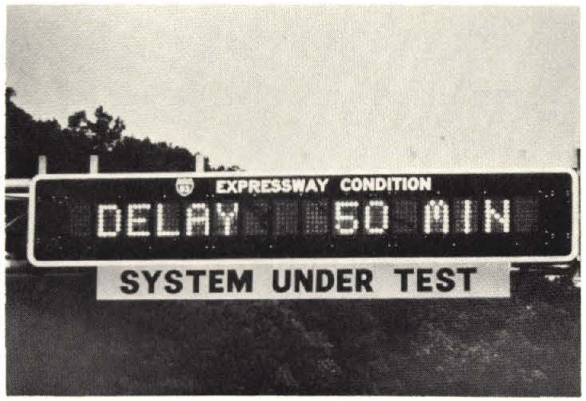
Integrated ramp control is a refinement that has gained widespread use. In this technique, ramp metering rates are based on total system operation and not on traffic flow just immediately upstream and downstream of a ramp. The control system monitors level of service performance at all access points to the freeway and, from this measurement, establishes an allowable ramp flow that will achieve a desired level of service for the entire system. By controlling the level of service in the system, overall higher flows can be achieved throughout the length of the freeway. Integrated ramp control is a complex operation that requires both sophisticated control strategies and centralized computer control. However, such a system can be responsive to individual variations in traffic demands and can be especially useful in responding to incidents that occur within the control section.

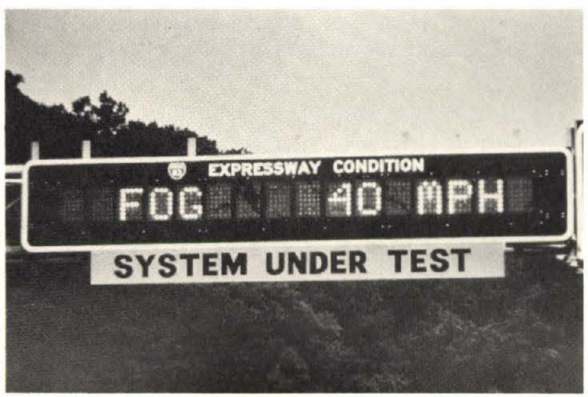
Freeway Mainline Control—Control of traffic on the freeway mainline involves regulation and guidance of freeway traffic with the intent of achieving more uniform and stable traffic flow as demand for the facility approaches capacity. Although freeway mainline control has not been used extensively in operating systems, there is considerable interest in the concept, and it is likely there will be more emphasis on research and demonstration projects in the future. The most common mainline control techniques include variable speed control, driver information systems, and mainline metering.

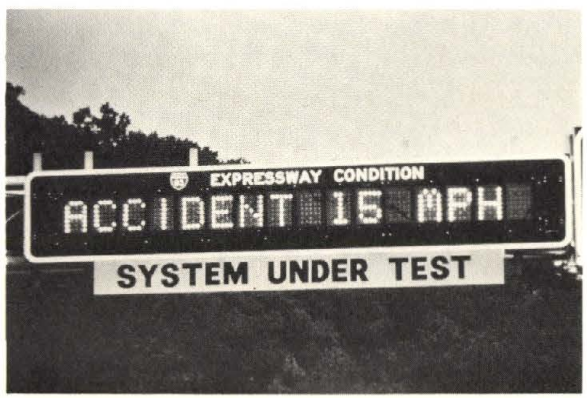
Variable-message signs are able to present current information on changing traffic conditions to the motorist. (California Department of Transportation, left; Texas Transportation Institute, right.) ▶

Variable speed control is intended to control the speed of traffic on a freeway to a level that achieves a uniformity of speeds and stable traffic flow. The theory is that, as the peak-flow demand on a facility increases, speed control can help improve the stability of flow and thus reduce interaction between vehicles in the traffic streams. This assumes, of course, that drivers are responsive to speed increase opportunities and thereby maintain minimum headways. When this is not true, speed control is not a viable concept for preventing congestion. However, improving the uniformity of speeds increases the probability of reducing the occurrence of rear-end collisions as congestion develops. Variable speed control can also be used during off-peak periods to alert motorists to a traffic hazard.

Experience with variable speed control has been limited and results have been somewhat mixed. In Detroit, motorists considered variable speed limits advisory rather than regulatory and thus did not decrease speeds to the posted limit unless there was an apparent reason to do so. It was also found that the control was not successful in increasing flow at critical bottlenecks. Many European countries, however, have found that variable speed signs on freeways are effective and produce favorable results in terms of improving the speed distribution and reducing the frequency and severity of accidents.







Driver information systems are used in mainline control to advise motorists of freeway conditions so that appropriate action can be taken by the driver to enhance the efficiency and safety of operations. The philosophy is to inform the driver of impending conditions with up-to-date information. This enables the driver to decide what actions should be taken; i.e., whether to divert from the freeway or continue on the planned route under some form of control. Signing and radio are examples of driver information systems used in mainline control.

Signing consists of visual information displays. Single-message signs—those capable of conveying only one message—are used to warn drivers of a closed lane, congestion, or a particular hazardous condition such as weather or environmental conditions. Since they are used only when a particular hazard occurs, their use is limited, although they can be very useful at locations where hazard is well-defined and occurs periodically.

Variable-message signs are able to convey a variety of information, which makes them more effective in presenting current information on changing traffic conditions. A number of these sign systems are currently installed on freeways and feature some of the principal systems given in Table 1. Although there are limited data on the effectiveness of these signs, it has been determined that motorists are less frustrated and aggravated when they are provided with information on the location of congestion and the expected length of delay to be encoun-

◀ *Driver information systems, used in mainline control, warn the motorist of freeway conditions. The motorist can then take any appropriate action to enhance safety and efficiency in operation.* (City of Baltimore.)

Table 1. Summary of Features of Some Variable-Message Sign Systems

Location	Type of Sign	Number of Displays	Type of Information
Dallas, Texas	Rotating drum	3	Alternate route
Houston, Texas	Lamp matrix	4	Freeway condition and alternate route
Los Angeles, California	Lamp matrix	35	Freeway condition
Denver, Colorado	Lamp matrix	4	Freeway condition

tered. This in itself tends to increase the safety and comfort of their trips as well as improve the overall efficiency of the system. It is important that the information presented to the driver, with both single-message and variable-message displays, be accurate. If motorists are given reason to believe the information is erroneous, credibility will suffer and the system will not serve its intended purpose. It is also important that variable-message sign systems not be left blank—motorists tend to think a blank sign is out of order.

Commercial radio is a common means of communicating freeway traffic information. Local broadcast stations in all major urban areas provide information on a routine basis during the peak periods of traffic flow; however, because much of the information broadcast by the local stations is not accurate, timely, or reliable, its effectiveness often is lost. Several urban areas now have cooperative arrangements between radio stations and freeway operating agencies—detailed traffic information is furnished to the stations at regular intervals by a freeway management agency and the stations are notified almost immediately of traffic problems resulting from accidents or other major incidents. This increased cooperation has resulted in a much more reliable system for providing real-time driver information.

Roadside radio is a communication system in which messages can be transmitted directly to the driver from local roadside transmitters. Its major advantage over commercial radio is that the messages can be more specific to the conditions at a particular location. Although this technique has not been fully tested in an operational environment, experimental studies have shown that the system is fully acceptable to motorists and can be used effectively to control vehicle speeds in hazardous locations. The major problems are FCC restrictions on frequency transmission and dependence on the driver to have a radio receiver in his vehicle. Also, commercial radio stations in some areas have opposed the system because the service is competitive with ongoing programs. If these problems can be overcome, it is likely that roadside radio will become a practical and widely used means of communicating freeway traffic information. It has the advantages of greater flexibility, lower cost, and the ability to convey more up-to-date information than other currently available driver information systems.

Another form of control involves *mainline metering*—controlling traffic entering a freeway control section via the mainline lanes according to input demand and downstream capacity. Although this concept creates congestion on the mainline upstream of the control section, it provides for noncongested flow on the mainline downstream through the control section. Its major objective is to control traffic demand at a mainline control point so that a desired level of service can be maintained on the freeway lanes downstream of this location. The desired level of service may be set to meet any of several criteria—to maximize throughput of a downstream bottleneck; to provide a high level of service to all vehicles downstream of the control point, particularly for buses and carpools that enter from nearby park-ride terminals; to distribute total delay in a more equitable manner; or to encourage diversion from the freeway because of normal traffic congestion or because of capacity-reducing incidents. This concept is being used on special controlled-access facilities such as tunnels and bridges to increase capacity and give priority to high-occupancy vehicles. However, there has been only limited testing on typical urban freeway systems.

Priority Control—Priority control provides preferential treatment for buses, carpools and other priority vehicles using the freeway. The basic intent is to encourage use of more high-occupancy vehicles and thus reduce the total vehicle demand on the freeway. The major types of priority control used on freeways are separated facilities, reserved lanes, and priority access control.

Separated facilities are limited-access roadways specifically constructed for the exclusive use of high-occupancy vehicles. They are used to provide express service between outlying areas and activity centers or for short bypasses at major freeway bottlenecks. In most cases, the separated roadways are located in the median of an existing freeway with some type of barrier to provide a physical separation from the main freeway lanes. The advantages of this technique are that priority vehicles can operate safely at high speeds, efficiency of the existing freeway is not reduced, and enforcement of priority control is more manageable. Some disadvantages are high capital costs and lack of use during off-peak periods. However, separated facilities have the potential for delivering long-term benefits, and this often is justification for the high initial capital costs.

Reserved freeway lanes have two configurations: *Concurrent-flow lanes* for priority vehicles moving in the same direction as the mainstream of traffic on the same side of the median; *contraflow lanes* on the opposite side of the median where priority traffic is against the flow of traffic.

Use of contraflow lanes seems to be preferred. In this technique, an off-peak-direction lane is used for peak-direction traffic; removable barriers normally delineate the lane, and access is limited to specific slip ramps or cross-over points at the beginning point of the system. There may or may not be a buffer lane to separate traffic on the contraflow facility from opposing freeway traffic. Implementation of this technique usually relies on highly directional peak-period traffic flow with sufficient excess capacity in the off-peak direction. Many of the facilities in operation today are reserved exclusively for buses, but some also permit carpools. Advantages of contraflow lanes are that the capacity in the peak direction is increased and the improvement can be implemented in a relatively short time at relatively low cost. The disadvantages are high operating costs, potential for serious head-on collisions (although the safety record has

▲ *Priority lanes provide preferential access to buses, carpools, and other priority vehicles.* (Minnesota Department of Transportation.)

▲ *Separated limited access roadways are constructed for the exclusive use of high-occupancy vehicles.* (Chicago Regional Office - Alan M. Voorhees & Associates.)

▲*Relatively inexpensive to implement, a concurrent-flow reserved lane gives high-occupancy vehicles a travel time advantage.* (Florida Department of Transportation.)

▲*In a relatively short time and at low cost, peak-direction capacity can be increased by the use of contraflow lanes.* (The Port Authority of New York and New Jersey.)

been good), and the need for handling breakdowns in the reserved lane.

A concurrent-flow reserved lane is a normal-flow lane with signs and markings designating that priority vehicles have exclusive access to the lane. One concept of this technique is to create a preferential lane by taking one freeway lane out of existing service and dedicating it to the use of high-occupancy vehicles (buses and carpools). An alternative concept is to physically add a lane to the freeway for the use of high-occupancy vehicles. The advantages of such a system are that the high-occupancy vehicles are given a distinct travel time advantage and that there are no adverse effects on the other traffic if the system is properly planned. The disadvantages are the potential hazards created by having a high differential in speed between the priority vehicles and traffic in the non-reserved lanes along with the increased weaving required for vehicles getting to and from the reserved lane. Also, enforcement is difficult, and the overall effectiveness is likely to be negated in the event of an incident.

Table 2 summarizes operational experience on four concurrent-flow reserved lane projects. The Santa Monica Freeway project is the only system where an existing lane was taken away from mixed flow and assigned to high-occupancy vehicles. The project operated for 21 weeks but was finally discontinued amid much controversy. On the positive side, the number of carpools on the freeway increased by 65 percent; on the negative side, freeway accidents rose markedly during the project, averaging about 2.5 times the weekly pre-project average. It was difficult to enforce the restrictions on access to these reserved lanes and sideswipe accidents were a particular problem. Thus, while the project succeeded in attracting riders to carpools and transit, the significant increase in accidents and the public opposition led to its discontinuance in August 1976.

The other concurrent-flow reserved lane projects are similar except that a reserved lane was designated at the same time a lane was added to the freeway. The added lane was provided either by widening or by restriping and using a portion of the shoulder. In most of these projects there was a significant increase in carpools but the safety of operation still remains a concern of the operating agencies.

Priority access control is another technique used to improve the level of service for high-occupancy vehicles. This type of control, used in conjunction with freeway ramp metering controls, either gives high-occupancy vehicles priority access to a ramp

Table 2. Characteristics of Four Concurrent-Flow Reserve Lane Projects

Location of Project	Date Initiated	Length in Miles	Number of Users	Time Savings	Hours of Operation
Portland, Oregon Banfield Freeway	December 1975	3.3 W.B. 1.7 E.B.	33 Buses Peak Period, 183 Carpools Peak Hour	1.2 Min W.B. 0.5 Min E.B.	6:30-9:30 am 3:30-6:30 pm
Miami, Florida North-South Freeway (I-95)	December 1975	7.5 Miles	40 Buses Peak Period, 334 Carpools Peak Hour	7-10 Min	6:30-10:00 am 3:00-7:00 pm
Los Angeles, California Santa Monica Freeway	March 1976 (Terminated August, 1976)	12.5 Miles	170 Buses And 4,592 Carpools Daily	4 Min E.B. 6.5 Min W.B.	6:30-9:30 am 3:00-7:00 pm
Marin County, California Redwood Highway	December 1974	4 Miles	96 Buses And 475 Carpools Peak Hour	3-6 Min	6:00-9:00 am 4:00-7:00 pm

bypass lane or designates exclusive ramps for their use. The concept is that the high-occupancy vehicles can avoid the delay caused by the ramp metering and can enter an uncongested freeway with minimum disruption. Priority entry can be installed and operated at relatively moderate cost and can provide a significant increase in the people-moving capacity of a freeway, without the degree of enforcement and accident problems associated with reserved lanes.

Corridor Control—The objective of corridor control is to obtain an optimum balance between traffic demand and capacity within a corridor. This is accomplished through the coordination of various control and driver information systems to facilitate the total movement of traffic on the freeway and adjacent urban arterial streets. The basic concept of this type of control is to monitor all routes in the corridor and divert traffic from overloaded facilities to those with excess capacity. Inherent in this type of system is the requirement for traffic-responsive capabilities and the ability to implement operational control strategies that will optimize traffic flow within the corridor. The facilities needed for a corridor control system include a detection system to provide real-time information on how the routes in the corridor are operating, control center equipment that processes this information using a control strategy, and a communication system that presents the decisions of the control system to the drivers.

Several corridor control projects are currently under development, with a notable application in Dallas, Texas. However, since most are still in the research stage, corridor control strategies have not advanced to the point that they can fully take into account all of the variables of freeway and urban street control. Freeway corridor and arterial network models developed for this purpose have been used on a limited basis to assess various operational strategies.

Geometric Improvements

Another approach to the management of recurring freeway problems is improving freeway capacity at the bottleneck locations. A basic solution is to add lanes, either by restriping the pavement and shoulder or by completely rebuilding the entire cross-section. The restriping is least costly, but it requires some sacrifice in design standards. In most instances, restriping is generally regarded as a temporary solution with a commitment to provide improved geometrics at some later date.

The major disadvantage of either solution is that provision of additional capacity may attract more traffic and increase demand to use the freeway, which results in demand approaching the new capacity. Therefore, when geometric capacity improvements are made, it is often desirable to implement management techniques at the same time to ensure that the benefits of the geometric design can be fully realized.

A major problem sometimes encountered in implementing geometric design improvements at bottleneck locations is the lack of downstream capacity to absorb the increased volumes. Any improvement should be part of a complete system or the problem could move to another bottleneck location downstream. For this reason, it is important that geometric improvements be planned on a systematic basis. Analysis and implementation of improvements should begin with the last bottleneck in the system and work upstream from that point. This avoids transferring the congestion problem to a new location.

Experience in improving freeway capacity through the use of geometric improvements has been good. In Los Angeles, four 12-foot lanes and a 10-foot shoulder were converted into five 11-foot lanes and a 3-foot shoulder; this resulted in an 18 percent capacity increase with no adverse safety effects. Other projects have reported similar results, and many agencies are now adopting this technique as policy.

Management of Travel Demand

A third approach is to reduce peak-period travel demand by placing greater emphasis on the use of fewer vehicles and encouraging off-peak use of the facilities. Techniques include work rescheduling, ridesharing, park-and-ride, and transit service improvements.

Work Rescheduling—The peak concentrations of work trips during the commuting hours are an evident cause of congestion. Thus, the main thrust of work rescheduling is an attempt to reduce congestion by spreading out the peak—i.e., increasing the total time during which commuting occurs, decreasing the percentage of commuter travel during the busiest period.

The two basic alternative forms of work rescheduling are:

- *Staggered hours,* in which changes in fixed schedules of starting and quitting times are implemented either for all employees or groups of employees within an employment location.
- *Flexi-time,* in which employees are permitted freedom to adjust their own working hours within certain limits.

Numerous cities have undertaken comprehensive variable work-hour programs. Experience has shown that, when coordinated with the transit system, work rescheduling has resulted in significant improvements in transit system operating efficiency, even to the point of increasing ridership. It has also been demonstrated that while work rescheduling strategies are not likely to produce significant changes in vehicle-miles of travel they can produce improvements (3 to 6 percent) in freeway levels of service during peak periods.

Ridesharing—Increased use of ridesharing has the potential for reducing total vehicular travel on urban freeways. By increasing vehicle occupancy, ridesharing reduces the number of vehicles used for commuting. Carpools are the most popular, but use of vanpooling and subscription bus service is increasing.

Ridesharing is most commonly used where a long trip is involved and public transit is either inconvenient or non-existent. It is most effective when both origins and destinations are concentrated within

Vanpooling, a form of ridesharing, is most commonly used for long trips where public transit is either inconvenient or non-existent. (San Francisco Regional Office - Alan M. Voorhees & Associates.) ▶

relatively small areas and arrival and departure times of the participants are similar. While ridesharing programs can be carried out as an isolated technique, experience has shown that they are more effective in achieving widespread participation if they are conducted in conjunction with other programs such as park-and-ride, priority control, and parking management.

Ridesharing is particularly applicable to large business and government organizations. Many of the more successful programs have been developed by single, large employers who are located in relatively isolated situations and draw their labor force from residential communities some distance away. The critical element in attracting riders seems to hinge on the type of service offered. Users will be attracted to direct, easily accessible, comfortable service that is not significantly more expensive than competing modes.

Evaluations of ridesharing programs have concentrated on the activities of individual employers rather than on their impact on the overall transportation system. Many employer programs have resulted in dramatic increases in ridesharing among their employees. For example, the Tennessee Valley Authority in Knoxville has:

- Increased carpool use from 30 percent to 41 percent of employees
- Increased vanpooling from 0 percent to 7 percent of employees
- Reduced "drive alone" commuters from 65 percent to 18 percent of employees.

Far less attention has been directed toward the areawide potential of ridesharing programs. However, the results of some of the most successful comprehensive areawide programs have indicated that the estimates of impact of reduced vehicle-miles of travel are fairly low, especially when compared with the benefits of corridor traffic control upgrading. Ridesharing programs benefit from standardized work-hour patterns; thus ridesharing and work scheduling programs implemented together may create conflicts and work at cross purposes.

Park-and-Ride Facilities — Provision of park-and-ride facilities to encourage transit and ridesharing is another technique used to increase the efficiency of a freeway corridor.

▲ (Florida Department of Transportation.)


▲ *Located at strategic points with easy access to the freeway, park-and-ride facilities can encourage transit use and ridesharing participation by serving as convenient collection points.* (California Department of Transportation.)

Public transportation can become more competitive with the private auto when express transit services are provided along the freeways. (California Department of Transportation.) ▶

Park-and-ride lots located at strategic points along a freeway corridor can serve as convenient collection points where users are subsequently shuttled to their destination by express bus or some other form of ridesharing.

Park-and-ride service is becoming increasingly common in the United States, particularly in urban freeway corridors. Los Angeles has developed a park-and-ride program that consists of 16 such facilities along the extensive freeway system. Most of the lots are shared-use facilities (i.e., drive-in theaters, shopping centers, etc.). A recent survey showed that 50 percent of the users of these park-and-ride facilities shifted from driving alone to riding the bus. Similar results are being reported in other major urban areas.

The advantages of park-and-ride facilities are that they shift the parking from dense activity centers to outlying areas and, when coupled with good service that normally includes other incentives such as priority measures, they can result in considerable commuter time savings. This makes park-and-ride an unusually attractive alternative to private auto travel.

Transit Service Improvements—Maximizing the use of bus transit is another technique to achieve more efficient flow along an urban freeway corridor. Its aim is to make transit more competitive with the private auto. Express transit services are provided along freeways; services are available at both ends of the commuter route by extended-area transit service in residential areas and circulation systems in the high-activity centers. Complementary measures such as park-and-ride facilities, reduced fares, and reserved lanes also provide additional incentives to transit use.

The effectiveness of transit service improvements in reducing peak-period congestion on freeways is dependent on the ability to provide improved traffic flow along the freeway and, in turn, on the number of peak-period drivers that can be diverted to the transit system.

The most recent experience with a program of this type was the Santa Monica Freeway Diamond Lane Project. Transit service in the corridor improved significantly with four new express routes that more than doubled the number of CBD workers living within walking distance of the service. In response to both the reserved lane and the significant increase in transit routes and service frequency, daily bus ridership in the corridor more than tripled, increasing from 1,171 riders per day to 3,793 riders per day. Survey results indicated that 96 percent of the trips were to and from work; of those interviewed, 39 percent previously drove alone in making the trip, 8.5 percent carpooled, 36 percent rode the bus, and 16.5 percent did not previously make the trip. It was estimated that at least 700 former drivers switched to riding the bus following the project's implementation.

MANAGEMENT OF NON-RECURRING PROBLEMS

Non-recurring problems are somewhat more difficult to manage. Their locations and times are not predictable, and the impact of their occurrence can be either significant, as in the case of a major lane-blocking incident, or somewhat insignificant, such as a disabled vehicle on the shoulder. Delay-causing incidents are a main concern since they are the most disruptive to traffic flow. Remedial countermeasures can be effectively used in these instances.

In the case of the delay-causing incidents where reduced capacity is encountered, the major requirement is to eliminate or prevent the cause, manage the demand that is approaching the incident, and restore the freeway to its normal service volume as quickly as possible. Thus, management of these problems requires a fairly extensive system of surveillance, services, and information.

The surveillance function is required to detect and evaluate the nature of the problem and determine the appropriate action to be taken. The services function provides the response in terms of incident removal or motorist aid and includes the resources needed to restore normal conditions. The information system provides the motorists information that will enable them to select and follow the best course of action (i.e., slow down, divert, etc.)

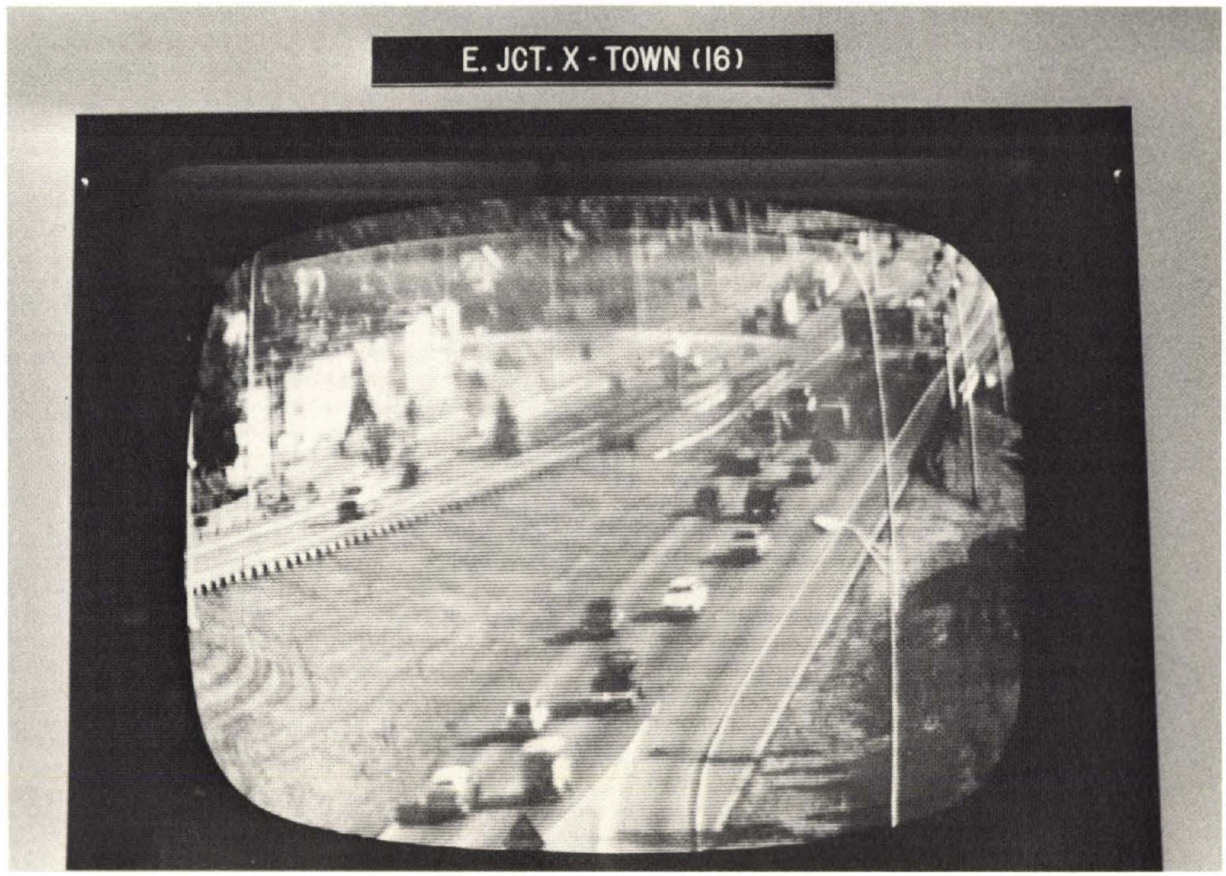
Surveillance Concepts

Various surveillance concepts are used for incident detection. Some systems convey information concerning the type of response required to remedy the problem that has been detected. In most cases, however, the detection process is an independent function, and some form of follow-up is required to ascertain the nature and extent of the incident and the type of response required. The most common surveillance concepts are:

- Detector-based surveillance
- Closed-circuit television
- Aerial surveillance
- Motorist call systems
- Citizens-band radio
- Police and service patrols

Detector-Based Surveillance — Incident detection by electronic surveillance is real-time monitoring of traffic data through use of detectors installed at critical locations along the freeway. When a delay-causing incident occurs, the capacity of the freeway is reduced at the point of occurrence. If it is reduced to some figure less than the existing demand, the traffic flow upstream of the incident will be affected. If the changes in traffic flow are greater than some predetermined value, occurrence of an incident is indicated. In this manner, incidents are detected by logically evaluating the variations in flow characteristics.

In the Los Angeles Freeway Surveillance and Control Project, changes in the percentage of time that a vehicle is present between adjacent detectors (lane occupancy) are used to sense congestion and indicate that an incident has occurred. A computer calculates the difference in occupancy between adjacent detector stations (in this case, spaced at ½-mile intervals). At the end of each sampling period and when the relative



Closed circuit television is part of the extensive system of surveillance, services, and information needed to manage non-recurring problems. (Minnesota Department of Transportation.) ▶

percent change between the present occupancy and that of the preceding sample for the downstream detector exceeds a certain value, an alert is signaled automatically by the computer. Additional information on traffic conditions immediately upstream of the incident is then obtained, and judgment decisions are made as to what response is needed.

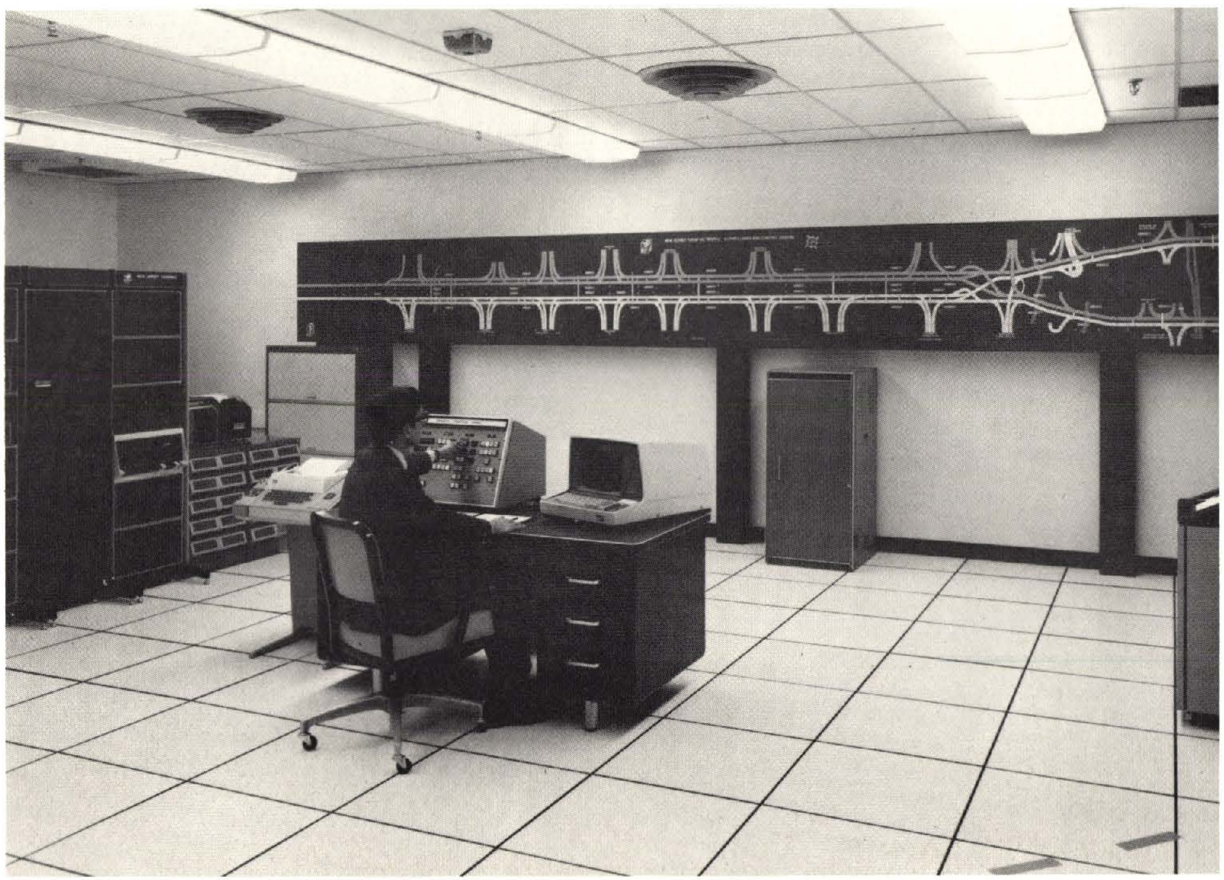
The main advantage of detector-based surveillance is that it provides a continuous network-wide monitoring capability at a relatively low operating cost. It can also be used for many other tasks such as establishing metering rates for traffic-responsive ramp metering systems. Its main disadvantage is that the nature of the incident cannot be readily identified and some follow-up surveillance is often required to determine what response is needed.

Closed-Circuit Television — Incident detection by closed-circuit television is performed using operators in a central control room who monitor traffic conditions at those locations where cameras were placed. When an incident occurs, the operator determines the nature of the incident and the type of response likely to be required. In general application, closed-circuit television is limited to those locations where delay-causing incidents are a chronic problem and fast response is essential. In this use, the television normally serves as a follow-up to electronic surveillance where incidents are detected automatically and an alarm is used to alert the operators.

The major advantage of closed-circuit television is that it provides a full view of a section of freeway. The major disadvantages are:

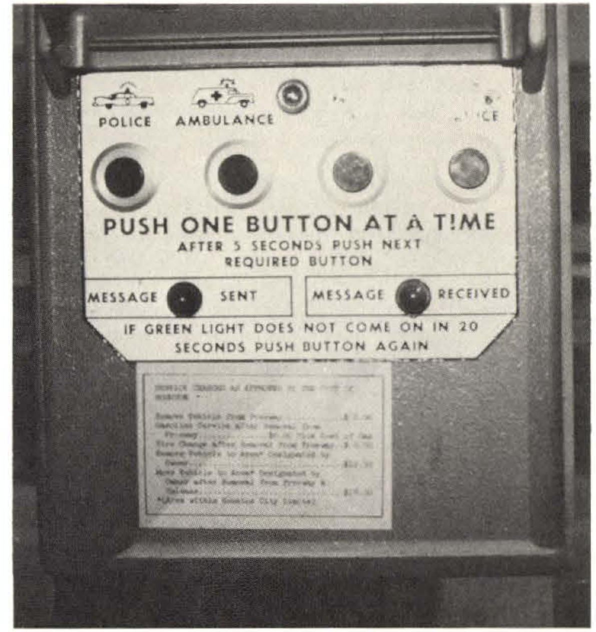
- It is expensive to install and maintain. However, recent technological developments may alleviate this problem.
- It is often difficult and expensive to obtain good monitor pictures under conditions of adverse weather, darkness and bright sunlight. However, new technology has resulted in provision of much better pictures under such conditions.
- Monitoring of the TV screen is a tedious task. Without an automatic alarm in a detector-based surveillance system, operators tend to lose interest and consequently fail to notice incidents immediately.
- Continuous monitoring of TV screens by qualified operators is expensive.

The value of closed-circuit television is primarily to confirm and provide information about the nature of incidents and other factors causing congestion in areas of known high frequency of recurring incidents. It has shown to be very useful in this regard, and there is a general concensus that television surveillance is a necessary element of an urban freeway surveillance system, especially if it is used on a selective—not systemwide—basis. In many freeway management systems, television is essential if the surveillance system is to attain credibility with po-



◀ *A prerequisite for effective corridor control is a network-wide continuous monitoring capability. A relatively low cost example is electronic surveillance.* (New Jersey Turnpike Authority.)

Motorist call boxes were one of the earliest incident detection systems used on freeways. They are an effective system for signaling a motorist's service need. (Transportation Research Board.)▶



lice and others charged with responding to surveillance alarms.

Aerial Surveillance — This type of surveillance is primarily used by police and commercial radio stations to get a general overview of traffic in a particular area or corridor. Through use of light planes or helicopters, they observe where the bottlenecks are occurring and determine whether they have been caused by incidents. Advisories of this information are then broadcast to motorists and assistance is dispatched to the scene of the incident. Due to the expense of this type of surveillance, a wide geographical area usually must be covered; consequently, there often is considerable time delay in identification and removal of incidents.

In general, it has never been conclusively demonstrated that aerial surveillance is a cost-effective technique for incident detection. The equipment and the labor requirements of the system are expensive and its effectiveness is sometimes limited by weather conditions.

Motorist Call Systems — One of the earliest incident detection systems used motorist call boxes or emergency telephones. Motorists experiencing, or witnessing, an incident used the nearest call box or telephone to inform the operating agency of the nature of the incident. Telephones are generally preferred because voice communication gives the motorist an opportunity to explain exactly what services are required. However, the call box with coded message buttons is less costly than a telephone requiring voice transmission.

The major advantage of a motorist call system is that it is an efficient system for signaling a motorist's need for service. A major disadvantage is the delay associated with the motorist's determining that an incident has occurred, determining that the proper action involves using the call box, locating the nearest call box, and then proceeding safely to the call box to inform the operating agency. This delay can be quite significant. Another major disadvantage is the large number of "gone-on-arrival" calls that are generated (i.e., the motorist remedies his problem through some other means and when the servicing agency arrives the disabled vehicle is no longer there).

Citizen-Band Radio — Another way freeway incidents can be detected is through use of citizen-band radio. Drivers of vehicles equipped with a CB radio report observed incidents to a central monitoring center which in turn transmits the information to the appropriate agency for dispatch of the required assistance. The key elements of this system are motorists who are knowledgeable about the system and are willing to report the incidents they observe. Because of this volunteer aspect, the detection capability of the system is always a function of the number of motorists on the freeway who have the necessary CB equipment and are willing to provide their cooperation. With the growing number of CB-equipped vehicles, this type of system has considerable potential; it has been working well in Detroit.

Police and Service Patrols — Various patrol systems have been used on urban freeways to provide incident detection. The most common is the use of police patrols that circulate in the traffic stream and have as their primary objective the identification

◀ *An effective incident management program must include service facilities which allow for rapid removal of the incident from the freeway.* (Florida Department of Transportation.)

of incidents, determination of the nature and extent of the incident, and dispatch of the type of response needed. The major advantage of police patrols is that detection and dispatch of response is one function. The major disadvantage is the large number of patrols required to effectively cover a freeway system and the high costs involved; in many instances, police involvement is not necessary.

Another system used to provide incident detection is the service patrol. This system involves the use of light-duty service vehicles and, similar to the police patrols, provides for detection of incidents. It also provides minor services such as fuel, oil, water, and minor mechanical repairs. As with the police patrols, this system is very expensive because of the large number of patrols required.

Since surveillance techniques are complementary, most operational systems utilize more than one concept to achieve a cost-effective surveillance and control system.

Incident Servicing

Once an incident is detected, the key to minimizing non-recurrent congestion is the speed with which the incident is removed. The longer the duration of response, the more severe the resulting congestion and delay for a given level of demand. Consequently, an effective incident management program must include service facilities which, upon location of an incident, allow for rapid removal of that incident completely off the freeway and out of sight of traffic in both directions.

One important consideration is the operational procedures used by enforcement, operating, and maintenance personnel in servicing an incident. Experience has shown that much of the congestion caused by an incident can be alleviated if operational procedures provides for the removal of disabled vehicles to a location off the freeway as rapidly as possible. Such a program involving accident investigation has been implemented with significant benefits on a 6-mile section of the Gulf Freeway in Houston.

Another important consideration in an incident-management system is the cooperation of the agencies responsible for providing the needed response. Normally, more than one department or agency is involved and, because the priorities within each agency are often different, it is sometimes difficult to achieve full cooperation of all the parties involved. Matters involving multiple jurisdictions can also complicate the management process. To overcome these differences it is sometimes necessary to create an incident-management team composed of representatives of the major agencies and/or governmental entities. Responsibility for initiating and coordinating all incident-management activities is given to this team; working together, they effectively formulate and implement strategies for response to freeway incidents.

Three operational incident-management systems that have been effective are the Chicago Area Emergency Traffic Patrol, the Los Angeles Area Freeway Surveillance and Control Project, and the traffic-management system for the Holland and Lincoln Tunnels in New York.

The Chicago system consists of a special radio-equipped fleet of trucks continuously on patrol to promote freeway safety and maintain good traffic flow. They provide mobile surveillance of 135 miles of the Chicago area freeway system, 24 hours a day, 7 days a week. The patrol vehicles are equipped and the drivers are trained to handle almost any emergency incident likely to occur, including accidents and disabled vehicles. The Illinois DOT Communications Center, serving as the coordination unit for the patrol, handles all incoming reports of incidents and directs the nearest available patrol unit to the scene. The Communications Center maintains direct contact with the Chicago police, the State police, the Chicago fire department, the Expressway Surveillance Project, the Chicago Traffic Engineering Center, the Illinois Tollway Commission, and local radio stations operating traffic aerial surveillance or traffic hotlines. An important aspect of this system is the information generated by the electronic surveillance network operated by the Expressway Surveillance Project. The network detects problems that disrupt traffic flow, identifies troubled expressway sections, and then notifies the Communications Center. The patrol is then directed to the problem site to expedite removal of the flow-reducing incident.

The Los Angeles incident-servicing system features an incident-management team in which the disciplines of police, maintenance, and traffic engineering are represented. A three-man team is stationed in a control center where it has access to incident detection information and to the communications facilities necessary for dispatching the services required for rapid incident removal. The key element of this system is the freeway electronic surveillance system. Once an incident is detected by the system, a tow truck and a helicopter equipped with closed-circuit TV are dispatched to the scene to confirm the occurrence of the incident and determine its nature and extent. With this information, the incident-management team identifies needs and implements necessary responses.

This system has been effective in that it has reduced the delay caused by incidents by more than 50 percent. However, the system is expensive and it appears that some components (such as the helicopter with the closed-circuit TV) may not be cost-effective.

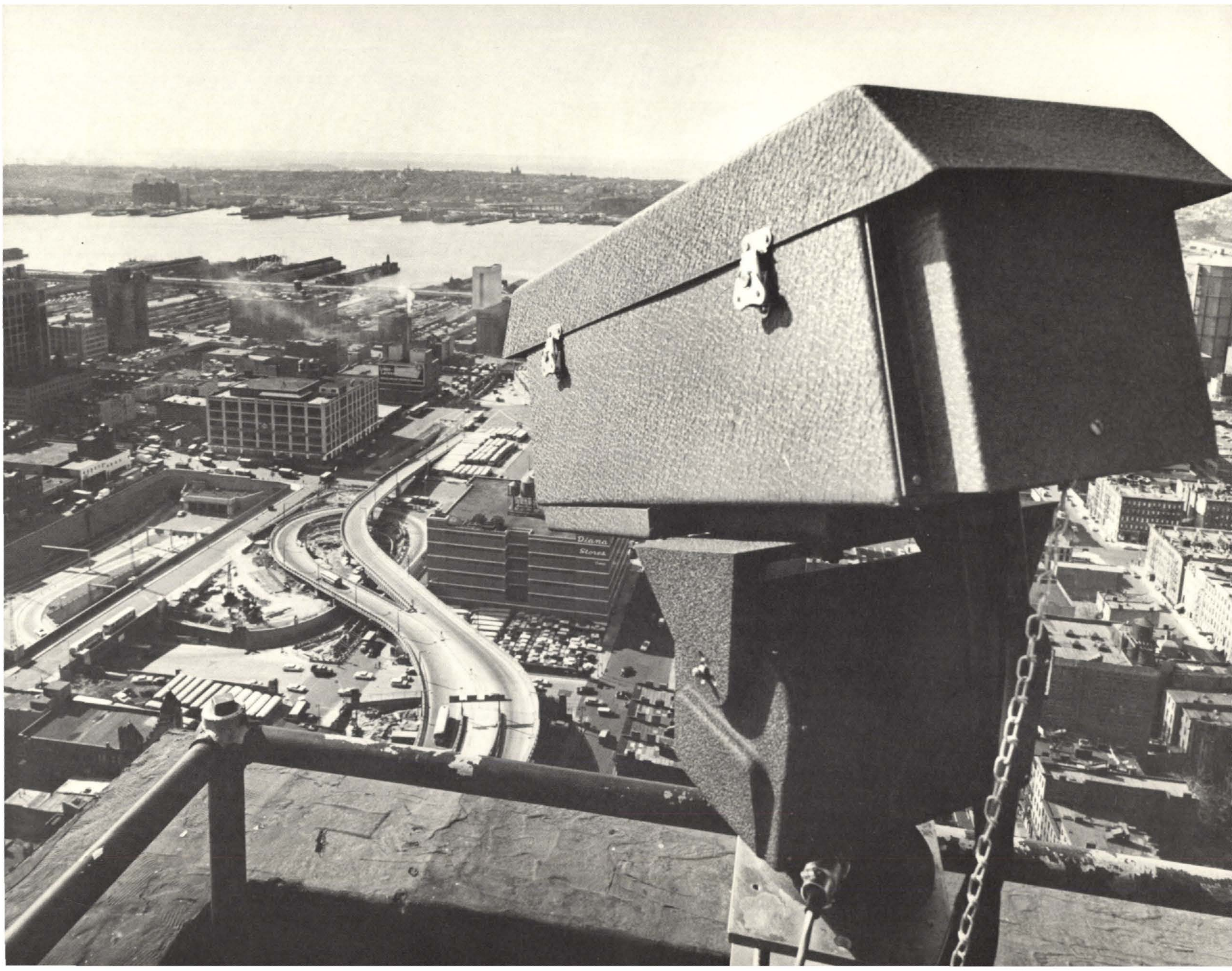
The major elements of the incident-management system in the New York tunnels include:

- An automatic surveillance and control system with vehicle detectors, minicomputers, alarms indicating when and where a stoppage has occurred, and changeable-message signs at each tunnel entrance to meter traffic ("Pause Here Then Go") when necessary to prevent congestion in the tunnels.
- Closed-circuit television and monitor screens at the police desk to enable an evaluation of the stoppage alarms.
- Two-way radio communication among all police assigned to tunnel operations.
- Monorail catwalk cars to allow rapid police movement in the tunnels.
- Rescue tractors capable of coping with all emergencies and removing obstructions rapidly.

Intensive surveillance is provided 24 hours a day, 7 days a week. When traffic flow, measured by the electronic surveillance, deteriorates to a point that it meets predetermined criteria, a stoppage alarm is signaled. This alarm continues until the police acknowledge it or the computer determines normal traffic flow has resumed. Through use of the closed-circuit TV, the police determine the probable cause of the alarm and assure that the necessary responses are implemented.

A most important element of the system is its high reliability combined with low operating cost. The surveillance system operates unattended, and TV monitoring is required only when an alarm is sounded. This system has contributed significantly to increasing the transportation service provided by the tunnels.

Chapter Four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Implementation Considerations

For many highway administrators, the technology of freeway traffic management is somewhat of a mystery. Terms such as incident control algorithms, multiprogrammed systems, multiplexing, digital transmission systems, and other highly specialized technical terms can be extremely confusing to those who are not technical specialists in freeway operations. Well-meaning researchers have contributed to this confusion by failing to distinguish clearly between day-to-day operational systems and research facilities such as the National Proving Ground in Detroit. Consequently, it is widely perceived that a freeway management system entails a multimillion dollar expenditure with elaborate computer facilities, expensive data collection systems, and a continuing monetary commitment of unknown magnitude. In reality, this is not true.

The controls on a freeway are similar to those used on a standard urban arterial. As an example, each intersection on a major urban arterial is signalized only as it becomes necessary. The traffic engineer installs the equipment needed for the control—detectors, signal displays, and controllers—and then monitors the intersection's operation after the system is working. Eventually, as more intersections are signalized, the system may become more complex with some form of central monitoring or control. Even then, the requirements are not altered significantly. Freeway management systems can evolve in the same way—entrance ramp by entrance ramp. Eventually, a series of entrance ramps can be regulated by some higher order of control, as in the case of a network of signalized intersections. However, the components employed in the control of the individual entrance ramps are the same as those needed for control of the entire freeway. Thus, freeway traffic control can consist of a very sophisticated system with centralized traffic-responsive control or it can be as simple as the installation of a few pretimed ramp metering controls. The type of system used will depend on the problems to be solved and the available resources.

◀ *Surveillance camera.* (The Port Authority of New York and New Jersey.)

One method of detecting the location of non-recurring problems is through a closed-circuit television system. (Minnesota Department of Transportation.) ▶

ANALYSIS OF SOLUTIONS

The basic procedures used for identifying solutions to freeway operational problems include:

- Establishing freeway management goals
- Locating and evaluating the problem(s)
- Defining alternative solutions
- Selecting the best solution

Establishing Goals

The first step in the analysis of potential solutions to freeway problems is to establish goals. Typical goals might include the following:

- Reduce recurring freeway congestion
- Minimize the effect of non-recurring problems
- Maximize safety of operation
- Provide facility users with information that will aid them in the efficient utilization of freeway facilities
- Provide aid to those who have encountered problems on the freeway (i.e., accidents, breakdowns, etc.)

These goals will help define the types of improvements that should be considered and lead to a statement of objectives from which measures of effectiveness can be derived.

Locating and Evaluating the Problem(s)

The next step in the analysis process is to define the problem areas. In the case of recurring congestion, the methods of locating bottlenecks are fairly straightforward. They include:

- Ground observation of traffic conditions by inspection and quantification using a range of direct and remote survey techniques
- Aerial surveillance of the system
- Complaints from the user

This provides for identification of the major bottlenecks and isolation of locations at which detailed studies of traffic characteristics should be made.

Once the recurring problems or bottleneck locations have been located, the magnitude of the problem must be determined. This will provide a definition of the detailed characteristics of the bottlenecks, an estimate of traffic demands, and an estimate of delay in quantitative terms. Detection of the location of non-recurring problems is a more difficult task, and the choice of methods by which the non-recurring problems are identified depends on the goals regarding incident management. If complete and instantaneous knowledge of the situation is required, a very sophisticated system will be needed (such as an automatic detection system or a closed-circuit television system).

On the other hand, if the goal is merely to provide aid to those who encounter problems on the freeway, some method of communicating with the stranded driver is adequate. The more difficult aspect in dealing with non-recurring problems, however, is determining the frequency of their occurrence, the reduction in capacity caused by the various types of incidents, and the effect that incidents have on the overall accident rate.

The most common measures of traffic characteristics used for determining the magnitude of freeway operational problems are:

- *Traffic volume* — Traffic volume is defined as the rate of flow measured at a point and expressed in terms of vehicles per unit of time (i.e., vehicles per hour). Traffic volume is the most basic traffic parameter but it has one major disadvantage in that it cannot be used exclusively for describing operations since low volumes can indicate both free-flow conditions and congested operation.
- *Speed and travel time* — Speed is a highly descriptive traffic flow variable and is used not only to locate problem areas but also to provide input for developing other measures of traffic flow, such as density. Travel time, the inverse equivalent of speed, is used to quantify the amount of delay experienced in a system. The difference between the normal travel time and the congested travel time is the delay attributable to bottlenecks in the system.
- *Density* — Density as a traffic variable is the number of vehicles within a section or length of roadway and is generally expressed in vehicles per mile. It is a good indicator of system performance and can also be used to pinpoint bottleneck locations.
- *Lane occupancy* — This traffic measurement (expressed as a percentage) is the percent time that vehicles are present in a detection zone to the sampling time. It is a function of the volume of vehicles and the speed of vehicles passing through the detection area. It is considered to be a good measure of freeway performance.
- *Capacity* — Capacity is the maximum volume that a particular roadway can accommodate under prevailing roadway conditions. It is primarily dependent on the physical features of the roadway and the characteristics of the vehicles and drivers that make up the traffic stream.

When collecting freeway operations data, it is important to know the operating conditions throughout the peak period. This is particularly important since the delay during the peak period is generally quite variable. It is also important to know the manner in which congestion builds up. This buildup forms the basis for estimating traffic demand, which is an estimate of the number of vehicles attempting to pass a point compared to the number that actually do.

Techniques for collecting traffic characteristic data have been well developed; the methodology is dependent on the types of data needed. Table 3 summarizes different methods of measurement and lists the measure each method is capable of determining. Some of the more commonly used methods are:

- *Manual counting* — This is perhaps one of the most commonly used methods for gathering freeway operational data to locate problem areas. Data that can be effectively recorded

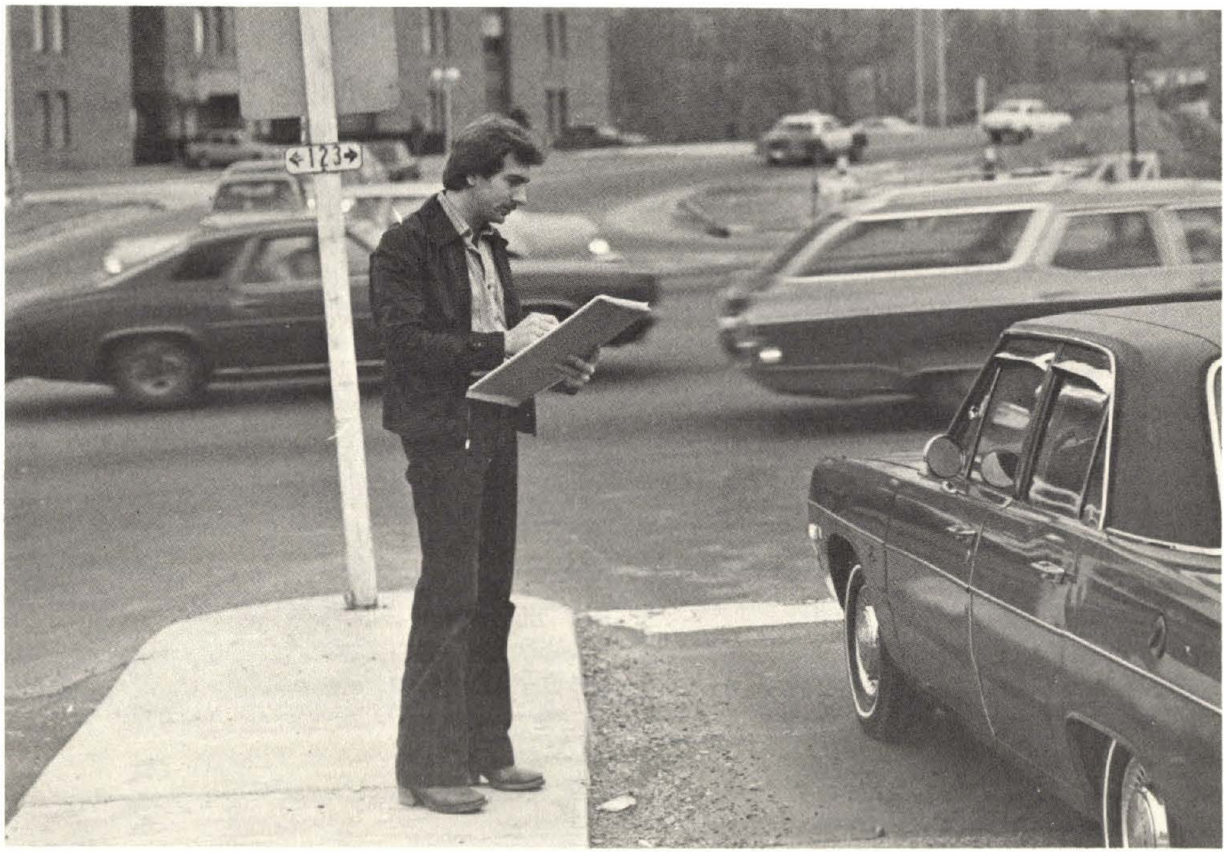
Table 3. Methods of Measuring Freeway Traffic Characteristics

Method	Measure							
	Volume	Capacity	Speed & Travel Time	Density & Occupancy	Speed Changes	Headways	Gap Acceptance	Queues
Manual Counts	●	●				●		●
Automatic Detectors	●	●	●	●	●	●		●
Moving Vehicles			●		●			●
Aerial Photography	●	●	●	●	●	●	●	●
Time-Lapse Photography	●	●	●	●	●	●	●	●
Closed-Circuit TV	●		●	●	●	●	●	●
Input-Output Studies	●	●	●	●		●		●
Origin-Destination Studies			●					

by manual counting include volumes, vehicle occupancies, headways, capacity, and queues. Manual counting is simple to perform and does not require sophisticated equipment. Its major disadvantage is that many man-hours are required to cover a large system. Consequently, manual counting can become very expensive.

- *Automatic detection* — This is another common technique for collecting freeway operational data. While portable or permanently installed detectors may be used, the most common are the portable detectors consisting of a sensor (road tube or tape switch) and a recorder system. The principal use of automatic detectors is the measurement of traffic volume, but suitable adaptation of the detector can be made to collect other traffic characteristics such as speed, density, headways, and queues. With automatic detection, data can be collected efficiently and economically at a large number of sites and over a long period of time.
- *Floating-car speed surveys* — This is an effective method of determining the magnitude of freeway operational problems. Vehicles are driven along a route and the drivers are instructed to maintain a speed comparable to other vehicles along the freeway. A recording device records a continuous profile of each vehicle's speed along with distance and location references. From these data, speed contours can be developed which indicate locations at which congestion is occurring, duration of congestion at any point, and extent of total freeway congestion at any point in time.
- *Aerial photography* — This is an effective means of obtaining a record of systemwide freeway traffic operation. It involves flying over a section of freeway during periods of congestion and taking overlapping time-lapse photographs. Vehicular speeds, headways, and densities are calculated from measurement of ground displacement of vehicles from one photograph to another. The information can then be plotted in the form of density contours to indicate the source, duration, and extent of congestion along the freeway section.

Other techniques that are useful for obtaining freeway traffic operational data include: time-lapse photography or closed-circuit television for studies limited to a small geographical area such as a freeway ramp or a critical bottleneck area; origin-destination surveys to obtain the travel patterns of vehicles using a section of a freeway; input-output studies to obtain a more definitive description of traffic flow within a section of freeway; and accident studies either at spot locations or along a section of freeway to establish performance measures.



◀*Factual studies (surveys) provide data on origin, destination, and traffic characteristics needed to determine the magnitude of freeway operational problems.* (Mark Herndon for Alan M. Voorhees & Asso.)

Defining Alternative Solutions

Once a detailed definition of the problem or problems to be solved is determined, the next logical steps are to establish specific objectives for the traffic control system and select specific actions that will achieve the stated objectives. Since each possible action will have a different impact on traffic performance, it is necessary to identify a combination of actions that when implemented as a group will make up a total system. For example, one freeway management project (the I-35W project in Minneapolis) established the following objectives for their system:

- Improve the freeway corridor level of service
- Increase the transit modal split in the corridor
- Improve the reliability of the freeway operation
- Improve the transit system performance in the corridor
- Obtain user acceptance of the freeway control system
- Obtain a positive environmental impact
- Implement the freeway management system in a cost-effective manner

To accomplish these objectives, a system of five functional elements was implemented, including:

- A real-time freeway surveillance, command, and control system
- A freeway ramp metering system
- Extensive express bus service in the corridor
- Priority access to the freeway via express or priority ramps
- Provision of certain amenities (such as park-ride facilities, bus shelters, signs) in the corridor

Warrants/Guidelines — Guidance for the selection of alternative systems can be obtained from the past experience with freeway management and control systems. Sufficient information is not available to permit development of all-inclusive numerical warrants applicable to a wide range of conditions. Some general guidelines for various control techniques follow.

Ramp metering should be used at those locations where control of entering traffic is needed to allow the freeway to operate at a high level of service. Installation of ramp metering may be warranted when the following conditions are satisfied:

- The expected delay to freeway traffic exceeds the expected delay to potential ramp users.
- There is adequate storage space for the ramp vehicles that will be delayed.
- There are suitable alternate surface routes available to accommodate the traffic that may be diverted from the freeway.
- The total volume of traffic on the right-hand lane of the freeway mainline and the entrance ramp does not exceed approximately 1,800 vehicles per hour.

▲ *Improving transit system performance is one of the many actions which can be taken to improve the level of service in a corridor. This system, pictured above, is part of a combination rail/bus transit system in the Washington, D.C. Metropolitan area.* (Mark Herndon for Alan M. Voorhees & Associates.)

- There is recurring congestion on the freeway due to traffic demand in excess of capacity or there is recurring congestion or a severe accident hazard at the freeway entrance ramp due to inadequate design at the ramp merging area.

Ramp metering may also be warranted to reduce sporadic congestion on isolated sections of the freeway caused by peak-traffic loads from special events or from severe peak loads due to recreational traffic.

Ramp closure may be justified alone or in conjunction with ramp metering when:

- There is a heavy entrance ramp movement that cannot be adequately stored behind the ramp signals during some portion of the ramp control operations.
- The mainline bottleneck condition is such that ramp metering at the minimum practical rate ($\simeq$ 180 to 200 vph) is too high.
- A combination of mainline traffic volumes together with an inadequate entrance ramp design makes it difficult for the on-ramp traffic to enter safely during a portion or all of the peak period.
- Entrance ramp volumes induce considerable lane changing and weave problems that significantly impair the capacity of the freeway.

Ramp closure can be used for a short period in conjuction with ramp metering or it can be used alone for the entire peak period.

Merge control is warranted at those ramps where turbulence is generated by vehicles entering the main stream of traffic. Factors to be considered with merge control include:

- Merge control operates effectively with ramp volumes of less than approximately 500 vph. Above this volume, the platooning on the ramps becomes excessive and some form of ramp metering is generally required.
- Merge control is most effective at the lower ramp volumes in the range of 200 to 300 vph.
- When merge control is used, the volume on the freeway lane adjacent to the ramp should not exceed a value such that the volume in this lane plus the ramp volume exceeds 1,800 vehicles per hour.
- Merge control is generally more applicable at those locations where the length of the acceleration lanes is 300 feet or less. With longer acceleration lanes, ramp metering is generally the preferred control.

Thus, the analysis of solutions for freeway management problems follows a very logical approach—problem definition, establishment of objectives, and selection of system components to achieve the objectives.

Benefits and Costs of Alternative Solutions

It is likely that a number of solutions might result from consideration of the available alternatives. The selection of the solution that is best suited for a given operational

Ramp metering is an effective means of control at locations where the control of entering traffic is needed to enable the freeway to maintain a high level of service. (Texas Transportation Institute.) ▶

Though freeway management projects bring varied results in differing situations, priority lanes for buses and high-occupancy vehicles have continually been the most cost-effective. (California Department of Transportation.) ▶

problem requires further analysis to develop an understanding of the benefits and costs associated with each alternative.

Benefits — The benefits achieved through freeway controls have been analyzed in many freeway management projects. Because of the variations in the magnitude of the problems encountered and cost of the controls that were implemented, the results vary considerably. This is understandable because a freeway that experiences extended congestion (i.e., two hours or more) would derive considerably more benefits than one congested for a shorter time. However, the costs of the controls could be the same. Similarly, the benefits for certain types of control systems (i.e., pretimed ramp control versus traffic-responsive traffic control) may be comparable but the costs of one may be much less than for another. Therefore, to compare benefits for different control system designs and for different locations can oftentimes be misleading.

Studies of benefits on the major freeway management projects have shown that efficiency of the freeways is improved, average speeds are increased, accident rates are reduced, and total travel times in the freeway system are reduced.

- In Dallas, it was estimated that the benefits of a freeway control system on the North Central Expressway for a two-hour p.m. peak period were a decrease of 477 vehicle-hours of delay (a 30 percent decrease in travel time), an increase of 23 percent in average speeds, and an 18 percent decrease in accidents.
- In Chicago, an analysis of operations covering a 4-year period demonstrated a significant change in the congestion patterns, reducing delays 19 to 29 percent. The four years of experience with the ramp metering system also indicated a 35 percent reduction in accidents related to freeway entrance ramps.
- In Minneapolis, the I-35W corridor control project significantly improved the general level of service for traffic in the corridor. Peak-period average speeds were increased from 44 mph to 50 mph northbound in the a.m. and from 36 mph to 46 mph southbound in the p.m. It is estimated that the control system is resulting in a daily peak-period savings of approximately 1,400 passenger-hours. In addition, safety was improved with a 58 percent reduction in a.m. peak-period accidents and an 18 percent reduction in p.m. peak-period accidents.
- In New York, the Northern Long Island Corridor feasibility study estimated that the recommended system would result in annual benefits comprising 2,850,000 hours of vehicle delay savings, 2,736,000 gallons of fuel savings, 6,000,000 pounds reduction in pollutants, and 200 fewer accidents.
- In Houston, a ramp metering system on a six-mile section of the Gulf Freeway provided an increase of average speed during the peak a.m. period from 20 mph to 33 mph, a 27 percent reduction in accidents, and a 25 percent decrease in total travel time.

Thus, numerous examples of improved traffic flow and/or accident reduction have resulted from freeway management projects. However, when it comes to relating

◀ *A freeway entrance ramp exclusively for buses and carpools. This type of management technique reduces total person delay in the system and helps increase corridor efficiency.* (Minnesota Department of Transportation.)

overall improvements to overall costs, there are complexities which make precise answers difficult, if not impossible. When comparing benefits and costs, it should be remembered that the benefits are not always instantaneous. Often, the payoff may be years ahead so that it is difficult to relate the benefits to costs at the time of improvement. Also, many of the improvement benefits may be hidden in the sense that they correct problems before they become apparent to anyone.

Costs — A major problem the highway administrator faces in operating a freeway system is that of allocating a limited budget among the many competing needs. With the recent inflationary trends, coupled with a corresponding drop in revenues, he must strive to achieve an operating system that will provide the greatest benefits at minimum cost. For this reason, the capital and operating costs of freeway management systems are sensitive issues in most operating agencies.

As with the case of benefits, generalizations of costs for freeway management systems are extremely difficult to develop. This is due primarily to the variabilities related to planning, construction, implementation, and operation of systems in widely scattered locations. For example, in some systems the basic planning and system justification is highly formalized and the design and implementation are let to bid to private contractors as a complete system. Under these arrangements, costs are well documented. In other instances, a staging process is used whereby the system is developed by in-house staff, over an extended period of time. In this process, costs are more difficult to define. The variability in labor and installation costs as well as the variability in salaries of professional, administrative, and technical support staff are also factors that tend to obscure the costs of various elements of freeway management systems. There are, however, some general figures that have been developed for certain system costs. They are:

- *Ramp control systems* — The simplest form of ramp control is pretimed ramp metering. The equipment consists of a traffic signal, local controller, and the ancillary facilities such as signs and pavement markings. The most basic configuration costs approximately $2,500 per ramp.

The other type of ramp control system is the locally actuated traffic-responsive system. This is somewhat more sophisticated than the pretimed control as it normally uses a microprocessor-based controller with input from both mainline and ramp detectors. The costs are approximately $5,500 per ramp, or about double those of the pretimed system. The increased costs are mainly due to the cost of the microprocessor controller.

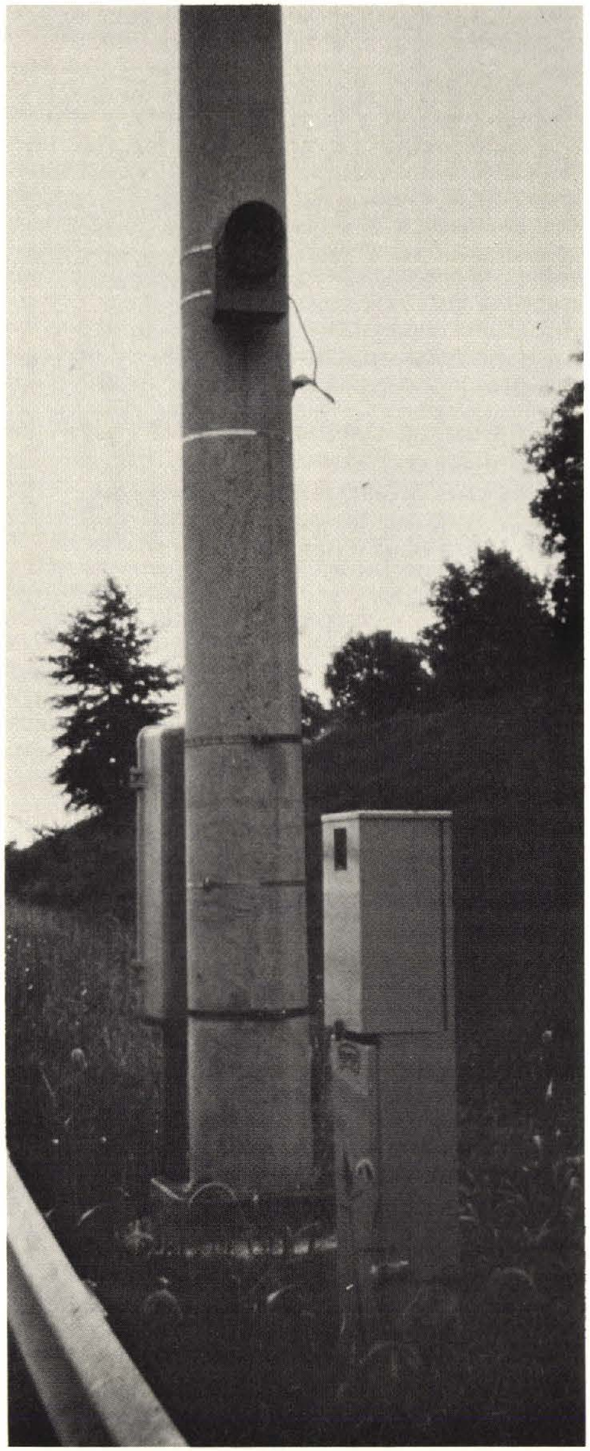
The centralized interconnected ramp control system represents the highest degree of sophistication in ramp control. It offers the full flexibility of normal control as well as incident-related control. Because there are wide variations in the configuration of centrally based control systems and because the number of ramps has an important bearing on total costs per ramp (i.e., computer control costs do not go up proportionally with the number of ramps added to the system) it is difficult to develop a specific per-ramp cost for this type of system. However, some representative costs for a large-scale system capable of controlling up to 50 ramps are $150,000 for the central control system and approximately $5,500 for the items required at each ramp.

The annualized capital costs for ramp control systems range from about $350 per ramp for a pretimed system to about $4,000 per ramp for a centrally controlled interconnected system.

- *Busways* — Costs for busways range from $1 million to $5 million per mile and are generally governed by construction type and level of service desired. Busways using existing rights-of-way generally fall in the $1 million-per-mile range, whereas busways requiring elevated construction or additional right-of-way average $3 to $5 million per mile.
- *Reserved lanes* — The costs of implementing reserved lanes are generally minimal, but the maintenance and operational costs tend to be significant. Cost for the 2.5-mile reversible-lane operation on I-495 in the Lincoln Tunnel (New York) was approximately $700,000, of which $134,000 was for construction and the balance for traffic controls. Annual maintenance and operational costs are approximately $200,000, or $80,000 per mile. Costs for implementing the 2.0-mile Long Island Expressway contraflow bus lane were $25,000 per mile and the annual maintenance and operational costs are about $75,000 per mile. Costs for implementing the bus and carpool bypass lanes on the San Francisco-Oakland Bay Bridge were approximately $60,000 per mile and the maintenance and operational costs are approximately $150,000 per mile, annually.
- *Incident management* — The costs of incident management systems are also quite variable depending on the specific requirements of the system, the type of system used, geographical locale, and procedures used. The emergency traffic patrol in Chicago, which covers 192 miles of the Chicago area freeway system, has an annual cost of approximately $1.5 million or approximately $7,800 per mile. Freeway courtesy patrols in Houston, which provide emergency vehicle service on 64 miles of freeways, have an annual cost of approximately $230,000, or $3,600 per mile.

Experience has shown that the annual maintenance and operating costs of freeway management systems are also quite variable, depending on the size of the system under control. In Chicago, the annual operating expenditures for the overall freeway surveillance and control systems average approximately 15 percent of the capital investment costs. In Minneapolis, the total system operating costs are $235,000 annually, or about 14 percent of the capital investment costs. Similar costs are being experienced in Los Angeles, and it has been projected that the total annual maintenance and operation costs for the Integrated Motorist Information System (IMIS) in the Northern Long Island Corridor will be approximately 5 to 6 percent of the estimated capital costs. All of these costs (the implementation as well as the annual

◀ *Variable-message signs can be used to warn motorists of ongoing maintenance, repair, and/or construction work ahead.* (Minnesota Department of Transportation.)



maintenance and operating costs) must be viewed with some degree of caution inasmuch as they do not take into consideration the impact of continuing inflation.

HARDWARE AND EQUIPMENT NEEDS

In implementing freeway management control systems, decisions must be made with regard to the type of hardware needed. For the simpler systems (i.e., isolated ramp controls) the hardware components are generally limited to the equipment needed for the control of traffic at a specific location. However, for systemwide surveillance and control systems, the hardware components generally consist of detectors, information and control displays in the field, communications links to and from a control center, and computer and display equipment in the control center.

Detection

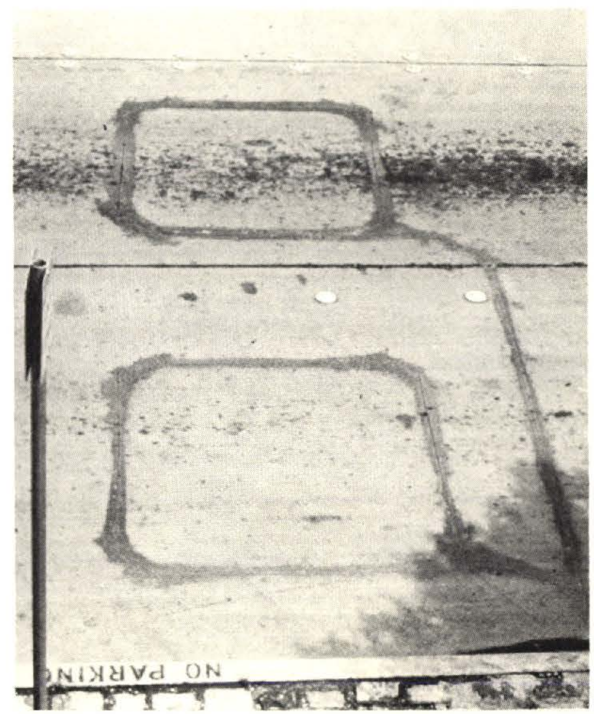
All freeway control systems require some form of data base. These data may be acquired either manually or through automatic detection. The most common means is the use of automatic detection, which senses individual vehicles in the system. These detectors have been used for freeways—ultrasonic, magnetometer, and inductive loop. Of these, the inductive loop detector is considered the best type currently available for freeway control applications.

◀*This detector is an example of those used for simpler control techniques, such as isolated ramp control.* (Alan M. Voorhees & Associates.)

The inductive loop detector helps gather information, from which a data base is formed, for freeway control applications. (Alan M. Voorhees & Associates.)▶

The inductive loop detector operates with loops of wire imbedded in the pavement. As a vehicle passes over the loops, a phase change is induced in the electrical current. When the circuitry senses these changes, it determines that a vehicle is present. This information is then transmitted to a computer for further processing.

Loops can be installed singly or in pairs. Single loops are used to indicate the presence or absence of a vehicle and as such can provide an indication of traffic congestion. This is accomplished by measuring the proportion of time that vehicles are over a loop—a measurement referred to as occupancy. This measurement is used to determine when and where there has been a slowdown in traffic. When pairs of loops are used, speeds can be measured by the time it takes a vehicle to travel from one loop to the next.



Ramp Metering Equipment

As a result of years of field experience, standards have been developed relative to the installation and use of hardware for ramp metering equipment.

Standard traffic control signals are used to control the flow of traffic entering the freeway. For the signal heads, the National Advisory Committee on Uniform Traffic Control Devices has established specific standards. They are:

- The standard display for freeway entrance ramp control signals shall be either a two-indication signal face containing red and green lenses or a standard three-indication signal face containing red, yellow, and green lenses.
- There shall be a minimum of two signal faces per ramp facing entering traffic.
- On entrance ramps having more than one lane there shall be a signal face mounted on the left side and on the right side.
- The required signal faces should be mounted such that the height to the bottom of the housing of the lowest signal face is a minimum of 4.5 ft. and a maximum of 6.0 ft.
- The height of any supplemental signal faces should be consistent with sound design principles and engineering judgment.
- All ramp control signals shall utilize vertically aligned lenses with a minimum nominal diameter of 8 inches.

Ramp metering signs are used to warn the driver that a ramp is under control and to give instructions as to what action to take. Advance-warning signs alert approaching traffic to the presence of a signal on the ramp and generally are placed to the right of the ramp a sufficient distance in advance of the signal to allow for adequate evaluation and reaction time (at least 200 feet). For increased visibility, an advance-warning sign with flashing amber beacons and bearing the legend RAMP METERED WHEN FLASHING is normally used.

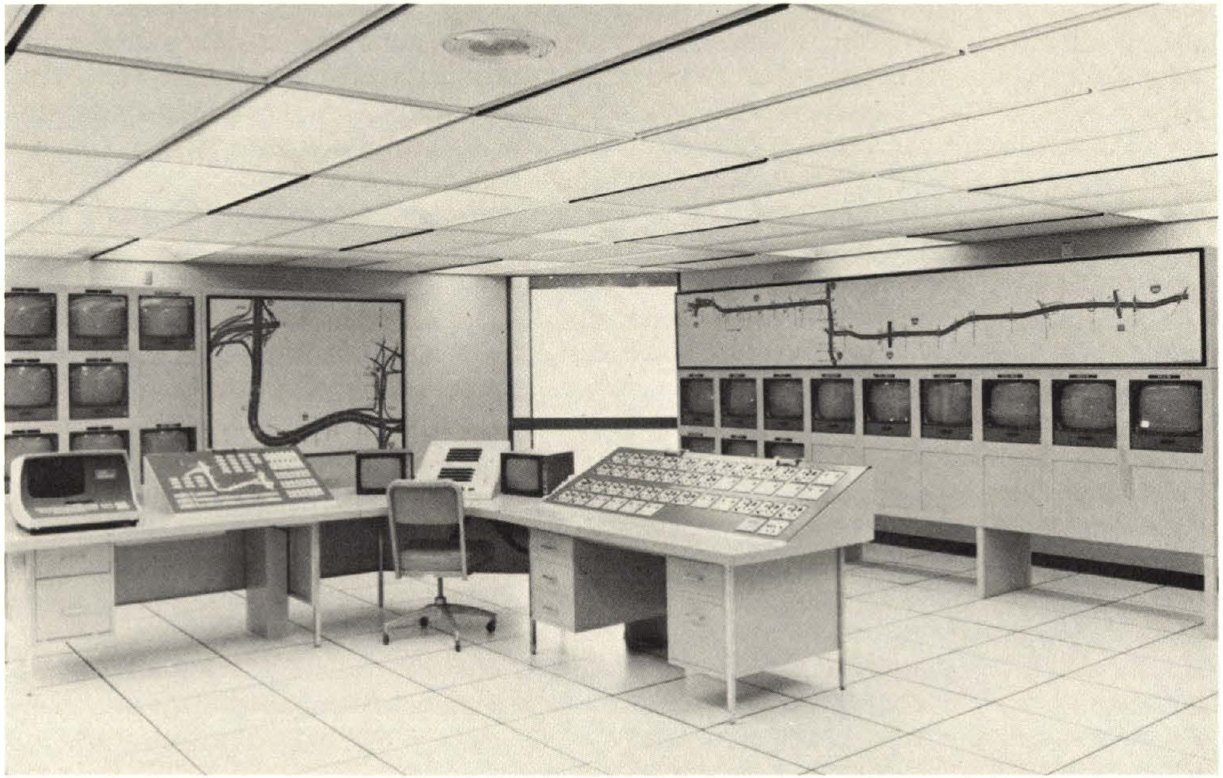
Signs are also used at the signal to define the actions that the driver is to take. In most systems it is standard practice to mount on the same pedestal as the signal head a sign bearing the legend STOP HERE ON RED or WAIT HERE FOR GREEN. Supplementary signs are sometimes used at the signal to indicate the number of cars to be metered during the green interval.

Pavement markings are used to augment the signs and channel the vehicles into the proper lane to facilitate their control. They normally consist of a stop line and other pavement markings needed to reduce a dual-lane ramp to a single-lane width or to delineate a separate priority access lane for high-occupancy vehicles (carpools, buses, etc.).

Three basic types of controllers can be used for ramp metering control—pretimed controllers, centrally located controllers, and locally actuated controllers. The pretimed controller is the simplest of the three and with most installations consists of a one- to three-dial controller operated by a time clock. The metering rates are pre-programmed based on historical traffic data. Although this is the lowest cost system, the limitation of not being able to be responsive to changing flow conditions is a major disadvantage.

The centrally located controller is a system whereby the controller functions are incorporated within a central computer and the need for controller hardware at the ramp site is virtually eliminated. Timing and control operations are provided by relays with instructions to the computer performed by software or by manual inputs. This type of system offers considerable flexibility in that almost limitless timing intervals can be stored in the computer memory and changes in performance can be easily achieved. One

◀*Hardware for ramp metering equipment includes the use of both traffic control signals and ramp metering signs.* (Arizona Department of Transportation.)



◀ *The control center is the focal point for all communications and control in a large-scale freeway management system.* (Minnesota Department of Transportation.)

disadvantage of this type of controller is the requirement for a fairly elaborate communication system between the field and the central control center. Another disadvantage is the loss of system operation in case of computer failure. This problem, however, can be overcome by use of a backup pretimed controller that is used in the event of computer failure.

The locally actuated controllers are basically small computers located in the field. They operate in a stand-alone fashion by selecting metering rates based on real-time information gathered from ramp and mainline detectors. They offer a great deal of flexibility in that they can perform all the local control functions and can serve as the basis for building a systemwide centrally controlled system.

Communication

All freeway traffic control systems require some form of data transmission system. The type of system used generally depends on the type of control used and the type of information to be transmitted. With local control, simple direct wire connections are usually used because the distances between the detectors, controllers, and displays are small. With central control, the distances over which the data must be transmitted are generally large and different means of data transmissions must be considered.

There are basically two types of carriers that can be used in long-distance data transmission—wire-cable and radio. Radio and some forms of microwave systems have been experimented with in recent years but for a number of reasons it has been found that these types of carriers are not particularly applicable to extensive freeway control systems. Some form of wire interconnection (i.e., conventional interconnect cable, twisted-pair cable, or coaxial cable) has been found to be most feasible.

Cable facilities for freeway control systems are either leased from the telephone company or owned by the operating agency. The major factors considered in a tradeoff analysis between these two alternatives are cost, reliability, and ease of incremental systems expansion. Maintenance capability and special conditions of utility franchises are also considerations. The owned-cable system has a higher reliability but the leased-wire system in most instances is less expensive and can be expanded more easily.

Control Center Equipment

The control center is the focal point for all communications and control in a large-scale freeway management control system. At the control center, information concerning traffic is received, analyzed, and evaluated, and decisions are made regarding the type of control to be used. The equipment normally found in a control center consists of the computer and its related peripheral equipment, communication console(s), display components, and equipment for dispatching emergency and maintenance vehicles to the problem locations.

The computer is the nucleus of most centralized freeway management control systems. It normally:

- Performs various functions according to a pre-established priority order
- Gathers information, calculating parameters, making decisions, and outputting control commands
- Operates in real-time so that events, as they occur, initiate pre-established priority-level programs
- Operates automatically on a continuing basis
- Records system performance and outputs the performance in printed form for permanent records, as well as in display form to allow operator interaction with the system
- Controls various kinds of systems, including signing and television subsystems, by turning on, turning off, or selecting equipment, based on previously programmed control and decision logic
- Performs technical analysis when the control system is in off-line mode.

A wide variety of computers is available for use in freeway management control systems. However, because the basic trend is toward greater use of dynamic measurements and more flexibility in system design, the majority of computers used for freeway control are general-purpose digital computers.

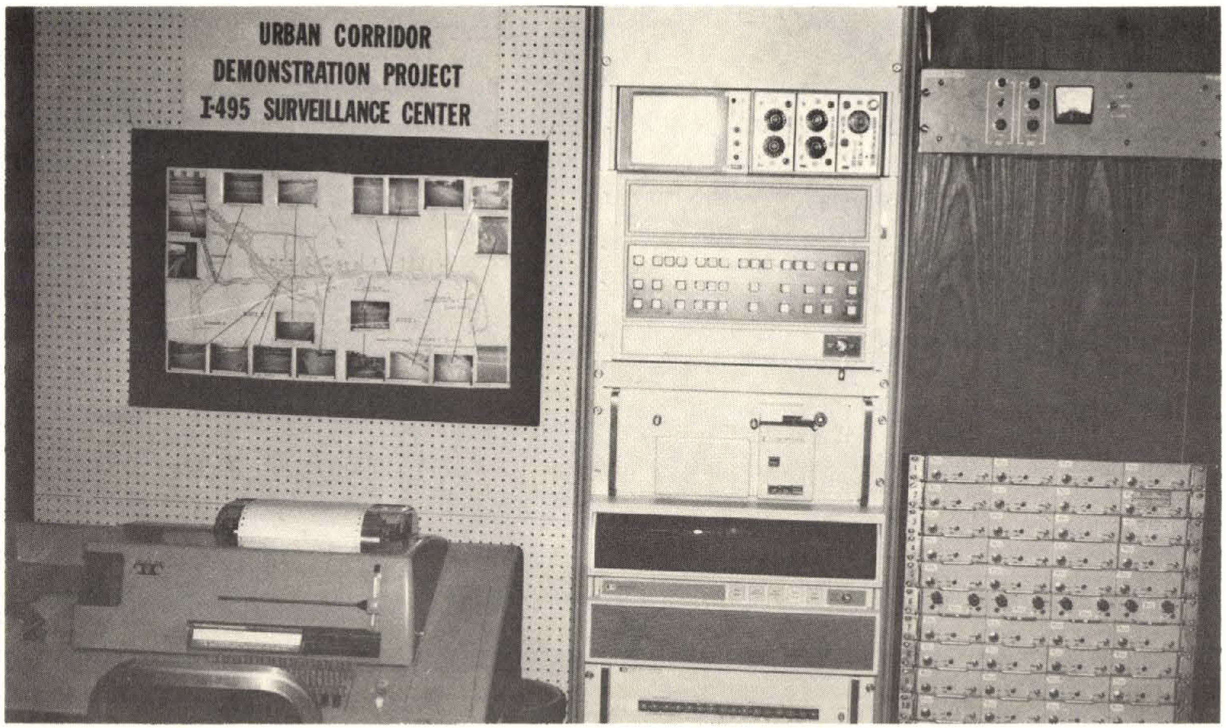
The peripheral equipment used in freeway control systems also includes interactive peripherals and storage devices. The interactive peripherals are those devices that enable the operator to interact with either the computer or the system. They provide a means of obtaining information as well as inputting commands or altering performance. They generally include a teletype, a cathode-ray tube display terminal and a display map. The teletype and the cathode-ray tube are the primary devices for communication between the computer and the operator; the display map is used primarily to provide a visual indication of how the system is working. The display map is often a scaled replica of the freeway control system with colored lights used to show the degree of congestion on the freeway. It is a valuable tool for the operator as it enables him to visualize congested sections and assists in the identification of incidents.

Because of the graphic nature of its display, the map also offers a public relations value in dealing with local officials.

The storage devices are magnetic recording devices (tapes or disks) used for storing large quantities of data on system operations. They are also used for storing programs that are external to the computer but can be called on as needed. Disks are the most flexible for use in freeway control systems and they are becoming an increasingly common peripheral.

STAFFING NEEDS

Staffing requirements for a freeway management control system will vary with the size and complexity of the system. Some small systems (e.g., a 4- or 5-ramp metering system) require only the skills of an experienced traffic operations engineer. These skills include a knowledge of freeway traffic flow concepts, performance evaluation and the ability to monitor the system's operation and make the modifications necessary to enhance performance of the system. In this mode of operation, the traffic operations engineer is responsible for the opera-



Although a wide variety of computers is available for use in freeway management control systems, the majority of them are general purpose digital computers. (The Port Authority of New York and New Jersey.) ▶

tion and maintenance of the system with part-time support from electronic technicians, maintenance staff, and data analysts.

In the larger systems, the tasks or functions that need to be performed tend to be much broader in scope and, therefore, a team of individuals is usually required. Typical functions for these larger systems and the types of skills that match these functions are shown in Table 4. Normally, one individual might possess two or more skills and can fill several functions in this matrix. For example, the traffic operations engineer could, and normally does, serve in the dual role of administrator and traffic analyst. He also assumes the responsibility for developing public relations and citizens information programs based on the operation and performance results of the control system.

In assessing staffing requirements it is most important to define clearly the tasks to be performed and the skills needed to perform these tasks. It is equally important to translate these needs into personnel equivalents, taking into consideration overlapping skills, cross utilization of personnel, and budgetary constraints.

From an organizational point of view, staffing for a freeway management control system needs to be integrated into a functional group with full responsibility for both operation and maintenance. This assures a unified effort in operating, maintaining, and updating the system and provides the opportunity for developing a skilled staff that can be more responsive to the requirements and needs of the system.

This specially designed tow truck, which is owned and operated by a police agency, is an example of interagency cooperation working within a freeway management system. (The Port Authority of New York and New Jersey.) ▶

SUPPORTING NEEDS

An element of considerable importance in implementing a freeway management system is the development of good interagency cooperation. No single agency is capable of handling every aspect of freeway traffic management. The disciplines most involved in freeway management are:

- Public relations, with news media primarily responsible for informing the public about real-time traffic conditions
- Law enforcement, with primary responsibilities for safety of the public
- Traffic engineering, with primary responsibilities for maintaining efficient traffic flows
- Maintenance operations, with primary responsibilities for roadway repairs, incident removal and general overall upkeep of the roadway facilities
- Transit operations, with primary responsibilities for providing public transportation services

There is considerable overlap or interrelationship between these diciplines, and it is essential that the agencies involoved understand and appreciate the overlapping responsibilities involved and work harmoniously so that each agency can better fulfill its role.

Although traffic, enforcement, maintenance and transit are the primary disciplines involved in freeway management, there are other disciplines that also contribute to increasing system efficiency. Included are agencies such as fire departments, ambulance services, utility companies, automobile clubs, and towing service companies. These agencies are generally only called upon to handle special problems, but their importance cannot be overlooked. Development of a good working relationship with each of them during the planning stages will greatly enhance the cooperation needed to ensure better overall system operation.

Public acceptance and citizen support are also critical elements in freeway management programs. The responsibility for achieving this support must be shared by the participating agencies, elected officials and the media. To enable these groups to fulfill their responsibilities, the public must be continually apprised of project development through informational press releases, project newsletters, and other forms of communication. There also must be a process whereby public input can be accomplished through public hearings, citizen committees, forums, and the like. The public at large needs to know the projects to be introduced, the reason for the projects, and the expected

Table 4. Position and Functions of All Possible Staff

POSITION \ FUNCTION	Administration	Systems Planning	Performance Evaluation	Computer Programming	Computer Operation	Computer Maintenance	Equipment Maintenance	Public Relations	Documentation and Publication
Project Manager	●							●	●
Traffic Operations Engineer	●	●	●					●	●
Systems Analyst			●	●					●
Computer Programmer				●					●
Computer Operator					●				
Electronic Technician						●	●		
Engineering Technician							●		
Data Analyst			●						

benefits. At a different level, the motorist who uses the corridor needs to know what changes are taking place and how these changes may affect his daily travel patterns. Failure to recognize the importance of public involvement can often lead to complete rejection of a freeway management program.

FUNDING SOURCES

With the increasing costs of operating and maintaining transportation systems, the highway administrator is constantly challenged with the development of funding sources that will meet the needs of the various programs within his system. Because freeway management and control systems normally involve fairly extensive capital improvement expenditures as well as a long-term commitment for operations, and because there are numerous competing programs, funding of freeway management control projects is always an issue. It is therefore important in the planning of a system that the full range of funding sources be carefully examined.

The most common funding sources for freeway management control projects are the Federal Highway Administration (FHWA) programs authorized by the Federal-Aid Highway Act. Funds under these programs are available for operational improvements as well as capital improvements on all freeways on the Federal-Aid highway system. Typically, a local or state agency initiates the projects and they are then submitted through the state agency to the Federal Highway Administration for review and approval. Once approval is obtained, the funds are apportioned to the state highway or transportation agency, which maintains administrative responsibility and control. Funds under these programs are typically on a 90-10 or 70-30 matching basis, with joint funding from both FHWA and the local and/or state agency.

The assistance that can qualify under these programs includes:

- Preliminary engineering, and system design
- Preparation of software and programming of systems operation
- Hardware acquisition and installation
- Housing for control and monitoring equipment
- Construction of priority vehicle facilities
- System evaluation

Special activities, such as those that encourage carpooling, vanpooling, ridesharing, and greater use of buses, are also eligible.

Other sources of funding for freeway management control projects are the various categorical funding programs of the U.S. Department of Transportation and special multi-agency funding programs. For example, the I-35W Freeway Surveillance and Control Project in Minneapolis was funded at the 100 percent level with funds from the Urban Corridor Demonstration Program (UCDP). It is also possible to fund certain study elements of a freeway management control system under FHWA's Federally coordinated program of research and development. However, the physical design, construction, operation, and maintenance of a system are not eligible under this program.

◀*San Francisco Bay Bridge toll plaza and metering signals, with HOV bypass lanes.* (San Francisco Examiner.)

Chapter Five

System Operations

Once a freeway management control system has been installed, it cannot be left to operate on its own—operation, evaluation and maintenance functions must be provided on a continuing basis. These functions include system monitoring, performance evaluation and system maintenance.

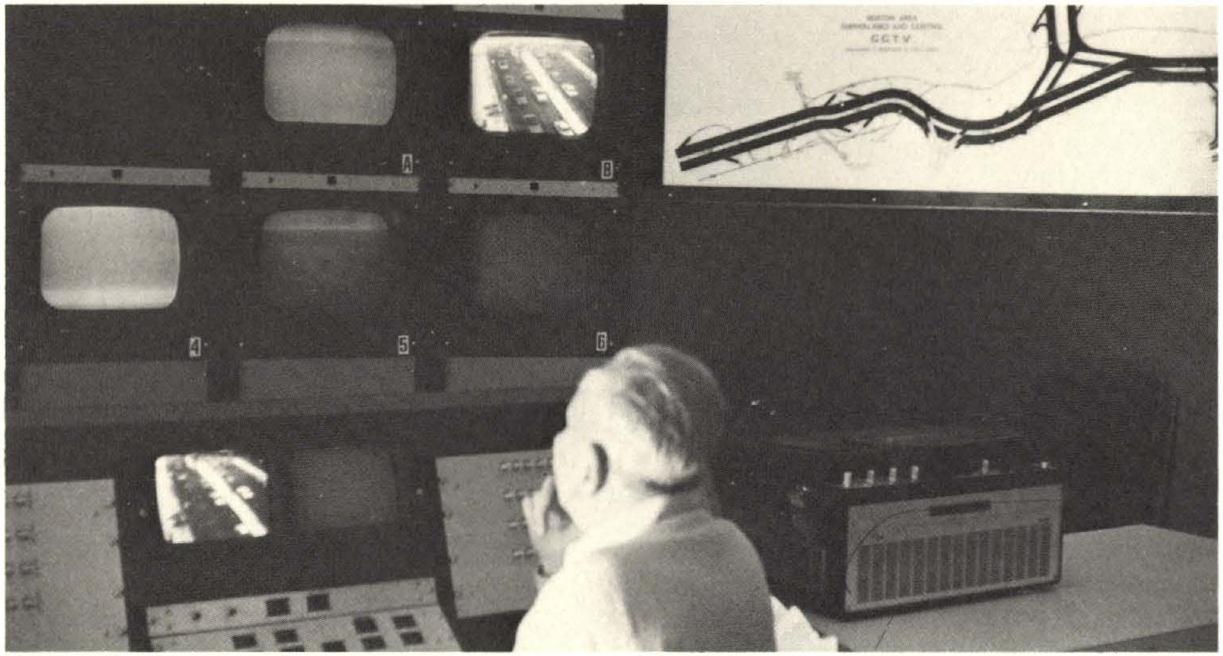
SYSTEM MONITORING

In monitoring a system, three levels are normally required. The first level is at the policy level and involves those who have various degrees of administrative responsibility (i.e., traffic commissioner, state highway agency director, police chief, etc.). At this level, freeway management projects are evaluated on the basis of their overall impact on the public, their relationship to other projects in the region, and their long-range effect on the region's total transportation and traffic needs. Day-to-day operational problems are of little concern, except for special events that may require high-level attention. The information input for this level of monitoring is usually in the form of summary reports from the freeway project staff; control is in the form of policy directives.

The second level of monitoring is at the engineering/technical level and involves those responsible for development and maintenance of operating procedures, traffic flow analyses, and performance evaluations. The primary objective at this level is to be responsive to changing traffic needs and to upgrade the system in response to those needs or because of technological advances that will permit a given function to be performed more efficiently. Input is obtained from operating reports, traffic surveillance statistics, traffic surveys, public relations, communications with other agencies, and special research and operational studies; control at this level is accomplished through exercise of adjustments in system parameters, control strategies, and operating procedures. This level of monitoring is mostly concerned with the evolutionary aspect of traffic control strategies and does not get involved with the day-to-day operation of the system except when unusual events occur that require substantial modifications to the system.

The third level of monitoring involves the

◀ *I-495 Beltway around Washington, D.C.* (Mark Herndon for Alan M. Voorhees & Associates.)



◀ *Day-to-day monitoring of a freeway management system involves constant surveillance of both operating conditions on the freeway and operating performance of the equipment.* (City of Boston.)

day-to-day operation of the system. An operator maintains a constant surveillance not only of the operating conditions on the freeway but also of the operating performance of the equipment. Information is obtained through computerized surveillance, television surveillance, police reports, private citizens, repair and maintenance notices, and computer alarms; control consists of some form of override or intervention based on operating procedures developed by the engineering/technical staff—i.e., the response to an alarm condition to ensure that proper action is taken or the implementation of an emergency strategy in response to a need to exercise more control.

PERFORMANCE EVALUATION

The primary objective of most freeway management control systems is to increase the safety and level of service of the facilities within a freeway corridor. In most cases, justification for such systems is made on the basis of some forecast of the benefits that may result. It is therefore necessary to determine the effectiveness of the system and to ascertain whether the expected results have been attained. Such an evaluation is also useful in identifying ways to increase the benefits further or to justify expansion or upgrading of the system.

Evaluation Criteria

Performance evaluation of a freeway management control system is not only desirable from the viewpoint of knowing how well the system is performing, but is also a requirement for those projects implemented with Federal funding assistance. The *Federal Aid Highway Program Manual* requires that all traffic control systems installed with Federal-aid funds be evaluated "at the earliest possible date that will accurately reflect stable operating conditions." These requirements include the following considerations:

- The evaluation should measure the effects of the system on safety and traffic flow quality.
- It must be an evaluation that directly compares the operation of the new system with the operation of the original system.
- Typical measures to be used in the evaluation include volumes, accidents, accident rates, travel speeds, travel time, delay, density, etc.

In general, four basic measures of effectiveness can be used in evaluating the performance of a freeway management control system. These are:

- Changes in congestion levels reflected through traffic measures such as volumes, total travel time, total travel speed, and duration of congestion.
- Changes in system costs, both to the user and to the system operator.
- Changes in safety, using factors such as decreased accidents or decreased accident rates.
- Changes in accessibility as indicated by decreased delays in the system.

Additional criteria, such as reduction of air pollution, decrease of fuel consumption, and increase of driver satisfaction, are measures of effectiveness that may also be warranted in an evaluation. However, these measures often are considerably more difficult to quantify and, when used, they are normally derived from basic traffic flow measurements.

Evaluation Planning

The performance evaluation is in reality an integral part of the system implementation; as such, the evaluation plan must be considered in the early stages of the development planning process. It involves identifying improvement objectives, determining what effectiveness measures are to be used, developing a data collection plan, and selecting an evaluation methodology. Common pitfalls are to collect more data than needed or to collect data on an ad hoc basis without knowing how the data will be used. Another common pitfall is the failure to clearly document conditions prior to implementation of the improvement program.

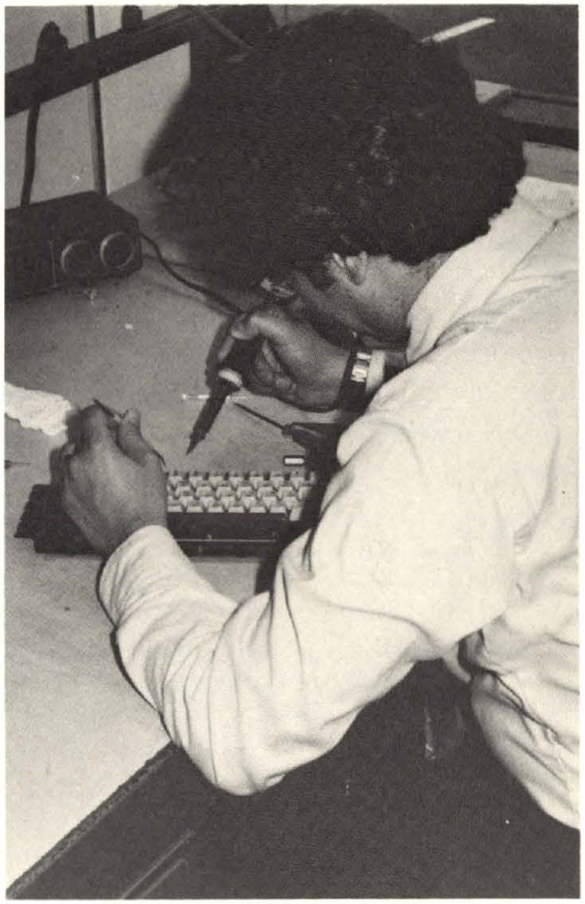
Two basic techniques normally are used in evaluating freeway management control projects—"before-and-after" studies and "control group" studies. The "before-and-after" technique is the method most commonly used in evaluating effects of new improvements. This approach establishes the "before" measurement as the base and assumes that the difference between the "base" condition and the conditions after the improvements have been installed represents the full effect of the improvement. In using this method, data collection efforts must be carefully planned to minimize the effect of time-related changes that may influence conditions between the before and after measurements. It is also important to recognize the limitation of not being able to differentiate between the impact of individual improvements—only the impact of the total system is possible.

The "control group" method of evaluation involves selecting a facility that has characteristics similar to the facility for which the freeway management system is to be implemented. This facility then serves as the control area. The effects of the improvements are then determined by comparing the conditions in the test area with those in the control area. Although this technique overcomes the problem of time-related effects, it often is difficult to identify a control area which has characteristics similar to those of the test area.

Regardless of the study technique used, the critical element in the evaluation of a project is selection of data and sampling technique. A careful design of the sampling procedure is of utmost importance to ensure that the effects of the improvements are properly represented.

The evaluation planning element must also take into consideration the changes in travel patterns that relate directly to the types of controls that are implemented. Some common changes that typically result from a freeway control system are bottleneck shifting, time shifts in demand, localized operational problems, localized increase in demand, and a general redistribution of traffic. All these changes have to be carefully evaluated and the various control strategies have to be modified to match the actual traffic needs as they evolve and change over time.

Maintaining equipment in proper working condition is essential to a freeway management system's ability to perform its intended function. (Alan M. Voorhees & Associates.) ▶



SYSTEM MAINTENANCE

The ability of a freeway management control system to perform its functions with optimum effectiveness is highly dependent on the quality and level of maintenance provided. The consequences of a breakdown or malfunctioning of system equipment include disruptions in traffic flow, increases in accident potential and, often, loss of credibility with the motoring public. There is also a legal implication. If an injury or damage occurs because some element of the system fails, there could be a case of liability against the operating agency. Therefore, maintenance is an extremely important aspect of the system operation.

Development of a maintenance management program for a freeway control system will vary depending on the type of system being used. For example, a centrally controlled system permits continuous monitoring of all the hardware elements of the system (i.e., controllers, detectors, communication links, etc.). With this type of extensive monitoring, failures in equipment performance can be detected early and maintenance response can be almost immediate if necessary. Thus, preventive maintenance purposes can be accomplished more efficiently. On the other hand, the non-centralized systems (such as an isolated ramp metering system) can create different types of maintenance management problems. In order to detect a malfunction or failure of these systems, frequent field checks are required which tend to be expensive and often take place even when the system is functioning properly.

The maintenance of the field equipment is often independent of the type of system used. Local controllers represent state-of-the-art equipment used in other traffic control applications and are usually low-maintenance devices requiring no special skills for their repair. A good practice, however, is to minimize to the extent possible the actual maintenance time at the field site. This can be accomplished through the total replacement of faulty elements in the field so that their repair can be more effectively performed at a maintenance station where test equipment and other repair facilities are readily available.

In the centrally controlled systems where digital computers are used, most agencies find that the best practice is to use maintenance contracts in preference to adding specialized staff. Such contracts can be made with the computer manufacturer or with some independent service firm. Typical contracts provide for both scheduled and unscheduled maintenance (including parts and labor), and the costs are always less than that of having full-time computer maintenance personnel.

Another important aspect of maintenance management is to properly develop and utilize service histories related to equipment performance. They form the basis for many maintenance decisions. They also help determine the level of inventory control needed for proper maintenance. As a general rule, a spare parts inventory of approximately 10 percent is considered adequate for an agency that performs its own maintenance.

An example of the distribution of maintenance time allocation and maintenance calls for the I-35W freeway management control system in Minneapolis is given in Table 5. These numbers are directly related to a detector-based system with relatively limited closed-circuit TV and therefore are not applicable to all systems. However, they do give an indication of where most of the maintenance problems normally occur —in the detection and communication system.

Table 5. Distribution of System Maintenance

System	% of Calls	Maintenance Time Allocation (%)			
		Adjusting	Field Repair	Shop Repair	Total
CCTV	12.4	1.8	15.3	4.9	22.0
Detectors	42.7	13.7	16.9	5.4	36.0
Ramp Controls	7.7	0.3	3.8	0.4	4.5
Changeable-Message Signs	2.4	0	3.6	0	3.6
Lane Signals	0.7	0	0.2	0	0.2
Communications	29.0	0.7	24.0	6.4	31.1
Miscellaneous	5.1	0.5	1.4	0.7	2.6
TOTALS	100.0	17.0	65.2	17.8	100.0

References

Information Sources

◀ *Route 580, Oakland, California. Beaumont Avenue ramp metering.* (California Department of Transportation.)

This section provides abstracts of six of the more significant documents that provide state-of-the-art summaries on freeway traffic management. It also provides a supplemental bibliography on the subject.

ABSTRACTS

Everall, Paul F., *Urban Freeway Surveillance and Control: The State of the Art.* Prepared for U.S. DOT, FHWA, 1972.

This report presents a state-of-the-art survey of urban freeway surveillance and control systems. It begins with an introduction to freeway problems that are subject to solution by surveillance and control techniques. Measures and methods to document operational problems are discussed to aid the analyst in determining what surveillance and control systems should be considered. Solutions to freeway problems are presented, along with descriptions of the detailed hardware requirements. A summary of existing ramp control projects is presented and a benefit-cost study of their effectiveness is provided. The report concludes with an extensive list of references identifying more than 200 articles and reports dealing with freeway surveillance and control.

Organization for Economic Cooperation and Development, *Research on Traffic Corridor Control,* November 1975.

The OECD Group International Corridor Experiment (ICE) Project was created to examine the strategies available for traffic corridor control and to outline potential international coordinated research that could be performed on a corridor facility of a member country on the basis of the needs of another member country. The Group's objective was to bring together and exploit the expertise on traffic control available in participating OECD countries in order to make the most rapid and efficient impact on the very complex subject of traffic corridor control. The experience of developments such as ramp control systems in the United States, coordinated signal control in Europe, and motorist warning systems in Japan provided the basis for the Group's work. The following five types of corridors, both in urban and in rural areas (intra-city and inter-city), were considered within the

framework of the program: (1) motorway and motorway; (2) motorway and coordinated area traffic control system; (3) motorway and street network (uncoordinated control); (4) motorway and suburban road network (including controlled arterials); (5) motorway and rural roads. The report contains six chapters, a list of key references, and eight annexes.

Peat, Marwick, Mitchell and Company, "Review of Current and Proposed Low-Cost Freeway Incident Management Systems," U.S. Department of Transportation, 1977.

This research report was prepared as an interim report for contract DOT-FH-11-8813, entitled "Alternative Surveillance Concept and Methods of Freeway Incident Management." The results of an in-depth review and preliminary analysis of the state of the art of various minimum investment, low technology, and freeway incident management systems are presented. This effort included an extensive literature review and interviews conducted with interested agencies working in the freeway incident environment. In addition, a number of on-site incident investigations were conducted and 15 videotape investigations provided the basis for the structure of six candidate freeway incident management systems, which are organized along functional lines. The detection, administrative, organizational, preplanning, and traffic control options of each of the candidates are presented with respect to their costs, characteristics, effectiveness, remedial potential, and several option-specific issues. Finally, data are presented to suggest a particular option effectiveness as compared with the total universe of all incidents.

Stanford Research Institute, *Guidelines for Design and Operation of Ramp Control Systems,* National Cooperative Highway Research Program Project 3-22, 1975.

This report is intended as a guide for designers of ramp-metering control systems. It is aimed at the working traffic engineer who has had a minimum of freeway operations experience. The emphasis is on practical and proven techniques, not on research or experimental procedures. As a first step, the report provides guidance in determining whether a proposed metering system is potentially effective. Assuming that cost and related criteria are met, guidelines are given for the design, implementation, and operation of systems using three types of metering: pretimed, locally actuated, and centralized. Multiple-system metering is also treated briefly. A final chapter cites the benefits and costs of ramp metering at a number of existing locations and describes techniques for a specific benefit-cost study.

Taragin, Asriel, *Summary of the John C. Lodge Freeway Research*, NCHRP, July 1976.

This report provides both the management background and a summary of the technical results of the long-continuing freeway surveillance and control research on the John C. Lodge Freeway in Detroit, Michigan. It describes the history and technical activities of the research conducted just by local agencies in Michigan, later under the more broadly supported National Proving Ground and, finally, through the mechanism of two successive NCHRP projects. A complete list of references and an annotated bibliography are also provided.

U.S. Department of Transportation, Federal Highway Administration, *Traffic Control Systems Handbook,* June 1976.

This handbook, which was developed in recognition of the need for compilation and dissemination of information on advanced traffic control systems, presents the basic principles for planning, design, and implementation of such systems for urban streets and freeways. The presentation concept and organization of this handbook is developed from the viewpoint of systems engineering. Traffic control studies are described, and traffic control and surveillance concepts are reviewed. Hardware components are outlined, and computer concepts and communication concepts are stated. Local and central controllers are described, as well as display, television, and driver information systems. Available systems technology and candidate system definition, evaluation, and implementation are also covered. The management of traffic control systems is discussed. Appendices are included which provide information on: freeway origin-destination study, freeway input-output studies, acceleration noise-mean velocity gradient, travel time and delay, measures of the quality of traffic service, information sources, costs checklist, costs of freeway ramp metering systems, and costs of selected urban street traffic control systems.

The handbook contains information on a systems approach to traffic control, traffic control studies, traffic control concepts for urban street systems and freeways, surveillance concepts, hardware, computer concepts, communication concepts, traffic detectors, local and central controllers, display, television, and driver information systems.

SELECTED BIBLIOGRAPHY

Allen, B.L., and Newell, G.F., "Some Issues Relating to Metering or Closing of Freeway Ramps: Part I. Control of a Single Ramp." (California University, Berkeley), *Transportation Science,* Vol. 10, No. 3, August 1976.

Anderson, et al., "Alternate Designs for CCTV Traffic Surveillance Systems." Texas Transportation Institute, August 1976.

Athol, P.J., et al., "Multiple Ramp Control for a Freeway Bottleneck," *Highway Research Record 456,* 1973.

Bather, Ringrose, and Wolsfeld, Inc., *Final Report for the I-35W Urban Corridor Demonstration Project.* August 1975.

Berger, et al., "Single Point Diversion of Freeway Traffic," *Transportation Research Record 601,* pp. 10-18.

Billheimer, et al., *The Santa Monica Freeway Diamond Lanes Volume II; Technical Report.* U.S. Department of Transportation, September 1977.

Bonsall, et al., *Contra-Flow Exclusive Bus Lanes; The Ottawa River Parkway Experience.* Roads and Transportation Association of Canada, 1976.

Buhr, J.H., et al., "Design of Freeway Entrance Ramp Merging Control Systems," *Highway Research Record 279,* 1969, pp. 137-149.

Carvell, J.D., "Dallas Corridor Study: Final Report." Texas Transportation Institute, August 1976.

Carvell, J.D., "Freeway Operations Manual, Dallas Corridor Study." Texas Transportation Institute, September 1974.

Cook, A.R., "Management of Urban Freeway Traffic," *Canadian Journal of Civil Engineering,* Vol, 1, No. 2, December 1974.

Cook, A.R., and Cleveland, D.R., "Detection of Freeway Capacity-Reducing Incidents by Traffic-Stream Measurements," *Transportation Research Record 495,* 1974, pp. 1-11.

Cooper, D.L., and Walinchus, R.J., "Measures of Effectiveness for Urban Traffic Control Systems," *Highway Research Record 321,* 1970, pp. 46-61.

Courage, K.G., "Freeway Surveillance and Control: A State-of-the-Art Summary," Paper presented at the Computer Traffic Control Workshop, University of Minnesota, March 20-22, 1974.

Courage, K.G., and Bissell, H.H., "Jones Falls Expressway Surveillance and Control System." Kelly Scientific Corporation, 1971.

Courage, K.G., and Levin, M., "A Freeway Corridor Surveillance, Information and Control System." Texas Transportation Institute Report 488-8, December 1968.

Courage, K.G., et al., "Operating Parameters for Main-Line Sensors in Freeway Surveillance Systems," *Transportation Research Record 601,* 1976, pp. 19-28.

Covault, D.O., and Bowes, R.W., "A Study of the Feasibility of Using Roadside Radio Communications for Traffic Control and Information," *Highway Research Record 49,* 1964, pp. 89-106.

Covault, D.O., and Kirk, R.C., "Influence of Off-Ramp Spacing on Traffic Flow Characteristics on Atlanta Freeway and Arterial Street System," *Highway Research Record 59,* 1964, pp. 39-52.

Daniels, et al., "Improving Commercial Radio Traffic Reports in the Chicago Area," *Transportation Research Record 600,* 1976, pp. 52-57.

Drew, D.R., "Deterministic Aspects of Freeway Operations and Control," *Highway Research Record 99,* 1965, pp. 48-58.

Drew, D.R., and Keese, C.J., "Freeway Level of Service as Influenced by Volume and Capacity Characteristics," *Highway Research Record 99,* 1965, pp. 1-38.

Drew, D.R., et al., "Gap Acceptance and Traffic Interaction in the Freeway Merging Process—Phase II." Texas Transportation Institute Report, 1970.

Drew, D.R., et al., "Multilevel Approach to the Design of a Freeway Control System," *Highway Research Record 279,* 1969, pp. 40-55.

Dudek, C.L., and Carvell, Jr., J.D., "Feasibility Investigation of Audio Modes for Real-Time Motorist Information in Urban Freeway Corridors." Texas Transportation Institute, Report RF953-8, April 1973.

Dudek, C.L., and Jones, H.B., "Evaluation of Real-Time Visual Information Displays for Urban Freeways," *Highway Research Record 366,* 1971, pp. 64-78.

Dudek, C.L., and McCasland, W.R., "Cost-Effectiveness of Freeway Merging Control," *Highway Research Record 363,* 1971, pp. 43-59.

Dudek, C.L., et al., "Detecting Freeway Incidents Under Low-Volume Conditions," *Transportation Research Record 533,* 1975, pp. 34-47.

Dudek, C.L., et al., "Evaluation of Commercial Radio for Real-Time Driver Communications on Urban Freeways," *Highway Research Record 358,* 1971, pp. 17-25.

Duff, J.T., "Accomplishments in Freeway Operations Outside the United States," *Highway Research Record 368,* 1971, pp. 9-25.

Emery, R.H., "Evaluation of Motorist Aid Systems." Federal Highway Administration, 1971.

Estep, A.C., "The Los Angeles 42-Mile Surveillance and Control Project," *Highway Research Board Special Report 128,* 1972, pp. 96-99.

Estep, A.C., et al., "Getting the Most Out of a Freeway System," *Transportation Research Board Special Report 153,* 1975, pp. 10-18.

Fambro, D.B., et al., "Cost Effectiveness of Freeway Courtesy Patrols in Houston," *Transportation Research Record 601,* 1976, pp. 1-7.

Foote, R.S., "Intensive Traffic Management for Critical Roadways," *Traffic Engineering and Control,* Vol. 15, No. 19, Nov. 1974.

"Freeway Operations Research Division, Closed Circuit Television Freeway Surveillance," Annual Summary, 1970. Washington Department of Highways, District 7, June 1971.

Gervais, E.F., "Optimization of Freeway Traffic by Ramp Control," *Highway Research Record 59,* 1964, pp. 104-118.

Goolsby, M.E., "Influence of Incidents on Freeway Quality of Service," *Highway Research Record 349,* 1971, pp. 41-46.

Green, R.H., "The 42-Mile Freeway Surveillance Loop," Freeway Operation Department, District 7, California Division of Highways, 1973.

"Guidelines for Design and Operation of Ramp Control Systems," *Transportation Research Board NCHRP Digest 86,* March 1976, 5 pp.

Hess, J.W., "Ramp-Freeway Terminal Operation as Related to Freeway Lane Volume Distribution and Adjacent Ramp Influence," *Highway Research Record 99,* 1965, pp. 81-116.

Highway Research Board, "An Inventory of Freeway Surveillance and Operation Control Activities by State Highway Agencies and Toll Facility Authorities in the United States of America," *Highway Research Circular 108*, 1970, 38 pp.

Hulbert, S., and Beers, J., "Research Development of the Changeable-Message Concept for Freeway Traffic Control," *Highway Research Board Special Report 129,* 1971, pp. 24-25.

"Incidents and Freeways Operations," *Transportation Research Record 495,* 1974, 91 pp.

Jones, H.B., and Dudek, C.L., "Real-Time Information Needs for Urban Freeway Drivers." Texas Transportation Institute, Report 139-4, 1970.

Lehmann, E.J., "Urban Automated Traffic Control (A Bibliography with Abstracts)," National Technical Information Service Bibliography, May 1975.

Lopatin, "Moving More People with Fewer Vehicles," *Traffic Engineering,* Vol. 46, No. 2, February 1976.

McCasland, W.R., *Design and Evaluation of Freeway Surveillance* *and Traffic Control Systems,* Federal Highway Administration, May 1976.

McCasland, W.R., "Review of Research on Controlling the Level of Service on Urban Freeways," *Transportation Research Board Special Report 153,* 1975, pp. 26-31.

McCasland, W.R., and Biggs, R.G., "A Study of Microwave Television for Traffic Surveillance in Texas," Texas Transportation Institute (Res. Rept. 165-9) August 1975.

McCasland, W.R., and Ibanez, J.H., "Study of Traffic Responsive Ramp Closure Control," Texas Transportation Institute Report, August 1972.

McDermott, J.M., "Incident Surveillance and Control on Chicago-Area Freeways," *Transportation Research Board Special Report 153,* 1975, pp. 123-140.

McDermott, J.M., et al., "Chicago Area Expressway Surveillance and Control." Draft Final Report State of Illinois, Department of Transportation, June 1977.

Madsen, L., "A Non-Recurrent Incident and Its Effects." California Division of Highways, District 7, Freeway Operation Department, Report No. 68-4, June 1968.

May, A.F., "Optimization Techniques Applied to Improving Freeway Operations," *Engineering Optimization,* Vol. 2, 1976.

May, A.F., et al., *Optimal Design and Operation of Freeway Incident Detection-Service Systems.* U.S. Department of Transportation, February 1975.

Miller, S.D., and Payne, H.J., "Design Technique for Priority- Access Ramp Metering," *Transportation Research Record 533,* 1975, pp. 110-121.

Morin, "The Traffic Engineers' Challenge—Preferential Treatment for High-Occupancy Vehicles," *Institute of Traffic Engineers, Proceedings, Vol. 4s,* August 1975.

Moskowitz, K., "Analysis and Projection of Research on Traffic Surveillance, Communication, and Control," *NCHRP Report 84,* 1970, 48 pp.

"Motorist Aid Systems," *NCHRP Synthesis 7,* 1971, 28 pp.

Murphy, R.J., "A Program to Upgrade and Control the Los Angeles Freeway Network." Division of Highways, District 7, California Transportation Agency Department of Public Works, July 1970.

Newman, "Bus-Carpool Freeway Lanes in San Francisco Area." *ASCE Journal of Transportation Engineering,* Conference Paper, November 1976.

Newman, L., et al., "Freeway Ramp Control—What It Can and Cannot Do," *Traffic Engineering,* Vol. 19, No. 7, June 1969.

Newman, L., et al., "An Evaluation of Ramp Control on the Harbor Freeway in Los Angeles," *Highway Research Record 303,* 1970, pp. 44-55.

Owen, J.R., and Urbanek, G.L., "Alternative Surveillance Concepts and Methods for Freeway Incident Management," Peat, Marwick, Mitchell & Co., March, 1978.

Payne, H.J., et al., "Ramp Control to Relieve Freeway Congestion Caused by Traffic Disturbances," *Highway Research Record 469,* 1973, pp. 52-64.

Pinnell, C., *Inductive Loop Detectors: Theory and Practice.* Federal Highway Administration, January 1976.

Pinnell, C., et al., "Evaluation of Entrance Ramp Control on a Six-Mile Freeway Section," *Highway Research Record 157,* 1967, pp. 22-76.

Port Authority of New York and New Jersey, "Implementation of the I-495 Bus Priority Transportation Management System." Federal Highway Administration, Urban Mass Transportation Administration, April 1976.

Pretty, R.L., "Control of a Freeway System by Means of Ramp Metering and Information Signs," *Highway Research Record 388,* 1972, pp. 62-72.

Roper, et al., "Alternate Route Planning: Successful Traffic Management," *Transportation Research Board Special Report 153,* 1975, pp. 141-144.

Sakasita, et al., "Development and Evaluation of Incident-Detection Algorithms for Electronic-Detector Systems on Freeways," *Transportation Research Record 533,* 1975, pp. 48-63.

Santerre, G.L., "An Investigation of the Feasibility of Improving Freeway Operation by Staggering Work Hours." Texas Transportation Institute Research Report 24-16, 1967.

Shaw, L., and McShane, W.R., "Optimal Ramp Control for Incident Response," *Transportation Research,* Vol. 7, Dec. 1973.

State of California, Business and Transportation Agency. *Los Angeles Area Freeway Surveillance and Control Project: Third Annual Report,* February 1973.

Stover, V., "A System to Facilitate Bus Rapid Transit on Urban Freeways: The Technical Feasibility of Using Traffic Surveillance and Control Techniques." Texas Transportation Institute, December 1968.

Tignor, S., "Operational Analyses of Freeway Moving-Merge Systems," *Transportation Research Record 533,* 1975, pp. 1-21.

Tignor, S., et al., "Signalization of Diamond Interchanges," *Public Roads,* Vol. 39, No. 2, September 1975.

Trabold, W.G., and Prewitt, T.A., "A Design for an Experimental Route Guidance System," *Highway Research Record 265,* 1968, pp. 50-61.

"Transportation System Management," *Transportation Research Board Special Report 172,* 1977, 163 pp.

Wang, J.J., and May, A.D., "Analysis of Freeway On-Ramp Control Stategies." California University, Berkeley, California, June 1973.

Wattleworth, J.A., "Peak-Period Analysis and Control of a Freeway System," *Highway Research Record 157,* 1967, pp. 1-21.

Wattleworth, J.A., et al., "An Evaluation of Two Types of Freeway Control Systems." Texas Transportation Institute, College State, Report 488-6, 1968.

Wattleworth, J.A., and McCasland, W.R., "Study Techniques for Planning Freeway Surveillance and Control," *Highway Research Record 99,* 1965, pp. 200-223.

Worrall, R.D., et al., "Merging Behavior at Freeway Entrance Ramps: Some Elementary Empirical Considerations," *Highway Research Record 157,* 1967, pp. 77-107.

Zove, P., et al., "Integrated Motorists Information System (IMIS) Feasibility and Design Study," Sperry Rand Corporation, May 1978.

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