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Accomplishments in Freeway Operations

5 Reports

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53	Traffic Control and Operations
54	Traffic Flow

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FOREWORD

The papers in this RECORD were presented during one of the special anniversary sessions held as part of the commemoration of the Board's 50th anniversary. Special credit is due Adolf D. May, chairman of the Committee on Freeway Operations, to whom the Group 3 Council gave major responsibility for development of the program. His knowledge of freeway operations throughout the world and the people who are working in this field greatly facilitated contributions of material to the 2 discussions on accomplishments within the United States and outside the United States.

In the report of the first discussion, Duff describes freeway operations outside the United States. Notable progress is reported from West Germany, England, Japan, Italy, and France. Although the extent of the freeway systems is smaller in these countries than in the United States, many similar problems are being addressed in ways that operations authorities will find of interest. Considerable detail is included relative to control schemes and systems in each of these countries.

For the United States, reporter Wattleworth summarizes operational experience in several locations, including Houston, Los Angeles, Chicago, Detroit, and New York City. He presents appraisals of accomplishments in the areas of improved freeway designs, surveillance and control, secondary benefits of surveillance and control, and improved safety. Among the benefits from these accomplishments are reduced delay and travel time, increased safety, and improved service to motorists.

A transcript of the discussion between audience participants and distinguished members of the 2 panels is included.

Foote discusses accomplishments in freeway operations from the standpoint of instrumentation and traffic flow theory and reviews the developmental milestones that have made today's advances possible. His perceptive overview leads also to conclusions regarding the path we are likely to follow toward more automatic real-time systems for surveillance and control in the future.

Schaefer discusses traffic management systems for freeways and makes a strong case for the necessity for authorities to operate freeways as well as to plan, design, and build them. His approach is to state several rather widely believed "myths" about freeways and then to systematically present contrary views based on extensive experience in freeway operations.

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INSTRUMENTATION DEVELOPMENT AND CONTRIBUTIONS FROM TRAFFIC FLOW THEORY

Robert S. Foote, The Port of New York Authority

•DURING the past 50 years, freeway operations has not generally been a major subject. In the mid-1960's when Cameron and Davis organized their excellent review of roads and highways for the Encyclopedia Britannica, the subject of operations was the last entry. In fact, it was just part of an entry called "Maintenance and Operations." One of the first entries in that article concerned the Roman roads, and that recalled an experience that I had while in Italy in 1968.

The Italian autostradas are among the outstanding highway construction accomplishments in the world today. In some cases the mileage consists more of tunnels and viaducts than of sections at grade. The autostradas generally incorporate the highest geometric design standards and safety features. It was the end of a 4-day national holiday when I saw them for the first time, and this magnificent system was littered for miles with accidents and congestion. This, of course, happens at times on the freeway systems in every country, but the contrast between the really beautiful road system and the level of traffic operations that night was especially sharp.

There seem to me to be 2 broad developments responsible for moving the status of freeway operations from an adjunct to maintenance to a major subject in its own right. One is the increasing dependence on freeways for travel, especially in urban areas. The other is the growth in knowledge and systems for improving freeway operations. This has taken place mainly in the past 15 years. Both of these broad developments seem likely to continue and to reinforce each other.

Freeway operations in the sense that I am using the term means applying intelligence to the minute-by-minute use of highways and giving the greatest possible service from the highways to the people who need to use them or are otherwise affected by them. The ability to apply intelligence depends directly on knowledge about the process to be controlled and on instruments available for sensing and controlling the process.

The sequence in which this ability is usually developed starts with some ideas or theories. Then a body of knowledge develops through the conduct of experiments using scientific instruments to measure and relate causes and effects. Based on this insight, larger systems of operating equipment are installed. These are justified by the predictions based on the small-scale experiments of benefits likely to be obtained. More knowledge then is gained from these larger installations and applied elsewhere. This is the stage we seem to be in now.

However, many of the accomplishments in freeway operations rest on traffic flow theory. The rapid development of instrumentation in the past decade has by itself enabled the implementation of many relatively straightforward ideas for improving traffic operations on freeways. For example, the ability to sense when traffic on the freeway is approaching capacity while there is still underutilized capacity on an adjacent service road enables the diverting of excess traffic to the frontage road. This provides a great improvement in operations in some cases and, of course, is just plain common sense.

The role of traffic flow theory in improving freeway operations is not so obvious as the role of a closed-circuit television system, for example. Traffic flow theory, however, has made some important contributions, and I believe it will be increasingly important in the future.

Sponsored by Committee on Freeway Operations and presented at the 50th Annual Meeting.

The starting point in traffic flow theory was to determine the relationships among traffic flows, speeds, and densities. Studies of these relationships have led to what I believe is the basic contribution made by flow theory to operations. That is, to define quite sharply the concept and characteristics of an optimum traffic operating condition. This occurs at a density somewhat less than 75 vehicles per mile. Peak traffic often does not flow naturally in this optimum range but instead tends to become congested with densities of about 150 vehicles per mile. One of the main purposes of freeway surveillance and control systems is to increase the proportion of peak time when traffic operates in this more free-flowing fashion.

The concept of an optimum range for traffic flow is certainly not original with the present generation of traffic researchers and operators. In 1946 a paper on this subject by Joseph Barnett was published in the ASCE Proceedings. About the same time the concept was referred to by O. K. Normann in the first edition of the Highway Capacity Manual. It is implicit in Bruce Greenshields' early hypothesis that speed and density have a linear relationship, which gives a maximum flow at one-half jam density.

The contribution of traffic flow theorists has rather been to define more explicitly the form of the relationships among the several variables of traffic flow. They have done this by analogy with other physical processes, by mathematical analysis, and by more precise and exhaustive experimentation than was feasible in the late 1940's and mid-1950's.

Dealing with traffic as a mass process having characteristics of speed, flow, and density leads naturally to comparisons of traffic behavior with the flow of fluids. One of the broad fields of activity in traffic research relevant to freeway operations has been the exploration of this analogy. To the extent that traffic behaves as a fluid, the relatively complete understanding that is available in the published literature on fluid-flow characteristics can be applied to understanding traffic behavior as well.

The classic paper in this field was published in 1955 by two English mathematicians, Lighthill and Whitham, and was titled "On Kinematic Waves II. A Theory of Traffic Flow on Long Crowded Roads." They had written previously on the behavior of kinematic waves in hydrodynamics and had used this to deduce a theory "of the propagation of changes in traffic distribution along... roads." They state, "The fundamental hypothesis of the theory is that at any point of the road the flow (vehicles per hour) is a function of the concentration (vehicles per mile).... The hypothesis implies... that slight changes in flow are propagated back through the stream of vehicles along 'kinematic waves,' whose velocity relative to the road is the slope of the graph of flow against concentration."

The shape of this curve tracing the relationship between flow and concentration (or density) is therefore of fundamental importance. It establishes not only the flow that will occur at any given density of traffic on a given road but also the wave speed. Lighthill and Whitham do not specify a particular form for the curve, other than that flow is zero when density is zero or when there are so many cars jammed on the road that none of them can move. Between these 2 intercepts of the zero flow line, at some density that Lighthill and Whitham called optimum, flow would be maximum.

To suggest a formula for this curve, Harold Greenberg assumed the flow of traffic was similar to the flow of a fluid in one dimension. This led to a relationship, shown in Figure 1, which was continuous and defined over the entire range of density from zero to jam. It appeared to fit the data available at that time at least as well as any other continuous formula. Some called this the Greenberg Law, and it led to a certain amount of dispute. The dispute illustrates the strengths and also the weaknesses of applying physical analogies to understanding traffic behavior, and it is worth reviewing briefly here.

When he saw Greenberg's work, Whitham protested that there was no intrinsic justification for the assumption that vehicles would behave in the same way that fluids flowing in one dimension behave. The gist of the reply was that there was no intrinsic reason not to make the assumption, that the resulting curve fit the available data at least as well as any other continuous model, and that making the assumption had some useful benefits.

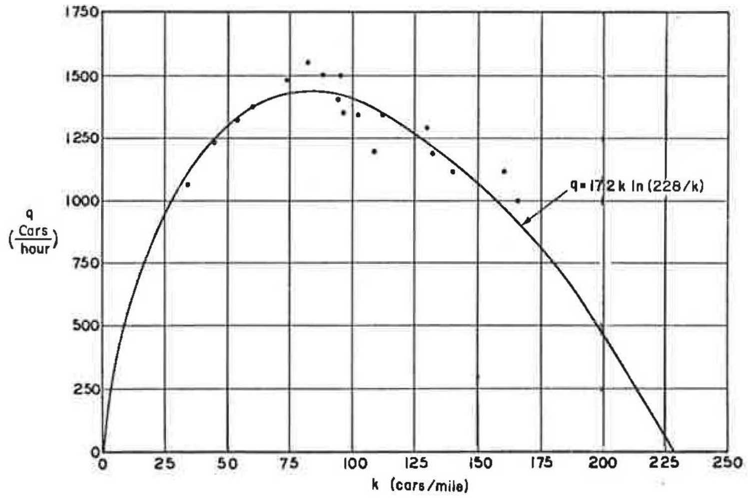

Figure 1. Flow, q cars/hour, versus density, k cars/mile.

Soon after this dispute we were able to obtain a larger and more precise sample of flow-density data. Based on this Leslie Edie published a paper proposing 2 separate equations for the curve (Fig. 2). One would apply at densities less than optimum and one at higher densities. The main point is that the data showed that the relationship between flow and density was probably not continuous in the region of maximum flow. The 2 curves Edie proposed did not meet: The one for low densities went to a higher value of flow.

This discontinuity in the flow-density relationship is a most important point to appreciate. It became evident only with a large sample of data, the processing of which

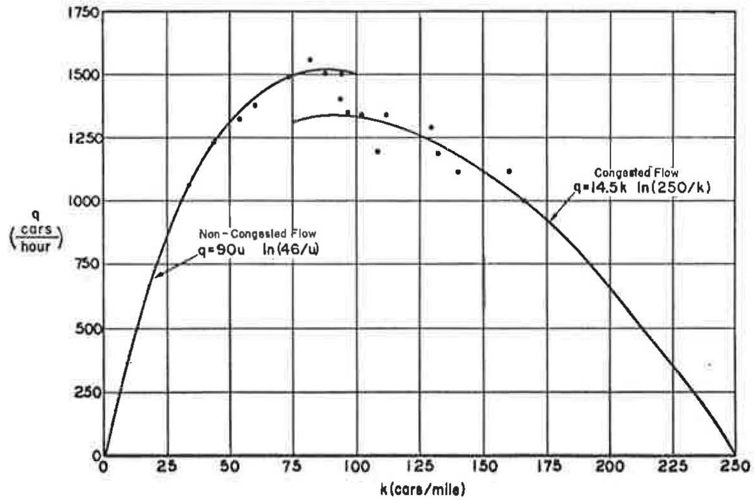

Figure 2. Flow, q miles/hour, versus density, k cars/mile, for congested and noncongested flow.

had previously not been feasible because there was not suitable instrumentation. With the development of an electronic traffic data acquisition system, that bottleneck was broken. The discontinuity indicates that there are limits in the application of hydrodynamics to describe traffic.

A particle of fluid accelerates or decelerates at rates that are determined by factors external to the particle. Whether an acceleration or a deceleration is called for makes no difference to the particle. In traffic, however, a vehicle and its driver have different mechanisms for accelerating and for decelerating. The perceptions and risks are altogether different in the 2 cases. Forbes showed experimentally in the late 1950's that drivers react more slowly to an opportunity for acceleration than to the need for a deceleration. This asymmetry appears to be related to the observed discontinuity in traffic behavior at optimum density.

There have been both strengths and weaknesses in the use of the hydrodynamic analogy to understanding traffic behavior. This analogy has produced valuable insights into the wavelike propagation of disturbances along a traffic stream. Carrying the fluid-flow analogy too far, however, tended to mask the discontinuity at peak flow, which is one of the most significant characteristics of road traffic behavior.

It is significant because it can explain why shock waves develop at a bottleneck and why flow through a bottleneck is lower when traffic is congested than when it is free-flowing. Harold Greenberg and another researcher at the Port Authority were first to demonstrate experimentally that more traffic would flow through a roadway if it were kept free-flowing than if it were allowed to become congested. One of the major purposes of the instrumentation we have developed since then has been to keep traffic densities below 75 vehicles per mile. Figure 3 shows the contribution this makes.

Figure 3 shows the end result of a cooperative study by staff at the Port Authority and at IBM in which a computer was applied to control tunnel traffic densities. When the controlled flow in April is compared with the uncontrolled flow in October, a major improvement is clear. To determine whether this was possibly due to seasonal effects, we compared flow in other tunnels for the same 2 periods (Fig. 4). If anything, flow in April is lower than flow in October.

Another area where traffic theories have made a contribution is in clarifying the measurement of traffic density, or vehicles per mile. This can be measured by counting traffic flow and dividing by average speed: Vehicles per hour divided by miles per

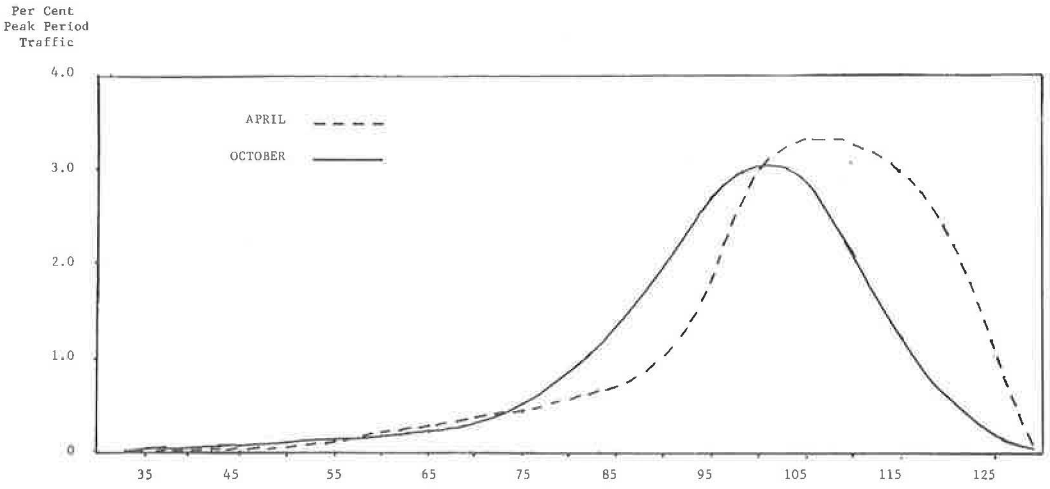

Figure 3. Controlled traffic flow in April versus uncontrolled traffic flow in October in the near lane of the Lincoln Tunnel south tube during p.m. peak.

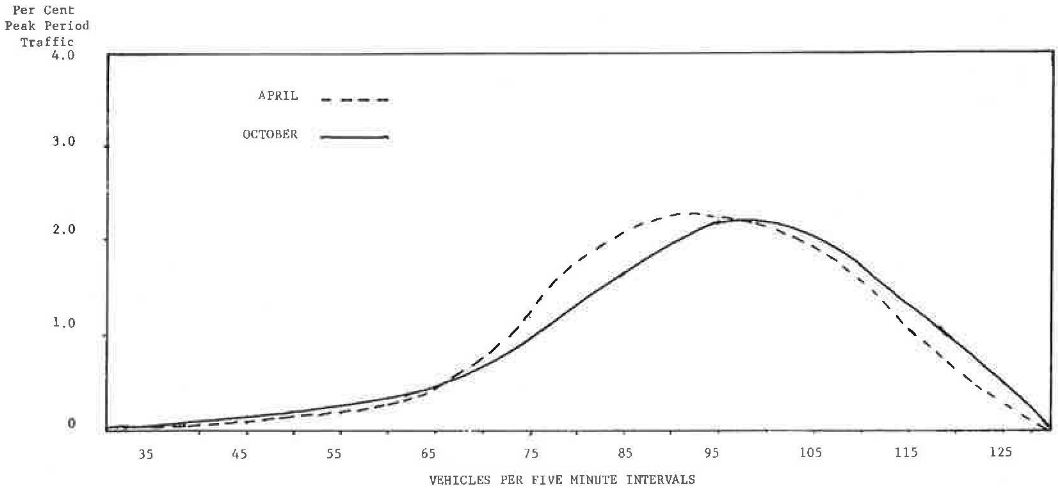

Figure 4. Uncontrolled traffic flow in April versus uncontrolled traffic flow in October in the north and center tubes of the Lincoln Tunnel during a.m. and p.m. peaks.

hour equals vehicles per mile. If both the flow and the average speed are determined at a point, there is no physical reality to the number derived by this calculation. This is a confusion that seems to be embedded in traffic analysis. It arises because of the 2 ways in which speeds can be averaged.

As Wardrop pointed out at the Road Research Laboratory in the early 1950's, the speeds of vehicles can be measured for some time interval as successive vehicles pass a point and then averaged. He called this time-mean speed. Or the speeds of vehicles present on a length of roadway at an instant can be measured and averaged; he called this space-mean speed. The dimensions for density are valid only when space-mean speed is used. This, of course, is far more difficult to measure than time-mean speed, but that does not alter the fact that densities derived solely from measurements at a point have no physical meaning. This distinction is important in freeway operations because density is an important predictor of flow.

These two illustrations of the contributions of traffic flow theory are drawn from just one branch of the science and only begin to suggest the scope of theory that has been defined. Valuable work has been done in studies of car-following behavior. Herman, Rothery, Potts, Gazis, and others have provided many insights, for example, into the stability and instability of traffic streams, the role of acceleration noise, and the relationship between these microscopic views of traffic behavior and the mass flow studies just described. Statistical aspects of traffic have been explored by many researchers such as Buckley in Australia and Jewell and Haight in the United States. Queuing theory has many applications in describing traffic operations. Computer simulation has been applied to the study of traffic flow by a great number of researchers. Both psychological and simulation studies of driver behavior have been made, and the work by Senders is especially noteworthy. Nearly all of this has happened in just the past 15 years, and in that time there has been created an extensive literature that constitutes a science of traffic flow.

Much of this work has been accomplished because mathematicians and physicists became interested in contributing insights from their basic disciplines to the understanding of road traffic behavior. This has resulted necessarily in contributions scaled to the resources available to the individual researchers and to their interests rather than to the needs of a coordinated effort to understand traffic behavior. The result has been to advance some aspects of traffic flow theory faster than others.

Chief among the important questions that still need answers is this: What determines the capacity of a freeway link? I believe an important part of the answer will be the description of how drivers process information. There seems now to be increasing interest in this question and also increasingly sophisticated instruments available for the researchers. Probably more than the other branches of traffic flow theory, however, this work did and still does require the development of instruments that force the state of the art. Instrumentation development has generally played an important part in the development of traffic flow theory, but this matter of driver information processing is especially dependent on it.

Full-scale experiments to measure driver reaction times in a range of roadside environments were reported by Forbes and others in the late 1950's. These used split-frame photography to show the roadside environment, the positions of the several cars to which the experimental driver was reacting, and the position of the controls on the experimental vehicle. Although the films were difficult to read, these experiments did capture the major variables. Since then considerable strides have been made in measuring the 3 principal elements here: the roadway, the vehicle, and the driver. Simulators have been developed by using both movies of actual roadside environments and TV camera views of model terrains. Vehicles have been highly instrumented and, in the case of the simulators, controlled movements are generated by computers to provide varying types of road feel to experimental drivers. The drivers are sensed for galvanic skin response, heartbeats, breathing, and in some cases brain waves. Several attempts have been made to measure driver eye movements.

There is still a long way to go in this effort, and the contribution this research will make to freeway operations is just beginning. For example, one of the most important elements in research on driver information processing is to determine where the driver's attention is being directed as he moves his vehicle through the road environment. The instrumentation to measure driver eye movements is still relatively cumbersome, and its presence may well influence experimental results. The brain-wave instrumentation is particularly liable to this form of error. There is a more serious difficulty in that, even with excellent measures of eye movement, brain waves, heartbeats, galvanic skin response, and breathing, psychologists are not agreed on the interpretation of the data. When the experiments are conducted in real driving situations rather than in simulators, there is a lack of instrumentation for sensing accurately the distance between the experimental vehicles and objects along the road, such as abutments and other vehicles. Furthermore, there is need for more research to quantify the information content of the actual environment.

These few examples suggest how much remains to be done in developing the basic scientific knowledge needed for freeway operations as well as for freeway design. This is certainly a worthy challenge for the kind of technological expertise that was marshalled so successfully for America's space program.

Although much remains to be done in developing instrumentation and knowledge concerning driver information processing, much has already been done in applying instrumentation to improve freeway operations. Historically a major focus of this effort has been to extend the limited-access feature, which is the prime characteristic of freeway design, by metering the flow of traffic onto the freeway when necessary to prevent congestion on the freeway itself. This work was initially based in part on the Port Authority experiments that I described earlier, but it rapidly developed independently of the tunnel work. Today, in fact, the kind of improvements we have obtained by keeping tunnel traffic moving plays little if any part in the benefits being obtained on the freeways. I believe there are places where the same type of operation being developed for the tunnels can also benefit freeways, but this will require more intensive surveillance and control systems than have been applied to date on the freeways.

The freeway benefits have instead come more from diverting excess traffic to other roads that are in the corridor served by the freeway and have capacity available. The access-control systems are also valuable in allocating priority movement to buses. In places where bus movements are heavy, this can be an output from the control systems and has an extremely high payoff in moving more people on the freeways with less delay.

Another major focus of the effort to improve freeway operations has been to sharpen the detection, handling, and removal of disabled vehicles and other incidents that reduce capacity. Such incidents occur every day and often cause a wide variation in the time required for trips. Now there is increasing attention being given to instrumentation that can inform motorists about these events and help them to find the best alternate routes.

The development of instrumentation for these purposes has occurred in about the same time frame as the development of traffic flow theory. In 1959 tunnel traffic flow control began on a pilot basis. The first major installation of surveillance equipment was on the John Lodge Freeway in Detroit in 1960 when 14 closed-circuit television cameras were installed to observe a 3.2-mile section. Shortly after, in 1962, ramp-metering operations began with a pilot system in Chicago. In 1964 ramp-metering experiments started in Houston as well. A few ramp closures were tried in Los Angeles, and then in 1966 ramp metering started there too. A few other cities have also conducted experiments and made plans for freeway surveillance and control systems, but these have been the major actors. I believe the development of such systems in Europe and Japan has been more recent.

The pace of instrumentation development during this time has been fast. For example the automatic stoppage detection system that we are using now at the Lincoln Tunnel is actually in its fourth generation. We started with an array of electromechanical timers in the late 1950's. Next was a vacuum tube electronic curcuit in the early 1960's. Then in 1965 we installed a system using solid-state devices but still wired in a special purpose circuit. Now, of course, we use computers and have far greater flexibility and logical power. This advance in logic has been paralleled by advances in reliability and economy. Similar advances have occurred in vehicle detection and in signal transmission. There are still weaknesses in the instrumentation available for surveillance and control, but these trends toward better performance at lower cost are likely to continue.

There will be new forms of instrumentation available soon. I believe the next major development in instrumentation for freeway operations will be in automatic vehicle identification. Although the electronic license plate for all vehicles may not be around the corner, the technology is available now for full-scale testing, and the potential benefits are important in many applications. Apart from traffic control, the wide application of automatic vehicle identification can assist motor vehicle administration, law enforcement, maintenance, planning, financing, and fleet operations. The initial application for bus identification is being made now at the Golden Gate Bridge, and we expect to have one in New York in the very near future.

A major theme in the development of instrumentation for these systems has been the role of television versus digital systems. In pioneering this broad field of traffic surveillance, Detroit researchers set a pattern that was generally not copied in other areas. Television has been a major element in city street traffic surveillance systems developed elsewhere during the 1960's, chiefly in Europe and Australia. For expressway surveillance, however, Chicago went the all-digital route in 1962. Even today the Chicago expressway surveillance system makes hardly any use of television. The pattern in Houston and in the tunnel surveillance and control systems has been to use both television and digital systems. Television is a valuable adjunct to a digital system for research and also for helping in the policing of roadway operations. I believe that over the long run it will gradually be phased out in favor of fully automated digital control systems. This, in fact, did happen in Detroit.

Inherent to some extent in this dichotomy between television and digital systems has been the role of police and engineers. Where surveillance is a supplement to existing police traffic operating groups, television has been especially useful. However, increasing demands on police for other functions and their increasing salary costs increase the stress on fully automatic systems.

It seems clear that the main burden of development in this field of freeway operations will continue to be carried by engineers relying on automatic equipment. We have a way to go yet before freeway operations can make much use of automatic control theory that includes prediction and feedback, but I believe that is where we are heading. On line, real-time systems will predict traffic demands and will target service levels for those demands; they will sense conditions that affect the service being given for that demand; they will alert police wreckers, ambulances, and debris-removal equipment; they will estimate the probable consequences of alternate control strategies and select the optimum; they will drive entrance ramp controls, diversion signs, and reversible lane devices such as lane signals and delineators; they will measure the traffic demands, densities, and delays actually on the system and analyze their own performance; they will call automatically for maintenance on defective system components; and they will learn from their experience. This is the challenge we have, and the ability to meet it is here.

ACCOMPLISHMENTS IN FREEWAY OPERATIONS OUTSIDE THE UNITED STATES

J. T. Duff, Great Britain Department of the Environment, London

•THE HISTORY of motorways or freeways began in Italy in 1924 when work started on the construction of some 50 miles of autostrada from Milan northward to the Italian Lakes. This road included the essential features of modern freeways save one; it consisted of a single carriageway carrying traffic in both directions. In Germany, construction of autobahns commenced in 1934, and here it was pushed ahead much more vigorously. By 1937, 950 miles were open to traffic and a further 1,100 miles were under construction. Today the autobahn system comprises at least 3,000 miles. In the United States, some short lengths of freeway were constructed in the 1930's, and the development of the great system of long-distance turnpikes commenced in 1940 when the 160-mile Pennsylvania Turnpike was opened to traffic. Freeways are now to be found in many other countries, including Holland, Belgium, France, Switzerland, Japan, Australia, and Latin America.

The main differences between freeways in the United States and those in other countries arise from the difference in size and the difference in the degree of motorization. Thus, the nearest rival to the United States with its 40,000 miles of interstate routes is Germany with some 3,000 miles of freeways. Few cities outside the United States have extensive networks of urban freeways with the exception of Japan where there are some 90 miles or urban freeways in operation in the Tokyo and Osaka-Kobe areas. Where traffic volumes are comparable, the operational problems tend to be similar throughout the world and, because of the free interchange of ideas, the approaches to their solution tend to follow a common pattern.

When freeways were first built, it was generally thought that the superior geometric design made it unnecessary to use signs, signals, and other control devices (except, of course, for direction signing and lane lines). Experience of operation, particularly in recent years with volumes of traffic growing and some roads working to capacity, has shown that these roads pose their own special operational problems that are likely to call more and more for the use of sophisticated surveillance and control equipment.

On rural freeways the high-speed operation can lead to dangerous conditions during emergencies and when road works are being carried out. Emergencies include weather conditions such as fog, snow, ice, accidents, and other incidents that result in vehicles becoming stationary on the traffic lanes. On urban freeways, in addition to the dangers that can arise during emergencies and road works, the high volumes of traffic can quickly lead to serious congestion and delay. These conditions can be aggravated by the fact that urban freeways, because of the high cost and difficulties of land acquisition, are sometimes built to less generous standards than the rural freeways (e.g., narrower medians or absence of hard shoulders). Apart from road works and emergencies, the sheer volume of traffic coupled with more frequent interchanges often leads to operational difficulties at peak hours. It would appear essential, therefore, that very early notification should be given to the police or other authority of any abnormal traffic condition so that prompt action can be taken to deal with the cause of the trouble (including other action associated with it such as calling of ambulance and fire services for accidents) to prevent additional traffic from pouring onto the road while it is blocked

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or obstructed and to warn drivers on rural freeways of dangers ahead. The basic requirements of such a system are as follows:

1. Warning of abnormal conditions and information on the nature of these conditions should be obtained automatically and continuously and returned to some central police post where full communications are available to enable appropriate action to be taken;
2. The warning should preferably be an audible one so that continuous watching of a screen or display is avoided;
3. Information on the exact location of the incident and its nature should be presented visually by means such as an illuminated display map or closed-circuit television; and
4. A centralized control system should be available for remote operation of warning signs on the freeway and its approaches. These signs will warn drivers of the incident and reduce the traffic coming onto the freeway while it is obstructed both to prevent queues from building up and to allow emergency vehicles to operate.

The various systems that have so far been tried or proposed may be broadly classified into ramp control, corridor control, and freeway control to achieve optimum flow and to deal with emergencies. These can be used singly or in combinations, and examples of all are available outside the United States. This general report deals with recent progress in the following countries outside the United States: West Germany, England, Japan, Italy, and France.

WEST GERMANY

As in other countries, traffic on the German freeways is increasingly characterized by high traffic flows and in particular by regularly occurring high peaks. Studies have been carried out to see whether the safe and efficient handling of these peaks can be influenced by control measures in order to obtain optimum flow. Optimum flow in this context has been taken to mean (a) that the spacing and speeds of the vehicles along the road are such as to permit maximum safety and capacity; (b) that, in the event of an unforeseen obstruction of a carriageway or lane, the vehicles can be diverted before reaching the obstruction so that major holdups can be avoided; and (c) that drivers are advised by remotely controlled signs and signals about the traffic conditions on the road sections ahead and about any hazards likely to be encountered so that they can adapt themselves to the situation in good time.

Trials have taken place with a set of variable, remotely controlled signs and signals on a 20-mile section of the Munich-Salzburg Autobahn (1). The system is capable of imposing variable speed restrictions, depending on the momentary traffic volumes; providing advance warning of accidents on the section ahead; and diverting traffic through one of the autobahn exits to the all-purpose road network. The first two are achieved by remotely controlled variable signs of the roller-blind type capable of giving the following indications: 100 km, 80 km, 60 km, END OF SPEED RESTRICTION, and ACCIDENT AHEAD.

These signs are installed at intervals of just more than 1 mile. The traffic diversion is obtained by means of 2 signal bridges that span the carriageway at intervals of about 1,200 ft on the approach side of the junction exit and show, for each lane, a sign indicating the diversion, together with colored-light signs for the control of traffic on each lane. The control center is also equipped with closed-circuit television (6 cameras) so that critical sites of the trial section can be observed.

The traffic is surveyed by visual observation on site or by the closed-circuit television, and the changeable traffic signs are operated manually in accordance with experience. The variable speed signs are switched on to show a speed of 100 km/hr when the traffic flow in one direction (on 2 lanes) is expected to reach about 2,000 cars per hour. The signs are changed to 80 km/hr when this rate of flow is actually reached. Speed studies indicated that when no speed limit was shown some 35 percent of car drivers exceeded 100 km/hr (about 70 mph) and some 90 percent exceeded 95 km/hr (about 60 mph). When speed limits were shown, almost no drivers exceeded 110 km/hr. When 100 km/hr was shown, 38 percent exceeded 95 km/hr; and when 80 km/hr was displayed about 8 percent exceeded 95 km/hr. The results also showed a reduction in the standard deviation of speeds from about S = 14 km/hr to S = 7 km/hr.

The effect of the signs on capacity was also studied. Higher flows were measured when a speed limit was displayed, and nearly all the flows of more than 2,000 vehicles/hour were obtained when 80 km/hr was displayed. However, this was to be expected because this was the basic criterion used for displaying the limits.

For a given traffic flow, the proportion of shorter and more dangerous time gaps (those less than 1.5 sec) was reduced. A reduction in speed coupled with a reduction in the standard deviation would be expected to reduce accidents. The comparable carriageway in the opposite direction was not equipped with the variable signs, and a significantly greater number of accidents and more severe ones were in fact observed on this section than on the trial section.

In view of the favorable results obtained with this trial, it has now been decided to equip other heavily trafficked autobahn sections with changeable traffic signs. It is also proposed to install detectors to assess the traffic situation by comparison with programmed traffic data in order to arrive at a more objective decision for operating the signs.

Investigations are being carried out on the following: control of ramps, distribution of traffic over alternative routes, and use of acoustic signal transmissions to influence driver behavior and route choice. So far as ramp control is concerned, a length of 8 miles of the Hannover-Cologne Autobahn near Kamen has been chosen for a trial in 1971. Six loops are to be used for flow measuring. So far as distributing traffic over alternative routes is concerned, a system of fixed diversions covering the whole autobahn network has been devised for use when a section of autobahn is obstructed by reason of an accident or other emergency (2). The diversions that run parallel to the autobahn are marked by special detour signs carrying numbers. The routes start at a given access point and lead via federal or rural roads to one of the following access points. The signs are blue with a white U, number, and arrow and are placed at all intersections along the U-route. A section of the Frankfurt-Heidelberg Autobahn has been chosen for a trial in 1971 of remotely controlled variable guide signs, with the object of improving flow and capacity of the autobahn by diversion to other stretches of autobahn. Loops will be used to measure traffic flow, but the diversions will be brought into operation by manual judgment.

Aural communication equipment has been developed and demonstrated by the German firm of AEG-Telefunken of Hannover (3). There are proposals for a trial on a 20-mile length of the Hannover-Cologne Autobahn. Buried loops are fed from a multitrack tape recorder. The signals are received on a receiver and a loudspeaker mounted in a vehicle, and for trial purposes about 10 percent of regular commuters would be provided with receivers. Messages initially would relate to emergency traffic situations only, and as many as 3 repeats of 20 to 30 sec each with a 5-sec interval are envisaged. The language problem might be overcome by using a different carrier frequency for each language.

ENGLAND

In England 2 trials were made with remotely controlled signals in the early 1960's, one on a rural length of freeway and one on an urban length. The rural system was installed on 24 miles of the Motorway M5 in Gloucestershire. It comprised 22 signs about 2 miles apart on both carriageways. The system is still in use.

Each sign contains alternative messages—SKID RISK, ACCIDENT, and FOG—in letters 1-ft high. One or more of these messages can be shown at a time, and they are always accompanied by the message SLOW. For example, if an accident occurs on a slippery surface, SLOW together with SKID RISK and ACCIDENT would appear on 2 or more signs in advance of the accident. In addition flashing amber beacons are displayed on the signs when they are in use.

The signs are about 11 ft wide and are mounted on steel platforms behind the hard shoulders with their tops about 12 ft above the level of the road. They are designed so that the messages are practically invisible until the lights are switched on. The brilliance of the lighting is regulated automatically to suit prevailing conditions. Control of the signs is exercised by the police from their headquarters at Hindlip Hall using Post Office telephone lines. A simple switch operation selects the message to be displayed and the sign on which it is to appear. A supervisory system is incorporated to give an alarm if there is any discrepancy between the message or sign called for by the control or if a spurious indication is given.

Police decisions on the warnings to be given are based on information received from patrols or from the public over the motorway telephones. Experiments are also taking place on the automatic detection at various points along the road of fog and icing conditions and automatic reporting of this information over the existing signaling system in order to reduce the time taken to display and cancel warnings.

The use made of these signs is as follows (the percentages do not add to 100 as on some occasions more than one message was displayed):

Message	Times Displayed (percent)	Average Duration (hours)	Signs Used Each Time (avg)
Accident	43	1.7	2.1
Skid risk	42	5.0	4.7
Fog	23	5.7	6.4

The effect of the signs on vehicles exceeding the speed (fast vehicles) and the reduction in the proportion of fast vehicles is as follows:

Item	40 mph	50 mph	60 mph	70 mph
Daylight, percent				
Fast vehicles, without sign			41	13
Fast vehicles, with sign			26	5
Reduction			36	61
Darkness, percent				
Fast vehicles, without sign	91	71		
Fast vehicles, with sign	39	33		
Reduction	59	54		

The urban system installed on the London end of the Motorway M4 had blank-out signs using neon tubes. They had the message M4 CLOSED—USE A4 and were remotely controlled from Hounslow Police Station. Detectors on the Motorway M4 and on the slip roads gave early warning of abnormal traffic flow, and the information was displayed on a mimic diagram at the control center. This system was replaced in March 1969.

At the end of 1966 the decision was made to equip the whole motorway network of 1,000 miles with remotely controlled signals to deal with emergencies. Three systems are at present in operation (M4 Severn Bridge, M4 Metropolitan, and M1/M18/A1(M) in the West Riding of Yorkshire) on approximately 80 miles of motorway. Systems for a further 400 miles are on order and due for completion during 1971. The motorway network will eventually be controlled from some 30 police control centers connected to 6 computer centers. All the computers required (12) are now on order.

Both of the trial systems described used worded signs and were controlled over telephone circuits from police stations. Motorway M4 signs were erected on the median and nearside verge and also on gantries spanning the carriageway on the elevated section. Additional signs were sited at strategic positions on the all-purpose roads approaching the motorway. These signs suffered from several disadvantages: (a) they could only be used for emergencies sufficiently serious for the motorway to be completely closed; (b) being only advisory in nature, many drivers ignored them; and (c) because each sign had to be individually fabricated, replacement of broken or faulty signs took a long time. Motorway M5 signs are sited on the nearside verges of the motorway at intervals of 2 miles and cover about 24 miles of the road.

Consideration of the 2 trial systems showed that to tell motorists the nature of the emergency and its severity requires impossibly large signs for motorway conditions. Those on Motorway M5 do not indicate the severity and only show three of the possible situations that may occur (e.g., split loads probably present a more frequent hazard than fog). Accordingly, for the permanent systems the alternative has been adopted of telling the motorist what action is required of him, namely, the appropriate speed or lane, or both, to use.

The design of the new signals has been governed by the following considerations:

1. Conspicuousness—This has been secured by the use of 4 amber lanterns that flash in pairs to call the driver's attention to the fact that the signs are in use. These lanterns have a clear daylight range of 1,500 ft. The flashing is in the vertical direction as for the temporary warning lights.
2. Adaptability—The use of a 13 by 11 lamp matrix allows the presentation of a wide variety of symbols. For simplicity of control, the number of symbols has been limited to 16, but changes within this number can easily be made.
3. Economy—All variants of the basic signal (for urban and rural use) are assembled from the same components, thus securing the benefits of large-scale production. In use, the signal consumes less than 150 W.
4. Reliability—There are no moving or exposed corrodible components, and all electrical components are underrun. Both the matrix indicator and the lanterns are sealed against the entry of dust and water. The indicator can be removed from the signal and replaced by a new one without the aid of tools in less than 1 min, thus the minimum of maintenance work has to be done on the motorway.

The urban signals, as used on Motorway M4, also include 4 red lanterns that can be flashed horizontally in pairs when it is necessary to stop motorists. The lamps in the indicator matrix can be dimmed at night by sending the appropriate control word from the central computer. Heaters can be switched on to prevent the indicators from icing in cold weather.

The initial systems have used a sign with a matrix of 13 by 11 lamps. For data transmission purposes, the number of symbols has been limited to 16. Future systems are to be equipped with matrix signs in which the individual lamps have been replaced by fiber optics. These signs have a number of advantages including the possibility of using colored symbols by placing a small filter glass between a lamp and the fiber optics. (The sign has one lamp per symbol.)

At the control center the operator is provided with a typewriter on which he types a simple instruction for a given aspect to be shown on a given sign. The computer then automatically plans the "sequence" of signals to be shown and prints the proposal on the typewriter. After checking the proposal the operator then presses a key, and the computer actuates the required motorway signals. The typewriter thus provides a timed permanent record of every system operation. This record includes the following:

1. Instructions from the operator;
2. Signal sequence proposed by the computer before the signals are actuated (a sequence is defined as a set of signals that, as the driver moves, show progressively more restrictive indications followed by the ROAD CLEAR indication);
3. Aspect shown by each activated signal in the system; and
4. Details of any system failure.

The use of a computer as the master controller enables a high degree of automation, and the system is programmed so that the police operator needs only to give instructions as to the message to be displayed on the sign immediately prior to an incident. The computer determines what other signs need to be illuminated to cover slip roads, to provide advance warning and countdown, and to give the all clear beyond the incident and what messages are to be shown on them. The instruction is conveyed to the computer, and as soon as the necessary analysis has been completed the computer causes the proposed sequence of signals to be printed out on the teleprinter after it first checks that the address is genuine and the message is a valid one. Operation of a further "actuate" key causes the corresponding instructions to be sent out to illuminate the signals on the motorway. The operator can at any time obtain a printed record of the condition of the motorway signals.

The new systems employ the latest solid-state techniques for high reliability and are designed to control automatically a number of responders or outstations (20 on Motorway M4) situated at intervals along the motorway. Each responder controls a number of signals, of the matrix type described earlier, each of which can display a number of different messages. The responders are connected to the central computer via 2 pairs of telephone lines (one to enable control messages to be sent from the computer to the responders and thence to the signals, and the other to enable the state of the signals to be returned to the computer). The functions of the responder are to detect and decode instructions from the control center; actuate the signals in accordance with these instructions; and advise the control center that the instructions have been obeyed or, if for any reason they have not been obeyed, to alert the control center and report the nature of the defect.

Only 2 pairs of lines are necessary for the complete system because all the control and reply information is transmitted in digital (binary) coded form (i. e., a sequence of 1's and 0's). Each sequence or "block" of information consists of 19 "bits" (a 1 or a 0). The control and reply words are made up as follows:

Function	Control Word (bits)	Reply Word (bits)
Word synchronization	3	3
Parity (allowing checks to be made before action is taken)	1	2
Address of responder	6	6
Information	9	8
Total	19	19

With 6 bits allocated to the responder address, the system has capacity to control as many as $2^6 - 2 = 62$ responders.

The output from the computer is used to modulate a voice frequency transmitter centered on a frequency of 2,520 Hz. A zero level transmits a frequency 120 Hz above the band center, and a one level transmits a frequency 120 Hz below the band center. The reply information is similar but centered on a frequency of 2,040 Hz. A maintenance telephone uses the frequency band below 1,600 Hz.

In addition to the teleprinter and computer, the control center includes an illuminated mimic diagram that enables the operator to see at a glance which signals are in use and a television monitor that enables him to see along the motorway by means of the remotely controlled television cameras. The mimic diagram has 1 lamp per traffic signal; the lamp is illuminated when the corresponding signal is in use. When a STOP signal is shown, the lamp on the mimic diagram flashes to give a more striking indication.

The main sources of information providing the inputs to the system are the emergency telephones situated along all motorways and, in the case of urban sections, loop detectors placed in the carriageways. The loop detectors are interrogated at regular intervals (about 7 sec) to determine the speed bracket of the vehicles passing the detector and, in particular, the presence of any queues. If these or other potentially dangerous situations are found, the appropriate time and space sequence of legends will be displayed automatically along the motorway. There will, of course, be long periods when no emergencies requiring signal operation occur. During these periods, the computer will at 5-min intervals check all responders and signals. In this way most faults will be detected and cleared before they have any effect on the operation of the system.

Signals erected on the verges or central reserve contain an accelerometer in the signal driver that operates if the equipment is struck by a vehicle. These accelerometers are also interrogated at 5-min intervals.

The Elliott 903 computer used in the London M4 system has 8,192 words of core storage and associated peripheral equipment that includes a 250 character/sec, 8-bit tape reader and a 110 character/sec tape punch. The computer has been programmed to (a) ensure that any very restrictive signal aspect, such as a low speed or STOP, cannot be displayed without adequate advance warning to drivers; (b) provide the operator with maximum flexibility to display on any signal the aspect he considers is required to control the traffic situation at any time; and (c) prohibit the display of contradictory aspects on adjacent traffic signals and speed aspects in excess of an existing fixed speed limit.

The control console has been designed to accommodate 2 operators; the layout of the panels has been so arranged that one operator can reach all controls comfortably. Two pull-out dials and 2 jacks for telephone handsets or headsets are fitted below the front of the desk top. Urban systems also include closed-circuit television coverage of critical sections. The M4 system has 4 cameras and 2 monitors. The mimic diagram provided in all control centers shows the layout of the motorways and interchanges and the positions and address numbers of the signals. Lamps on the London M4 system mimic are as follows:

Purpose	Color
Lamps that are associated with loop detectors on the motorways and that light up if the detectors are occupied continuously for more than 5 sec	White
Lamps that are illuminated whenever the corresponding signal on the motorway is actuated, e.g., when a signal is set to STOP, the associated red lamp flashes	Red
Four lamps that are associated with a secret type of diversion sign having the legends M4 CLOSED—USE A4 on the all-purpose road approaches to parkway and airport interchanges	Blue
Four lamps that are associated with the 4 television cameras and that light up when the associated camera has been connected to a monitor	Green

Current systems, in all cases, rely on a human operator to interpret the information received from various sources and to initiate action. The computer interprets the human decision and performs the actual operation. With more sophisticated and reliable detection systems, it is likely to become increasingly possible to eliminate the human operator and achieve completely automatic operation.

The use made of the signals during a 4-month period in 1970 on the 2 systems is given in Table 1. The 2 motorways are, of course, quite different in character, the M1/M18/A1(M) being rural and the M4 being partly rural with heavy commuter traffic including an elevated section of substandard design. Excluding use for road works, signals were in operation on the M1/M18/A1(M) Motorway for an average of 0.7 occasion/mile/month lasting 2.85 hours on the average while those on the Motorway M4 were in operation for an average of 5.9 occasions/mile/month lasting 0.64 hour on the average.

The number of times and duration of display of different messages are given in Table 2. On the M1/M18/A1(M) Motorway, fatal and serious accidents were reduced from 18 to 12 in comparable periods of 7 months. On the Motorway M4, the position is complicated by road resurfacing that has been carried out since the signals were installed. During a period of 3 months prior to the resurfacing total, accidents fell by 18 percent (compared with the corresponding 3 months before signals were operating). A comparison of injury accidents in the 6 months following resurfacing with those in the corresponding period prior to installation of the signals is given in the following (the reduction in this case may be partly accounted for by the improved surface):

Section	Injury Accidents	Injury Accidents per 10^6 Vehicle-Miles
Elevated		
B	36	1.16
A	18	0.58
Change, percent	-50	
Open		
B	47	0.5
A	27	0.29
Change, percent	-43	
Both		
B	83	0.66
A	45	0.36
Change, percent	-46	

TABLE 1

USE OF SIGNALS

Reason	M1/M18/A1(M)		M4 Metropolitan	
	Times Used	Duration (hour)	Times Used	Duration (hour)
Traffic				
Accident	44	41	27	16
Congestion	2	1½	4	9
Road works	78	677	114	287
Vehicle stranded	14	5	265[a]	95
Vehicle shedding load	17	7	7	4
Other	2	½	6	35
Subtotal	157	732	423	446
Weather				
Visibility	49	282	7	8
Ice-frost-snow	37	73	13	52
Rain	—	—	—	—
Wind	13	101	—	—
Other	—	—	—	—
Subtotal	99	456	20	60
Total	256	1,188	443	506

[a]The elevated section of M4 has no hard shoulders.

TABLE 2

USE OF MESSAGES

Message Displayed	M1/M18/A1(M)		M4 Metropolitan	
	Times Used	Duration (hour)	Times Used	Duration (hour)
Speed indication				
10 mph	—	—	54	26
20 mph	8	48	168	121
30 mph	11	43	67	40
40 mph	33	197	19	39
50 mph	63	314	10	41½
60 mph	31	128	1	½
Subtotal	146	730	319	268
Divert	—	—	4	10
Stop				
1 lane	73	274	91	200
2 lanes	37	184	28	17
3 lanes	—	—	1	11
Subtotal	110	458	124	238
Total	256	1,188	443	506

JAPAN

Reports have been received from Japan on 388 miles of rural freeway and on 91 miles of urban freeway. Locations and mileages are as follows:

Area	Mileage
Urban	
Tokyo	45
Osaka-Kobe (Hanshin Expressway)	46
Subtotal	91
Rural	
Tokyo-Nagoya	216
Nagoya-Kobe	119
Tokyo-Fujiyoshida	53
Subtotal	388
Total	479

All freeways are equipped with variable-message signs to deal with emergencies. Unlike the British system where the decision has been made to tell the driver only what action to take, the conciseness of the Japanese written language makes it possible to tell drivers both what action to take and the reasons for it being necessary. Details of current systems and future proposals are given in the following.

Rural Freeways

The scale of the problem may be seen in the following:

Freeway	Trips per Day	Accidents per Day	Breakdowns per Day
Tokyo-Nagoya	114,000	7.8	172
Nagoya-Kobe	124,000	7.7	132
Tokyo-Fujiyoshida	24,000	1.5	24

On the Tokyo-Nagoya Freeway, congestion occurs 6 times in 10 months due to excess demand and 12 times in 1 month due to accidents and breakdowns for an average duration of 43 min. Ramps are often congested on Sundays. Particular sections of the Nagoya-Kobe Freeway are often congested at morning and evening peaks. Congestion occurs on the Tokyo-Fujiyoshida Freeway in a 2-lane 2-way tunnel 2 km in length when volume exceeds 25,000 vehicles per day. In addition to accidents and breakdowns due to normal causes, temporary closures of through lanes occur on these freeways about 5 to 6 times a month in the winter. Most incidents are reported from the emergency telephones that are provided on each side at 0.6-mile (1-km) intervals. The interval is reduced to 650 ft (200 m) in tunnels.

Control of traffic on these rural freeways is exercised by means of variable-message signs. Information is obtained from the emergency telephones, from radio patrol cars, from toll areas, from closed-circuit television installed in long tunnels, and from vehicle detectors. Details of the variable-message signs are given in Table 3. The equipment and signs installed on the 3 rural freeways is as follows:

Freeway	Emergency Telephones	Variable-Message Sign					Television Cameras	Vehicle Detectors
		I	II	III	IV	V		
Tokyo-Nagoya	789	40	44	19	20	0	66	48
Nagoya-Kobe	157	11	7	0	0	11	0	135
Tokyo-Fujiyoshida	146	0	11	3	8	3	0	10

Fairly elaborate traffic control was introduced temporarily on the Nagoya-Kobe Freeway during the EXPO-70 period. On-ramp traffic regulation, route guidance suggesting that drivers change lanes or detour, and compulsory off-ramp diversions were employed. Research has started into the methods and equipment required to control rural freeways in the future to cope with the much more frequent congestion expected.

TABLE 3

VARIABLE-MESSAGE SIGNS ON RURAL FREEWAYS

Type	Where Used	Type of Information	Sign	
			Row	Message
I	On ramps	Traffic conditions on freeway	Top	LANES CLOSED; LANES REDUCED; SLIPPERY; CHAINS; DRIVE WITH CARE; SAFE SPEED 50, 60, OR 70 km/hr
			Middle	Location
			Bottom	ACCIDENT; ROAD WORKS; DISASTER; FIRE; FOG; SNOW; ICE; HEAVY RAIN; STRONG WIND; CONGESTION
II	Expressway approaches to an interchange	Traffic conditions ahead of next interchange	Upper	CAUTION; LANES CLOSED
			Lower	ROAD WORKS; ACCIDENT; CONGESTION; DIVERT HERE
III	Open sections of expressway in mountainous areas	Weather conditions (operated automatically by detectors)	Upper	REDUCE SPEED
			Lower	FOG; ICY SURFACE; ACCIDENT
IV	Entrances to tunnels	Traffic conditions in the tunnel	Top	IN THE TUNNEL
			Middle	REDUCE SPEED; DO NOT ENTER; USE RIGHT LANE; USE LEFT LANE
			Bottom	ICY SURFACE; ACCIDENT; FIRE; ROAD WORKS
V	On surface roads	Traffic conditions on the expressway		

Urban Freeways

The Hanshin Expressway is an urban freeway system in the metropolitan Osaka and Kobe areas of Japan. The present length of the system is 46 miles, and an additional 34 miles are to be added by 1975. In the metropolitan area of Tokyo there are at present 45 miles of urban freeway and this network is also growing. Average accidents and breakdowns on these 2 systems are as follows:

System	Length (mile)	Trips per Day	Accidents per Day	Breakdowns per Day
Metropolitan Tokyo	45	350,000	10	56
Hanshin	46	220,000	6	60

Congestion occurrences, i.e., when queues are greater than 0.6 mile (1 km) in length, are as follows:

Cause	Times per Month		Average Queue Length, Tokyo (mile)	Average Duration, Tokyo (hour)
	Hanshin	Tokyo		
Excess demand	44	136	1.25	2.7
Accident	22	35	2.25	1.2
Breakdown and other	13	10	2.87	1.6
Total	79	181	1.50	2.3

Incidents are reported to the control room by emergency telephone system (at 1,200-ft intervals); radio system (police or corporation patrol cars); exclusive telephone at tollgate; and closed-circuit television. More than 60 percent of the reports come from the emergency telephones.

Control of traffic is by means of changeable-message signs, most of them of the matrix type. In the Tokyo area, the messages are composed of 4 blocks as follows:

Message	Block
Location of incident (25 different places can be displayed)	1
AREA ACCIDENT ENTRANCE (only at surface terminals of major on-ramps) ROAD WORKS	2
CONGESTED COMPLETELY CLOSED CLOSED (used with ENTRANCE in the second block)	3
Reserved for future use to indicate the degree of congestion (either length of queue or minutes of delay)	4

The equipment installed on the two systems is given in the following:

System	Changeable Signs	Emergency Telephones	Vehicle Detectors	Television Cameras	Data Processor
Metropolitan Tokyo	61	266	177 (at 88 sites)	15	1 CD 507 16-K core 16-K drum
Hanshin	38	≈300	122	11	Facom 270-30 32-K core 262-K internal drum 262-K external drum

The Tokyo and Hanshin systems include a mimic diagram in the control room on which traffic conditions are displayed in 3 colors. The criteria for operating the signs on the Tokyo network are as follows:

1. For congestion due to excess demand, queue length more than 1¼ miles (2 km);
2. For congestion due to accidents, queue length more than 1,600 ft (500 m) or delay of 5 min or more; and
3. For congestion due to vehicle breakdowns, queue length more than 1¼ miles (2 km) if vehicle is standard size and queue length more than 1,600 ft (500 m) or delay of 5 min or more if vehicle is large.

Although temporary on-ramp closure at the time of excess demands is a normal control measure, ramp control in the accepted sense has not been tried. There are proposals for this. There is no definite warrant for ramp closure; judgment depends on the control officers. The experience on the Tokyo network in the latest year is given in the following:

Cause	Average Times/Month	Average Duration of Closure (min)
Excess demand	68	43
Accident	24	56
Other	8	66
Total	100	48

In the Tokyo area, the Japanese Society of Traffic Engineers has been conducting research on methods to keep unexpected delay time below a certain value and to decrease driver complaints and irritation. Other objectives, such as maintaining travel speed above a critical value, have been rejected as unrealistic. The following measures have been proposed: radio broadcasts of traffic conditions, display of degree of congestion at on-ramps, temporary closure of on-ramps, changeable signs at the junctions of the radial freeways with the loop advising drivers which direction to travel on the loop to avoid a congested section, and changeable signs advising drivers to divert from the freeway at a given off-ramp. All of these except display of degree of congestion at on-ramps are at present applied manually. A fairly dense network of loop detectors is also proposed, most of them sited in pairs (5-m spacing) in each lane in order to derive the time mean concentration of traffic during a given period.

The following data processing is proposed:

1. Computation of delay time at bottlenecks, which can be done fairly accurately by comparing the concentration and flow at points upstream and downstream of the bottleneck;
2. Detection of accident occurrence to determine difference in concentration or flow or both between 2 points;
3. Forecasting of traffic conditions (concentration and delay time) in the near future by 2 methods; and
4. Determination and execution of advisory control by computer and of compulsory control after checking by operations officer.

The first forecasting method is an empirical method whereby the computer stores every day in the form of tables the traffic condition at a given site at time t + T (T is forecasting time, say 10 min) and those at other upstream points at time t. The table would relate to times of day at which congestion is expected. This method would only apply for normal traffic. The second method is a simulation method that can be applied to forecasting congestion due to various emergencies.

Research on the Hanshin system has been carried out by the Expressway Research Foundation for the past 3 years. The objectives, which are different from those in the Tokyo area, are to maintain smoothly running conditions on all sections and to maximize the number of trips.

A linear programming method of ramp control is proposed for steady-flow conditions. The idea is to cut off the surplus trips so that the expressway is not oversaturated under the condition that the total number of trips cut off is a minimum. Long queues that are expected to build up on the regulated ramps are expected to create difficulties. Traffic signals are not proposed to effect the control, but adjustment of the rate of collection of tolls may be used.

An elaborate theoretical method has been proposed for estimating the trip distribution between pairs of ramps based on ramp volumes. The method does not require interviewing or other O-D surveys.

ITALY

Work in Italy has been concentrated on 2 problems: (a) safety in long tunnels by means of queue detection, telemetering of signals indicating the presence of queues, and control of tunnel entrance by means of traffic lights; and (b) prevention of queue formation in tunnels that are close to toll barriers. So far as the first is concerned, a system has been in operation since January 1969 in the S. Fermo Tunnel (2,300 ft long) on the Como-Chiasso Autostrada. Safety problems in tunnels arise from 3 main causes: (a) variation in illumination level from outside to inside and the degree to which drivers are able to adapt themselves to these changes; (b) presence of carbon monoxide in proportion to the vehicle flow; and (c) absence of emergency lanes due to the high cost of tunneling.

A forced stop inside the tunnel not only increases the risk of minor accident due to head-tail collisions but can also lead to a dangerous buildup of carbon monoxide. Although accidents in tunnels are comparatively rare, any one has the potential for creating a disaster of catastrophic size (e.g., if a vehicle catches fire).

The S. Fermo Tunnel has 2 independent bores each containing 2 traffic lanes. The electronic system is capable of detecting the presence of standing vehicles or of a queue of vehicles at certain points and can automatically control access to the tunnel by means of traffic lights placed at the entrances. Both bores are controlled. Green is normally displayed to drivers; this is changed to red when a queue situation has been detected. Green is automatically restored only when the situation has been cleared. Both bores can be closed if necessary (e.g., if vehicles are trapped, to enable those in 1 bore to return via 1 of 3 service bypasses into the other bore or if a buildup of carbon monoxide in 1 bore affects the other).

Each detection station has 2 loops, one for each traffic lane. The stations are at 270-ft intervals along each bore, the last being about 170 ft past the tunnel end. A multicore cable is used to transmit information from a cabinet in the tunnel to the control room.

The spacing of 270 ft (80 m) was selected on a theoretical basis. In the case of an accident or formation of a queue immediately upstream of 1 detection station, one has to wait for the queue (or slow down in speed) to reach the next station upstream. This response time is a function of the traffic volume; the higher the volume is the shorter the response time is. The following are the response times calculated according to various volumes:

Volume (vph)	Maximum Response Time (min)		Response Time Not Exceeded in 95 Percent of Cases (min)	
	160 m	80 m	160 m	80 m
1,200	1½	¾	1	½
600	3	1½	2	1
100	18	9	12	6

Thus for practical purposes the response time will generally be less than 1 min with an 80-m spacing.

The output signals from each detector are analyzed to see whether they exceed a given time threshold (which may not be the same for every detector). Any loop occupied for longer than its threshold operates the lights at the tunnel entrance. The lights remain operated so long as any detector is occupied and for a preselected period afterward. Slowly moving queues are dealt with by shortening the threshold time of a detector immediately after operation and release.

It is proposed to use the installation for study purposes. The following studies are under way or proposed: uneven spacing of detectors, optimum number of detectors, and average speed at points in the tunnel. This will be compared with different threshold times so that slow speeds may be detected and centrally displayed and possibly used to input the control system instead of queue detectors.

Some Italian autostradas in mountainous regions have many tunnels. The network near Genoa is typical. It sometimes happens that a toll barrier has to be placed at a short distance from a tunnel. Because of the terrain difficulties, the number of tollgates is kept to the minimum to deal with normal flows. At times, therefore, queues inside the tunnel could cause danger through high concentrations of carbon monoxide and risk of rear-end collision with stop-and-go traffic under conditions of reduced visibility.

Two loop detectors (one per lane) are installed just at the exit of a tunnel together with one or more near the toll barrier. The loop detectors have different functions according to their positions. Signal outputs of the detectors at the tunnel exit are analyzed to see whether they exceed a given time threshold. The outputs of those at the toll barriers are analyzed to see whether the loops are free (i.e., not occupied).

During normal conditions of flow, a green signal is displayed at the tunnel entrance. Even if the detectors at the barriers are occupied, no action is taken. When the queue reaches the tunnel exit, the actuation of one or both of the loops there will cause the signals to change to red. This condition will persist as long as one or the other of the loops at the exit is occupied, and also after they are both free until such time as a signal is received that the loop or loops at the barriers are not occupied. Thus, when the lights change to green, drivers will find both tunnel and toll plaza clear of traffic. The system has been arranged so that when the first vehicle that has been stopped reaches the toll plaza the last vehicle in the queue will be at the tollgates.

The first of these systems was installed in May 1968 near Genoa. This has operated satisfactorily, and no accidents have been reported since.

The Monte Olimpino Tunnel is 670 ft long on the Como-Chiasso Autostrada and is followed by a traffic-actuated signalized intersection between the autostrada and the Bellinzona National Highway. If the intersection queue is long enough to cause vehicles to wait in the tunnel, a signal is sent to the intersection controller so that at each cycle the autostrada phase receives an additional preselected time of right-of-way.

The Mont-Blanc Tunnel under the Alps joins France and Italy and has 2 traffic lanes with laybys at 1,000-ft intervals on alternate sides for vehicles that break down. Traffic in the tunnel is controlled according to 3 conditions: (a) that the average quantity of carbon monoxide does not exceed 150 ppm; (b) that the headway or distance between 2 following vehicles is not less than 330 ft (100 m) (this a consequence of the first condition); and (c) that the maximum speed of vehicles does not exceed 50 mph (80 km/hr) (this is a consequence of the second condition).

Inside the tunnel there are 9 devices that analyze the concentration of carbon monoxide at different points and transmit this information every 26 sec to the control room. There are also 9 opacimeters that show the rate of reduction in visibility caused by exhaust fumes. The visibility is measured by perceiving a beam of light 100 ft distant. This information is also transmitted to the control room every 26 sec.

Access to the tunnel is prohibited if the average concentration of carbon monoxide exceeds 150 ppm and if the strength of the beam of light is reduced by more than 25 percent for more than $\frac{1}{2}$ hour. The ventilation plant is capable of introducing 600 m^3/sec of fresh air into the tunnel. Assuming that each vehicle emits 30 liters/min of carbon monoxide, the practical capacity of the tunnel is about 1,000 vehicles/hour with a headway of 300 ft.

There are 28 counters inside the tunnel that measure vehicle headways and flash a light if a driver reduces his headway below 300 ft. Speeds are also measured, and a warning light is flashed if a driver exceeds 50 mph (80 km/hr) or goes slower than 30 mph (50 km/hr).

In motorway control and surveillance systems at present under consideration or under project, slow-speed detection rather than queue detection has been preferred as a criterion for the production of signals to be telemetered or to be used as a starting basis for a control action to be automatically performed. The slow-speed criterion obviously incorporates in the control system an inherently faster response to an emergency or congestion situation.

It is anticipated that outside of tunnels—in motorway sections where daily volumes exceed 20,000 to 30,000 vehicles—2 speed thresholds will be used against which average speed of preselected numbers of vehicles will be compared. If average speed is below the higher threshold, a light indicator in the central control room will be switched from green to yellow and at the same time a first-level caution sign will be lighted upstream from the low-speed stretch on the motorway. If average speed is below the lower threshold, the light indicator in the control room goes from yellow to red and a more stringent caution sign will be lighted upstream on the motorway.

In tunnels the same criteria as those just described will be followed and a third higher (less sensitive) speed threshold will be used; in case average speed is below this third threshold, but not below the other two, flashing caution yellow lights will be operated inside the tunnel and upstream of the section where the slow speed has been detected. Cautionary amber flashing in tunnels may, therefore, be activated by a slow column of vehicles that cannot overtake a large and slow vehicle in front. If average speed falls below the lowest threshold, entrance to the tunnel will be blocked by means of traffic lights—which will, however, turn back to green only when no presence of standing vehicles is detected on all the loop detectors in the tunnel bore that was closed by the traffic lights. The average speed situation in detection stations inside tunnels will, of course, also be displayed centrally.

Variable-message signs are not only remotely but also automatically controlled. It is expected that future systems will have the control and surveillance strategies implemented by means of a digital computer, which will also steer variable-message signs indicating to motorists approaching the motorway entrance ramps the state of the ramp (free, metered, or blocked) and eventual congestion situations in intermediate stretches on the motorway.

These strategies are also complemented by "accident detection" by means of absolute and relative comparisons between upstream and downstream occupancy.

Considerable work has been devoted to a study of the application of the Lighthill-Whitham model to the problem of motorway control and surveillance. The problem has been studied analytically under the theoretical assumption that the volume-density fundamental diagram is a parabola and also studied graphically on the basis of a measured fundamental diagram. It was determined that a more significant analysis based on realistic (measured) fundamental diagrams can only be attempted by means of a digital computer, and the necessary programs are being flow-charted.

Preliminary results indicate the possibility of tying detector spacing with desired system response time in various situations and particularly in traffic conditions represented by points on the descending unstable branch of the volume-density diagram. As a consequence of this type of reasoning, rather close spacing of the speed detection stations appears advisable. Spacings of 250 m outside tunnels and of 125 m inside tunnels have been provisionally selected in very heavily trafficked urban motorways.

FRANCE

In France the problems of freeway operations have recently been highlighted by the construction of 2 parallel freeways, A6 and H6, to the south of Paris. These 2 freeways, together with 2 existing all-purpose roads, N7 and N20, form a complex network connecting Paris with Orly Airport and the new Rungis market. The A6 Freeway also connects Paris with the south of France. A preliminary study was started in 1968 with a view to ensuring optimum use of the network under all conditions.

The first task was to define what was meant by optimum use. The following criteria were considered: minimization of overall travel time; equalization of travel time, or minimization of individual travel time; reduction in the number or duration of stops; and minimization of waiting time before joining the freeway.

However, to be really useful a criterion must above all be simple, sufficiently representative of the quality of service that is demanded on the network, and measurable. For this reason the final choice made was that of the time spent by vehicles in the system. This parameter is one of which drivers are particularly conscious, and it is easily shown (by using some simple assumptions) that minimization of the total time spent in the network is equivalent to maximizing the entry flows.

The means of influencing drivers that were considered were (a) light signals with 3 colors on the different access ramps and at the junctions with the all-purpose roads, (b) variable route signs at different choice points in the system, (c) speed regulation, and (d) arrangements for lane control designed to facilitate the convergence and divergence of traffic.

The study showed that the regulation of traffic could be broken down into the following 2 levels:

1. For the whole system, a control with a sufficiently long cycle (of the order of 10 min) that would fix the route indications as well as the access control; and
2. A local control to make up for any imperfections in the overall control and to attenuate any perturbations produced at certain points on the network.

This local control, which would have a fairly short cycle (of the order of 1 min), would actuate the control of access, signs controlling converging lanes, speed signs, and signal controllers at all-purpose road junctions.

The overall regulation consists of determining at each instant the number of vehicles to be admitted at each entry to the system and the routes to be recommended to drivers within the network in such a way as to minimize the sum of the times spent in the network (including time spent in waiting at the entries). This is a linear programming problem details of which may be found in another paper (20).

The equipment required to achieve control consists of the following:

1. Three categories of variable signs that include direction signs to orient drivers at the boundaries of the system and within it according to the state of traffic, lane indication signs with green arrows and red crosses showing whether a green lane is inaccessible, and speed signs indicating recommended speeds that comprise 2 curtains sliding vertically or horizontally;
2. Access ramp signals that consist of 2 sets of lights at each controlled ramp, the first set sited at the beginning of the ramp to indicate whether the access is open or shut and the second set situated on the ramp to exercise the control proper;
3. Four types of measuring equipment that includes queue detectors comprising 2 magnetic loops that minimize the risk of detecting a queue when vehicles are traveling slowly as well as not detecting a queue when vehicles are stopped on either side of a loop, flow detectors that are required at all entries and exits as well as a certain number within the network, saturation detectors that measure the degree of saturation by associating the measurements of flow and speed and plotting them on the speed-flow curve for the freeway and by determining the rate of occupation of the carriageway, and radar speed meters;
4. Transmission equipment to connect the control center and the various outstation equipment over Post Office telephone lines by using frequency division multiplex; and
5. Control center equipment that has not yet been finally decided on but will probably include a mimic diagram showing the state of the detectors giving queue length and saturation and the state of signs, a control desk giving the operator indications of the state of traffic and enabling him to choose some overall strategy or to operate individual signs or signals, television monitors corresponding to a certain number of cameras on the network, and a computer with a capacity of the order of 16-K words of 16 bits.

The installation of this control system is expected to take place in phases. In the first phase, signs and light signals on the access ramps will be installed as well as a certain number of detectors. At the control center choice of signs and lights will be made by the operator with the aid of a book of instructions. In the last phase the number of detectors will be increased in such a way as to furnish the computer with maximum information on the instantaneous conditions of the traffic. The computer will no longer rely on preset programs but will function in real time with the aid of an optimization program. The first phase is expected to be in operation during 1971.

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ACCOMPLISHMENTS IN FREEWAY OPERATIONS IN THE UNITED STATES

Joseph A. Wattleworth, Civil Engineering Department, University of Florida

•THE FIELD of freeway operations is about 2 decades old and, hence, is considered to be a new field. The concern for freeway operations has naturally followed the beginning of the major freeway construction that began in the early 1950's in many areas of the United States. In spite of the short life of the field of freeway operations, a great deal of progress has been made, and there have been numerous significant accomplishments.

The original concept of freeways was that of a facility on which large volumes of traffic would move at high speeds. Also it was thought that these superhighways would operate properly with little or no attention from public agencies. During most hours of the day, this concept is correct. During other periods of the day, many urban freeways are plagued by recurring peak-period congestion that is caused by the traffic demands exceeding the capacity of the facilities.

One can ask, Why do freeway facilities—even some that have been only recently planned and built—suffer from congestion? There are at least 2 answers to this question. First, the urban transportation study results, although as good as possible, are simply not accurate enough for purposes of facility design. Unforeseen changes in land use or development can completely change the travel patterns in an area and, hence, can have great effect on the facility operation. Second, the transportation planners use traffic assignments based on transportation networks that are planned for completion 20 years in the future. However, until the planning horizon is reached, partial systems are in operation, and portions of these systems must carry the loads that will later be handled by new facilities.

The very nature of freeways create other operational problems. The high-volume, high-speed characteristics are responsible for this. For example, a stranded motorist is exposed to a great accident hazard. A spilled load from a truck can create severe disruptions. The motorists' needs for services that will aid them during emergencies are increased. Signing becomes complex because of the short time available for the drivers to make decisions.

As a result of these needs, several groups began to look into the problems of freeway operations and to seek solutions to these problems. These groups include the Port of New York Authority, the California Division of Highways, the Illinois Division of Highways (Chicago Area Expressway Surveillance Project), the Michigan Department of State Highways (Detroit Project), and the Texas Transportation Institute. The high costs of freeway construction made it necessary to seek means to operate the existing freeway systems as efficiently as possible.

In this discussion, 4 general categories of accomplishments will be presented: improved designs; surveillance, communications, and control; secondary benefits of surveillance and control; and improved safety.

IMPROVED DESIGNS

One of the first areas of concern of freeway operations was the development of improved freeway designs. This is a function of 2 factors. First, the design standards

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on many of the early freeways were quite apparently inadequate. Second, most of the engineers who dealt with freeways and their operation in the early 1950's were from the design field so it is natural for design to be an early field of study.

Freeway Design Standards

In the late 1950's and early 1960's research was conducted by the California Division of Highways and the Texas Transportation Institute to determine operational characteristics of drivers on entrance and exit ramps. The purpose of this research was to identify the driver requirements for ramp designs and to develop ramp-design standards that meet these requirements and standardize the situations encountered by drivers on entering or leaving a freeway. The results of these efforts are ramp-design standards that have been adopted by nearly all states and that result in more efficient operations on freeway ramps—smoother merges and increased safety of entering or exiting vehicles.

Reversible-Lane Concept

The reversible-lane concept is one of the first attempts to balance the demand and the capacity of a facility. Under this concept, the directional use of part of the facility is changed to meet the changing requirements of demand during peak periods.

The first applications were operational and were used on existing facilities. These facilities include the Lake Shore Drive in Chicago and bridges and tunnels in New York and elsewhere. Later applications were designed into new facilities. The Kennedy Expressway in Chicago has a 2-lane reversible roadway built in the median and extends for 8.5 miles northward from the downtown area of Chicago. The outer roadways have 3 lanes over part of the length and 4 lanes over the remainder and operate in the normal unidirectional fashion. Interstate 5 in Seattle has a reversible facility extending 8 miles north from the downtown area of Seattle and built in the freeway median. The reversible roadway in Seattle differs from the one on the Kennedy Expressway. Several interchange points are provided on the reversible roadway in Seattle, while the one on the Kennedy Expressway is an express facility with no entrances or exits between the terminals of the roadway.

As a result of these experiments it has been shown that the cost of a facility can be reduced by use of reversible lanes where directional distribution is proper. This is due to the fact that the peak demand in each direction can be accommodated on the same roadway.

SURVEILLANCE, COMMUNICATIONS, AND CONTROL

Because the operational problems on freeways during peak periods have become severe in most urban areas and because of the high costs and difficulties involved in additional freeway construction, several concepts of freeway surveillance and control have been explored and developed. These concepts involve the use of some means of sensing to determine traffic conditions and the feedback of control or communications to the motorists to increase the efficiency of traffic flow. Most of the freeway surveillance and control systems that have been developed make extensive use of electronic sensing, communications, and computing devices to accomplish the desired objectives.

The following is a chronological summary of the major developments in the field of freeway surveillance, communications, and control.

Metering Tunnel Traffic

Inadequate tunnel capacity and extremely high tunnel construction costs led the Port of New York Authority to begin detailed operational studies of tunnel traffic flow in the mid-1950's. The researchers did a great deal of theoretical and empirical work to develop a better understanding of traffic stream flow. They found that the flow rate through a tunnel decreased when congestion was allowed to develop in the tunnel. This was a particularly significant finding because it suggested that an appropriate traffic control system might improve both the quality of flow and the quantity of flow.

This finding led them to conduct the first experiments dealing with "metering" traffic flow to keep it at prescribed levels of speed and density. They found that the volume of traffic through the tunnel could be increased about 5 percent by controlling the input traffic to the tunnels and that this decreased the period of congestion by about 30 percent and greatly reduced the delay to vehicles. A fringe benefit was substantially lower ventilation costs and fewer stalled vehicles.

Because of the success of these experiments, the Port Authority has developed automatic systems to accomplish the metering and has refined the control logic considerably. These systems are currently in operation in the Lincoln and Holland Tunnels in New York.

Television Surveillance and On-Freeway Control

In the late 1950's the need for development of freeway surveillance and control was recognized. The Michigan Department of State Highways began experimenting with closed-circuit television surveillance techniques and by 1960 had a system of 14 cameras and monitors installed on a 3.2-mile section of the Lodge Freeway in Detroit. Research was also conducted on "on-freeway" controls such as lane-control signals and speed-control signs. The development of TV surveillance was a great help to future surveillance systems that used closed-circuit television. This phase of the work in Detroit extended through 1966.

Electronic Surveillance and Access Control

A parallel concept of surveillance and control was developed in Chicago on the Eisenhower Expressway in the early 1960's by the Chicago Area Expressway Surveillance Project, which was staffed and sponsored by the Illinois Division of Highways. This concept involved the use of electronic detection for surveillance and the restriction of access to the freeway. Thus, it relied on "blind" (non-TV) surveillance and control of vehicles before they had entered the freeway. The metering concept was developed on this project. Under this concept vehicles are stopped at entrance ramps and allowed to enter the freeway at rates that will prevent (or reduce) the overloading of the freeway. Many of the mechanical problems of accomplishing this process were overcome by the research on this project and a control philosophy was developed during this time.

A 7-mile section of freeway was placed under electronic surveillance and ramp control in 1963, and operation continues to the present time. Additional sections of freeway have also been placed under ramp-metering control in the Chicago area.

This project demonstrated the feasibility of a ramp-access form of control system and also documented the benefits of this type of control to the freeway motorists.

Diversification and Refinement of Access-Control Concepts

The Texas Transportation Institute during the period from 1963 to the present did a great deal of work in Houston and at other locations to develop additional concepts of access control and to refine control systems. This work was conducted on several projects and sponsored by the Texas Highway Department and the Federal Highway Administration. One of the major accomplishments was the detailed study of the freeway merging process and the development of a gap-acceptance form of ramp control. Under this concept, individual vehicles on entrance ramps are released from the traffic signals at times that will project them into a specific gap on the freeway. Additional types of metering systems, including a system optimization technique using a linear programming model, were also developed.

The Gulf Freeway in Houston was selected as a study site, and it was instrumented with an electronic detection system and a closed-circuit television system. Many experiments on traffic control were conducted from 1964 to the present time, and the ramp control system is still in operation. Two of the major findings were that peak-period travel time was reduced about 25 percent and accidents were reduced about 40 percent because of the operation of the control system.

Corridor Considerations

Early studies were concerned primarily with the improvement of freeway flow, and the effect on adjacent streets was an important but secondary consideration. Later work was oriented to the consideration of the entire freeway corridor as a system and the optimization of operations in the entire corridor.

In 1967, the Texas Transportation Institute was awarded a contract under the National Cooperation Highway Research Program to continue the research on the Lodge Freeway in Detroit. During 1967 a metering system, including an electronic detection system, was installed on 8 entrance ramps on the Lodge Freeway. This system made use of a digital computer that had been previously operated by the research staff of the Detroit Project. The evaluation of this system included the evaluation of the total effect of ramp controls on the traffic operations in the corridor, including both the freeway and about 50 miles of arterial streets. It was found that the total travel time in the system was reduced considerably with little adverse effect on the street system. A cost-effectiveness analysis indicated that a cost of about 15 to 30 cents would be expended to save each vehicle-hour of travel time on this facility with an operational ramp-metering system.

In addition to control of traffic in a freeway corridor, the need to provide better information to drivers was also recognized. With adequate information on the conditions of several alternate routes, the drivers could select the best routes and reduce the need for restrictive control. Changeable-message signs were evaluated by the Chicago Project and by the Texas Transportation Institute in Detroit in 1968. In 1969 the University of Michigan assumed responsibility for the work on the Lodge Freeway in Detroit and continued the development, refinement, and evaluation of driver-information systems as well as investigated incident-detection schemes. This work is still under way.

In 1968 plans were formulated for a project in Dallas to be conducted by the Texas Transportation Institute. This project is intended to develop a surveillance, communication, and control system that will optimize traffic flow in the entire corridor of the North Central Expressway. This project includes freeway metering, control of network traffic signal, and driver information displays all controlled by a single control center. Thus, the optimization of the entire system will be possible. This project is in the equipment installation phase, and experiments are expected to get under way soon.

Freeway Network Considerations

Most of the early research in Detroit, Chicago, and Houston involved an intensive investigation of fairly short sections of freeways. In 1961 the California Division of Highways began to study the operations on the entire 400-mile freeway system in Los Angeles. They identified the bottlenecks, determined the amount of delay caused by each, identified the most cost-effective solution to each, and established priorities for completion of the solutions. This work differed from past work in that it involved much less detailed studies of a much larger area of freeway and in that solutions other than control were considered. Emphasis was placed on geometric modifications (such as addition of a lane throughout the problem area, ramp redesign, and reconstruction) or other operational changes in addition to ramp control.

The need for continuous surveillance of the freeway systems to detect accidents and other impediments to traffic flow was established, and several sections of freeway are currently being instrumented for this purpose. Several ramp-control installations have also been made.

The Chicago Area Expressway Surveillance Project also expanded its scope of activities to include all of the 300 miles of freeways in Chicago. Currently several other freeway sections have been placed under surveillance and ramp control, and plans are now being developed to extend this to the rest of the Chicago freeway systems. Freeway surveillance and control are now designed into all new freeways in the Chicago area.

Moving-Merge Control System

The Federal Highway Administration currently has under development a moving-merge control system. This system requires ramp vehicles to stop only when it is necessary from a capacity or safety point of view to do so. When it is not necessary for a ramp vehicle to stop, a moving band of green light paces the motorist on the ramp so that he will arrive at the merging point positioned properly relative to an acceptable gap in the right lane of the freeway. A prototype of this system was installed and tested on an entrance ramp in the Boston area.

Coordination of Freeway Surveillance and Control With Transit Operation

In 1967 and 1968 the Texas Transportation Institute conducted a feasibility study of the use of freeway surveillance and control to provide express buses a priority service in a mixed-mode operation on the freeway. Buses would have free access to the freeway but automobiles would enter on controlled ramps. The buses would operate in a mixed-mode with automobiles on the freeway, but the number of automobiles is maintained at levels to guarantee a high travel speed for buses. Thus, the control system would provide priority service for buses. The study indicated the concept to be quite feasible, and one or more of these systems are expected to be installed and tested in the near future.

SECONDARY BENEFITS OF SURVEILLANCE AND CONTROL

The development of freeway surveillance and control systems and their subsequent successful evaluations have caused these systems to be a recognized and accepted, though advanced, form of traffic control. In the development of these systems, the researchers were oriented primarily toward the reduction or elimination of recurring congestion, that is, the congestion that is caused by normal variations in traffic demand. Largely as a result of the research on freeway surveillance and control, several other operational problems of and alternate approaches to solutions of freeway operational problems were recognized. Development of solutions to these problems was carried on in some cases by existing staffs of freeway surveillance and control projects and in some cases by separate research groups. Some of these problems and alternate approaches are rapid detection of incidents that reduce the capacity of the freeway and rapid removal of these incidents; provision of adequate service to stranded motorists; improvement of police operations to minimize the interference of police activities with freeway operations; and improved scheduling of maintenance operations to minimize interference with freeway traffic flow.

Freeway Incidents

Traffic accidents, disabled vehicles, spilled loads, and similar incidents can produce major sources of congestion and accident hazards on urban freeways, especially during peak periods. On many urban freeways it has been found that the majority of peak periods experience the effects of some type of incident.

The nature and severity of the operational problems caused by these incidents have provided an impetus for the search for ways to reduce the frequency of such incidents, detect the occurrence of such incidents as rapidly as possible, and provide a means for the rapid removal of these incidents.

The investigation of electronic techniques to detect these incidents has been conducted by the freeway surveillance and control staffs in Chicago, at the Texas Transportation Institute, and at the University of Michigan. Several techniques have been developed and are in use at these locations as part of the existing freeway surveillance and control systems.

Emergency communications have been provided on several urban freeways that are not under electronic surveillance. One form of such emergency communications is the call boxes or emergency telephones that are located at intervals along several freeways. Motorists who need assistance can walk or drive to the nearest call box or emergency phone and can summon aid. Another, more sophisticated, form of emergency communication is the citizens band radio system under evaluation in Detroit. In this system the city of Detroit operates a base station that can monitor broadcasts from automobiles equipped with citizens band transmitters and located on any Detroit freeway. Motorists with CB units report incidents to the base station, and aid is dispatched.

Improved police patrolling is also a means of decreasing the response time to an incident. The police cars that patrol the freeways in Detroit are equipped with heavy-duty bumpers so that, in addition to responding quickly to incidents, these units can also move a high percentage of the incidents off the travel lanes of the freeway. This is a particularly effective system of reducing the length of time the freeways are blocked by incidents.

A fleet of about 40 emergency patrol vehicles is operated on the freeway system in Chicago by the Illinois Division of Highways. These vehicles are 1½-ton trucks that are equipped with a wrecker boom, heavy bumper, fire extinguishers, spare gas and water, compressed air tanks for pumping up flat tires, public address system equipment, flashing warning lights, and other miscellaneous equipment. The function of these vehicles is to protect stranded motorists and to move stranded or disabled vehicles from the freeways. This system is quite successful, but it is quite expensive.

The Illinois Division of Highways in Chicago also has a freeway operations engineer who is responsible for restoring freeway operations during unusual incidents. A high frequency of spilled loads provides the bulk of the situations to which this official must respond.

Motorist Services

The items previously discussed were oriented primarily toward removing incidents that are disrupting traffic. However, many motorists are stranded during other periods of the day with mechanical trouble, flat tires, and so forth. They do not disrupt traffic, although they represent an accident hazard, but they still, in many cases, need assistance. Three of the systems that were previously mentioned provide means for detecting or assisting stranded motorists. These are the emergency communication system, the citizens band monitor system, and the emergency patrol vehicle system.

Improved Police Operations

The police who patrol freeways perform a vital set of services and are quite important in the maintenance of good freeway operations. However, in several areas it was found that the police were employing practices that were somewhat detrimental to the traffic operations on freeways. The intensive surveillance that resulted from the freeway surveillance and control research pointed up several of these practices. In many areas, some of these practices were very simply changed, and the result was great improvement in traffic operations.

The first area of concern is that of an emergency that blocks part of the freeway. In many cases the officers were allowing the blockage (perhaps an accident) to remain on the freeway too long before moving it. Then, after it was moved to the shoulder, the incident was allowed to remain on the shoulder for too long a period of time. Finally, the officers frequently remained on the shoulder with a warning light flashing until they had completed their report of the investigation. Each of these acts produced a disruption to traffic flow.

As a result of freeway operations research and the concerns of freeway operations personnel and enlightened police officers, procedures have been developed in many urban areas whereby police operations produce a minimum interference with freeway traffic flow. The police remove incidents quickly from the roadway—in many instances completely off the freeway right-of-way—and then complete the necessary reports. Emphasis is placed on, first, the early removal of the incident from the traveled way and, second, the early removal of all evidence of the incident, including the vehicles of the investigation officers, from the freeway right-of-way.

Improved Scheduling of Maintenance Operations

Maintenance operations in many urban areas are not scheduled by freeway operations personnel, and frequently maintenance operations cause excessive delay to motorists on a freeway. Basically the capacity of the freeway during the maintenance operation is less than the demand on the freeway.

The California Division of Highways recently developed field procedures for use by maintenance forces to determine whether they can initiate a maintenance operation without causing congestion on the freeway. Such procedures allow the maintenance personnel to schedule their activities in such a way as to minimize the delay to the motorists and to maximize the safety of the motorists and the maintenance forces.

IMPROVED SAFETY

Several freeway safety improvements have been developed through extensive research and have resulted in considerable reductions in the number and severity of certain types of freeway accidents. One of the first freeway safety studies was conducted by the Texas Transportation Institute and has as its objective the correlation of geometric elements to accident frequency. Later work at the General Motors Research Laboratories determined the need to maintain minimum levels of lateral clearance in order to prevent many single-vehicle accidents.

Full-scale crash tests were used by the California Division of Highways and the University of California, Los Angeles, to test several alternative median-barrier designs. As a result of these tests a standard median barrier using chain-link fence and cables was developed for use in California and other states. In addition, a great deal was learned about the dynamics of automobile occupants in the event of an accident. In recent years the Texas Transportation Institute has been a pioneering developer of many devices that have greatly reduced the severity of certain types of freeway accidents. First, the breakaway sign supports and luminaire standards were developed. These devices merely yield on impact from a vehicle and greatly increase the survival probability of the automobile occupants. These breakaway sign supports and luminaire standards have been adopted for use in most states at this time. Another development at the Texas Transportation Institute is that of impact-attenuation devices. These devices attenuate the kinetic energy of a vehicle that hits a stationary object on the freeway and do so at a rate that will decelerate the vehicle at the maximum safe rate. These devices are receiving increased application at this time.

Many other safety improvements have been developed. For example, the California Division of Highways has developed a signing system for use on freeway exit ramps to prevent wrong-way maneuvers onto the freeway.

SUMMARY

In spite of the fact that freeway operations is a new field, there has been a great deal of development and progress in the field. These accomplishments can be attributed largely to several active research groups. The accomplishments have produced important documented benefits in terms of reduced delay and travel time for motorists, increased safety, and improved service to the motorists.

INFORMAL DISCUSSION OF FREEWAY OPERATIONS IN THE UNITED STATES AND OTHER COUNTRIES

The 2 preceding papers in this RECORD summarize the discussion by 2 panels regarding accomplishments in freeway operations. Following this discussion, the panelists were asked questions by those in the audience, and this paper is a transcript of these questions and answers. Members of the panels were Joseph A. Wattleworth, University of Florida; Patrick Athol, Illinois Division of Highways; Donald Cleveland, University of Michigan; Robert S. Foote, The Port of New York Authority; W. R. McCasland, Texas A&M University; William E. Schaefer, California Division of Highways; J. T. Duff, Ministry of Transport, England; M. Frybourg, Ministry of Transport, France; Masaki Koshi, University of Tokyo; Roberto Vacca, Campagnia Generale Automazione, Italy; and R. Lapierre, Institut für Strassenwesen Erd-und Tunnelbau, Germany.

Question

Mr. Foote mentioned that his measurements showed that he was able to increase the output of the tunnel by reducing or by limiting the input. A number of other projects have showed similar results, usually with another result that some queues are formed at the input where the limitation has taken place. This can often produce a certain adverse public reaction. What was the public reaction in this case?

Robert S. Foote

The basic purpose of this tunnel-flow control operation is to increase the amount of throughput. Although it is true that in this operation we do create a delay at the entrance of the tunnel earlier than would otherwise be the case, the net impact is to reduce the overall delay. There are other benefits too: a faster, safer, and smoother trip through the tunnel; fewer disabled vehicles; and less air pollution. This operation is really still on a prototype basis. Not until a later time will we be controlling flow in all tunnels full time. We have been controlling flow periodically on an experimental basis at 1 tube of the Lincoln Tunnel. Bus operators in particular seemed to understand what it is we are trying to do. The control is exercised by a sign that comes on and reads PAUSE HERE—THEN GO, and there is nothing that is very commanding about it. When we first started this control, people did not pay much attention to the sign by itself, so we augmented it with some other devices. During a period of months as we gained experience we found we could discontinue the other devices. People did seem to obey the sign more. They had an appreciation of what we meant by pause. They would just come to a stop for a second or so and then start again. Therefore, people were moving normally into the tunnel in fluid movement. When the sign comes on, generally within 3, 4, or 5 vehicles a driver will pause. Once that happens then usually the succeeding drivers will also pause until the sign is turned off. We have had good public reaction and compliance for the past several years during the extended tests.

Question

I have a 2-part question relating to the impact of ramp metering on local streets. The first part is about cost effectiveness. Mr. Foote mentioned that throughput has

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been increased. What about the urban network where, because of ramp metering, traffic is diverted to local street systems? Here we have additional delay to nonfreeway traffic that uses the local street system because the freeway traffic from one ramp must use the local streets to go to ramp B, C, or D. Has any work been done on the cost effectiveness of this aspect? The second part of my question relates to communicating with the driver. There has been an extensive discussion in the United States and abroad about variable-message signs. In Japan information is given to the motorist at the on-ramp. Do we have these variable-message systems on the local streets to tell motorists how to find the next ramp? Has any work been done on local street communications as part of the process of diverting the traffic from one on-ramp to another?

Patrick Athol

A misleading impression may have been given, and that is that the corridor studies followed the earlier work. Of course, this is merely in terms of instrumentation so that most of the control studies that were undertaken in the early days did attempt to measure the specific problem to which you refer. Benefits really mean network benefits even though the instrumentation was limited to, in most cases, the freeway. What happens, however, is that the diversion through the network in many cases is beyond the ability to measure so that the traffic to which you refer that leaves the entrance ramp and travels through the network is so diffused throughout the network that if often has a very small and not measurable influence on delay to the network. The other problem that ties in with whether we are getting any benefits is that many of the projects that do not involve tunnels are not able always to get improved capacity on the freeway. In other words, in the tunnels where there is congestion there is a lesser flow. On a freeway this is not true. In many cases, one has to actually trade off the level of service on the freeway for this capacity. Essentially what one is doing is setting a level of service criterion for the freeway. Considering that there is a discontinuity of flow, we are getting a sizable improvement in reduced delay on the freeway essentially by striving to stay within the better or higher level of flow situation and avoiding the breakdown. We are getting a major saving on the freeway and a diversion throughout the network. Because of the sizes of the networks we are dealing with, in most cases, it is not possible to measure any increased delay to other vehicles, and so there is a net benefit from the system.

Donald Cleveland

With regard to the second part of the question about information systems, we have been experimenting with a network in Detroit that can be visualized as a ladder with 3 vertical members rather than 2 and with 8 cross pieces equivalent to the 8 ramps that were metered when the Texas Transportation Institute was operating the system. These are major streets in the corridor and have a total length of approximately 6 miles and a width of less than 1 mile, slightly twisted at the middle. As a part of this project to optimize flow through the corridor, we have recently completed some experiments in which the display system exists at 2 levels. With the cooperation of the local highway agencies, we placed more than 100 typical trail-blazer static devices that move traffic toward the northbound Lodge Freeway. At between 20 and 30 key intersections, we have had dynamically operated, simple-to-complex displays during the afternoon peak. These indicated to the motorists which of these binary choices they should follow if they were interested in moving some distance north on the freeway and in optimizing their individual travel time through the network. Wherever we have used a variety of these displays there has been some small (more than 10 percent but less than 40 percent) response to our suggestions. In many cases we have been able to consistently deliver a faster trip to those who have used the network.

Question

In this country we are using changeable-message signs, and apparently they are doing so in Germany and Japan. I wonder whether representatives from these countries and others would express their opinions concerning the need for international symbolism and the possibility of achieving such on changeable-message signs.

Masaki Koshi

Characters in the Japanese language are quite different from alphabet characters in other languages. We are a member of the international road traffic organization, and we use symbols according to international rules. I am afraid, however, that we cannot use symbols in changeable signs because we want to give as much information as possible to drivers. If we study how the changeable signs affect drivers in selecting the surface street or freeway, we find very little difference in route-selection behavior. If we do not give drivers the cause of the congestion and only tell them CONGESTION AHEAD, they pay no attention to the sign. If we give them ACCIDENT—CONGESTION AHEAD they do not use the freeway. For this reason, I do not think we will be able to use or adapt international sign symbols.

R. Lapierre

In Germany we have developed only changeable signs with speed limit information. These use internationally known symbols, and we have no trouble on our motorways because this is a sign that all drivers know and therefore understand.

J. T. Duff

In England, the indications that we give on our changeable signs are all completely symbolic. We either display a number that gives the advised speed of travel or indicate a symbol showing which lanes are open or closed. We can show a symbol diverting traffic from one lane to another or onto an off-ramp. The all-clear symbol is the international symbol—a circle with a diagonal bar. All signs are in accordance with international standards in Europe.

Roberto Vacca

In Italy, the organization responsible for establishing the national standards for signs is the Ministry of Public Works, and it has not yet determined a national standard for variable-message signs, although one for fixed signs exists. What we have in mind for freeway control systems now under project is to display written signs with a variable message indicating the names of stations between which there is congestion or a total blockage. We would display separately the names of the beginning and the end stations and the cause of the impediment, that is, congestion or total blockage. These signs would be put just before the ramp at the last possible decision point. All the signs that we are thinking of installing are similar to those installed in Chicago; they indicate the ramp situation. Apart from the name of the ramp or the symbol indicating the ramp, it would certainly be appropriate to devise some kind of international symbol for indicating whether access to the ramp is unimpeded, difficult, metered, or impossible. Although international symbols exist for many other traffic situations, a symbol for the state of a ramp does not exist. I think it would be highly appropriate for one to be devised.

Question

What is meant by the optimum flow of traffic? Different studies seem to have adopted different criteria for the optimum flow. It was stated that capacity and safety are optimized although those do not always go together. It was also stated that actually capacity and level of service are traded off. There is also the problem of travel time or delay, and that does not necessarily coincide with maximum capacity. It depends on alternatives available to the traffic that is diverted or slowed down or controlled at one facility. Can panel members give examples of how clearly these criteria have been adopted for their respective work.

W. R. McCasland

This is a very interesting area because I think this points the finger to the decision-maker who is in charge of determining just what a control system will do. In my own experience, I have the responsibility in effect for the decision as to what goals or objectives we should try to achieve on the Gulf Freeway Project. Based on the engineering analyses of the area, it was found that the area did not have suitable alternate routes. There were high demands, and therefore our decision was to do all we could to increase the throughput, if necessary at a reduction in level of service. I know that in other places there are better alternatives for the diversion of traffic, and I would prefer to assign a higher level of service. This is one of the key points in the design of a control system: Establish goals early, have one person in charge of determining what the goals should be in a system, and then find out what other consequences are going to result as a result of achieving these goals.

DEVELOPING AN EFFECTIVE FREEWAY TRAFFIC MANAGEMENT SYSTEM

W. E. Schaefer, California Division of Highways

•I WOULD like to discuss the traffic management system in terms of what I call the myths that have grown up around our superhighway networks in urban areas. The logical emphasis on the completion of the Interstate System has defined the objectives of most highway departments and highway engineers as simply planning, design, and construction of a network of freeways. With the exception of maintenance, there was relatively little thought as to what happens after the freeway is opened to traffic.

Among the myths that have developed as a result are the following:

1. If only we can improve our ability to forecast traffic and complete a freeway network, the traffic load on the various freeway segments will be balanced, and our congestion problems will be solved;
2. The freeway is the principal carrier of traffic so it is not essential that we be concerned about other highway facilities in a traffic corridor (this view is further encouraged in many areas by the conflicting jurisdictions and responsibilities);
3. Highway engineers are in the highway business and not the transportation business; and
4. The "real-time" traffic operation of an urban freeway network will be either unnecessary or of minor consequence, and the real problem is and will be maintenance.

With regard to the first myth, I believe it has been pretty well demonstrated that man is unable to forecast anything—whether it be weather, foreign affairs, or traffic—very accurately. Land use and traffic demands change radically because of decisions and events that occur after the freeways are constructed.

Today, with traffic planners forecasting daily traffic volumes of 300,000 or 400,000 or more, we find ourselves in somewhat of a dilemma. It does not seem reasonable (or even possible in some cases) to provide for these kinds of peak-period volumes. Yet if we do not, traffic congestion seems inevitable.

Freeway entrance ramp control appears to offer a way out of the dilemma. Entrance ramp control can limit the "manifest" demand. I believe one of the most promising features of ramp control is that we may be able to construct and operate a truly balanced system of highways. By balanced, I mean that the relation between demand and capacity would tend to be uniform throughout the network.

It seems obvious that completion of a system will not balance the traffic load and eliminate congestion on our existing urban networks. The increasing attention given to ramp control as a means of relieving peak-period congestion demonstrates this pretty well. Ramp control, as used in Chicago, Houston, Detroit, and Los Angeles, is basically an attempt to balance the freeway by controlling or restricting the amount of traffic that can use critical segments of freeway. Ramp control is increasingly seen as a permanent part of an urban freeway. For example, the urban network in Chicago is expected to be completely controlled within the next few years.

In California, we certainly do not expect the completion of the network to eliminate congestion. We have under way a $115-million program to widen critical freeway sections and install ramp control on a network-wide basis. The concept is to add lanes or capacity to existing bottlenecks to accommodate the current demands on the system and

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use ramp control to avoid future imbalance. Most of our future urban freeways will incorporate ramp control in the initial construction. This $115-million program is really a "catch-up" one. We do not foresee being able to build a freeway network in which the demand and capacity will stay in balance over a period of time without some form of control.

These control projects have destroyed the second myth by forcing us to recognize that we are dealing with traffic corridors that include both freeways and arterial streets. In almost all instances, control of freeway traffic (however crudely done) affects the arterial street system. What we are really talking about, then, is the manner in which corridor traffic control is accomplished, that is, the degree of sophistication. In Los Angeles, we have demonstrated that, even using simple fixed-time control systems, we can make not only more effective use of the freeway but also more effective use of the other traffic facilities in the corridor.

The third myth relates to whether we are in the highway or transportation business. It is a commonly accepted concept in the business world that every organization must periodically sit down and decide not only what business they are in but what business they should be in. I believe that we should have realized years ago that we are in the transportation business.

Urban transportation is a complex and interrelated system of many modes and facilities. Highway engineers may not be able to plan and control all modes and facilities, but they must consider them and they must assure themselves that they are getting the most from their part of the system—the most, in terms of the movement of people and goods.

The U.S. Department of Transportation has many demonstration programs under way throughout the country; they involve things such as exclusive bus lanes and preferential treatment of buses. In Los Angeles, we are designing an exclusive busway in a major freeway corridor. In several ramp control projects, as a matter of routine policy, we provide means for buses to bypass the waiting cars.

We are also discussing a project to demonstrate the improved bus service that can be provided where ramp control produces free flow on the freeway. This could very well be a more effective solution than exclusive bus lanes. We have projects planned to develop more facts about car pools and staggered working hours. Many of these would seem to be "not our business." We often hear this comment, even within our own organization, but we never hear exactly whose business it is. A void exists and, if we are to make the best use of our highways, it must be filled. I believe we are responsible for ensuring that the best use is made of our systems, and we are equipped to do it. Certainly any system of traffic management must include these techniques.

The last myth I mentioned was that the "real-time" traffic operation of a freeway network would not be a major effort. I think that it is becoming pretty evident that we cannot forget the motorist once he is on the freeway.

As more and more urban freeways have been completed, we have become aware of the problem of incidents, such as accidents, spilled loads, and the like, that affect traffic. In Los Angeles, we think this problem is just as serious as the daily peak-period congestion; the total delay to traffic is about equal. Faster detection of disruptions to traffic flow and early restoration of normal capacity seem to offer a tremendous payoff in reducing this delay. Currently, there is a lot of activity in this area. The surveillance system in Chicago is being used to detect incidents on the freeway. Several detection logics for use with electronic surveillance systems have been tested on the Detroit Project.

Of course, we must do more than just detect that an incident has occurred; a coordinated response that includes equipment to clear the roadway is required. In Chicago a service patrol operates that is capable of clearing most scenes. In Los Angeles, we will be using state-owned tow trucks on our 42-mile experimental project.

I mentioned the potential payoff in this area. In Los Angeles, we have what we call a major incident involving a truck or its load or both about every other day. One typical incident involved a truck carrying a load of cabbage that overturned shortly before the peak period. It required nearly 1½ hours to completely clear the debris. About 27,000 vehicles were delayed an average of more than 15 min by this incident. In this case, if we could have cleared the roadway 30 min sooner, we would have cut the delay in half.

Just restoring traffic flow does not seem sufficient. The motorist needs to know what is going on. He usually does not account for these unexpected events in his travel plans. Very often, it means he will be late for work or an appointment. If he is given adequate information, he may be able to select an alternate route or, even in some cases, to delay his trip.

In most urban areas, the commercial radio stations broadcast traffic advisories that seem very popular to the motorists. In Los Angeles, as a part of our project, we will be trying changeable-message signs and roadside radio to warn and advise the motorists, and we will be providing up-to-the-minute traffic information to all the commercial stations who will use it.

The motorist is also demanding attention to his individual needs and assistance if he becomes stranded on the freeway. The Los Angeles County Board of Supervisors has installed more than 2,000 telephones on the metropolitan freeways and hope to install some 1,200 more. The phones are tremendously popular with the motorists. A very large question remains as to whether this is the best way to provide service, but the phones are there.

So far I have discussed freeway traffic management systems without defining them. In a way, freeway traffic management is a new term for the not-so-old term of freeway operation. The new term focuses on the "real-time" management of the system, but it also emphasizes the need for effective coordination among the many agencies involved in the operation of a freeway network. It visualizes a more aggressive effort to increase the efficiency of our highways in terms of moving people and goods.

The inclusion of the word management in the term may not be obvious. There is a good analogy between the definition of management and the process we follow in solving freeway operational problems. I think one of the better definitions of management is "the creation of an environment in which an organized group can work effectively and efficiently toward a commonly understood goal." This analogy becomes clear when we define freeway traffic management as the creation of an environment that allows the effective and efficient use of the freeway system by minimizing delay, maximizing safety, and providing the motorist with a general sense of well-being. The essence of the analogy is the effort necessary to eliminate or reduce the obstacles (either to the worker or to the motorist). This is the creation of an effective environment.

In these days, many tend to see an either-or approach to the urban transportation problem. Some people are saying that, as an urban transportation mode, the freeway is obsolete. They could not be more wrong. We must emphasize the full utilization of the freeway networks. We must provide for conscious, concerted operation of urban networks. Our concept must be planning, building, and operating. If effective freeway traffic management systems can be implemented, the urban freeways will maintain their place as a viable and major part of the urban transportation system for many years to come.