ACCOMPLISHMENTS IN FREEWAY OPERATIONS OUTSIDE THE UNITED STATES

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•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 I	II	III	IV	V	Television Cameras	Vehicle Detectors
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 $1\frac{1}{4}$ 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 $1\frac{1}{4}$ 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 ½ 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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