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ANALYSIS AND PROJECTION OF RESEARCH ON TRAFFIC SURVEILLANCE, COMMUNICATION, AND CONTROL

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RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY OFFICIALS IN COOPERATION WITH THE BUREAU OF PUBLIC ROADS

SUBJECT CLASSIFICATION:
TRAFFIC CONTROL AND OPERATIONS
TRAFFIC FLOW
Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Bureau of Public Roads, United States Department of Transportation.

The Highway Research Board of the National Academy of Sciences-National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway departments and by committees of AASHO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Highway Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.
This report will be of special interest to persons responsible for operating highway systems, to state and city traffic engineers, and to research administrators involved with formulating future research programs that concern traffic surveillance, communication, and control. The research includes an analysis of on-going traffic operations research in the United States and abroad. In addition, a listing of traffic operations research needs is presented, together with a gross estimate of the funding requirements.

Since 1963 the American Association of State Highway Officials has, through the National Cooperative Highway Research Program, been sponsoring research in the area of traffic operations and control. With the completion of several of the NCHRP traffic operations projects, it was recognized that significant related research was being undertaken by other agencies, not only in the United States but also in foreign countries. It was to put the NCHRP results in this subject area into context with this other work, both old and new, that Project 3-9, reported here, was initiated in the fall of 1966.

The objective of the research was to evaluate the state-of-the-art of traffic surveillance, communication, and control, and to set forth guidelines for the determination of rapid-payoff research that could be undertaken through NCHRP and the state highway departments. The research was carried out by the highway management consulting firm of Roy Jorgensen and Associates, who for this project teamed with the expertise of Karl Moskowitz, a well-known traffic engineer and author of several reports on traffic research. Mr. Moskowitz's services were made possible by the California Division of Highways granting him a brief leave of absence.

The method used to determine the recommended program of research was to digest and interpret all pertinent literature, followed by field visits to learn at first hand how the experiments were really working, and finally to arrive at subjective evaluations based on the principal investigator's thirty years of traffic engineering experience. The analysis of current research includes freeway control, system control of traffic signals, communication between vehicles, and other traffic systems research.

The report provides a tabulation of specific research needs in the area of traffic surveillance, communication, and control. The list of recommended projects includes high-payoff research dealing with the removal of disabled or wrecked vehicles from freeways, development of inter-vehicle rate of closure devices, improved signal system control strategies, improved airborne observer advisories for motorists, and the development of a low-cost traffic detector.
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The report is based on work done by and interviews with a large number of persons, listed in Appendix H. The willingness of these persons and organizations to share their knowledge is deeply appreciated.
SUMMARY

When the National Cooperative Highway Research Program was begun in 1962, highway administrators throughout the nation were asking a question that can be paraphrased, "Is there any magic (preferably electronic) solution to traffic congestion?" Two of the initial projects were intended to answer that question "yes" or "no," or "partly." These were Projects 3-2, "Surveillance Methods and Ways and Means of Communicating with Drivers," and 3-3, "Sensing and Communication Between Vehicles." They were intended to be long-range, continuing projects, and although the whole problem was stated in the initial project statements, it was intended that after the first or second stages in each, the results would be reviewed and decisions would be made as to the directions that the research should take in subsequent stages. (Project 3-2 was originally estimated to cost up to $3½ million).

In the meantime, practical experiments in surveillance and control—"prototype research"—have been undertaken by various agencies throughout the world, and much has been learned that should be taken into account by those who are charged with projecting future research.

The objective of this report is to describe and summarize this research and these experiments, to identify promising and non-promising areas, and to identify voids or gaps in the state-of-the-art.

In pursuit of this objective the final reports of the NCHRP projects were analyzed. The freeway surveillance and control projects in Houston, Chicago, Detroit, and Los Angeles were visited as were the "area traffic control" projects in San Jose, Toronto, New York, London, and Dusseldorf; and about a hundred individuals working in this general area, including those responsible for the projects named, were interviewed. There was also an attempt to evaluate the myriad projects being launched by the U.S. Bureau of Public Roads Traffic Systems Division.

Freeway Control Projects

The most immediately promising development in the field of traffic surveillance and control is the concept of freeway ramp control being practiced in Houston, Chicago, Detroit, and Los Angeles on short sections of congested urban freeways.

Although the techniques vary, the principle is the same in all of these places. The principle is to control the rate at which vehicles can enter the freeway, by stop-and-go signals on the entrance ramps, so that the capacity of the freeway downstream of the entrance is not exceeded. The reason why ramp control works is that it increases throughput in the corridor. (Throughput is defined as rate of accommodating vehicle-miles of travel.) It does not increase capacity of the freeway, but by diverting or storing traffic that wants to come in "at the head of the line," it allows more traffic to use the freeway upstream of that point.

The result is not only a smooth-running freeway, and a substantial reduction in
peak-period accidents, but the aggregate delay to all traffic in the corridor is reduced. In addition to the reduction in delay, the freeway users are getting a real improvement in journey speeds. From the point of view of the highway administrator, this may be the most important result of all. It furnishes an answer to the loose statements being made around the United States that "freeways will never work".

There are many unanswered questions regarding the extent to which ramp control can be effectively applied. They fall into two groups—mechanical, and operational. In addition to these questions, none of the freeway control projects has solved the problem of the freeway tie-up caused by accident or incident.

A few of these questions are suitable for directed research and development projects, but most of them can be answered only by practice and engineering design of individual cases. Highway administrators will never be able to buy a system, install it, and let it run itself. They will have to face the fact that there is such a thing as operation, and create an organization to operate completed highways. It appears that the most practical way of propagating freeway operational techniques would be to create teams of experts who could act as resident engineers during the formative stages of the operating departments.

It should be noted that the maximum increase in throughput attainable by any control methods (ramp metering or otherwise) cannot exceed the amount by which present throughput is less than capacity. There are very few miles of freeway in the U.S. where this difference is more than 10 to 25 percent, and, even there, only during peak hours. Operational control is therefore no substitute for new freeway construction, which will inevitably be required to absorb the increased vehicular travel that is certain to occur during the next 20 years. (Freeways now open to traffic occupy 1 percent of the Los Angeles urban area and carry 40 percent of the travel there.)

Area Control of Traffic Signals

Everyone has experienced frustrating stops at traffic signals that appear to be needless because nobody on the other street is using the intersection either, and everyone has been caught in huge queues on the approaches to signals.

Because of the ubiquity of these situations, and because, even in the most freeway-oriented cities, upward of 60 percent of all travel is on streets that have traffic signals, any improvement in timing the red and green intervals would have an enormous payoff, and this is considered one of the most promising areas for development of advanced control methods. However, there is nothing on the horizon that will justify statements to the effect that electronic surveillance and high-speed computers can eliminate congestion in urban areas, or "double the capacity" of the surface street system.

In San Jose (California), Toronto, and Dusseldorf, there are networks of traffic signals being controlled by centralized, digital computers. In London and Glasgow experiments are being planned which also involve centralized high-speed computer control of traffic signals. These experiments were not operational in the summer of 1967 but were expected to be on line in the autumn, and the New York City system was expected to become operational in 1968.

All but one of these systems (the one being designed for Glasgow) essentially depend on a library of pre-engineered control strategies. The computer selects and executes one or more of these strategies on the basis of current information about traffic received from several hundred detectors placed throughout the network. Except in Glasgow, where some entirely new concepts will be tried, these strategies consist of variations in cycle lengths, splits and offsets. ("Split" refers to the pro-
portion of green allotted to each leg, or phase, at a given intersection; “offset” means the elapsed time along a given arterial between the start of green at one intersection and the start of green at the next intersection in either direction, or, in other words, the nominal speed of progression).

Of course, standard 3-dial interconnected signal systems do the same thing, and in fact about all anybody can do with a traffic signal is change the cycle, the split, or the offset. There are also in common use in the United States traffic-responsive analog-computer controllers which are capable of doing this. The difference between these systems and the large digital-computer-controlled systems is that the number of variations or “strategies” that the large computer is capable of is almost limitless. The systems in San Jose, Toronto, London, and Glasgow also collect and can analyze quantities of data by which the performance of the system (number of cars stopped, delay suffered, etc.) can be evaluated periodically or continuously. A further and very important by-product is continuous surveillance of hardware in the street, to assure absence of malfunctioning.

There are very few jurisdictions in the United States where the existing “primitive” signal controllers are adjusted to achieve the maximum efficiency of which they are capable. In fact, the controllers are hardly ever adjusted, because there is almost nobody engaged, as a full-time occupation, in adjusting signal timing. Optimum signal timing, with or without computerized equipment, is one of the highest arts or sciences in the traffic engineering profession, and there are only a handful of people in the entire United States who are capable of doing this and have the required training in principles of traffic flow and delay.

If the traffic department of a given jurisdiction had such a man and assigned him full time to the task, and gave him a half-dozen helpers (computer programmers and traffic engineers), the effectiveness of this staff could be greatly multiplied if they had at their disposal a suitable large, fast controller and centralized surveillance by which they could have a pretty good indication of what is going on throughout the system and would also have the capability of making rapid changes in operation. But it appears that providing this staff should come before ordering the equipment.

Research on traffic flow theory, simulation of traffic at signalized intersections, and dissemination of operating knowledge would all be fruitful areas for future research expenditures.

Communication Between Vehicles

In pursuing research under NCHRP Project 3-3, Ohio State University has constructed a pair of instruments mounted in vehicles that inform a following driver of his rate of closure and, when he is close, the approximate distance to the car ahead. The leading car transmits an infrared signal which is chopped at a frequency proportional to the speed, and the following car receives this signal and compares it with its own speed in an electronic device. The output is a current that causes a calibrated galvanometer in the following car to register the difference in speeds. The distance to the car ahead is also available, and is obtained by measuring the magnitude of the signal.

The present equipment is fairly crude and needs more research to answer such questions as how to distinguish the car ahead from a car in an adjacent lane, and even whether infrared with a chopper is as effective and inexpensive as another light-emitting diode system might be. The importance of this research is that the instruments are inexpensive (less than the cost of smog-control devices or car radios) and that they work. In other words, a real breakthrough in inter-vehicular communica-
tion is not as far in the future as many had thought. This is a promising area of research in the medium-long range.

The improvement and standardization of rear-end lighting systems on vehicles is an engineering and legal problem and should not be allowed to flounder in protracted research.

**Other Traffic Systems Research**

The U.S. Bureau of Public Roads held a “Program Review meeting on Research and Development of Traffic Systems” in December 1966. In the introductory session the scope of this meeting was defined as “a pretty complete survey of the whole field—a comprehensive statement of the state-of-the-art, present and future.” Since what the Bureau calls “traffic systems” covers the same field as what the NCHRP calls “traffic surveillance, communication, and control,” the Proceedings of that meeting essentially fulfill the objectives of this report. However, the Proceedings of the Bureau meeting were longer—more than 800 typewritten pages of summarized research.

The most promising areas reported on at the meeting were (1) timing of traffic signals in an urban street network, (2) the freeway ramp control projects, (3) development of an instrument to measure car-following behavior, and (4) aid for the stranded motorist.

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**CHAPTER ONE**

**INTRODUCTION**

The subject, “traffic surveillance, communication, and control” is not as mysterious as the multisyllable words would imply. Nor is it new. For more than 50 years traffic policemen have been surveying the situation, communicating with drivers, and controlling traffic. But there lies the rub: methods used in 1917, when rapid transit was in its prime, are not adequate for the motor age, when nearly everybody wants to go nearly everywhere at nearly the same time in his own car. Although research (with a lower case “r”) and improvements in methods of traffic control have been more or less continuous since 1917, Research with a capital “R” received a tremendous impetus in the late 1950’s when aerospace research created public awareness of what it could accomplish.*

At about the same time that this awareness of research became general, another fact began to be apparent: traffic congestion was inevitable, even on freeways. Or was it inevitable? This question needed an answer, and when the National Cooperative Highway Research Program was inaugurated in 1962, it was one of the first ones that the American Association of State Highway Officials asked.

Of course the criterion was very high. When demand was low, travel on freeways was (and is) very fast—a mile a minute in urban areas, which prior to the advent of freeways was simply unheard of. (Delay to an automobile driver begins at any instant—the instant he desires to start his trip or to arrive at a destination—not at a scheduled departure time.) A 5-min delay, which is not only tolerated but is considered minimal when making a trip by any other mode of transportation, from elevators in a building to jet air travel, results in freeway journey speeds of 17 to 30 miles per hour for typical trips of two to five miles (see Figure 1). This is considered by many to be intolerable when compared with the 60 mph they have been accustomed to in off-peak hours. This delay manifests itself to the driver as stop-and-go driving, or congestion, and the driver is likely to refer to the freeway as “one vast parking lot.”

It is conceptually feasible, by providing off-freeway storage for vehicles, to ensure that travel speed on the freeway will remain high throughout the day, including the

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* Although research is not quite the same as Systems Engineering, the terms are frequently (and confusingly) used interchangeably, even by persons engaged in one or the other. For the purpose of this report, “Research” is used in the broad sense of discovering or developing something new, even when Systems Analysis or Systems Engineering might be more accurate.
peak hour. The off-freeway storage at any instant would be fewer cars than are now being stored on the freeway itself and the service rendered by the freeway would be greatly improved. If the rate of demand stays constant, the delay to the cars stored off the freeway would be no greater than the aggregate delay is on an uncontrolled freeway system, and the delay to "innocent victims"—i.e., cars that are caught in a traffic jam upstream of a bottleneck but which are destined for an exit also upstream of the bottleneck—would be eliminated.

The delay being suffered during peak hours on uncontrolled freeways in Los Angeles (an urban area of more than seven million population) is in the order of magnitude indicated in Figure 1, as can be seen by entering the figure from the abscissa at journey speeds which have been experienced by readers who are familiar with that area. Whether it would be worthwhile to provide the control and storage facilities, particularly at freeway-to-freeway interchanges, necessary to make this system operate like a railroad where the trains run on time but the customers wait before getting on the train (or between trains when changing from one line to another), is an economic feasibility question.

Improvement in flow and reduction in over-all delay can in many places be achieved by entrance ramp control even without providing off-freeway storage, particularly if there is unused capacity on alternate routes.

When the AASHO handed the problem to the NCHRP in 1962, it was evident that freeway surveillance and control were foremost in many people's minds, although it was also evident that improvements in surveillance, communication, and control could be made on conventional urban streets and thoroughfares, and that because the level of service provided by freeways was already so high, a greater early payoff might be accomplished by research on surveillance and control of conventional roads and streets. The NCHRP broke down the whole subject of traffic operations into six major projects:

3-2. Surveillance Methods and Ways and Means of Communicating with Drivers.
3-3. Sensing and Communications Between Vehicles.
3-4. Means of Locating and Communicating with Disabled or Stopped Vehicles.

Projects 3-2, 3-3, and 3-4 were closely related and were primarily oriented toward development of logic to improve freeway operations. Project 3-2 in particular was a kind of omnibus project for freeway operations research. The project statement included the following language:

The hypothesis is that (1) information regarding traffic flow can be obtained; (2) this information can be transmitted to control centers; (3) with the information in the control center, a decision can be made regarding action that can be taken by drivers; (4) this decision can then be communicated to the drivers; (5) the drivers will act or react; (6) there will be results in the form of improved conditions of traffic flow.

Prior to the time this project statement was written, city and state authorities had recognized first in Detroit and later in Chicago that freeways, as well as other facilities, were subject to congestion, accidents, and stoppages when traffic demand exceeded the capacity of the facility, and research was already going on in those cities. A question was being asked by highway administrators throughout the nation which can be paraphrased: "Is there any magic solution to congestion?" The intent of Project 3-2 was to answer this question "yes" or "no," or "partly."

It was also conceived at the time the project statement was written that the subject was important enough that funding of the research and development would be in the order of $3 or $4 million. Actually, the competition with other projects resulted in only $100,000 being available for the first year of Project 3-2, with no assurance of continuation, so that the course of the research was completely altered from what was contemplated.

Projects 3-3, Sensing and Communications Between Vehicles, and 3-4, Means of Locating and Communicating with Disabled or Stopped Vehicles, were also aimed at obtaining magic solutions to freeway operation problems not directly connected with recurrent congestion caused by excess of demand over capacity. The communication-between-vehicle project was supposed to be a first step in a long-range development of an automated highway, although it can be seen that improved communications be-
 tween drivers could have an immediate payoff in safety, and a possible payoff in reduced delay if improved communication could reduce the mean headway between vehicles (cause people to drive closer together). The disabled-vehicle problem is an immediate one and is not unique to freeways, although disabled vehicles on urban freeways do present special problems.

Although research can rarely be described as completed, final reports have been written on the three NCHRP projects. In the meantime, research and experimentation in the same problem area have been going on under other auspices in various parts of the world, and much has been learned which should be taken into account by those who are charged with projecting future research. The objective of this report is to describe and summarize this research and these experiments, to identify promising and non-promising areas, and to identify voids and gaps in the results.

The Highway Research Board publication *Highway Research in Progress* lists 246 research projects under the heading “Traffic Control and Operations.” NCHRP Projects 3-2, 3-3, and 3-4 are included in this category. Many other related projects are listed under other headings. No attempt is made in this report to describe, or even to list, the titles of all of several hundred projects that are going on.

What was done was to analyze the final reports of the NCHRP projects. The freeway surveillance and control projects were visited in Houston, Chicago, Detroit, and Los Angeles, as were the area traffic control projects in San Jose, Toronto, New York, London, and Dusseldorf. Also, interviews were conducted with about a hundred individuals working in this general area, including those responsible for the projects named. An attempt was also made to evaluate the myriad projects being launched by the U.S. Bureau of Public Roads, Traffic Systems Division.

Chapter Two contains an analysis of these projects and Chapter Three is a projection of research in promising areas, together with some recommendations on how results are likely to be achieved. Descriptions of the more important projects are contained in the Appendices.

CHAPTER TWO

ANALYSIS OF CURRENT RESEARCH

Because of the indefinite nature of what could be called research on traffic surveillance, communication, and control, it is necessary to place boundaries on the subject area and to divide it into digestible subareas. This chapter is therefore organized as follows:

1. Freeway Traffic Control Projects.
2. System Control of Traffic Signals.
3. Communication Between Vehicles.
4. Other Traffic Systems Research.

Although the three NCHRP Projects (3-2, 3-3, and 3-4) comprise portions of all of these subareas, they are summarized separately and in more detail than other individual projects because they were singled out in the problem statement for this report. These summaries are the subjects for Appendices B, C, and D, and are referred to in 19, 29, 39, 44, 45). *

FREEWAY TRAFFIC CONTROL PROJECTS

Freeway traffic control projects are being conducted on short sections (2.5 to 5 miles in length) of the John Lodge Freeway in Detroit, the Eisenhower and Dan Ryan Expressways in Chicago, the Gulf Freeway in Houston, and the Hollywood Freeway in Los Angeles. See Figures 2 and 3 for control consoles.

* Reference numbers are items in the Bibliography, Appendix I.

Although the techniques vary, the principle is the same in all of these places. The principle is to control the rate at which vehicles can enter the freeway, by stop-and-go signals on the entrance ramps, so that the capacity of the freeway downstream of the entrance ramp is not exceeded. The capacity is not increased above what it would be without control. (The Port of New York Authority has increased the capacity of single-lane flow in tunnels by about 5 percent, controlling input on a different principle. See Appendix E.) On the other hand, there is a good possibility that the rate of flow in the bottleneck may be decreased, by inadvertent or unavoidable over-control, from what it would be without control. However, it is not necessary to increase capacity in order to achieve significant improvements in traffic operation and reduction in total system delay.

By controlling the input rate to be equal to or just less than the service rate (capacity), delay on the freeway could be virtually eliminated. Actually, to optimize travel time in the system, including alternate routes, it has been found desirable to use the full capacity of the freeway, and, to be sure that no slack occurs on a transient basis, the arrival or input rates are allowed to exceed capacity during short periods, with the result that there is some delay to freeway traffic. When the system is operating optimally, journey speeds on the freeway are in the 30-40 mph range, which reflects some delay and considerable speed variation as
compared with free flow, but shock waves are dissipated before they become serious enough to build up long queues of standing vehicles. The result is not only a smooth-running freeway, but the aggregate delay to all traffic in the corridor is reduced. However, the delay to some drivers may be increased; that is, there is a shifting, or redistribution, of the net delay which remains even though aggregate delay is lessened. This imposes a constraint on the amount of reduction in aggregate delay that can be achieved. You can't make one driver wait 20 min at one spot even though doing so might result in 40 min of savings to 20 other drivers.

It has been very difficult to measure the reduction in aggregate delay. This is because the diverted traffic disappears into the surface street network, or enters the freeway itself at other ramps upstream of the control section. Report No. 17 of the Chicago Area Expressway Surveillance Project, entitled "The Operational Effects of Automatic Ramp Control on Network Traffic" (4), concludes that a net over-all savings of 256 vehicle-hours daily were realized by control of 2.5 miles (four ramps) on the outbound Eisenhower Expressway. The 256 vehicle-hours consisted of 296 vehicle-hours saved by expressway users minus 40 vehicle-hours additional delay to metered and diverted ramp traffic. The savings to expressway users and the delay to metered ramp traffic was measured (Figure 4), but the delay to diverted ramp traffic was only guessed at (the report says, "It seems reasonable to assign a two-minute increased travel time to all diverted vehicles for the purpose of delay computation, thereby consuming 20 vehicle-hours of total extra surface street travel time"). Report No. 24-13 (70) of the Texas Transportation Institute (July 1965) concludes that during a short experimental test in the fall of 1964, the net savings to users of the Gulf Freeway and frontage roads was about 360 vehicle-hours daily and the delay to users of other streets was about 23 vehicle-hours daily, for a net saving of 330 to 340 vehicle-hours in the aggregate, and here again the 23 hours was largely a guess, based on observation of a few intersections.

After controls have been in operation for a few weeks or months, shifts in travel patterns, including drivers diverted
at a ramp one day who do not show up the next day, obscure the effects of diversion so that it becomes nearly impossible to make a direct comparison of control versus no control. In the spring of 1967, two ramps on the Hollywood Freeway in Los Angeles were put under control, and during the first week of operation a fairly accurate estimate of the reduction in delay to freeway users minus the increase in delay to diverted and metered traffic was made, showing a net improvement of 442 vehicle-hours per day during a 2-hr peak period. The 442 was made up of 485 vehicle-hours savings for freeway users less 43 vehicle-hours loss to diverted and delayed ramp traffic. However, it was found that within 3 months after imposing ramp control, the main line freeway demand rate increased by an amount equal to 50 percent of the rate at which vehicles were being diverted. It is surmised that this increased demand included some diverted vehicles which entered the freeway upstream of the controlled ramps, and which during the before (uncontrolled) condition had been using an unnatural route in order to bypass congestion on the freeway. In other words, before control, drivers had diverted voluntarily, but after control increased the attractiveness of the freeway, they got back on again, upstream. This caused the travel time on the freeway to increase, although not as much as it was decreased initially. The time savings for this new traffic at the new freeway speed is almost impossible to estimate. This raises the unanswerable question of what should constitute the normal travel time for a fixed input/time function. NCHRP Project 20-3, "Optimizing Freeway Corridor Operations Through Traffic Surveillance, Communication, and Control," dealing with the Detroit area will make the most ambitious effort to date to quantify travel time in the whole affected universe ("corridor").

It is not necessary to measure in vehicle-hours or vehicle-minutes the absolute amount of delay to diverted traffic in order to prove that ramp control reduces aggregate travel time. One sure method of knowing whether positive results have been achieved is to observe how long congestion lasts (if it can be assumed that demand rate has not changed...
between observations). If congestion lasts one hour before control and only 45 min after control, it is certain that the population as a whole is getting to destinations sooner.

In Chicago, Houston, and Los Angeles there have been positive and significant reductions in length of peak period congestion—i.e., the backup of waiting vehicles at the controlled ramps drops off to zero (because the freeway achieves free flow) at an earlier time of day than it did under the uncontrolled condition.

In addition to the reduction in delay, the freeway users are getting a real improvement in journey speeds—from stop-and-go driving to 30 or 40 mph in the worst part of the peak period, and to 50 or 60 mph in the part of the peak period that no longer has any congestion. From the point of view of the highway administrator, this may be the most important result of all. This is because unreasonable writers and others who are not disciplined in quantitative analysis of traffic operations often make loose statements to the effect that freeways will never work, and these statements receive credence from the public. This can be a reduction in the rate of constructing new freeways. This would be very unfortunate because new freeways are the most promising way of taking care of the inevitable growth in vehicular travel which is going to take place during the next two or three decades.

Another important result of ramp control is the following: It was found both in Chicago and in Houston that delay during peak periods caused by accidents or incidents was very significant. Seventy-five percent of all peak periods on the Eisenhower Expressway project suffered some degree of capacity reduction because of accidents, weather, disabled vehicles, or other special events. However, in both Chicago and Houston the number of accidents during peak periods was reduced because of smoother operation when the controls were in effect, and this in turn reduced delay by a significant amount which would be almost impossible to quantify.

**Peak-Period Ramp Control and Reduced Aggregate Delay**

Peak-period ramp control is certain to result in a reduction in aggregate delay, even when alternate routes have no available unused capacity. A more elegant explanation is given by J. A. Wattleworth in TTI Report 24-15 (12). (This report was also published in *Highway Research Record No. 157, 1966*.)

In the following explanation, for simplification it will be assumed (for the purpose of calculating vehicle-miles) that distance for a given trip on the alternate route is equal to the distance on the freeway route. It could be either longer or shorter, with a good probability of its being longer via the freeway, in which case it is conservative to assume equal distances.

When the input at an entrance ramp is controlled, it means that it is reduced. This in turn means that the vehicles that are denied access to the freeway either must be stored temporarily or they must be diverted to alternate routes. If there are alternate routes which have available capacity to handle the diverted traffic, the system production rate will increase; that is, the vehicle-miles-per-unit-of-time will be higher and the total time required to accommodate the desired travel in the corridor will be reduced. Weinberg (19) provides mathematical proof that maximizing vehicle-miles-per-unit-of-time results in minimum travel time.

**Vehicle-Miles-Per-Unit-of-Time**

This is a parameter of traffic flow. It is suggested that a good word for this parameter is "throughput." Writers and discussers of traffic flow and delay have used the word throughput for various meanings, including rate-of-flow and capacity, but it is not in such common use that it would be too late to ascribe a special meaning to it, and it is here proposed to do so. At least in this report, whenever the word *throughput* is used it means "vehicle-miles-per-unit-of-time." This is a rate, and is not to be confused with vehicle-miles in a specified time. The distinction is similar to the distinction between rate-of-flow, which is number per unit of time \( (dn/dt) \), and volume, which is number in a specified time \( (N/T) \). Persons who do not make this distinction have endless problems in understanding the relation between demand, capacity, and delay.

An apparent anomaly has been discovered in the Houston (Gulf Freeway) project and confirmed in the Los Angeles project which deserves explanation but at the same time serves as an explanation. Obviously, diversion of traffic from the freeway to alternate routes increases the throughput of, as well as total travel on, the alternate routes. But it simultaneously increases the throughput (vehicle-miles per hour) of the freeway itself. The throughput of the corridor is thus increased in two ways without increasing the total amount of travel during the peak period. Total travel in the corridor stays the same, travel on the surface streets increases, both in amount and rate, and the rate of travel (throughput) on the freeway increases when it is most needed, i.e., during the peak period. The only way all of this can come out right arithmetically is for the duration of the peak period to be reduced, and this is exactly what has happened on the Gulf Freeway, on the Eisenhower Expressway, and on the Hollywood Freeway.

If there is no available capacity on alternate routes, the vehicles must be stored. Although this does not result in as dramatic a change in the over-all picture as does increased utilization of alternate routes, it still can result in reduced aggregate delay because throughput will be increased in the portion of the system upstream of the point at which control is being exercised.

Figure 5 is a traffic flow diagram of a stretch of freeway including an exit ramp and an entrance ramp. The numbers shown \( (\text{vph}) \) represent a rate of flow, not a number in a designated time period of one hour. The capacity of the main line is 5,700 vph. Figure 5-a shows the uncontrolled condition with 5,700 vph on section C-D (which is capacity), 400 vph exiting at B, and 700 entering at C. Also shown are \( n \) vph using alternate routes from C to D. The throughput of the freeway is \( 5,700 \times 0.5 + 5,000 \times 0.4 + 5,400 \times 1.0 = 10,250 \) vehicle-miles per hour. The throughput of the alternate route is \( 0.5 \) \( n \) vehicle-miles per hour.
If we stipulate * that the demand, or arrival rate, at A is 5,700 vph, the condition shown in Figure 5-a will create "jam" density in the section A-C within a fraction of an hour, because more cars are entering the section than are leaving. The speed will be variable, depending on how long it has been since capacity flow began at C, but after this density is reached, the length of time for a car to go from A to B can be computed as follows:

Say jam density $= 100$ vehicles per mile per lane (this means that there are 100 cars ahead of the car at Point A),

and output at B $= 1,800$ vehicles per hour per lane;

then time required $= \frac{100}{1,800}$ hr for 1 mile, or 18 mph.

Figure 5-b shows what will happen if 300 vph are diverted to an alternate route between C and D. The flow from A to B would rise to 5,700, etc. But from Figure 5-a, $400/5,400$ of this traffic will get off at B, and $400/5,400 \times 5,700 = 423$. So the control of ramp C would be set to divert 277 as shown in Figure 5-c. Since the input and output rates at A and B are equal, the freeway will be free-running and speeds will be in the order of 40-50 mph. (If a jam has been allowed to build up prior to operating ramp control at C, it will take about 3 to 5 min for the front end of the jam to recede to A.) The vehicles entering the system at A will save about 2 min apiece. This is not necessarily 5,700 vehicles, but depends on how long the peak period lasts. The vehicles diverted to the alternate route at C will lose a minute apiece by the time they get to D, and more if they go farther, but all the desired travel, including those vehicles, is certain to be accomplished in less time because the rate of accommodating it is higher.

The throughput of the freeway in Figure 5-c is $5,700 \times 1.0 + 5,277 \times 0.4 + 5,700 \times 0.5 = 10,660$ vehicle-miles per hour and the throughput of the alternate route is 0.5 $(n + 277)$ or 0.5 $n + 138$.

By subtraction it is seen that the throughput of the system in Figure 5-c is 548 vehicle-miles per hour greater than in Figure 5-a, and 410 of this increase was on the freeway itself.

The proportion is unrealistic and is owing to the arbitrary fixing of the system boundary at D only 0.5 mile downstream of C. Nevertheless, the point is made that a large amount of the total savings is attributable to improved efficiency of the freeway, and the surface street system does not suffer the whole burden of diversion. In fact, surface streets between A and B will be relieved of more travel than will be imposed on surface streets between C and D, in the example. Although not proven here, where only a small subsystem is depicted, it is mathematically certain that in the whole urban area, the greater the throughput of the freeways, the less the required throughput of the surface streets will be. The disappearance of diverted traffic in Houston, Chicago, and Los Angeles can be partially explained by this phenomenon which at first seems so anomalous (diverting traffic to city streets relieves city streets of traffic).

Now what happens if there is no available capacity on the alternate route (a special case would be a bridge where there is no alternate route)? If ramp C is controlled to a rate of 423 vph and the rest is stored, there will be a trade-off but no net change in delay to all vehicles exiting the system on the freeway at D. However, the 423 vph exiting the system at B will still save in the order of 2 min apiece, so there will be a net gain in aggregate savings to the motorists in the urban area (not necessarily $423 \times 2$, but a function of the integral of $dn/dt$ where $dn/dt$ is arrival rate).

Parenthetically, it may be remarked that it is very likely that capacity of alternate routes is also controlled by a few bottleneck locations (signalized intersections) on those routes. Many of these bottlenecks can be alleviated or eliminated for money—widening, isolated separation structures, improved signal control, etc. The amount of money could be less by an order of magnitude than the amount required to obtain the same effectiveness by widening or otherwise altering the main line of the freeway. This is an economic feasibility question that can only be answered case by case.

* This is a reasonable stipulation since if the entire freeway is under control, the arrival rate would be controlled to exactly 5,700 as long as the demand was sufficient to supply this many.

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1 Storage requirements cannot be obtained simply by subtracting 423 from 700. Storage at any instant is a function of rate and time as shown in the discussion accompanying Figure 8.
It can also be seen that if the exit rate is small on ramps upstream of the bottleneck, the allowable entrance rate at each successive entrance ramp as one proceeds downstream will become smaller and smaller, and some logic must be developed which will prorate the demand in an equitable fashion, or otherwise whole sections of the city will be denied use of the freeway during peak periods.

A theoretical approach to this question has been outlined in the Wattleworth paper previously cited (12) but it is felt that this question can only be answered by intensive study of individual cases, along with practice. In other words, it cannot be answered by directed research, the results of which would be universally applicable. Highway administrators will never be able to buy a system, install it, and let it run itself. They will have to face the fact that there is such a thing as operation, and create an organization to operate completed highways. Perhaps the word "operation" is unfortunate in highway department language because in many places it has been preempted by construction and maintenance operations. This semantic problem should not be as difficult as it is.

The highway administrator must also recognize that the payoff from traffic operational control is great, and when he sets up the operation department it should be well staffed. In other words, the department should be equal in status to the traditional departments and should be staffed with sufficient personnel to get the job done.

The answers to many questions will come through spontaneous research which will be performed by these operation units. It would be very difficult for an outside research agency to develop the questions or to find answers in response to directed research problem statements.

Advantage of Auxiliary Lanes Between Interchanges

It can also be seen from the preceding discussion that on a loaded freeway the throughput could be greatly increased by providing auxiliary lanes between interchanges. In the standardized case, auxiliary lanes between interchanges would accomplish about the same order of magnitude of improvement that ramp control would, without diverting traffic. No further research is necessary to prove this, but some method must be found to let highway designers know it, because very few highways are so designed at present.

Ramp Control in Systems of Freeways

The question whether a whole system of freeways can be operated by exerting ramp control so as to eliminate congestion everywhere on the system has not been answered. It immediately raises another question, which is this: At an interchange between two freeways, which freeway should be controlled in order to make the other one work? This is not an altogether unanswerable question. One answer, probably unacceptable, would be to meter all the upstream entrance ramps on freeway A sufficiently to reduce the turning movement into freeway B to a rate that would avoid overloading freeway B. The reason this might not be entirely acceptable is that it would entail denial of freeway A to many drivers not destined for freeway B, and would unnecessarily reduce throughput on freeway A. Another answer might be to provide off-freeway storage on the turning roadway, even if this amounts to several hundred vehicles. But the same amount of money might be used to widen the exit leg and eliminate the need for storage.

Different Techniques of Control

It was pointed out in the beginning of this section that the principle of freeway control is the same wherever it is being practiced—i.e., Houston, Detroit, Chicago, and Los Angeles—but that the techniques vary. In Chicago, lane occupancy in one lane upstream of each entrance ramp is calculated by a central digital computer, which then commands the ramp signals to change at appropriate cycle rates; in Houston, the flow in all lanes upstream of an entrance ramp is measured by an analog computer and the ramp signals release a vehicle whenever the integrated demand thus measured, subtracted from capacity integrated over the same time period, attains a value of one vehicle; and in Los Angeles one ramp is simply closed for an hour and one-half at a preset time each day, while another ramp has signals which release vehicles at a constant preset rate for the same time period. At Houston, an additional technique called "gap acceptance mode" is being tried experimentally. Other techniques for determining allowable input rates are possible. The questions are: what is the most efficient method, or more accurately, the most effective method when cost is considered; is a sophisticated computer better than a clock? If a computer is used instead of a clock, how are the potential ramp users to know what conditions they are likely to encounter today? What kind of detectors are most efficient, and what kind of computer? Are any detectors good enough?

Freeway Tie-Up Caused by Accident or Incident

None of the freeway control projects has solved the problem of the freeway tie-up caused by accident or incident. The Chicago project has established the fact that this is a very important problem. The surveillance system in Chicago does give an immediate signal in the control center when congestion develops, and thus tends to minimize response time of emergency equipment. The Illinois Division of Highways also operates a fleet of emergency patrol vehicles that assist in clearing up accidents. Furthermore, a substantial reduction in the number of accidents has been achieved simply as a result of maintaining freer flow during the peak period. But when an accident happens, it takes a long time to restore normal flow.

It is believed that the single most important problem in urban freeway traffic operations that may (possibly) be subject to solution by directed research is the one listed as No. 402 in the Smith-Tallamy report (52) which they paraphrase as follows: "Determination of how to detect stopped vehicles, how to approach them under severe and limited operating conditions, and what equipment and organization are necessary to move or remove the stoppage."
Over-All Potential of Freeway Surveillance and Control

An urban area generates travel which can be measured in vehicle-miles. Because of the necessity for people to do business with one another, the rate of demand varies, peaking in the morning and evening. The rate can be expressed in vehicle-miles per minute. This is called throughput in the preceding explanation of why the ramp control projects work. Delay is caused whenever the actual throughput of the road network is less than the demand. The same number of vehicle-miles will be generated, but if the road throughput is insufficient, it will take a longer period of time to service them; in other words, people will be delayed, and the delay is manifested in congestion. There are other causes of delay, too, but this one—demand exceeding capacity—is the most important one.

The only way to reduce this kind of delay is to increase throughput. It will have been noted that the freeway ramp control projects do increase system throughput, but this increase is limited to the amount by which present throughput falls short of capacity or demand, whichever is least. (See Figures 6 and 7.) It is an order of magnitude less than the increase in throughput that would be achieved by construction of a new freeway.

Because of the relatively low cost of ramp control, it is likely that the unit cost of reducing delay or of increasing throughput that can be achieved by ramp control where it is practical would be considerably less than the unit cost of throughput obtainable by new freeway construction. But in view of the inevitable increase in travel (vehicle-miles) which will occur during the next twenty years, it is a mistake to hold out the promise that electronic control devices can be substituted for increased road capacity. It is very unfortunate that technical persons who have access to the facts have made public statements which carry this implication. Such statements are often motivated by the groundless fear that new highway facilities to provide for the inevitable new travel will consume so much urban area that there will be no room left for anything else. It would be better for highway-oriented people to cite something that is a fact: the most extensive urban freeway network in the world (Los Angeles) carries 40 percent of the travel in that urban area and occupies only 1 percent of the space.

Probably the most important result of ramp control will be to control the demand rate. Demand has a tendency to rise to meet capacity and theoretically is infinite, in a mathematical sense. For example, if one relatively minor shop with 50 employees closes at 5:00 PM (or at 4:30), there will be a demand for 50 vehicles to exit from the parking lot at an instant, which is zero time, and 50 divided by zero is infinity. In order to eliminate delay, it would be necessary to provide infinite capacity. The same thing happens to freeways, and it will therefore probably be impossible to eliminate delay regardless of how wide they are made. For example, the capacity of a freeway in Sacramento, California (urban population 600,000) was increased from 4,000 vph to 6,000 vph one day in 1966, when a new lane was opened to traffic. Prior to this, there was congestion in the morning peak for about 40 min, during which the demand exceeded 4,000 vph. During the first week after capacity was increased, there was no congestion, and it was determined that the peak demand was 4,800 vph. By the end of the second week, demand had risen to 6,000 vph but only for 5 min, and delay again occurred for a few drivers who had by this time found out that they could have a second cup of coffee at home and still get to the office at the same time.

Ramp control, by creating small amounts of delay before the cars enter the freeway, can result in leveling out the demand over a longer period of time, and provide a more predictable level of service for everyone.

Ramp Metering on New Freeways

Patrick Athol has suggested that surveillance should begin the day a freeway is opened to traffic, and ramp control should be exerted before the demand has built up to the point where it exceeds capacity. In other words, the actual flow on the freeway can be held to the design-hour volume if control is exerted early enough, and nobody will be diverted because traffic which is not allowed to enter the freeway has (historically) never entered the freeway anyway. Suppose that a freeway is opened on May 1. Demand for ramp A is 200 vph, and the demand for the main line, including ramp A traffic, is 5,000 vph. Capacity is 5,700 vph. By August 1, demand for ramp A has increased to 300 vph and demand for the main line has increased to 5,699 vph, including the 300. On August 2, demand for the ramp is 302 and control is initiated, diverting or delaying 2 vph so that the capacity of the freeway is utilized by 5,400 from upstream and 300 from the ramp. Superficially, these last two cars would never know the difference because they are new on August 2. The trouble is, the two individual drivers may not be the new ones. They may have been using the freeway ever since May 1 without delay, and suddenly they are confronted with a stop-signal that prevents them from entering. A hypothetical example can be set up as follows (see Figure 8):

Let the demand from upstream main line remain constant at 5,400 vph for an indefinite length of time.

Say that the demand from (or on) the ramp is 302 vph for 10 min and then drops to 290 vph. The metered rate will be held constant at 300 vph, in order to be sure that the demand for the downstream main line stays at 5,700.

Then, as shown in Figure 8, there will be 60 vehicles delayed and the ramp will be metered for 12.0 min. The 50th vehicle will suffer the maximum delay, which in this case is 0.067 min or 4.0 sec. The other 59 cars would each be delayed by lesser amounts. As the calendar rolls on, the delay and the length of time metering is in effect would tend to increase, but there would never be the shock that occurs if the ramp flow is reduced by several hundred vph from one day to the next. When the delay per vehicle becomes significant, some of the ramp traffic will choose alternate routes and hopefully equilibrium will be reached before any noticeable storage problems develop, and without any large fluctuations from day to day which would occur if the ramp input were drastically reduced.

Of course, the preceding example is highly theoretical in assuming that arrival rates and service rates can be held
absolutely constant, and in assuming that cars can be delayed for periods of less than 1 sec. But it does illustrate truthfully the principle involved; it shows that instead of two cars being delayed long enough to allow capacity to catch up with demand (12.0 min), 60 cars are delayed for insignificant amounts, and it shows that if controls were exerted initially, the delay will be imposed very gradually.

SYSTEM CONTROL OF TRAFFIC SIGNALS

Everyone has experienced frustrating stops at traffic signals that appear to be needless because nobody on the other street is using the intersection either, and everyone has been caught in huge queues on the approaches to signals that seem to take endless time to get through—"traffic was backed up a mile" is one of the commonest expressions in American conversation.

Because of the ubiquity of these situations, and because even in the most freeway-oriented cities upward of 60 percent of all travel is on streets that have traffic signals, any improvement in timing the red and green intervals would have an enormous payoff. This is considered one of the most promising areas for development of advanced control methods. However, there is nothing on the horizon that will justify statements to the effect that electronic surveillance and high-speed computers can eliminate congestion in urban areas, or "double the capacity" of the surface street system.

In San Jose (California), Toronto, and Dusseldorf, there are networks of traffic signals being controlled by centralized, digital computers. In London and Glasgow, experiments are being planned which also involve centralized high-speed computer control of traffic signals. These experiments were not operational in the summer of 1967, but were expected to be on line in the autumn.

All of these systems except the one being designed for Glasgow essentially depend on a library of pre-engineered control strategies. The computer selects and executes one
or more of these strategies on the basis of current information about traffic received from several hundred detectors placed throughout the network. Except in Glasgow, where some entirely new concepts will be tried, these strategies consist of variations in cycle lengths, splits and offsets. ("Split" refers to the proportion of green allotted to each leg, or phase, at a given intersection; "offset" means the elapsed time along a given arterial between the start of green at one intersection and the start of green at the next intersection in either direction, or, in other words, the nominal speed of progression.)

Of course, standard 3-dial interconnected signal systems do the same thing, and in fact about all anybody can do with a traffic signal is change the cycle, the split, or the offset. There are also in common use in the United States traffic-responsive analog-computer controllers which are capable of doing this. The difference between these systems and the large digital-computer controlled systems is that the number of variations or "strategies" that the large computer is capable of is almost limitless. The systems in San Jose, Toronto, London, and Glasgow also collect and can analyze quantities of data by which the performance of the system (number of cars stopped, delay suffered, etc.) can be evaluated periodically or continuously. A further and very important by-product is continuous surveillance of hardware in the street, to assure absence of malfunctioning.

Although the operating systems have achieved significant reductions in delay when compared with what existed at those places prior to computerization, it is difficult for the average driver to discern much improvement over conventional signal systems that are well-timed. (The system in Dusseldorf, West Germany, is a possible exception. See Appendix F.) Delay and stop-and-go driving along a given arterial certainly have not been eliminated. This is probably because there are two fundamental laws about traffic flow in a system of signalized intersections that cannot be repealed by any amount of electronic surveillance or high-speed computation. One is that in order to achieve progression at a reasonable speed in both directions on a two-way street, the signalized intersections must be appropriately spaced. The other is that vehicles in any one file follow each other at intervals of 2 sec, plus or minus a few percent, as long as the light is green. If the arrival rate at a given intersection exceeds the departure rate even though all the green time is being utilized, there will be delay. The best that a computer can do is to assure that all of the green time is utilized, and in the most efficient manner (this involves the number of lanes having the green).

There are very few jurisdictions in the United States where the existing "primitive" signal controllers are adjusted to achieve their maximum efficiency. In fact, they are hardly ever adjusted because there is almost nobody engaged in a full-time occupation of adjusting signal timing. Optimum signal timing, with or without computerized equipment, is one of the highest arts or sciences in the traffic engineering profession, and there are only a handful of people in the United States who are capable of doing this and have the required training in principles of traffic flow and delay.

If the traffic department of a given jurisdiction had such a man and assigned him full time to the task, and gave him a half-dozen helpers (computer programmers and traffic engineers), the effectiveness of this staff could be greatly multiplied if they had at their disposal a suitable large, fast controller and centralized surveillance by which they could have a pretty good indication of what is going on throughout the system and would also have the capability of making rapid changes in operation. But it appears that providing this staff should come before ordering the equipment. There is no such thing (and probably never will be) as a package that can be bought, installed, and forgotten that will operate a system of traffic signals optimally without a lot of attention and supervision by human brains.

The cost, size, memory capacity, and speed of the several digital computers vary greatly, and spending more money does not assure better performance. To really assure optimum performance at every signal it would be necessary to have detectors on every approach lane at every signal, and some very fast, costly computers do not have the capacity to absorb this much information. As the size of the system is expanded, the number of wires from the field into the central location becomes fantastic, even when multiplex channels are used. For example, it is costing $400,000 simply to move the computer at Toronto, largely because of the rewiring necessary. This is not a large sum when divided by the more-than-500 intersections being controlled, but does give an indication of the magnitude of the electrical engineering problem involved.

It appears that computerized signal control systems should be a matter of engineering design more than research and development. Although computer manufacturers can supply invaluable consulting service, the engineering should not be done by them. If a given city is contemplating such an installation, the preliminary engineering would include as a minimum the following:

1. An Appraisal of the Existing Signals.—This should include identification of problems (poor progression, lack of capacity, excess delay, wasted green, etc.). This appraisal can be made by time-sample observations; i.e., a few peak-period observations and a few off-peak observations. Time lapse photography, floating cars, aerial observation, traffic counts, queue-length measurements are some of the techniques that could be used. If the present average speed (vehicle-miles divided by vehicle-minutes) is in the order of 25 mph or better, the chance of improvement is not great, unless there is a wide variability in speed or delay among subsegments of traffic or among geographic districts.

2. Use of the Computer.—For each identified problem, the question should be asked (and answered): How would a computer be used to solve this problem? A by-no-means complete set of auxiliary questions are: What would be the input, what would be the computer program, how much storage is needed, and how fast would the calculation have to be made? Would such a program improve on what is already there? In what way? Could the same thing be accomplished by merely adjusting the timing of the present controller? Is what is required a computational matter, or a matter of physical design (e.g., substitution of presence detectors for event detectors in left turn lanes)?

3. Necessary Computer Performance.—The computer
functions and performance necessary to solve the identified problems and request bids for equipment should be specific. The field installations and telemetry should be designed and the cost should be estimated.

(4) Cost-Effectiveness Analysis.

An example of the kind of analysis required is given by Weinberg (29).

Much is being learned by the personnel involved in the various operating projects. This kind of experience is, of course, an essential feature of the preliminary engineering process just listed. How to disseminate it most effectively and quickly will depend on decisions that need to be made both in administration of research and operation of street systems.

In the United Kingdom, the government is assuming the risk for two local experiments and presumably will make consulting services available to other local jurisdictions. The Greater London Council has already appointed a staff to operate the West London Experiment (West London is only a small district of Greater London) and this staff is acquiring knowledge during the design stage which will be invaluable if the system is expanded or if other installations are made in other parts of Greater London.

As in the case with many other innovations, the border line between research and engineering is not distinct. In general, it is accepted that research does not have to pay off on each and every try, whereas engineering and construction of an engineering system does. On the other hand, research, especially pooled research, is expected to produce transferable results—i.e., results that can be utilized in engineering systems elsewhere than where the research is performed, whereas preliminary engineering of a given system is not expected to be transferable. But the knowledge acquired in performing the engineering is transferable, and it could well be true that widespread implementation of new discoveries which have had the greatest impact on Western civilization has depended far more on dissemination of knowledge than upon research reports.

(If this is true, it would indicate that the educational function of universities is more effective than the research function.)

This raises a very interesting question regarding the administration of research funds. Agencies that are awarded research contracts inevitably acquire knowledge over and above what can be disseminated by mere fulfillment of their contracts. If the research is paid for out of pooled funds, how can this knowledge be made available to all the sponsors? Industrial research, which is so often cited as a shining example to prove that research is worthwhile, is not faced with this problem. Industry has exactly the opposite problem, which they call "pirating."

COMMUNICATION BETWEEN VEHICLES

In pursuing research under NCHRP Project 3-3 (39), Ohio State University has constructed a pair of instruments mounted in vehicles that inform a following driver of his rate of closure and, when he is close, the approximate distance to the car ahead. The leading car transmits an infra-red signal which is chopped at a frequency proportional to the speed, and the following car receives this signal and compares it with its own speed in an electronic device. The output is a current that causes a calibrated galvanometer in the following car to register the difference in speeds. The distance to the car ahead is also available, and is obtained by measuring the magnitude of the signal. The energy received varies inversely with the square of the distance, so it is not very sensitive at distances such as 500 feet, but when the distance gets close (which is when it is most important), the needle swings rapidly, and the accuracy improves. If the car ahead is stopped, which is often the case in real-life rear-end collisions, the driver of the approaching car gets two indications: (1) a rapid rate of closure, and (2) a rapidly changing indication of distance. Both of these could be displayed to or impressed on the driver in any form (including tactile) that human factors research indicated was the most effective way.

The present equipment is fairly crude and needs more research to answer such questions as how to distinguish the car ahead from a car in an adjacent lane, and even whether infrared with a chopper is as effective and inexpensive as another light-emitting diode system might be. The importance of this research is that the intrinsic cost of the components of the instruments is not large (less than the retail cost of smog-control devices or car radios) and that they work. In other words, a real breakthrough in intervehicular communication is not as far in the future as many had thought. This is a promising area of research.

It would not be necessary for 100 percent of the cars on the road to be equipped in order to do some good. If the car ahead is not equipped, a driver in the subject car would be no better off or worse off than he is now. But if the car ahead is equipped, he is better off. Suppose it was decided that all 1972 and later automobiles would have this equipment. In calendar year 1973 this would help drivers during about 10 percent of their driving because 10 percent of other cars would be equipped. In 1974, this would become 20 percent, and so on, so that by about 1980 the system would be 90 percent effective. Ninety percent, or even 10 percent, is a lot better than nothing. If improved communication can help increase capacity, as discussed in the next paragraph, 10 percent would be very important.

The only way capacity of a given road can really be increased is to reduce the average headway between vehicles. In a saturated-flow situation, the average headway is 1.8 sec, which sounds small, but the modal headway is only 1.3 sec, meaning that more drivers drive at this headway than at any other. This suggests the possibility that still more drivers would adopt the shorter headway if they had better information about their closure rate and distance to the car ahead. However, there is also a possibility that the variation in headway occurs randomly. Suppose a platoon of a dozen cars is going down the road at 1.3-scc headways at 60 mph. Now a car in the middle changes lanes—perhaps the driver sees a chance to go faster in the adjacent lane, or perhaps he is preparing to exit from the freeway. The instant he pulls out there is a 2.6-scc head-
way. It will be some time—several seconds at least—before this headway is closed up, and for an even longer time there will be variable gaps as the rest of the platoon closes up. An observer standing at the side of the road is certain to record some fairly long headways during this transient condition which have nothing to do with the driver's psychological desire to allow a particular headway based on information available to him.

Many researchers in the theory of traffic flow and in the field of intervehicular communication are pinning great hope (from the standpoint of increased capacity) on coming up with methods of reducing the well-known variability of vehicle headways which have been observed at stationary points. To provide a more realistic estimate of how much reduction can be accomplished along this line, some research should be done which would establish the frequency distribution of headways experienced by single drivers at various flow-rates as they move along the road. Dr. Treiterer, at Ohio State, has made some preliminary investigations of obtaining this sort of information by plotting vehicle time-distance graphs from aerial time-lapse photography (39). Another approach would be to make continuous records of headways for a large sample of subject drivers operating a vehicle equipped with a range finder. Both of these methods are tedious and expensive, but the information is very basic to all future (and current) research concerned with vehicle headways—meaning all research in traffic flow—and at present it is unavailable.

Another area that needs more research, principally for the edification of researchers, is the nature of rear-end accidents. Many researchers form opinions about rear-end accidents from reading newspapers instead of accident reports, and this results in unclear concepts of the problem they are researching, especially if the problem has to do with car-following. Journalists naturally emphasize spectacular accidents involving many vehicles, and the researcher associates them with dense traffic moving at very short headways. Actually, accidents involving more than two vehicles comprise a minute proportion of all rear-end accidents, and usually they occur in bad weather—fog, snow, or slippery pavement. The flow rate at the time of the spectacular accident is usually low. At a rate of flow of 500 vph—less than one-tenth of the rate on urban freeways during peak periods—it takes only 6 min to involve 50 vehicles in a multiple car pile up, which can and usually does consist of several separate rear-end collisions.

The common two-car rear-end collision, which is a very important contributor to congestion, is what needs more research. It is not known what proportion of these occur when there is a large difference in initial speed (speed at the time of crisis) as compared with those that occur when the difference is small. Because there cannot be a great difference in speed between cars following at close headways, it could be hypothesized that more accidents occur when headways are large than when they are small. On the other hand, theoretical work by Treiterer under Project 3-3 has shown that the very small headways which are actually observed on freeways are only marginally safe.

Research is needed to explain why these marginally safe headways in real traffic result in so few accidents, when compared with accidents that occur when the headways are "safe."

Studies of driver response to rear-end signals were also conducted by Ohio State University under Project 3-3. These studies confirmed that drivers do respond to visual signals, consisting of changes in lamp color or intensity, transmitted from the rear end of a vehicle being followed. This should encourage engineers who are faced with the problem of setting standards for rear-end signal systems for automobiles in the near future. Two or three non-conventional signal systems were used in testing driver response, but the purpose of the tests was not to design or set standards for vehicles. The systems tested could give misleading information; e.g., a green light on the rear end of a car going 5 miles an hour as it accelerates away from a stopped position.

OTHER TRAFFIC SYSTEMS RESEARCH

The U.S. Bureau of Public Roads held a "Program Review Meeting on Research and Development of Traffic Systems" in December 1966 (51). In the introductory session, the scope of this meeting was defined as a "pretty complete survey of the whole field—a comprehensive statement of the state-of-the-art, present and future." Because what the Bureau calls "Traffic Systems" covers the same field as what the NCHRP calls "Traffic Surveillance, Communication, and Control," the proceedings of that meeting essentially fulfill the objectives of this report. However, the proceedings of the meeting were longer—more than 800 typewritten pages of summarized research.

Promising Areas

The most promising areas reported on at the meeting were (1) Timing of Traffic Signals in an Urban Street Network, (2) The Freeway Ramp Control Projects, (3) Development of an Instrument to Measure Car-Following Behavior, and (4) Aid for the Stranded Motorist.

This report comments on the same areas as follows:

1. Timing Traffic Signals.—It has been pointed out elsewhere in this report that there is a shortage of persons whose function is timing traffic signals, and there is a further shortage of persons who are qualified to time traffic signals. Work begun under the title SIGOP (57) and related simulation of traffic at signalized intersections will be of great value when it has progressed far enough to produce a user's manual which can be placed in the hands of the few hundred traffic engineers in the United States whose job it is to time signals. Merely exposing these engineers to the theory involved, in a format that they can understand, would accomplish a great deal even if they do not use the canned programs. In discovering why they cannot use them, or proving to themselves that they can develop better strategies, there will evolve a better understanding of principles at the place it will do the most good—right on the

* See also Appendix G.
firing line (researchers would say "at the interface" between the engineer and the public).

2. Freeway Surveillance and Control.—The freeway ramp control projects are reported in a preceding section of this report.

3. Communication and Sensing Between Vehicles.—It is pointed out in another previous section of this report that research on, or quantification of, gap variability experienced by a vehicle moving down the road is basic to all other research aimed at reducing this variability and it is therefore encouraging to know that an instrument to accomplish this research is being developed (57). It would be hoped that a by-product of this development would be a refinement of the rate-of-closure device envisioned in the Ohio State research on communication between vehicles, but the cost of the research instrument being developed under the Bureau program is hundreds of times higher, and apparently devices for mass application will have to be developed separately.

4. The Stranded Motorist.—Regarding the stranded motorist problem, Airborne Instruments Laboratory is going ahead under BPR auspices (47) from where they left off under NCHRP Project 3-4. In that project they defined the scope of the problem (NCHRP Report 6) and furnished guidelines for making cost-effectiveness studies of various means of aiding the stranded motorist. They found that on busy urban freeways the problem of servicing the disabled vehicle is more difficult, expensive, and time consuming than locating it and communicating with it. They also found that 23 percent of the disabled vehicle problem would be solved if a fool-proof method of preventing vehicles from running out of gas could be devised. This does not seem like an insurmountable chore for the automobile industry to accomplish.

Because it appears that instrumenting a noticeable portion of the highway system for the detection of and communication with stranded motorists will not be economically feasible for a very long time, the Airborne Instruments Laboratory is now engaged in a study of the feasibility of reporting disabled vehicles by cooperative motorists—i.e., by passersby. They have found that passersby do cooperate and that disabled vehicles can be located in this way. One of the things that has not been resolved yet is that the enforcement agencies are not sure they want to be notified every time a motorist stops on the shoulder. They do not consider it their normal job to furnish gasoline or change tires for the public. Moreover, most of the stops are voluntary and the stranded motorist really does not want to be rescued.

In addition to the four areas just mentioned, many projects were reported at the Bureau of Public Roads meeting for which the promise of return is more distant or more abstract. Research in the more distant category could in some cases be speeded up by huge increases in financing. Research in the more abstract category should be, and doubtless is being, reviewed continually as it progresses, with the view of re-directing it into more concrete channels.

The Bureau has employed the systems engineering approach to the whole problem of using "modern science and technology for solving traffic congestion and safety problems." In applying this approach, the problem has been subdivided "into several subareas of work which, when completed, will provide a solution designed to meet the specific objective."

The following paragraph is not intended to be critical of the systems approach, or to imply that such an approach should not be taken, but points out some of the problems that this approach generates.

In dividing a problem area into several preconceived subareas, it is inevitable that some of these subareas are of great importance and some are of little importance, some hold promise in the near term and some will be fruitful only in the long range. And despite the master design, the research is done by many individuals. Doing the research will cause them to ask questions of themselves. They will research some questions that need answers, some that do not need answers, and some that are probably unanswerable. At the same time, they will overlook many questions that are continually arising in real life, that if answered might solve the over-all problem. To illustrate what this means, the research reported at the Bureau’s meeting is analyzed in some detail in Appendix G of this report.

CHAPTER THREE

PROJECTION OF FUTURE RESEARCH

As pointed out in Chapter Two, promising areas that are already being worked on are:

1. The freeway control projects.
2. Timing traffic signals.
3. Improved communication between vehicles.

Although progress is being made in each of these areas, it must be admitted that the results, looked at from a national viewpoint, have not produced a serious impact
on transportation efficiency in the United States at the present time. This is sufficient reason to conclude that the work should be carried on. Put in another way, if the progress to date has been the result of research, it can be hoped that more progress can be achieved through more research.

First, it is noted that NCHRP Projects 3-2, 3-3, 3-4, and 3-5 were all directed toward one or more of these areas, and the reports all contain some useful information which can be used to advantage by future workers. This shows that the general directions projected by the program advisers in 1962 were sound, and that fruitful areas can be projected, or forecast. On the other hand, the most positive results have been achieved by practice and experimentation. This is not surprising when the relative amounts of money being spent are considered. For example, the annual expenditure of any one of the freeway operation projects is greater than the 5-year total expenditure on Project 3-2, and that project also delved into the subject of traffic signal system control.

FREeways CONTROL PROJECTS

It is not believed that larger dollar amounts for contract research aimed at specific preconceived objectives would have accomplished the results that are being obtained by experimentation and evolution in the operation of highway systems such as the freeway control projects.

If it is stipulated that the desired end result of research is improved traffic flow that can be seen and felt by the traveling public, there should be some way of channeling research effort into operational projects to encourage their proliferation and to speed them up. The local agencies (and the public) within whose jurisdictions the experimental projects take place first will receive special benefits that are not immediately transferable to other locations, but they will compensate for this by contributing effort and by experimenting with first-generation hardware which later communities can skip over. Stated the other way around, the early co-operators will be burdened with the birth pangs and some expense, but they will start enjoying the payoff sooner than the latecomers who wait until the process becomes firm.

There are existing provisions for supplying research funds to local and state agencies that desire to set up experimental projects—namely, the Federal HPR funds administered through the State Highway Departments. These projects, especially in Houston and Chicago, have lighted the path. But, assuming that it is desired to emulate them in Los Angeles, San Francisco, Seattle, New York, Washington, and so on, there are three problems. First, emulation is not considered (up to now) to be research, i.e., nothing new is being discovered—at least the prospectus will not have anything new in it. (However, just as certainly, every new project will make discoveries and will find out new and better ways of doing things that were totally unforeseen at the time the prospectus was written.) Second, there is not and probably should not be enough research money earmarked for traffic surveillance and control to do the preliminary engineering and actual supervision of traffic operations on a large number of operating projects. Third, what the local jurisdictions need more than money * is knowledge—"how to do it."

This seems to be leading inevitably to the conclusion that a national effort could be implemented most expeditiously by creating teams of experts—task forces—who would be available on call to move in and assist local agencies in getting operations units off the ground and to train a cadre of permanent personnel who would remain to operate the project indefinitely. These task forces should not necessarily have to conform to a preconceived project statement or work plan with new research objectives. Each new project that is started will start from where the last one left off (or more accurately from where the last one is at the present point in time), and there is little doubt that something new will develop.

It is suggested that these teams would actually be resident in the projects, not visitors, although it might work out that several teams would be under the general supervision of a headquarters staff who would visit the projects of a given category.

Initially, the logical source for such teams would naturally be the personnel who have been operating the going projects, but they are needed where they are, so it would probably be necessary to train the trainers during at least the first year, by offering their services free to any operating agency that is showing progress and could utilize such services.

The preceding concept and recommendation is radical when viewed in the frame of reference traditionally associated with research administration. But it is not a new idea when it is thought of as supplying answers to two old goals that keep arising: (1) the administrator's desire to get an early payoff from research, and (2) the researcher's desire to see the results of his research implemented.

An alternative, which probably would not be nearly as satisfactory as the task force approach, would be to allocate research funds to the production of how-to-do-it manuals, as contrasted with research reports that are primarily concerned with explaining the theory and in validating the results of experiments. The field of traffic surveillance and control is too new to write how-to-do-it manuals. The closest thing to such a manual would be a how-we-did-it report. Because the person who did it is usually going on to new fields, he is bored with the task and a better job could be done by sending in an outsider who had not had initial responsibility for the project. In any event, a book of instructions by whatever name could not accomplish the purpose, which is to propagate advanced control techniques.

It should again be emphasized that these projects will generate research into specific questions or objectives which cannot even be named at the present time, and certainly cannot be incorporated into a vast all-encompassing research proposal. The most important national objective is to get lots of projects going, so that these questions and specific objectives will come to light.

* They will need money, too, but the place to get this is from general operating funds, not from research. However, research projects can be used for the purpose of evaluating experimental operational procedures, with the view of showing the cost-effectiveness in such clear terms that administrators of highway funds will provide these general operating funds.
TIMING TRAFFIC SIGNALS

Improvement in timing traffic signals can come about through several approaches that can go on simultaneously.

Continued Theoretical Research on Traffic Flow

The work of Webster, Miller, Gazis, Potts, Newell, et al. forms the foundation on which experiments like Toronto, San Jose, Glasgow and London are built. It also provides a foundation for network control algorithms such as the one developed by Weinberg (29), and provides simulation researchers with models to simulate.

Administrators should not look for an immediately usable conclusion from theoretical research of this kind. The outcome may be soon, or may be more distant, and probably will be seen only after applied research such as NCHRP Project 3-14, "Optimizing Flow on Existing Street Networks," makes use of the findings.

However, theoretical research is modest in financial demands and is suitable for dissemination of results in the form of one-item reports or papers in technical journals. It should be scattered among many independent workers because it is the kind of field where two or more heads are better than one; a single large project is not apt to produce more than one basic new idea.

Continued Work In Simulating Traffic Signal Control

As with theoretical research, this also should be divided among several researchers working independently for the same reasons, and should continue from where Project 3-5, NCHRP Report 32, left off (36).

Closely linked with signal simulation is the development of computer programs for timing conventional traffic signals, one of which was reported by Irwin in the BPR Program Review Meeting (51). More programs should be written, perhaps by independent workers, and they should be placed in the hands of practicing traffic engineers for trying out. It will probably be necessary to send a man along with the book, and it would be desirable to have a national research contract for evaluating the programs in many different cities. It is believed that this project would have early results because it is so easy to implement and that assisting practicing traffic engineers to execute programs should be included in the research. It is also believed that the results could be very important in magnitude.

It is recommended that Weinberg's algorithm (29) be tried out in San Jose and Wichita Falls, Texas, where equipment is available, and in Toronto if a way can be found to work a small network problem without interfering with their 500-signal network.

Development of a Low-Cost Presence Detector

It is not sure that a low-cost presence detector can be developed. There have been many detectors developed by private industry during the past 10 years and it is known that they have had many private and public disappointments. It is not known how much money went into this development, but it is no doubt large as compared with individual NCHRP research contracts. However, in discussions with researchers on both sides of the Atlantic, a subject that kept recurring continually was the cost and accuracy of vehicle detectors or sensors. The most dependable and most accurate sensors now available essentially detect only an event and most of them will not tell the time of the event very closely; e.g., the Port of New York Authority tunnel control project needs to know time to 0.01 sec and had to develop their own detector to do this. Weinberg, in both NCHRP Reports 28 and 29, points out the problems involved in trying to compensate for variations in shape, frequency, and magnitude of signals produced by detectors. The so-called presence detectors will say whether the space above them is occupied, and approximately how long it is occupied, which if traffic is flowing in a more-or-less steady state can be converted by computers into a kind of measurement of density. But they still tell the density only at a point—the point where the detector is.

Almost all researchers would like to know how many cars there are on a stretch of road, and where they are, at a given instant. The control logic and computations involved in deciding when to change a signal or when to allow another vehicle onto a freeway would be greatly simplified and the computations could really be made in real time. Available detectors are so expensive and cause so much clutter either in the pavement or overhead that it is impractical to instrument the whole road. Therefore, control algorithms are usually based on point detection. When presence and speed are known at only a few points on the road, many assumptions and complex calculations must be made to estimate how many cars are on a stretch of road. Most advanced control methods have to rely for these estimates on a projection of historical data (where the history can be from 40 sec to an hour, or even an hour yesterday at the same time of day).

The human eye can discern cars on a long stretch of road and with proper lighting conditions so can a television camera. It is suspected that radar could be adapted to yield this kind of information. However, if presence detectors could be made small enough to insert in or on pavements and inexpensive enough so that it would be practical to divide the whole road into small blocks, they would be better.

As has been said, it is not known whether directed research and development, no matter how adequately financed, could produce something that has not been produced so far at considerable expense, but if it could, the payoff would be enormous. It is recommended that at least a feasibility study be made with the object of arriving at a more firm conclusion of the probability of success and cost of the final product than can now be provided.

Three separate studies (which are discussed in a later part of this chapter) have come up with the idea that it will eventually not be very expensive to equip every vehicle on the road with a transmitter of some kind of signal that can be received either by another vehicle or by a roadside instrument. In the long range, this might provide a new and better way of detecting vehicles for surveillance.
and control, but one should not have to wait until every vehicle is so equipped before being able to know precisely what the state of traffic is on critical sections of streets and highways.

**Digital Computer Control Systems**

The project statement for NCHRP Project 3-14, "Optimizing Flow on Existing Street Networks," contains the following sentence: "Development of sophisticated systems for computer controls and electronic guidance are being studied elsewhere and would not be included."

It is not known what the words "electronic guidance" mean in this sentence, as applied to street networks, but it is known that if "sophisticated" means large, high-speed digital computers, the only places in the United States where such systems are installed (1967) are San Jose, Calif., and Wichita Falls, Texas. No comprehensive reports on these systems have been published. The amount of studying going on is pretty small. Hewton has published a comprehensive report on Toronto (31c), but the amount of studying going on in Toronto is pretty small, too. The only places where real studies are being conducted are London and Glasgow, and although traffic and driver behavior are very much the same throughout the world, computers and philosophy about objectives are different, and, in any event, it does no harm to duplicate a certain amount of studying with some fresh viewpoints.

One or two independent teams of experts (possibly including English and Australian personnel) should be sent into those cities to develop and validate algorithms for control (provided, of course, that the cities are willing, and it is believed they would be). Some other cities might also be willing to cooperate in this type of research. Because it is possible that such an experiment would fail, the research project should pay for the initial hardware installation, but the local agency should contract to acquire whatever hardware remains in use when the research is finished, assuming that they wish to continue its operation. The local agency should also be required to furnish an adequate staff to operate the system and acquire knowledge during the residency of the outside team.

The team should not confine its work simply to programming and operating the computer. The kind of engineering referred to in Chapter Two should be done, particularly the part about changing the physical design of the surveillance and control hardware when this is required instead of computing. The report should clearly differentiate computation from other improvements. For example, it is well known that if the split is held constant, short cycles cause less delay than long cycles, and that interconnected signals along an arterial cause fewer stops than non-interconnected signals. But it is not necessary to use a large computer to set short cycles or to interconnect signals. The report should show what the computer does that cannot be done by conventional procedures, or, in case it is used to duplicate one or many conventional procedures, how much it would cost to do the same thing by other means (some traffic-responsive signal systems cost in the same order of magnitude as the digital computer systems).

**IMPROVED COMMUNICATION BETWEEN VEHICLES**

**Electronic Sensing Devices**

Vehicle-mounted instruments that emit signals that can be received and interpreted by electronic equipment have been developed separately in at least three research projects: NCHRP Projects 3-3 (NCHRP Report 51) and 3-4 (NCHRP Report 40), and the BPR project "Development of an Instrument to Measure Car-Following Behavior" (57). The potential benefits of such equipment in safety, especially during reduced visibility, and in aiding drivers to reduce variability in headways (which may be closely related to capacity) are obviously very great.

The work done under Projects 3-3 and 3-4 convinces one that it would be feasible to equip all new vehicles, starting in the reasonably near future, with instruments that would keep drivers informed of the rate of closure and distance to the car ahead.

More research is needed into the question of the most effective way of transmitting the information to the driver, including alarm systems. What is also needed is to design and build a prototype of the complete system, together with a firm estimate of the cost per vehicle if it became required equipment. But the main thing that is needed is a cohesive feasibility study which will consolidate the odds and ends of research going on in the several areas for various purposes, present a unified course of action, and an estimate of cost of implementation. The authors of NCHRP Report 40, in Appendix J of that report, give an outline of needed research under the headings (1) Application and Cost Analysis Program; (2) Motorist Aids Using Infra-red Techniques; (3) Field Tests. Although they were, by direction, primarily concerned with the disabled vehicle problem, these headings are suitable for the unified research here recommended in the whole field of intervehicular communication. The field testing, especially, should be expanded to include more than just testing the disabled vehicle application.

**Rear-End Lighting**

The recommended research should not be used as an excuse to delay improvement in current methods of transmitting information through rear-end lights.

The design and standardization of rear-end lighting and vehicular signal systems is an engineering and legal problem and should not be allowed to flounder in protracted research. Further discussion of this subject is given in Appendix A.

**MISCELLANEOUS RESEARCH NEEDS**

Several specific research needs are mentioned in Chapter Two and Appendix B which are not covered in the preceding projection of future research.

1. Removal of disabled or wrecked vehicles from freeways: This problem is of the highest priority from the standpoint of importance of results. The probability of achieving results through research may be low but, because of the importance, it would be worth the risk. If a research project is launched, it should be a big one,
including design of equipment, if equipment is what is needed. It is not believed that a mere study of practices and recommendations for organizational procedures will solve much that is not being solved in an evolutionary way at present.

2. Research on frequency distribution of headways experienced by individuals along a length of road.
3. The nature of rear-end accidents on freeways.
4. Research on improving airborne observer advisories to motorists.

CHAPTER FOUR
RECOMMENDED RESEARCH

FREEWAY CONTROL—RAMP CONTROL

Principles are established but propagation and refinement are needed. The promise is excellent both near-term and long-range. Spontaneous research and engineering design are likely to pay off sooner than formulated research.

Establishment of task forces is needed to assist operating agencies to design and install operating systems, and to report periodically on problems and new developments. Problems will include methods of prorating demand among ramps; how to meter freeway-to-freeway ramps; storage of queues; whether the system should respond to traffic or traffic respond to system (i.e., clock vs computer); and hardware improvement—reliability, cost, and functioning. The amount that could be usefully expended the first year is $100,000, and a total of $2 million in five years. Probability of success is 0.9; importance is 1.0.

There should be theoretical research projects on what to try. These should be unencumbered "grants" in small amounts—one-man projects by operations analysts who have demonstrated ability and interest in the subject. Merge control should not be considered. It has been overdone. The amount that could be prudently risked is $50,000 for the first year, with a total of $200,000.

Probability of usefulness of results is 0.2, but, if useful, the payoff could be great.

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* Follow-up projects would not take place unless probability for success, as determined in first stage, is high.
FREEWAY SURVEILLANCE AND COMMUNICATION WITH DRIVERS

This includes detection of non-recurrent congestion owing to incidents and accidents, and driver information systems. The following areas are important.

1. More Effective Radio Broadcasts. The method should be directed research and field trials using airborne observers. Importance is 2nd on a scale of 5. Probability of success is 0.8. Cost is estimated at $400,000 in three years.

2. Blank-Out and Changeable Message Signs. These should be designed and tried out on the freeway for emergency warning and re-routing and off the freeway for re-routing and informing approaching drivers. The probability of success is 0.5 and the estimated cost is $200,000 in 18 months, with a possible $400,000 follow-up.

3. Improvement of Sensors. A feasibility study is recommended with the objective of deciding whether it is technically feasible to develop detectors which would economically sense the presence, or absence, or density of vehicles on long stretches or roadway. Cost of the study is estimated at $100,000 with possible follow-up development work at $400,000.

4. Service Patrols. There should be evaluation of existing systems and cost effectiveness of various levels of service; relationship between mileage, volume, and size of patrols needed, development of equipment, and relation to enforcement patrols. Development of service patrols will be an evolutionary rather than an inventive process. Cost is estimated at $50,000 in one year.

REMOVAL OF DISABLED VEHICLES FROM CONGESTED FREEWAYS

It is recommended that techniques and equipment for rapidly getting to the site (after detecting and reporting) be developed. Project is to include methods of rapidly removing disabled vehicles from freeways during periods when volume is heavy enough for the disablement to cause congestion. Cost is estimated at $500,000 in three years.

IMPROVEMENT IN TIMING TRAFFIC SIGNALS

The following are important areas:

1. Continued Theoretical Research on Traffic Flow. It is recommended that there be several small $10,000 to $20,000 grants. It is estimated at $50,000 in three years.

2. Simulating Traffic Signal Control Algorithms. Two or more separate projects are recommended, estimated at $500,000. Probability of successful payoff is 0.8.

3. Digital Computer Control Systems. In cooperation with operating agencies it is necessary to develop and validate algorithms for operating signals with sophisticated controllers. Method should include engineering design of surveillance and interface hardware. Task force could be set up as in the first part of this chapter. Project is estimated at $1 million in five years.

IMPROVED COMMUNICATION BETWEEN VEHICLES

It is recommended that prototype vehicle-mounted equipment be developed and produced that will inform drivers of rate-of-closure and distance to vehicle ahead in all weather. Cost estimated at $750,000 in four years. Probability of success is 0.8; importance is 1.0.

APPENDIX A

VEHICULAR SIGNAL SYSTEMS

In Chapter Three it is pointed out that the design and standardization of rear-end lighting and vehicular signal systems is an engineering and legal problem and should not be allowed to flounder in protracted research. For that reason, the material in this appendix was not included in that chapter, titled "Projection of Future Research." Nevertheless, it is pertinent to the subject of this report, and is therefore being included here. Discussions with Mr. E. R. Ricker, Chairman, and other members of the Joint Vehicular Signal System Committee, with the former administrator of highway transportation in California, and with members of the SAE Committee on Lighting, indicate that it is important to print the following analysis.

Many proposals have been made by both qualified and unqualified persons for radical revisions in signal systems, and these generally involve colors other than red. Psychological research in which the superiority of one system or another would be proved beyond statistical doubt could be a nearly bottomless pit. However, it is time to adopt some kind of system in which there is a much greater contrast between separate meanings than is now obtainable on standard American automobiles.

To draw an analogy, the present system used for the rear-end of cars, if applied to street traffic signals, would result in dull red for go and bright red for stop. Although it might be very difficult to show by psychological research...
that drivers behave differently approaching a green signal than they do when they approach a red signal, it really is not necessary to conduct such research in order to convince sensible men that it is better to have different colors or other different symbols for the two meanings.

What is needed is the establishment of a relatively small technical committee, or commission, with enough prestige and authority to accomplish the desired ends. This committee should include representatives of government, and representatives of the automobile industry, and should make deterministic decisions.

The automobile industry has made many changes in lighting and rear-end signaling during the past 20 years, and changes will continue to be made in the future. Engineers in the industry are equipped with brains, money, and facilities to accomplish in a few meetings more than outside organizations could accomplish by years of research, and more importantly they know the practical problems involved and are in a position to take effective action. All they need is the impetus.

There are very large problems involved in securing agreement among all the interests involved in this subject. For example, it took the automobile industry several years to obtain enabling legislation for such a simple change as changing the front turn signals from white to amber. The size of the problem should not be permitted to discourage its solution. But it must be understood that the problem can be solved only by decisions, not by research.

A primary objective should be to establish a set of standards and specifications that would control such items as color, intensity, and positioning of rear-end lighting within practicable ranges. One of the reasons that this should be done at an early date is to prevent the proliferation of innovations by manufacturers which will preempt certain standards which later investigation might prove to be necessary to serving a particular function. The extremely wide and brilliant turning signals on the 1966 Thunderbird and Charger are examples. There may be nothing wrong with these tail-lighting systems, but the existence of them to accomplish functions that are now being accomplished by much lesser systems might preclude their use for a new function.

The following problems do not need further research but they do need early agreement and executive action:

**Uniformity.**—It is evident that the driving task will be simplified if the signal or pattern of lighting on the car ahead means the same thing whenever it looks approximately the same. Upper and lower limits of brightness and of spacing should be set within fairly narrow ranges in order to accomplish this. One of the problems with present systems is that there is no "reference brightness" which enables a following motorist to distinguish at first glance whether he is approaching a car with its brake lights on or a car with unusually bright tail lights.

**Distinctly Different Signals for Distinctly Different Meanings.**—With existing signaling systems, the distinction between indications listed below is not great enough, especially as between indication 3 and indications 1 and 2:

1. Indication of a vehicle proceeding in a normal manner.
2. Indication to following drivers that the brakes are being applied and that the vehicle is stopping.
3. Indication to following drivers that the vehicle is stopped. The most important cause of rear-end accidents, both in clear weather conditions and in conditions of reduced visibility, is the failure of following drivers to recognize when the preceding vehicle has stopped in the traveled way. The signal for this condition must be different from the signal for braking or deceleration and must be one of the most attention-getting signals used for any indication.

**Variable Intensity for Variable Ambient Conditions.**—It is probable that lights that would be bright enough in a fog at 7:00 AM in the winter, would be unacceptable on a clear night, and lights that would be desirable on a clear sunny afternoon would also be too bright on a clear night. There should be definite and reasonably limited ranges of brightness for at least these ambient conditions.

It might not be feasible to develop standards to accomplish these objectives that would be literally applicable to all the vehicles on the road (for example—large trucks, motorcycles, and small foreign cars). But if these standards were to be achieved for, say, 60 percent of the vehicles on the road after a period of 6 or 7 years, a very large improvement in inter-vehicular communications would be achieved. As is true of other attacks being made on the over-all problem of highway safety, it is not necessary to attain a 100 percent solution to all the problems in order to make a very significant improvement.
APPENDIX B

NCHRP PROJECT 3-2: "SURVEILLANCE METHODS AND WAYS AND MEANS OF COMMUNICATING WITH DRIVERS"

PURPOSE OF THE RESEARCH

The project statement for Project 3-2, NCHRP Reports 9, 28, and 29, reads in part as follows:

The hypothesis is that (1) information regarding traffic flow can be obtained; (2) this information can be transmitted to control centers; (3) with the information in the control center, a decision can be made regarding action that can be taken by drivers; (4) this decision can then be communicated to the drivers; (5) the drivers will act or react; (6) there will be results in the form of improved conditions of traffic flow. It is desired to test the hypothesis using real traffic on a real road system which includes an operating freeway network. . . .

Stage 1 is to develop and practice the decision-making process (item 3 of the hypothesis) and report the results. Practice decisions would be made, based on a wide range of real traffic situations reported by observers in the field or in the air. Decisions would be made using several types of information (time of day, volume counts, queue lengths, speed, "density," accident, etc.), and the report would state how often each type of information was used.

At the time the project statement was written, it was not clear what kinds of instructions could be communicated to drivers that would improve traffic flow, or what kinds of information would be required in order to formulate these instructions (decide what to do). It was thought desirable to answer these questions before installing hardware.

However, the research agency assumed that fully instrumented facilities were already in existence, and that decision-making could not be practiced without them. When it was found that no such facilities existed, and that certain kinds of decisions were being practiced in Chicago, Houston, and Detroit, the project was reoriented to encompass a limited number of objectives which were not being pursued elsewhere.

As finally performed, the research consisted of the following four items:

(1) Theoretical development of a method for predicting travel time on an urban freeway when an unusual event occurs causing congestion.
(2) Evaluation of airborne observers reporting to drivers through commercial radio.
(3) Cost estimate for a tethered-balloon TV system.
(4) Synthesis and cost estimate of a digital-computer-controlled traffic signal system for a small city.

RESULTS

Prediction of Travel Time on an Urban Freeway

As stated on page 4 of NCHRP Report 28, the objective of this phase of the research is to "determine, in the event of an incident, the reduction of service level that will occur on the freeway, by a forecast of travel time, and to signify when the forecast indicates that motorists would be better served by using the surface street system," and "... to implement controls to direct traffic from the freeway . . . ." when this occurs. It is not intended to be used for regular recurrent congestion owing to normal excess demand during peak periods. Ramp metering such as is being practiced in Chicago and Houston during peak periods is not compatible with this objective, since traffic diverted by ramp metering will suffer greater delay than freeway traffic.

The theoretical development of a method for predicting travel time on a congested freeway was based largely on the calculation in real time of volume-density curves. When the method was tested on the John Lodge Freeway against television observations of travel time, the correlation between calculated (predicted) travel time and actual travel time was poor, but later trials, based on corrected assumptions, showed improvement.

Prior to their suggested use in this project, volume-density curves were used by some analysts to portray historical data obtained by observing traffic flow at a point on a road. The data were not time-related; i.e. adjacent points on the curve could have been observed at any time and very rarely represented consecutive instants. Furthermore, the curves do not represent traffic characteristics on a length of road. However, at the time this research was begun, many persons engaged in traffic research believed that travel time could be predicted by looking at a "q-k" curve, or a "speed-volume" curve representing flow at a point instead of on a stretch of road.

It is therefore important to note that the authors of the report (NCHRP Report 28) conclude (page 12): "All that is needed to find travel time from any station to the bottleneck is to sum the number of vehicles between the station and the bottleneck and to divide it by the bottleneck flow rate."

The same discovery was made several thousand years ago, when the hourglass was invented. Nevertheless, it is good to see it stated again, as a result of an exhaustive study by an aerospace research organization, because some of the speed-volume theorists believed that modern space-age technology would be able to overcome the natural law relating time to capacity; i.e., that somehow delay could be reduced by speeding up cars, using electronic surveillance and communications procedures, even though the bottleneck flow rate, or capacity of a road, remained constant.

The report does not answer directly the method by which the number of vehicles between the station and the bottleneck can be estimated, but other research has shown that for a given section of road, the number of vehicles in a
queue is nearly proportional to the length of the queue and the density in the queue. Corrections would have to be made for cars entering and leaving the freeway between the upstream end of the queue and the bottleneck. On a highway equipped with sensors at frequent intervals, it would be fairly straightforward to determine queue length and density by lane-occupancy sensors (this is being done on the Eisenhower Expressway Surveillance Project) and to convert this into numbers of cars by direct calibration of the road. Assuming that the purpose of this procedure is to estimate travel time when an unusual incident, such as an accident, happens, it would be necessary to measure the rate-of-flow at the bottleneck in real time, since the rate-of-flow depends on the nature of the incident and can vary from zero up to 75 percent or so of the normal capacity of the highway.

Another important conclusion of the research is found on page 61 of NCHRP Report 28, where the author states: “Stoppages can occur at relatively moderate densities if an accident or other unforeseen incident occurs. No warning system is envisioned that can predict such a situation, but this is no reason to hold it in low regard if that is its only failing.”

This raises a couple of very interesting questions, which may be unanswerable, but which at least make it seem unimportant to predict delay owing to a back-up caused by an accident very accurately (say, with a possible error of less than five minutes). Suppose that the number of cars in the queue is known (say, 500) and the rate of flow at the bottleneck is known (say, 3,000 vph). The travel time for a driver upstream of the present queue at this instant can then be calculated. It is 10 min. Now a wrecker comes along and changes the rate-of-flow to zero for 5 min while it jockeys and maneuvers around. The calculated delay nominally increases to infinity, based on zero flow. (If the duration of zero flow [5 min] could be predicted, the calculated delay would suddenly change from 10 min to 15 min.) Then the wrecker removes the cause of the bottleneck and the rate-of-flow suddenly increases to, say, 7,200 vehicles per hour. The predicted delay instantly changes from infinity (or from something greater than 10 min) to a much smaller number, perhaps 5 min, and then rapidly decreases to zero during the next 7 min. During all this time, the predicted delay has been wrong by an order of magnitude. When the approach time of the individual drivers who are being kept informed while en route to the scene is considered, the error is increased by another order of magnitude; i.e., the prediction is stale by the time they reach their route decision point.

The stated reason for developing a method for predicting travel time on a freeway after an accident causes a tie-up is to divert traffic from the freeway when the travel time via the freeway threatens to exceed the travel time on alternate routes. Because of limits on the extent of research funded under Project 3-2, no attempt was made to develop a method for estimating the travel time via the alternate route. Nevertheless, anyone who has been caught by an accident-caused jam on a freeway can readily see the value of being advised, preferably before entering the freeway, of the probable delay he will encounter, even if he does not have an accurate estimate of the alternate route. The advice could be transmitted by several means, including radio broadcasts as well as roadside displays. The driver could then presumably make his own estimate of the time it would take to make his particular trip via an alternate route, and make a choice.

There are several reasons why this choice will be very difficult. First, the driver probably is unfamiliar with the alternate route and does not know how long it would take, even if he were the sole additional traveler on that route. Second, if the communications system were effective, there would be several hundred, or perhaps thousands, of other drivers diverted to the surface street system and the travel time on the alternate route would increase, perhaps enormously. Third, the predicted delay on the freeway route is probably fluctuating wildly for reasons previously described, and fourth, his information, if he is a considerable distance upstream of the bottleneck and receives it by radio, refers to conditions that will have changed by the time he arrives at the location where he must make a choice of route.

All of these difficulties still do not negate the value of keeping drivers informed of the current situation. However, they do suggest that precision in measurement and calculation is not as important as speed in transmitting the information.

They also suggest, indirectly, that the most urgent problem is speedy removal of the bottleneck, whether it is a police officer writing a summons, a pretty girl with a flat tire, or a serious accident. This problem kept showing up in the review of all the various research and experimental projects involving freeway surveillance. In view of this, it may seem surprising that no organized research effort is being directed at improving methods of removal of wreckage or incidental restrictions on flow. This lack of recognition may stem from the fact that when confronted with a problem, two basically different approaches may be taken: (1) to study the problem and develop a solution, and (2) to eliminate the problem. The systems approach to writing research problem statements is vulnerable in this regard, and care must be taken to avoid researching the wrong thing. An example of this kind of research is the very large effort being made to solve the problem of merging at a stingy on-ramp, instead of eliminating stingy on-ramps.

Another example of the two points of view is contained in the case given in NCHRP Report 28. A road contractor's employee placed a barricade on a heavily traveled route at 7:30 AM, and the airborne observer spent the next hour and a half telling motorists to avoid that route, and thereby reduced their aggregate delay from 1,021 vehicle-hours to 660 vehicle-hours, a saving of 361 vehicle-hours. If the airborne observer had taken the other point of view, he might have communicated through appropriate channels with the contractor instead of the motorists, and saved them 1,000 vehicle-hours. It is not meant here to imply that the airborne observer was a researcher or that he took the research point of view. There is, however, a parallel with the problem that researchers have of communicating with administrators, and vice versa. (There is an incidental fur-
Evaluation of the Airborne Observer in Traffic Control

As stated in NCHRP Report 28 (page 14), "Within the past decade there has been an increasing use of airborne observers for the purpose of reporting on traffic conditions. Usually the operation is conducted over a metropolitan area and in conjunction with commercial broadcast radio stations."

There has been considerable speculation in the traffic engineering profession about how much good these commercial broadcasts do for traffic, but very few objective analyses have been published. This project therefore undertook to evaluate one such service, in Buffalo, New York.

The study was confined to the effectiveness of airborne observers in alleviating congestion caused by unusual events or incidents; not recurrent peak period congestion. In this respect it was parallel to the first phase of the research.

By recruiting ordinary citizen observers to report their actions or reactions during traffic tie-ups that were also covered by alternate route advisories from the airborne observer, estimates were made of the delay reduction in nine incidents in the Buffalo area. It was estimated that the savings to motorists averaged $465 per incident, based on vehicle-operating cost of $1.25 per hr for vehicles caught in traffic jams. (This is a very conservative unit cost, and does not include value of the motorist's time.) A log of all incidents reported during a year indicated that 104 incidents, or $48,000 per year savings, were being realized in Buffalo from the airborne observer "advisories."

The research agency suggests that light airplanes are just as good as and a lot cheaper than helicopters as long as the weather is good, and suggests that helicopters be used only when weather does not permit the use of airplanes. On this basis, they estimate that airborne observation for 500 hr a year, which would be 2 hr a day on workdays only, would cost $15,000. (This estimate seems low, and does not include communications.)

The airborne-observer study was a kind of by-product of the main research effort and no claim is made that it is definitive. However, the order of magnitude of the estimated costs and benefits indicates that this mode of surveillance and communication should receive far more attention from governmental agencies than it has to date.

The case study in Buffalo contains what seems to be an anomaly. Costs were estimated on the basis of operation for only 2 hr per working day, which presumably would be one morning peak hour and one evening peak hour. Yet the class of tie-up that was evaluated was the "unusual" incident tie-up. These incidents happen at all times of the day on metropolitan freeways, and in fact they can be just as aggravating during the off-peak as they are during peak periods. Also, there is a much greater probability of successful rerouting during the off-peak, because during peak periods most of the surface-street thoroughfares are operating at near-capacity levels.

A systematic trial of the airborne observer in a large metropolitan area on at least a 12-hr per day schedule should be made. Even if the cost estimate in NCHRP Report 28 is low because it was used on operations during peak periods only, the cost of such a trial would not be large and the results could be very impressive. Among other things, the following need research or practice:

1. The observer must be trained. As part of the training he must have feed-back as to how close his guesses are.
2. Some way must be developed to divide up a large area so that motorists in one part of the metropolitan area do not have to listen to so many broadcasts that do not concern them.
3. Once a tie-up is observed and reported, continuous bulletins (revisions of the original estimate) should be issued. The agency in charge should have control of the broadcast time, or at least priority, so that the traffic information would be current and not wait for the next break in entertainment programming.
4. The reliability must be improved.

Tethered Balloon TV System for Traffic Surveillance

The cost and limitations of using a balloon-mounted closed circuit TV camera for traffic surveillance purposes were investigated. It was estimated that the balloon and platform would cost $13,435, not including the camera or transmission cable, but including $2,250 worth of helium which would presumably be used each time the balloon was lofted. The design was based on 20-mph wind velocity, meaning that the balloon would have to be brought down whenever wind exceeded that amount. The cost of launching and installation was estimated at $1,000, which may be very low when the problem of fastening the platform to three wires anchored at about 800 feet apart on the ground, with the intervening distance filled with buildings, poles, power lines, traffic, and trees is considered.

The report also brings out the following additional limitations:

1. FAA regulations limit the altitude of a moored balloon to 500 ft above the surface, or less if within the clearance envelope of an airport. (At the site of the John Lodge Freeway surveillance project, the altitude would be 400 ft above the surface.)
2. Definition of the image ("resolution") on the face of a TV receiver would limit the amount of roadway that could be usefully surveyed, holding the camera stationary. Based on a vehicle being 6 ft wide, it is estimated that about ¼ mile of road could be encompassed in the field of view with the camera aimed vertically downward. Longer stretches of road could be observed either by wide-angle lens or higher altitude, but the cars would become too small and indistinct on the receiver tube.
3. At an altitude of 500 ft, the field of view for a 1.0-in., 41-degree angle lens looking down vertically would be about 360 ft. However, by tilting the camera and using a zoom lens, a longer section of highway could be observed. No estimate was given in the report of the amount of highway that could be surveyed on a roving basis using a zoom lens, but it seems logical that the foreshortening and masking associated with oblique viewing could be tolerated up to
some limit, perhaps 70 degrees from the vertical, and this would extend the range considerably, although the problem of resolution would require that the length of road that could be observed without moving the camera at that range. It is well known that a TV receiver can show a baseball clearly at a range of 400 ft, if the field of view is narrow enough. It is also well known that vehicles on a highway can be spotted (by eye) within a vehicle-length of their true location at angles approaching horizontal, as viewed for example from an overcrossing, or from a 200-ft building at a half-mile.

The profession is indebted to this research for pointing out the problems involved, in addition to the problem of wobble which is the first thing that comes to the average traffic engineer’s mind when he toys with the idea. All in all, it is difficult to conceive of a traffic study that would warrant the expense of launching a balloon to mount a TV camera. A large crane of the type used for erection of tall buildings would seem to be a better solution for detailed, stationary studies of traffic on small sections of road.

**Synthesis of a Digital-Computer-Controlled Traffic Signal System for a Small City (NCHRP Report 29)**

When this research was begun, there was a lot of loose thinking about how much could be accomplished by computing. There were no digital-computer signal controllers in the United States. *NCHRP Report 29* does some very tight thinking about what a computer can do, and provides a cost estimate for a typical small city with 116 signals.

Most of the report is concerned with development of an algorithm to minimize delay in a signalized network by changing signal indications using real time computations based on current traffic counts throughout the system. In this respect it is different from the systems in San Jose, Wichita Falls, New York City, and West London, all of which primarily depend on libraries of pre-engineered programs of offsets, cycles, and splits.

Weinberg (29) shows that to minimize delay in a network, intersections may be considered one at a time, and all intersections downstream of the considered intersection may be neglected. (This is a special case of the theory he proved in *NCHRP Report 28* that vehicle-miles per unit of time should be maximized. The sooner one “gets rid” of the traffic upstream of any intersection, the sooner one generates vehicle-miles downstream, and the sooner one generates them, the higher the rate is.) However, the state of the upstream signal for each approach leg will have a lot to do with how many cars will arrive at the subject signal during the next \( \Delta t \) sec, so the method divides the network into subnetworks which include the upstream signals.

At a typical intersection of two two-way streets this results in a subnetwork of 5 signals each. To minimize delay at the signal in the center of the subnetwork, every two seconds a comparison is made between (1) predicted delay to traffic on all legs if the signal indication is changed “now,” and (2) predicted delay if the indication is changed at another time in the future. On the basis of whichever is least, the computer commands the signal to extend or terminate the current phase. All of this is subject to constraints such as minimum time for pedestrians, maximum red, etc.

The input information comes from two detectors on each approach to each signalized intersection; one several hundred feet upstream and one at the stop line.

The problem with the whole scheme is, as Weinberg himself puts it, “one of the problems that plagues even the most advanced traffic signal system... is its reliance on certain expected values”—i.e., one has to predict how many cars will arrive during the next \( n \) seconds, because one cannot count them. Weinberg suggests that these quantities “may be obtained by combining simple linear regression, multiple linear regression, and average values, with a weighted moving average technique.” Thus, it turns out that one is not computing in real time; * one is projecting historical data, although the history is very recent. However, it should be noted that if location and speed of all the vehicles within 1,500 ft (30 sec at 50 fps) upstream were known, then the only “averaging” necessary would be in estimating the number of vehicles generated or sunk by turning movements in that stretch. Because people coming into a stream are not nearly as discouraged by an initial delay as those who are already in the stream, errors incurred by this averaging would be tolerable, and it might even be preferable in many cases to ignore delay to the newcomers in order to provide smoother platoon flow.

The report presents flow charts for the computer program and from these determines how many calculations would have to be made per second, and how many bits of information would have to be stored, for the 116 signals in White Plains. Two digital computers are considered, and either would cost approximately $445,000 over a 5½-year period, or $6,740 per month.

In addition to this, there would be $229,000 worth of detectors and other field hardware (not counting the existing signals and local controllers), and telephone lines at $2,000 per month. The total would be about $13,000 per month, or $112 per month per signal.

* It should be noted here that conventional full-actuated signal controllers for isolated signals do calculate in real time when the signal should change phase, and do not depend on predictions of or provide for future events, such as a platoon of cars coming along 10 seconds from now.
APPENDIX C

NCHRP PROJECT 3-3: “SENSING AND COMMUNICATIONS BETWEEN VEHICLES”

PURPOSE OF THE RESEARCH

The project statement for Project 3-3, NCHRP Report 51, included the following language:

Research Problem Statement:
On expressways and interstate highways where greater volumes of traffic desire to move at higher speeds wherein there would be decreased time for making correct decision there is need for inter-vehicle communication to:
1. Reduce probability of accidents.
2. Permit each vehicle to move at higher speed.
3. Allow the movement of a greater volume of traffic.

Objectives:
The investigation and evaluation of operating requirements for systems of communications between vehicles on divided expressways, freeways, and interstate highways. The requirements should be determined in light of decreased time for making correct decisions. Consideration should be given also to providing for compatibility with an automatic vehicle control system.

The immediate objective is to establish the operating requirement of the communication system. The long-range objective is the development of equipment based on the established operating requirements.

Although the objectives are vague because of the abstract terms used, it is clear that the research was intended to be a step toward improved operation of freeways (as opposed to conventional roads and streets) based on the following hypotheses:

1. Accidents—especially rear-end accidents—could be reduced by supplying more information to drivers regarding the activity of other vehicles in the traffic stream.
2. Capacity could be increased if the headway between vehicles is reduced. Improved communications between vehicles might result in reducing mean (average) headways, because when the mean headway is 1.8 sec, or 2,000 vph, the modal headway (the headway utilized by more drivers than any other headway) is only 1.3 sec, or 2,800 vph.

RESULTS OF THE RESEARCH

Research conducted at the Ohio State University and published in NCHRP Report 51:

1. Has confirmed the hypothesis that drivers respond to visual signals, consisting of changes in lamp color or intensity, transmitted from the rear end of a vehicle being followed. The signals tested included signals not conventionally used on American automobiles.
2. Has demonstrated the feasibility of equipping vehicles with instruments that will furnish drivers with quantitative information about the rate of closure (or separation) between vehicles.

Both of these results are potentially of great importance, although many more steps of research and development will be required before they have a significant effect on traffic operation in the United States. This additional research and development is not overwhelming and if implemented could be accomplished in the near term, as contrasted with long-range results.

The research on the project was conducted separately by the Systems Research Group and by the Transportation Engineering Center of the Ohio State University. Results were reported separately on several different studies.

SYSTEMS RESEARCH GROUP STUDIES

Four studies were performed by the Systems Research Group. All of these were based on performance of a sample of subject drivers in instrumented cars. The subjects were male college students. The four studies were as follows:

1. An Experimental Evaluation of Four Intervehicular Communications Systems (Driver response to rear-end signals).
2. Evaluation of a Velocity Display Signal System (Extension of the rear-end signal system study).

Driver Response to Rear-End Signals

The first study, or group of studies, was concerned with the response of the subject drivers to various systems of rear-end lighting signals on a car being followed by the subject during several maneuvers. It was found that the drivers did respond; e.g., when brake lights are displayed, drivers in the following cars respond much sooner than when no brake lights are displayed, for the same deceleration rate of the leading vehicle.

It was also found that drivers respond to unconventional signals. Conventional rear-end signals on American cars do not differentiate between constant velocity and coasting, (with either brake or accelerator depressed). Two signal systems were tried which did differentiate this maneuver, and the subject drivers responded to these new signals in about the same time as they did to conventional brake lights.

There were four signal systems, eight maneuvers (gradual stop, sudden stop, etc.), nine subjects and four replications, making 1,152 field trials. This resulted in a plethora of material which was subjected to statistical analysis. The quantity of data, the painstaking accuracy and concomitant elaborateness of instrumentation, and the statistical analysis itself all contributed to make the study pretty expensive for what was found out, namely, that drivers respond to rear-
end signals. (It may not be very important to know whether
the car ahead is coasting at a very moderate deceleration
rate.)

Reacition time of nine male college students to deceleration
of the lead vehicle is from 0.6 sec to 1 sec when a
signal is given, and from 2.0 sec to 3.5 sec when no signal
is given. (The NIL—no light—system is no signal, and the
conventional system is no signal at the coast maneuver.)
All of the trials were made from an initial trailing distance
of 200 ft, and thus no interpretations are possible as to what
response times might have been obtained at typical very
short headways (1.3 sec) that occur in heavy traffic. Also,
of course, it would be hazardous to form a judgment regard­
ing response time of the driving population based on tests of
male college students.

The AID system was a complex system involving 20
lights, which indicated magnitude of deceleration or ac­
celeration by varying the number of red or green lights that
were illuminated. The Tri-light system used red for brake
actuation, green for gas pedal actuation, and amber for
neither gas pedal nor brakes.

It is pointed out in the final report of the Systems Re­
search Group that the Tri-light system would give misleading
information under some conditions. This raises the
question as to whether either one of these systems would
be practical for use on the highway, because they both
indicate green for acceleration, which could mean a slow
truck climbing a hill or leaving a stop sign or traffic signal.
What is needed in real traffic, for both safety and capacity,
is an indication of closure (positive or negative) with
respect to the vehicle ahead, and even more importantly,
in heavy traffic, of the Nth vehicle ahead. Also needed is
an indication of whether the car ahead is stopped. This is
a special case of closure, but is the most important one for
safety. Neither Tri-light nor AID systems cover this case.

As previously stated, the important conclusion of this
portion of the research is that drivers do respond to any
visual signal, and the simpler the signal the faster the
response. Additionally, because of the rigorous experimental
design, the findings of this research will be of some value
to engineers faced with the problem of designing a rear-end
signal system that would provide more information than
does the current system on American cars.

Evaluation of a Velocity Display Signal System
This was essentially just one more rear-end signal system,
including sixteen green lights. Two lights indicate 40 mph,
four lights indicate 45 mph, and so on, up to 16 lights for
75 mph.

The experiment did not work out too well. The report
states, “Due to unavoidable differences in operating pro­
cedures one is precluded from making valid comparisons
between mean values obtained on this study and the means
of other investigations.” These differences are unexplained,
but the mean values of response times were much greater
than those found in the other series of tests, and the con­
ventional brake lights were found superior to the velocity
display system.

The report also says, “This should not be taken as a
condemnation of all velocity displays. Another display with
some combination of (brake lights) and velocity might
prove superior to the conventional in all types of maneu­
ers.” Development of a good rear-end signal system is
essentially an engineering design problem and was not in­
cluded in the scope of the project conducted at Ohio State.
Some constraints are that any system must be simple, must
furnish at least as much information as the conventional
American system does, and must not furnish misleading
information, either direct or inferred (by absence of a
signal) in any situations where the conventional system
does not.

Exploratory Study of Passing on a Multi-Lane Expressway
This study was an attempt to find out something about gap
acceptance in the lane-changing maneuver. According to
the final report, “the ultimate objective of this type of re­
search is to see if a highway's volume of traffic can be
improved by increasing the information available to the
driver relevant to his passing decision.” (The way capacity
would be increased would be by filling up gaps by lane
changing.) As a beginning, the research group sought “to
describe the [driver's behavior] without any decision aids.”

The experiment design was so limited in scope and so
unrealistic that the value of this research for the stated
purpose is questionable.

The experiment was conducted on a four-lane divided
freeway using two experimenter driver cars and one subject
car, as shown in Figure C-1.

1. Car 0 was driven at constant velocity \((V_o)\) by an
 experimenter.
2. Car 1 was driven by the subject at a constant velocity
(either 50 or 60 mph) with use of his rear view
mirrors denied.
3. Car 2 driven in Lane 2 by an experimenter traveling
at \(V_o + 10\) mph (60 or 70 mph) as he approaches
Cars 1 and 0.
4. When a predetermined value of space headway, \(H_{1-2}\),
was reached the subject was given the use of his rear
view mirrors and required to decide whether or not to
pass Car 0. Twelve levels of the headway, \(H_{1-2}\), were
used.

The experimenters recorded the decision time and the
percentage of “go” responses. The decision time was
measured from the point in time \(H_{1-2}\) was reached and the point
when the subject depressed the gas pedal to make the pass.

The percentage of “go” responses as a function of head­
way varied widely between subjects. In general, the subjects
accepted headways less than those recommended by the
National Safety Council.

The researchers concluded that both safety and capacity
may be increased by providing additional information to
(1) “the driver who passes only at values of \(H_{1-2}\) in excess of
that needed for safety,” and (2) the driver “who passes at
headways which are at a value low enough to cause the
closing car to decelerate.”

The task assigned the subject drivers—to change lanes
without having time to size up the situation—is so for­mida­
able that it is difficult to see how the results of the experi­
ment can be interpreted for application to real-life situa­
tions. Instead of "describing the characteristics of a driver's decision to pass without any decision aids," as promised, the experiment actually assessed the driver's reaction to a sudden and very drastic increase in the amount of aid he received; i.e., from no-rear-vision to rear-vision.

Drivers on crowded freeways do not make sudden decisions to change lanes, unless they are confronted with a sudden emergency that causes them to react instinctively, or unless they are unusually foolish. They usually have been wanting to change lanes for some period of time—several seconds—and have been judging the speed of traffic in the adjacent lane during that time, as well as looking in the rear view mirror. Then, when they see a gap coming along (it takes two cars to define the boundaries of a gap), they prepare for it before the lead car (a car not used in the experiment) goes by. When the lead car goes by, the lane change is begun almost immediately. Although the headway behind the subject car is safe, the headway ahead of the subject car is unacceptably short (but also safe, because the subject car is going slower than the car he is now following). The driver of the subject car allows the headway ahead of him to increase to an accepted amount (about 1.3 sec) and this causes the headway behind him to decrease, due to the laws of arithmetic. This often causes the lag car (Car 2 in the experiment) to slow down, and a shock wave can be set up if saturated flow is already in existence. This could very well create unsafe closure rates and can even result in collision upstream, without placing the lane-changing car in an unsafe position at any time.

These phenomena have been studied macroscopically. It is known that shock waves are set up in this manner whenever demand exceeds capacity, and it is known that the rate of flow on the freeway as a whole (all lanes) is increased above what would obtain with no lane changing. Although it would be possible to study the phenomena microscopically, using subject drivers, it is believed that such a study would not be too fruitful, and in any case would require a different and more realistic experiment design. It is not believed that observing a subject driver's behavior with no mirrors at all, which would truly deprive him of decision-aiding information, would be useful research.

An Exploratory Study of Driver Control Behavior and Roadway Geometry

This was actually a study of gas pedal movement related to speed, acceleration, and gradient of the road.

Traces on a high-speed chronographic recorder were made for several subject drivers (number not given in the report) on a 100-mile round trip on an interstate highway with minimal interference from other vehicles on the road. These traces were then digitized and collated with the highway profile, and the data subjected to exhaustive statistical analyses. Findings were not startling.

The study results are as follows:

1. The amount of gas pedal movement varies with the individual driver's compensation for gradient. Apparently, the driver who observes his speedometer frequently and attempts to maintain a constant speed will vary gas pedal pressure to do so as the grade of the road either supports or retards the velocity of the car.

Drivers who apparently are not concerned with velocity maintain relatively constant gas pedal pressure and permit vehicle velocity to vary with vertical curvature.

It was found that the former kind of driver can be confused by gradual changes and variability between grades. This often results in excessive velocities followed by a reduction to the desired velocity level.

2. On hilly sections "the frequency of gas pedal movements decreased while the amplitude of these movements increased."

3. Deviations from desired velocity levels "occurred most often on the upgrades and downgrades of sags and crests."

It was pointed out that accident experience usually is greatest at these locations.

4. "Several regression analyses indicated that gas pedal movements have a time based relation to acceleration and velocity. Differences between subjects prevented the quantification of the effects of time."

This finding, which is quoted verbatim from the final report, must mean that the time which elapses following a change in velocity until the driver moves the gas pedal
depends on the velocity and acceleration; i.e. it is not constant. It does not mean, as one might think at first, that when one steps on the gas the velocity changes.

In an interview, it was learned that the study was aimed at developing insight into the feasibility of an intervehicle communication system which would open or close the throttle or actuate the brakes of a following vehicle upon receipt of inputs from the lead vehicle, either automatically or through the driver of the following vehicle. In this context, the useful result of this portion of the single car study is that it shows that automatic car control depends on many factors besides proximity or behavior of other vehicles in the stream.

TRANSPORTATION ENGINEERING CENTER STUDIES

Miscellaneous Studies

The Transportation Engineering Center at Ohio State has been working on the development of hardware for communication and sensing between vehicles and, as noted in Chapter Two, this work is very promising. NCHRP Report 31 contains several peripheral studies. Three of these studies, and the findings, were as follows: (1) accident types: 36.4 percent of all accidents on rural Ohio freeways were rear-end or stopped or stopping vehicle type accidents and 59 percent of all accidents on the Ford and John Lodge Expressways were rear-end type accidents; (2) the relationship between headway distributions and accident rate—accident rate increases with the percentage of vehicles traveling at small headways; and (3) the use of turning signals—"signaling frequencies increase with responsibility, the complexity of driver maneuver, and higher traffic densities."

As the reader will perceive, these studies really did not need to be made in order to develop criteria for a sensing system, which were concluded by the researcher to be as follows:

1. The system "must be a longitudinal control system if the improvement of traffic safety on divided highways is a primary objective." (Objective 1, reduce the probability of accidents.)
2. "It must be a longitudinal control system, which is aiding the driver or can operate automatically, if the velocity of vehicles is to be increased safely." (Objective 2, permit each vehicle to move at a higher average speed.)
3. It basically must "be a longitudinal control system with a range of at least 160 ft if increased traffic flow and the prevention of traffic jams is a major objective. Lateral control to facilitate lane switching must also be considered." (Objective 3, allow the movement of a greater volume of traffic.)

Development of an Infrared Source-Sensor System

Infrared light was chosen as the medium and two versions of an infrared system were designed. A prototype of the source-sensor system was built at a materials cost of $100.

The lead vehicle transmits to the rear a pulsed infrared beam which is received by the following vehicle and analyzed electronically to determine the relative velocity between the two vehicles. The pulse frequency in both transmitting vehicle and in the receiving analyzer is linked to the vehicle drive shaft to obtain velocity input.

By measuring the radiant energy of the light source, the apparatus also indicates the distance between vehicles. Although the apparatus is not very sensitive at 500 ft, the sensitivity increases as the distance closes. A needle dial is used to display the distance.

The relative velocity is displayed on a dash-mounted galvanometer. Dr. Treiterer both in the report and in discussions indicated that he is thinking beyond the infrared system to such systems as a magnetic coding strip along the highway which ultimately can be used for vehicle guidance in a fully automatic system. The magnetic strip can be installed as either a magnetic tape or evenly spaced embedded magnets. The approximate cost of a magnetic strip would be $0.50 per foot or $2,500 per lane-mile. It is believed that the researcher is over-sanguine about the practicality, including durability and maintenance, of a coded magnetic strip or paint stripe on top of a pavement. However, it is agreed that the possibility for improvement in information systems by coded electronic signals is so great that further exploration of this idea is well worth some research and development effort, with a view toward long-range payoff.

Studies of Traffic Flow

Theoretical studies of (1) the continuity of traffic flow—traffic flow depends on two factors, the delay time in propagating change and the ratio of the density of traffic in a jam condition, (2) the propagation of disturbances, and (3) longitudinal control systems for platoon movement were made to test the ability of Infrared Source Sensor system to meet the objectives of the research.

This portion of the Ohio State Research was a mathematical study and included a rehash of many other papers that have been written in journals dealing primarily with the theory of traffic flow. The principal contribution made by Ohio State was a study of car-following by aerial photography. Although the method proved to be very tedious, the research showed that it is possible to plot vehicle time-distance graphs from time-lapse aerial photographs, and since the information obtained is so basic, further practice in this area is warranted. With further practice, it is believed that data extraction and manipulation procedures can be greatly improved and made less expensive, and more practical for traffic studies of many kinds.

The conclusions of the Transportation Engineering Center's part of the report are as follows:

1. The infrared sensing and communication system is reliable up to 400 ft and should be developed further.
2. Theoretically the system meets all study objectives.
3. Further research into real-world conditions of variation of braking efficiency and of coefficient of friction will be necessary for application of the theories expounded in the report.
4. It was determined theoretically that a combined acceleration and relative velocity control system will yield a substantial increase in possible traffic volumes.
APPENDIX D

NCHRP PROJECT 3-4: “MEANS OF LOCATING AND COMMUNICATING WITH DISABLED OR STOPPED VEHICLES”

PURPOSE OF THE RESEARCH

Before Project 3-4 (NCHRP Reports 6 and 40) was carried out, nobody had much knowledge of the problem of the disabled vehicle. Many people, motivated probably by natural compassion more than anything else, were urging that something be done for the stranded motorist, without considering the economics of the problem or the equity of subsidy of one class of motorist by another.

The principal class distinction that the question of subsidy should apply to is (1) motorists who happen to be on an instrumented freeway when they need help, versus (2) motorists who pay user taxes as they drive on non-instrumented freeways and other roads where the need for obtaining assistance is much more critical.

The problem is by no means novel or peculiar to freeways, although public opinion and pressure on highway officials to do something seem to be confined to that type of highway. (The reason for this may be that the stranded motorist on a high volume freeway is observed by such a large audience, all of whom identify with him.)

NCHRP Reports 6 and 40 have compiled all the data that can be obtained on this elusive problem, and highway and law enforcement officials can use them, particularly NCHRP Report 6, as a source of information upon which decisions can be based. The reports do not contain yes-or-no answers to individual problems, but it is believed that they provide all the background that research can furnish to the person who has to make a decision. One thing is now clear: In the foreseeable future, nothing is going to replace the highway patrolman as a key element in surveillance and communication with motorists. Another major point made in NCHRP Report 6 is that assisting the stranded motorist is a more difficult and time-consuming process than locating him or communicating with him. The cost figures presented in NCHRP Report 6 indicate that the mileage of highways that will be equipped with any communication devices will be very limited, and the chance of any individual motorist’s being on one of those highways when he finally has a breakdown and a need for communicating with someone is pretty small.

RESULTS

The following summary of what the reports contain is taken from NCHRP Report 40 (pages 1 and 2):

Initial Phase

[An analysis is made of] the many possible objectives that may serve as the basis for the eventual solution of the disabled vehicle problem; for example, (1) to increase safety, (2) to maintain or increase the capacity of the facility, (3) to offer service to the motorist, and (4) to aid in law enforcement. The fact that the objective is dictated by road type, traffic volumes, and the desires of the cognizant authorities is discussed and the unsuitability of the same objective for different road types is shown.

The basic types of sensors are examined as to their capabilities and limitations, costs, and ease of maintenance. A number of novel ways of detection, communications, and servicing are discussed. Some that are considered worthy of further investigation are (1) specialized patrols, (2) signaling devices, (3) means for the distressed motorist to call for aid, and (4) devices to render services in a manner consistent with some specific objectives. It is concluded that only one basic communication from the driver is required—a request for aid.

Several representative problems are hypothesized and realistic objectives for each are formulated. A logical procedure is then followed in choosing elements of detection, communications, and service so that the objectives can be met. The cost of implementing the complete system is assessed in terms of dollars per assist.

The road types examined are (1) an urban expressway; (2) an urban bridge or tunnel; (3) a cross-country turnpike or toll facility; and (4) a network of unlimited access roads consisting of a mix of major, intermediate, and small rural roads. The four examples are intended to serve as guides for dealing with most road types; they point out the close interrelationship between the elements of detection, communications, and service.

The first solution sought for the examples chosen was in systems achievable either immediately or in the future at reasonable costs. It is concluded that when police patrols are available, they should stand ready to render the basic services required by the disabled vehicles. It is cheaper to expand existing law enforcement agencies than to form and equip new agencies devoted to detection or service exclusively. In all cases, the manpower costs were greater than equipment costs; therefore, automatic devices should be used when they can perform as well as a man. However, the increased cost of automatic equipment without removing men is usually out of proportion with the improvement achieved in fulfilling the objectives.

Technically, communications to the motorist are much more easily achieved than communications from the motorist. However, it is shown that most problems can be solved without such complications.

A solution that does not require a motorist to invest in equipment is believed superior to one that requires compulsory investment. The degree to which the system relies on the motorist to help actively in his detection should likewise be kept to a minimum, or altogether avoided.

Final Phase

Based on the conclusions of the initial phase of research, the final phase as reported herein is a develop-
ment program to investigate and demonstrate the technical feasibility of an automatic surveillance system that will instantly detect and locate all stopped vehicles on the freeway and adjacent shoulder areas. This development program proceeded through the following phases:

1. Investigation of solid-state infrared light-emitting diodes and detector diodes.
2. Investigation of the system optical requirements.
3. Design and construction of an experimental laboratory test model.
4. Design and construction of an engineering model of a completely solid-state vehicle-detection system.
5. Field test evaluation.

The results of this development program demonstrate that an infrared disabled-vehicle detection system is technically feasible. This system operates reliably to a range of 750 feet and covers a field 60 feet wide. This would ensure adequate coverage of three lanes plus the shoulder of a road. This system operates with pulsed signals. Therefore, pulse coding techniques may be employed to transmit a variety of discrete messages. This capability could extend utilization of the system to uses other than just detecting disabled vehicles.

The solid-state infrared devices used in the equipment are relatively new developments. It is reasonable to assume that with further technological advances their performance will surpass that of present day devices, and their cost will decrease with increased production. The approximate cost of implementing the proposed detection system amortized over a ten-year period is $1,627 per year per mile.

This cost figure does not include the cost of equipment that would be required in each vehicle that needs to be detected.

It will be noted that the infrared detection system described under the heading "Final Phase" is apparently contradictory to the concluding paragraph under the heading "Initial Phase," in that it does require motorist investment. The reason is that the initial phase was aimed at immediate objectives, and the final phase was requested by the sponsors to afford a glimpse into possible long-range objectives. As pointed out in Chapter Three, this research is believed to have been very productive and should be continued for its long-range possibilities.

APPENDIX E

FREeway SURVEILLANCE AND CONTROL PROJECTS

THE GULF FREEWAY PROJECT

The Gulf Freeway in Houston, Texas (7), is a six-lane freeway with one-way parallel frontage roads (however, the frontage roads are discontinuous at two critical locations). Entry to and exit from the freeway are accomplished through slip ramps connecting the freeway with the frontage road which is at the same elevation as the freeway, plus major junctions with two State highways at the upstream end of the control section.

Traffic entering the inbound roadway at eight successive entrance ramps covering a distance of about 6 miles is controlled during the morning peak period by standard traffic signals (red, yellow, and green) mounted on short poles on the left side of the ramp. The signals are at about drivers' eye height and are about 200 ft from the nose of the ramp (more distance would be allowed if the ramps were longer). The signal sequence is:

<table>
<thead>
<tr>
<th>Signal</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>1 1/2 sec (constant)</td>
</tr>
<tr>
<td>Yellow</td>
<td>2 sec (constant)</td>
</tr>
<tr>
<td>Red</td>
<td>1/2 sec to 15 sec</td>
</tr>
</tbody>
</table>

The minimum cycle is thus 4 sec, or 900 vph. They have found by experience that the maximum cycle tolerated is 15 sec, or 240 vph. Rates lower than 240 vph require closing the ramp and when rates higher than 900 vph are permissible, the metering is discontinued. When the current researchers last visited the project in April 1967, the metering operation was being exercised only during the peak period (AM). When the freeway reached free flow conditions because of dropoff in demand, the ramp control signals went dark. When the signals were on, there was an advance two-light yellow flasher with the legend "Ramp Metered When Flashing." Traffic obeyed the signals, for all practical purposes reacting in the same way as to a conventional traffic signal, except of course that only one car went on each green interval.

The metering rate (length of red interval per cycle) is established by one of two modes that were being tested experimentally (it is understood that late in 1967 there were some more modes being tested, together with digital computer control). The modes were:

1) The Gap Acceptance Mode. This mode detects gaps and speed in the outside freeway lane as cars pass a detector several hundred feet upstream of the on ramp. As described by Drew, et al. (7), "... when a gap is detected that is equal to or greater than the designated acceptable gap size, it is projected in the controller (an analog computer) at a rate defined by the vehicle speed. If a ramp
vehicle is waiting at the ramp signal, a call for the green signal is made when the projected gap reaches the position in time at which the travel time to the merge area is the same as the travel time of the ramp vehicle from the signal to the merge area."

(2) The Demand-Capacity Mode. In this mode, the mainline flow is measured in all three lanes upstream of the entrance ramp. Counts are converted to flow rate in an analog computer. This flow rate is compared with a pre-set capacity of the freeway downstream of the entrance ramp. The algebraic difference between capacity and demand is integrated over time, and whenever this integral reaches plus 1, one vehicle is released from the ramp signal. There is a presence detector at the ramp signal and if no car is waiting, the signal rests on red.

Both modes provide override controls governed by presence detectors in the merge area so that ramp traffic is not released if there is a car standing in the merge area or if traffic is backed up from downstream main line. However, when everything is working, neither of these events is likely to happen.

In April 1967, the above modes were being executed by a local analog computer, requiring one controller at each metered ramp. It is understood that the project is now experimenting with centralized digital computer control. The local analog computer was built to satisfy functional specifications written by project personnel.

THE EISENHOWER EXPRESSWAY PROJECT

As of June 1967, the westbound roadway of the Eisenhower Expressway in Chicago (4) was instrumented for surveillance for 6 miles (extensions were being planned at that time). Five entrance ramps were being metered, covering a distance of 4½ miles (Austin Avenue to 25th Avenue). The freeway in this stretch is three lanes and is immediately downstream of a four-to-three transition. Back-up into the four-lane stretch at this transition has not been eliminated but has been greatly reduced by keeping the three-lane section flowing at capacity. This is accomplished by limiting the input from the ramps in the three-lane section. Before controls were installed, travel on the three-lane section was stop-and-go with average speeds ranging from 20 to 35 mph on different days. (The Eisenhower Expressway project is probably the only freeway traffic study ever made in enough detail and over a long enough period of time to establish the day-to-day variability of traffic flow characteristics on a statistical basis.)

After controls, the speeds ranged from 30 to 40 mph, with almost no stop-and-go operation.

The freeway at this location is essentially a depressed section with diamond interchanges having long downhill entrance ramps and generally adequate merging areas. Entering traffic is controlled by signals on the right and left side of the ramp roadway, mounted about 4 ft from the ground and about half-way down to the freeway grade. There is plenty of distance, including the merging area, for cars to attain freeway speeds after being released from the ramp signal.

The signal sequence is red-green-red with no yellow. A detector just upstream of the signal "puts in a call" whenever there is a car waiting there. The central computer commands the signal to turn green and the signal remains green until a car crosses a detector immediately downstream of the signal, and this causes the signal to turn red. Thus, the second car waiting always sees a red light before he gets to the lag line.

Presence detectors are installed in the center lane of the main line upstream of each on-ramp. These detectors are connected by telephone lines to a central digital computer. The computer scans the detectors 60 times per sec and thus determines what percent of the time the detector is occupied during a moving preset time period of 20 to 40 sec. From experience, it is known what percent occupancy in the center lane represents capacity of the freeway. This preset capacity occupancy is compared with the actual occupancy at any time, and if there is a net positive difference, the difference is used to set the allowable ramp entrance rate, which is converted to cycle length by a solid-state timing device designed by project personnel.

Although percent occupancy is used in most of the computational procedure, the output is in terms of vehicles per minute (inverse of cycle length), and for all practical purposes, the system consists of subtracting main line demand from main line capacity and supplying the difference with ramp vehicles. The actual ramp flow rate varies from 4 to 12 vehicles (signal cycles) per min. Rates lower than 4 per min cause ramp drivers to assume the signal is not functioning.

The digital computer is a process control computer which has no moving drums, disks, or tapes, and has capacity to handle a great number of ramps and surveillance detectors. When the system is expanded to other sections of the freeway network, the cost of telephone lines will probably govern the decision of how many computers are needed, rather than the computer capacity. The computer rents for $1,900 per month, which means that it is a fairly modest computer. Project personnel had to learn enough about computers to order one that was just right instead of using one that was too big in some respects and too slow or too small in other respects, which is an all too usual procedure with traffic engineers.

THE HOLLYWOOD FREEWAY PROJECT

One section about one mile long on the outbound Hollywood Freeway in Los Angeles is three lanes wide. This section is fed by a four-lane roadway and two entrance ramps (Sunset Boulevard and Hollywood Boulevard), and during the PM peak period the demand exceeds the capacity. The capacity is 5,600 vph (three lanes on a plus 5 percent grade).

Before control, the 5,600 were composed of 4,700 vph from the main line, 600 vph from Sunset Boulevard and 300 vph from Hollywood Boulevard. By aerial photography, it was determined that the demand rate from the main line was 5,300 vph. (During the first week of control, the pre-estimate was verified by actual counts within a few percent.) The demand was estimated by counting the cars in the congested section upstream of the bottleneck and
deducting therefrom the number of cars that would be in that section in free-flow conditions. Density contour maps were prepared (showing length of queue and density as a function of time of day) and these were used instead of literally counting the cars from the photographs, but it amounts to the same thing.

From these preliminary counts, it was decided that if the ramp demand could be reduced by 600 vph, the main line demand could be accommodated. Inasmuch as the Hollywood Boulevard ramp served only 300 vph, or 5 veh per min, it was decided that this rate could not be reduced by a fractional amount but might as well be reduced to zero. This was done by placing a barricade across the ramp every day at 4:30 P.M. The decision to close the ramp instead of metering was also based partly on the fact that waiting cars would have blocked Hollywood Boulevard. The Sunset Boulevard ramp was metered down to 240 vph (4 vehicles per min), using a 3-indication portable traffic signal showing green, yellow, and red on command of an operator who showed a green light 4 times per min. The control equipment was a wrist watch showing Pacific Daylight Saving time and a timer that buzzed every 15 sec.

The results in the form of increased throughput and reduced delay to freeway traffic were about the same as the results achieved in Chicago and Houston; i.e., speeds on the freeway went up from stop-and-go to about 40 mph and delay per vehicle was reduced by 3 to 5 min per vehicle (the delay varies with time during the peak period). Delay to diverted traffic increased by 2 to 5 min per vehicle. Net savings in the corridor were about 450 vehicle-hours per peak period, which is about \( \frac{1}{2} \) to \( \frac{1}{2} \) greater than obtained at the other ramp control projects, although the controlled section was much shorter. Postcards were handed to exit ramp vehicles downstream of the control section and many complimentary comments were returned. The travel time savings estimated by the freeway users varied from twice to ten times the amount of time they really saved.

Shortly after ramp control was started, main line demand picked up by 300 vph, and arrived at the bottleneck at an earlier time of day. Based on results of the postcard Q&D survey, it is surmised that these cars were former users of the controlled ramps who had been bypassing the queue on the freeway but are now entering the freeway at upstream ramps which are more natural for them to use. Although freeway speed has slowed down from the initial month of control, it is still much better than before control and the unmeasurable delay which used to occur to these bypassers has been reduced.

In the fall of 1967, it was being planned to make the Sunset Boulevard on-ramp signal automatic (as opposed to manual). It will be a fixed time signal with a manually adjustable cycle consisting of 2 sec green, 2 sec yellow, and variable red.

PORT OF NEW YORK AUTHORITY TUNNEL FLOW EXPERIMENTS

The Port of New York Authority (14, 15) has been a leader in research on traffic flow and operational control for many years and the freeway control projects described in Chapter Two owe much to pioneering basic and applied research done under the Port Authority's program.

The first objective was to detect stoppages in the tunnels by mechanical means. This could result in cash savings by permitting a reduction in police surveillance which had previously been required, and thus the program pays for itself while producing many by-product researches aimed at finding out all that can be found out about traffic flow and how to increase it.

Flow in the New York tunnels is basically different from freeway flow in that lane-changing is not permitted, so that when a shock wave forms at a bottleneck the long gaps that appear downstream of the shock wave are not filled. In other words, the studies have been concerned with single-lane flow. Peak hour flows are in the range of 1,250 vehicles per lane hr, as contrasted with 1,800 on freeways. Corresponding maximum recorded flows are 1,440 in the tunnels and 2,200 on freeways. Merging geometry at the tunnel entrances is not as good as most freeways, and this would probably limit the capacity if the in-tunnel bottlenecks were not a control. The actual bottlenecks are at the beginning of the upgrades on the exit ends.

Equipment has been developed that will measure events (such as the passage of the front and back ends of vehicles) to the nearest 0.01 sec, and process this information by computers. The output is space density, speed, flow, vehicle length, headways in ft and in seconds, relative speed of successive vehicles, and acceleration.

They have found that the most effective parameter for predicting congestion is space density; i.e., the number of vehicles in a section of tunnel. They measure this density by in-and-out counts on the section upstream of the bottleneck and they measure speed and flow at the beginning of the uphill section. These quantities are processed in real time to predict jam density at the bottleneck (using historical data for the equation coefficients) and to establish a metering rate at the tunnel entrance that will prevent jam density in the bottleneck from occurring. Flow is thus kept free and the capacity is increased by about 5 percent, or in the neighborhood of one vehicle per minute. As shown in Figure 8, a small change in flow rate can result in a great difference in the length of time that congestion lasts. However, the increased speed and freedom from stop-and-go driving is probably equally important from the drivers' point of view, and the ventilating problems as well as likelihood of accidents are also reduced.

The Port Authority researchers have demonstrated the value of true space density detection. Advanced researchers in the theory of traffic flow and experimenters in developing signal control techniques all recognize this same need, but many of them, recognizing that space detection equipment is not available, have spent many hours developing compromise algorithms which arrive at space density through the back door, using event detection and speed, and even projecting past trends in order to estimate present density that can be used for real-time control.

The Port Authority method of knowing current density depends on photoelectric detectors spaced at close intervals (there are six pairs of detectors in 6,000 ft of one-lane tunnel). This type of sensing would pose serious physical
problems on a multilane roadway with no roof. The in-and-out count method of determining the number of vehicles in a section requires “correcting up” at frequent intervals, since a single overcount or undercount has a cumulative effect on the calculated density from then on. They have developed an ingenious computer program to start the count anew whenever a unique vehicle train passes the several successive detection points. One kind of “unique” train is a vehicle greater than 22 ft long followed by a vehicle less than 13 ft long.

The most important contributions of PNYA research which have general application to highways and streets have been in basic flow theory validation and in equipment development.

APPENDIX F

TRAFFIC SIGNAL SYSTEMS

THE SAN JOSE (CALIFORNIA) DIGITAL COMPUTER TRAFFIC CONTROL PROJECT

This project (21) consists of 18 signals along 3½ miles of a principal thoroughfare (San Carlos Street) and 41 additional signals on a downtown grid incorporating the easterly mile of San Carlos Street. There are 400 detectors in the system—at least one detector in every approach lane to each of the 59 signals. The detectors and signal controllers are connected by wire to the centralized digital computer which is an IBM model 1800 with 16K core, 1 disc drive, a card reader and punch, typewriter and printer. It is estimated that this computer could handle up to 500 intersections, accommodating 128 different background control patterns including “micro-loop” strategies for critical intersections. However, with 500 intersections under control, there would be capacity for receiving information from only 250 detectors.

The way the system works in very general terms is as follows: There is a detector in nearly every approach lane to every signal. This detector is placed at the beginning of the block; in other words, it is approximately a block upstream of the signal on each approach lane. Each vehicle actuation is transmitted into the computer. By manipulating these counts with respect to time and observed field speeds, an estimate can be made of the number of cars in the block at any instant. This number integrated over time gives an estimate of travel time for whatever program is in effect at the time. Thus, any program can be evaluated, in terms of vehicle-hours, with respect to a base or with respect to any other program.

The machine also has the capability of sending instructions to each individual intersection controller as to when to change the light from green to yellow to red. The equipment on the street consists of old-fashioned electromechanical pre-timed signal controllers, which is by no means the most desirable kind considering the capability of the computer to give these instructions. However, it does constitute a fail-safe during the experimental stage, because whenever the computer malfunctions, the old fixed-time controllers go into operation at any given intersection.

About the only control function that the computer was being used for at the time the project was visited was to interconnect the signals so as to provide a progressive band in each direction, with cycle length and offset being modified from time to time throughout the day as a PR system would do, depending on relative demands by direction on the main street and some counts on the side streets.

Several micro-loop programs to govern the mode of operation of individual intersections have been written. However, it was not clear just exactly which one if any of these micro-loop programs was actually being used in San Jose.

The important thing about the San Jose experiment is that the machine is capable of doing almost anything that can be named for signals to do. The big problem is that nobody knows enough about traffic control to name what is wanted to happen. One thing that the machine does is to gather tremendous quantities of data; that is, all these counts coming in all the time from the several hundred detectors. By making certain assumptions it is possible to calculate the travel time and delay and the number of cars that are caught in queues individually by the intersection and in the whole system. The strategy can then be changed and the evaluation repeated, and thus the optimum strategy, among the ones tried, can be adopted.

One of the things that has been found out is that there are two intersections which constitute bottlenecks where most of the delay in the whole system takes place. These intersections are both three-phase intersections and actually one of them (Race Street and San Carlos) has a lagging green on the cross street, so that one might say it is four phases, or at least three and one-half. As is the case everywhere, it would not take a very sophisticated surveillance computer to find out where the bottlenecks are on a particular street. What the computer has done is to quantify this in what are called vehicle-seconds.
Probably the only way to reduce the delay at this intersection is to make a much sharper cut-off on the minor movements; i.e., the left turns. This could be done by installing a presence detector of considerable length—for example, 50 ft—so that a geographic gap can be detected and instantaneous action taken whenever a 50-ft gap occurs in the left-turning traffic movement. A sophisticated computer would not be needed for this, but if a sophisticated computer is connected to all the signals in town, it is not necessary to order a special machine to put it into effect at this location or any other location where special problems or designs occur.

The point about the large, fast digital computer as a master controller for a whole series of signals is that not only can this experiment be tried, but if it does not work, something else can be tried. In fact, the traffic engineer can try anything that the human brain is capable of thinking up. The computer also has a capability of gathering data and evaluating these changes to show whether the trial did any good.

THE WEST LONDON EXPERIMENT

The West London Experiment (31a, 31j) in traffic control covers an area of about 6 square miles near what Americans would call "downtown." It lies on a major commuter corridor, and includes 32 miles of commuter routes as well as many traffic generators such as shopping areas, auditoriums, and football grounds. The principal street is Cromwell Road which carries 38,000 vehicles per day. Over a quarter-million vehicles enter the area on a normal weekday, and one intersection (at Knightsbridge) handles 50,000 vehicles per day. Before installation of the central control system, there were 70 vehicle-actuated signal-controlled intersections in the area and 30 signalized pedestrian crossings.

The experiment consists of connecting all these signals to a central computer which will have the capability of overriding the local controllers when the current situation calls for such override. Mr. B. M. Cobbe, who has overall responsibility for the project, describes the computer function as follows (31a):

... the broad function of this computer when fully programmed is to gather traffic data from the vehicle detectors throughout the area; to analyse the data as a preliminary to the selection of an appropriate strategic control plan; to control the intersection controllers as required by the selected plan; to monitor the signals to ensure that the plan is being followed; to monitor the traffic situation to determine whether the plan applied is satisfactory; to apply tactical modifications to the strategic plan as may be found necessary; to measure its own performance and to supply edited reports and statistics. Ultimately it may be found possible to go even further and for the computer to improve on its own control by self-adaptive or self-optimizing processes. However this possible extension is not included in the present programme of development work.

The installation will also include closed circuit television surveillance of several critical intersections, and a display board (map) and a console through which operators can override the computer.

One of the unique features of the system will be a procedure for detecting queues that threaten to back up into a signalized intersection; it will then revise the phase split so as to avoid pouring more traffic into the queue and let the non-affected movements use the time instead. As is the case in San Jose, the controller is very flexible and new strategies can be (and probably will be) developed as experience is gained.

The capital cost is estimated at £550,000 (pre-devalued) or $1,540,000, and annual costs are estimated at £37,000 or $103,600. It has been estimated by the project that a reduction in delay of only 2.03 percent would cover these costs.

During a visit to the project in May 1967, the system was not operational, but the thing that was most impressive was the very large effort (compared with any American cities) that was going into preliminary engineering design and writing computer programs. There were two large offices full of people working on these programs. One was for the Federal Ministry of Transport, which is underwriting the experiment, and the other was for the Greater London Council, which will take over operation on a permanent basis, assuming the experiment is successful. The Road Research Laboratory was also furnishing consulting services, and the equipment purveyors were putting in an outstanding amount of engineering.

The approach in London is primarily an engineering approach (as distinguished from scientific or research approach), with the objective of doing as much as present technology and scientific theory can provide, to improve traffic flow and reduce congestion. The emphasis is on doing instead of learning, but the learning is an important by-product.

NEW YORK CITY SIGNAL SYSTEM

[Note: — The following description of the New York City system was written in 1967. It is understood that basic changes have subsequently been made regarding the type of computers that will be used.]

The City of New York is constructing a computerized signal control system (27) that will have about 2,700 signalized intersections initially. These signals will not be driven by commands from one gigantic computer.

The whole city is divided into major zones (master) and minor (submaster) zones. Several hundred sampling detectors will transmit counts and presence information to the master controllers, which then send out commands through the submasters to the local controllers.

The background cycles, splits, and offsets are being worked out in advance on the basis of historic traffic information, using graphical methods. When the system goes into operation, there will be many field observers checking out the pre-engineered programs. Then the programs will be adjusted, depending on what the field observer sees. The principal advantage of computer control over conventional interconnect schemes is that it will be so convenient to change the cycles, splits and offsets at hundreds of signals that they really will be changed, which would be almost impossible by manual methods. More-
over, there will be many more programs available than the customary 3-or-so offsets and 3-or-so cycle lengths. They can, for example, go to a minus offset if observation shows that this is called for at certain times of day at certain locations (e.g., at diamond interchanges where many vehicles enter the stream on the arterial instead of crossing the arterial).

One of the advantages of the system being planned is that the traffic engineer can see what he is doing both on graph paper and on the street.

Essentially what is being done in New York is not so much a research project as it is a straightforward engineering design project in which the City is taking known efficient and practical methods of controlling traffic and making it feasible to execute changes in strategy on a large scale and frequently.

**DUSSELDORF CENTRAL TRAFFIC CONTROL COMPUTER**

When Dusseldorf was visited (May 30, 1967) there were 253 signalized intersections on 10 km of thoroughfares linked and operated from a central digital computer (Siemens VSR 16000). Included in the 253 are 31 more-or-less complicated intersections where several legs come in close together, creating problems similar to those at diamond interchanges. Special programs are in effect for these intersections so that they are worked into the progressive through bands by phasing sequences and timing insuring that traffic does not get trapped between closely spaced signals.

Dr. von Stein, the chief traffic engineer of Dusseldorf, is of course well-known for his "green-wave" principle: Once a car is moving, keep it moving. This is the progressive through-band principle used in the U.S. However, in Dusseldorf instead of just drawing a time-space green band in which the slope is equal to the nominal speed of the lights, they actually draw the traffic, including cars that have turned into the stream during the red. They vary the offset to let these cars move out before the front of the "through" platoon arrives.

Essentially the computer operates from library of programs based on very careful engineering analysis of individual problems. The programs are changed rapidly depending on the sample counts and what prior analysis has shown would be the most efficient method under the circumstances. There are only 13 intersections out of the 253 that operate on independent micro-loop control strategies.

Advisory speeds which change during the cycle are mounted between signalized intersections. They show illuminated white numbers on about a 12-in. black background and read 30, 40, or 50 (meaning 18, 25, or 32 mph) depending on how fast one should go to stay with the green wave. Actually the speed of traffic is controlled by volume and the state of the signals themselves and it is believed that this feature is not too significant.

Commands for every signal change are sent to the local controllers from the central computer. The local controllers do not have timing functions. (This is in contrast to systems which send commands to change from cycle A to cycle B, for example).

The installation in Dusseldorf is actually on line and working. They have been through the shake-down phase; the program is working the way they want it to work, and they know what they want. Dr. von Stein took the researchers with a bus load of German traffic engineers for a tour of the system and it is true that the tour never stopped because of a red light. The party did dismount at a few locations to watch traffic. It was impressive to stand at a complicated intersection of two six-lane streets with protected left-turn movements and see nobody on either main line waiting. When a platoon would come down the street three abreast, the light would turn green just before they got there.

It is believed that the key to the apparent success of the Dusseldorf system is that they have combined old-fashioned but high-powered traffic engineering with an extremely flexible controller so that the traffic engineer can actually do what he wants to do, even if this is several dozen different things, instead of being able to do only a few things or wishing he could change something but being unable to because it would mean ordering and installing a special piece of equipment.

There was a meeting of the traffic signal committee of the German Highway Research Board, at which several Englishmen, including J. A. Hillier, were also guests. The following notes made at the meeting may be of interest:

Because of Von Stein's emphasis on producing through bands, Hillier had the idea that the Germans have a different philosophy, that is, they have a philosophy of minimum stops on routes, rather than minimum delay in a network. This brought up the question that keeps coming up in the United States also; what is the measure of effectiveness of a traffic signal system—do we want to minimize stops or do we want to minimize delay?—and of course, somebody ought to be able to prove that every time you increase stops, you increase delay, at least for the people that have to stop. None of them mentioned that if you are going to minimize over-all delay, the thing to do when you're operating at a saturation or near-saturation rate, with queues on all legs, is to keep the phase with the most lanes moving most of the time early in the peak, later switching to increased green on the narrower approach. This is according to Gazis' theory, in which he shows that the total out-put of the system of course is increased if you let a road approach with three lanes go for a longer period of time than you let the one with one lane go.

During the discussion, the following seemed to be the consensus of both the English and the Germans, as well as the Americans. The only thing that a computer can do that is not already being done with a PR system or a plain three- or four-dial fixed-time system is the following: When capacity itself is not exceeded anywhere in the network—that is to say, when there are no intersections that have queues that build up over more than one cycle—then our objective should be to optimize offsets on each street so that the turning traffic and leftovers are considered on a cycle-by-cycle basis. The purpose of this would be to take account of fluctuations from platoon to platoon or from cycle to cycle. Typically, one cycle might be loaded but the next cycle wouldn't be. Now, if one
cycle is loaded, this means that at the following downstream signal, some of these cars are going to get caught by the red light if you have a pre-timed progressive band. It should be possible for a sophisticated, large and fast computer to measure this amount of cars and allow for them so that you then change the offset for the succeeding cycle, meaning that you would change the phase length, without changing the basic cycle. Now this is very well as long as capacity itself is not exceeded, but then at some point in time, a bottleneck will develop that starts to build up queues that you can't clear without radically changing the split, or cannot otherwise be cleared. Then the philosophy should be changed to the complicated system that Hillier was explaining which would minimize delay by calculating the number of cars within some predetermined distance of the intersection. In other words, when a particular intersection starts to build up queues that make the progression meaningless, then you should kick that intersection out of the basic through-band background and let it operate independently just to be sure that you don't have any idle green time and also that you operate the legs that have several lanes for a longer time than you operate the minor movements, or the legs that have narrow widths, according to the Gazis theory.

APPENDIX G

BUREAU OF PUBLIC ROADS PROGRAM FOR RESEARCH AND DEVELOPMENT OF TRAFFIC SYSTEMS

As mentioned in Chapter Two, the U.S. Bureau of Public Roads held a Program Review Meeting on Research and Development of Traffic Systems in December 1966. The scope of this meeting was defined as "a pretty complete survey of the whole field—a comprehensive statement of the state-of-the-art, present and future." Proceedings have been published (51).

The meeting was divided into nine sessions, each with a separate subject, and this appendix attempts to analyze and evaluate the research reported at those sessions in numerical order. However, these evaluations are not intended to be abstracts or synopses of the research. They are intended to put in perspective some of the difficulties involved in the problem-statement method (systems approach) of defining research requirements. These difficulties include separation of important questions that need answering from important questions that cannot be answered by research, and from unimportant questions or questions that do not need answering because the answers are already known. The papers in the Proceedings are essentially summaries in themselves, and readers who are interested in synopses should obtain the Proceedings.

SESSION I. Vehicular Control In Overtaking and Passing Maneuvers

This project is the first step toward solution of the problem of the two-lane rural highway. It was pointed out that there are 3.1 million miles of two-lane rural highways in the United States, and in 1965 approximately 33,000 fatalities occurred on them as a result of millions of accidents. Although only 35 percent of the accidents were non-intersection collisions between two or more vehicles, many (number not stated) of the latter involved overtaking, following, or passing another vehicle. It was pointed out further that the service level, or the volume for a given level of service, on a two-lane highway is reduced when passing opportunities are reduced. Thus the stage is set for research on overtaking and passing: it is important because 3 million miles of road and millions of accidents could be affected, and improvement in passing practices will reduce accidents and increase the level of service. This is the over-all problem, and up to December 1966 six aspects of the problems had been tackled; these involved the following studies, or projects:

"Defining Requirements of Overtaking and Passing Maneuvers" (Carl A. Silver, Franklin Institute Research Laboratories)

In a well-designed experiment using "subject" drivers as a sample of the population, and dividing the problem into many cells (flying passes, non-flying passes, no-passing zones, passing in the face of on-coming traffic, etc.) it was found that knowing the speed of oncoming traffic makes the driver's decision whether to pass or not to pass more consistent and more conservative. The excellent experimental design and number of replications required makes this research very expensive and time-consuming to answer a question that some people would take for granted.

"Remedial Aids for Overtaking and Passing on Two-lane Rural Highways" (Arno Cassel, Franklin Institute)

In a well-designed experiment using "subject" drivers as a sample of the population, and dividing the problem into many cells (flying passes, non-flying passes, no-passing zones, passing in the face of on-coming traffic, etc.) it was found that knowing the speed of on-coming traffic makes the driver's decision whether to pass or not to pass more consistent and more conservative. The excellent experimental design and number of replications required makes this research very expensive and time-consuming to answer a question that some people would take for granted.

"Remedial Aids for Overtaking and Passing on Two-lane Rural Highways" (Arno Cassel, Franklin Institute)

The objective of this study was to "prepare functional specifications of recommended prototype remedial aids." In the course of arriving at these specifications the researcher is developing a computer program for a traffic flow model "to simulate the movement of vehicle traffic
on two-lane rural roads with different road geometrics and traffic volumes. During the simulation, which spans a specified interval of time, vehicles will, under certain conditions, attempt and execute passing maneuvers in order to attain and maintain their individual desired speeds." The research concludes: "The preliminary results seem to indicate that if existing no-passing zones could be utilized for passing maneuvers, then a marked increase in 'throughput' could be obtained."

It is hard to classify this kind of research. It is interesting and sophisticated, but it is also what some people call "bottomless-pit research." Presumably the objective is to improve the knowledge of capacity on two-lane roads, because in the unlikely event that any electronic device can ever be made reliable enough to be used for the purpose of telling drivers to pass another car when they can't see far enough to know they can pass safely, each potential location for such a device would have to undergo an individual cost-effectiveness analysis in which the question would be whether to widen the pavement or use the electronic device.

It is true that the effect of no-passing zones on the capacity of a two-lane road is not known very precisely. But it is known that a two-lane two-way road will handle from 1,000 to 1,400 vph in one direction, and at this volume there is very little passing whether in or out of a no-passing zone; the problem is not to encourage passing but to discourage it. At low volumes, the service level could be improved somewhat by utilizing no-passing zones for passing maneuvers, but it may not be important to know how much, because there are so many miles and so few taxpayers on each mile who would receive the benefit of improved service levels under these conditions. For example, more than 80 percent of all the travel on the California State Highway System occurs on highways having four lanes or more.

California is probably unique, but may be representative of the future in other states that will eventually have large volumes of traffic and some congestion. There are still in the order of 120,000 miles of rural two-lane highways in the State, and the head-on accident problem on these roads will always be important, but it is very difficult to conceive of a highway department doing much worrying about congestion on a road that carries only 2,000 vehicles per day, and when the highway starts carrying 5,000 or 7,000 vehicles per day it is time to think about four lanes.

A very small proportion of the 120,000 miles in California and the 3 million miles in the U.S. suffer a reduced level of service because of traffic volume. Instrumenting a two-lane road that carries 900 vph will not thin down the traffic in the opposing direction. When a two-lane road becomes intolerable enough to spend money on, the volume will be high enough that improved information will not solve the problem; the information system will not reduce the public demand for four-laning the highway.

"Translation of Visual Information to Vehicular Control Actions" (Raymond E. Reilly, BioTechnology)

This was a very practical real life experiment in which it was found that at night, drivers judge the distance to the car ahead of them by the angle subtended by the tail lights. They also found that bright tail lights 60 inches apart were much better for this purpose than dim tail lights close together.

"Effects of Impedance and Traffic Volume on Driver Acceptance of Passing Opportunities" (Robert Hostetter, HRB-Singer)

This might be subtitled, "Do You Get More Daring as You Get More Impatient?" In pursuing this research, movies were taken from the rear of a panel truck which drove at a slow speed, deliberately creating impedance to following traffic and building up queues on stretches of one to five miles of highway that were marked for no passing. Many side findings should result from these movies. They could be useful to engineers who have to decide where and how long no-passing zones should be.

"Sensing and Communication Between Vehicles" (Robert Stafford, Ohio State University)

The fifth project was an experiment at Ohio State, closely connected with but not part of NCHRP Project 3-3, in which it was found that if a car is equipped with amber running lights and red brake lights, there is less chance for a following driver to err in identifying whether the brakes are on than there is when both brake lights and running lights are the same color (red).

"Partial Replacement of the Driver in the Control Loop" (Robert L. Cosgriff, Ohio State University)

In the Proceedings, this project is labeled "Transportation Research Activities of the Communication and Control Systems Laboratory" (at Ohio State University). It is very difficult to get any information out of the report printed in the Proceedings. For example, it says, "The systems approach has been employed at all levels of the activities of CCSL. The staff members use the analysis and synthesis procedures outlined in the common textbooks' treatment of systems engineering. Likewise, certain entirely new approaches not documented in textbooks have been explored or are under exploration for solving problems . . . ", and it says in another place, "Another analytical tool that has evolved in the study of this system is an asymptotic representation for the analysis of platoon dynamics. This approximation has the interesting property of becoming more accurate as the length of the platoon increases."

However, there is one fact hidden in five pages of this kind of language. At least, it appears to be a fact. If it is, it represents a very important finding. The report says, "An aiding system for the driver which overcomes the basic limitations of the sense of sight has been road tested. This aiding system makes use of a moving finger within the control stick which is sensed tactually by the driver . . . Phenomenal results have been obtained. Variances of headway have been reduced by a factor of 100."

Although many assumptions must be made in order to understand this last statement, it seems to imply that driver response to a tactile signal (received through the palm of his hand) is much faster than response to a visual signal.
The variance in estimating headways cannot be what was reduced. The machine that creates the signal estimates the headway, and the error would be the same whether the signal was transmitted visually or tactually. The hand cannot estimate distance.

It appears that the implication is that if a car goes, say, 25 ft at 60 mph before a driver reacts to a visual signal, it would only go 0.25 ft before he reacts to a tactile signal. At any rate, it appears that tactile transmission of information might be an excellent adjunct to the communication-between-vehicle project that was begun under NCHRP Project 3-3 at Ohio State.

It can be seen that the preceding six projects have made only slight impact on the problems of two-lane road research. The problem is to improve safety on two-lane rural highways, and one way to improve safety is to reduce unsafe passing practices. Many projects have been launched which have to do with threshold behavior and increasing passing opportunity, but nothing apparently has been done to develop devices that will tell drivers that it is unsafe to pass, or to find out whether they will pay any more attention to any devices that may be developed in the future than they do to devices that are already in use.

Another thing that has been overlooked is that passing maneuvers are entirely different on two-lane roads that are 40 ft wide without shoulder delineation than they are on two-lane roads that are divided into two 12-ft lanes and two 8-ft shoulders. Forty feet has been the AASHO standard width for rural two-lane highways for a quarter of a century and there must be quite a few miles built to that standard. If they are built with a continuous crown from edge to edge (i.e., with no break in cross slope at the shoulder) and surfaced with a uniform texture, with just one stripe down the middle (creating in effect two 20-ft lanes), traffic tends to drive farther from the center line than it does on a 24-ft pavement with 8-ft shoulders. The result is that during a passing maneuver, the passing car is on the wrong side of the center line for a considerably shorter distance than it would be on the 24-ft pavement. This naturally increases the service volume for a given level of service, and it could very well increase safety, although there is a trade-off between head-on collisions and collisions with parked cars. Research on this facet of the two-lane road problem could well result in more improvement (and earlier) in traffic operations than all six going projects combined. It also might cause many of the details of the six projects to be revised. In fact, none of the projects seems to be concerned with or to pay any attention to the fact that there are many varieties of two-lane road cross-sections.

SESSION II. Energy Absorption as Related to Highway System Modification

This session was essentially concerned with safety design of highway furniture and does not strictly belong in a summary of research on traffic surveillance, communication, and control.

SESSION III. Development of Urban Intersection Control Systems

Despite the title, nothing in this session was related to traffic signals, which were reported on in Session IX. The chairman of Session III led off by saying that uncertainty at intersections contributes to delay and to accidents. He considers accidents, turbulence, and conflicts all one big package. Four researches were reported, as follows.

"Sensing and Surveillance System, Phase 2, Advanced Engineering Model" (I. L. Stillman, Cornell Aeronautical Laboratory)

It turned out that what the researcher is trying to sense and survey is accidents. The BPR has entered into a contract with CAL to develop a TV tape recording system which can be set up at a given intersection to photograph on a continuous loop TV tape and then hold and photograph onto movie film the last few seconds of action prior to the crash, if there is an accident. The idea, of course, is to study accidents by watching them happen. This is something that many people have thought of, but did not know would be nearly as complicated as the Bureau and CAL seem to be making it. Their big problem is trying to transfer this TV tape image onto movie film and do it automatically without the intervention of any human beings. They are trying to develop a detector which will actually "hear" automobile crashes and thus set the permanent recording part of the system into operation. They have already spent in the order of $30,000 to $50,000 trying to develop this system.

This seems to be a case of going all-out on a facet or a refinement of techniques that will not necessarily produce any better results than one could get by fairly crude methods. Many people have thought that if one had a TV camera and tape recorder, in which the repeat-and-erase cycle was approximately one hour, there would be time for the traffic officer on the beat who answered the accident call to shut off the machine and thereby save the portion of the tape that had the accident occurring in it. One might miss one or two accidents in the course of a year, but one is only getting a sample at best. The only problem that was not solved according to the TV tape recorder salesman was that they had not yet developed a method of spooling a tape of approximately an hour's length in such a way that one could pull the tape out of the middle of the spool and wrap it up on the perimeter. However, it would be possible to use a battery of spools operating and rewinding sequentially with an hour's worth always saved.

"Defining Requirements for Crossing Maneuvers" (Edwin A. Kidd, Cornell Aeronautical Laboratory)

This project is an attempt to set up a simulation model for examining the problems involved where two two-lane roads intersect and one of them is protected by stop signs (in a way, this is reminiscent of NCHRP Project 3-6). Included in the input to the simulation model will be such things as the weight of the vehicle; the driver's view of the surrounding territory; etc. It is proposed to have the simulated vehicle arrive at the intersection and to "look at" the simulated situation every 0.1 sec.
As far as results are concerned, all they have done so far is to generate a document about the difficulties they have encountered in programming this simulation. There is so much real traffic going on in the world which nobody has ever looked at analytically that it is difficult to see why such items as entering a two-lane arterial from another two-lane road should be tackled in this imaginary manner.

"Linear Closure at Urban Intersections" (Paul A. Carpenter, MEVA Corp.)

The objective of this study is to find something out which might aid traffic engineers to develop devices that would reduce rear-end collisions. The approach taken to date leans more toward human factors than physics. It is much more realistic and if results can be obtained, more useful than the first two studies described in this session. At least they are working with real traffic. One of the first things they did was to analyze all the rear-end accidents that happened in the City of Santa Ana for 18 months—that is, the ones that were reported by the police.

They also interviewed Hughes Aircraft employees who had rear-end collisions in the recent past and confirmed that all the situations which were hypothesized that would cause rear-end accidents actually did so. They found, for example, that when a person stops to make a left turn while waiting for a gap in the opposing traffic, he is more likely to get run into from behind than if he did not stop.

In analyzing all the rear-end accidents in Santa Ana during a period of 18 months, the investigator sorted out what he called "accident prone" intersections from those that did not have any accidents at all during the period. He paid a visit to these intersections and did not see what made some of them good and some bad. What he is going to do now is to analyze these accident-prone intersections in depth by taking movies of traffic until he has enough so that he can study and restudy the near misses and so on. He is also going to take movies of the non-accident intersections and analyze what traffic does at those places. In this way, he hopes to come up with something that might be different about these intersections. If he does come up with something, of course, it would be very valuable information for traffic engineers everywhere. Another thing he is going to investigate is eye behavior—that is, what do people look at as they approach an intersection. This should be very useful background for deterministic remedial measures at intersections.

"Application and Expansion of a Traffic Simulation Model" (Andrew D. St. John, Midwest Research Institute)

This report was not directly concerned with intersections, which is the subject of Session III, but did report on progress being made in a long continuing project to develop and validate a general model for traffic flow simulation. At present, they are in the process of trying to get input values for various kinds of drivers. The researcher calls them "stable" and "unstable" drivers. He also divides drivers into the following two classes: "close followers" and "conservative drivers." (These two classes do not seem to be mutually exclusive.) The trouble is that the simulation model keeps causing people to have collisions all the time when they drive with mean headways of 1.8 sec.

SESSION IV. Driving Control Processes

Both papers in this session give promise that the projects will produce knowledge that is necessary to advance the science of traffic flow and communication.

"Development of an Instrument to Measure Car Following Behavior" (Robert C. Distler, Raytheon Company)

Raytheon has designed an infrared range finding system so that the distance between the instrumented car and the car ahead of it in a traffic stream can be continuously recorded on magnetic tape ready to go into a computer. Dr. Distler said that infrared energy is used because it can be projected in a very narrow beam width. This is as opposed to radar, which has a very wide beam and would pick up a lot of "noise" unless a very large antenna was used. They use a 500-kilocycle modulation to identify their infrared beam from other infrared light in the area.

They shoot out a beam of this modulated infrared light beam and get a reflection from the reflector (which are red, of course) that are built into tail lights of all American automobiles. They then measure the amount by which the reflection is out of phase with the transmission and this gives them differential speed and distance. The results of all of this are put on a continuously running seven-channel digital computer tape. The instrument is very ingenious and complicated. The transmitter and receiver are mounted into one telescope-like device about the size of a headlight. In fact, it was mentioned that when the device was mounted in a vehicle it looked like a headlight and thereby does not attract attention or cause a change in behavior of surrounding traffic.

They have even designed a servo mechanism so that the telescope will always point at a given car once it locks on to it. All of this, of course, makes the equipment very costly. Dr. Distler estimated that after the development costs were paid, the hardware involved would be in the order of $30,000.

The intriguing thing is that one possible output of this research would be the development of a much simpler system, in which they would not necessarily have the servo mechanism or the ability to put all the data on a computer tape, which would be appropriate for use in inter-vehicle communication of the kind that Treiterer of Ohio State is trying to develop. Treiterer's infrared transmitter and receiver and computer all amounted to about $100 worth of equipment. Reference is also made in NCHRP Report 40 to the potential development of low-cost (when mass-produced) intervehicular communication equipment based on modulated light-emitting diodes. When these diodes are produced on a mass production basis, they could be quite inexpensive. The transducing equipment developed at Ohio State is similar, from the standpoint of complexity and parts required, to a pocket transistor radio receiver. This is a far cry from the $30,000 machine that Raytheon is de-
veloping. The point is that Raytheon's machine is essentially a research machine to study the theory of traffic flow and incorporates many things that would be unnecessary for the purpose of creating a signal in one vehicle that would show how fast the car ahead is going or what the differential in speed is between one car and the car ahead. Hopefully, the research that Raytheon has done will be available so that future researchers can take what they need from it in order to develop a simple practical scheme for communicating between two vehicles.

“Driver Information Processing and Vehicle Control Behavior” (John W. Senders, Bolt, Beranek and Newman)

The objective of this study is to quantify, in numbers, what a person really looks at when he drives. They put an occluded motorcycle visor over the subject driver's eyes and measured the amount of time and also the number of times per mile or per foot that the driver had to look at the road. They found that on a given road (depending, of course, on how crooked it is) the driver looks at the road every so many feet regardless of speed. In other words, the faster one goes the oftener one looks. The information is stored a bit at a time, but if one is driving in poor visibility conditions where he can only see 400 ft ahead, he must acquire and store all the bits of information continuously.

This kind of research, while very fundamental, will provide numbers to use in all kinds of other studies that are being made and particularly for studies such as the problem of what to do about driving in periods of low visibility, such as fog.

SESSION V. Effects of Environmental Factors on Traffic Operations

There were only two papers under this heading. One was on headlight glare and the other one was on skidding. Neither is concerned with surveillance, communications, or control in the sense that these words are used in this report. (Headlights are needed for surveillance, all right, and they do communicate information to other drivers; and traction is needed for control of a vehicle.)

SESSION VI. Improved Utilization of Interchanges

This session had three papers on statistical aspects of freeway traffic flow and one on driver communication requirements. The latter is concerned with factors such as signing, striping and other delineation, and map relatability. This is a very important subject but it is believed outside the purview of this report—not because it is not communication in the same sense that a traffic signal is, but because a boundary line had to be drawn somewhere.

Two of the papers on freeway traffic flow were not directly related to freeway surveillance and control.

“Exit Ramp Effects on Freeway System Operation and Control” (Walter W. Mosher, University of California at Los Angeles)

This is a study to determine the probability distribution, by lanes, of cars exiting from a freeway at various distances upstream of exit ramps. This is going to be done by aerial time-lapse movies of traffic on Los Angeles freeways. It is estimated that it will require 21 hours of data reading time for each minute of real time traffic that is photographed. This kind of statistical information is not required to set up or operate control systems such as those described in Chapter Two of this report. It is not really needed to design freeways, either, although it is hoped that it will furnish some data to validate one or another of several charts showing weaving effects that have been published in the Highway Capacity Manual.

“Digital Computer Simulation of Diamond Interchanges” (A. V. Gafarian, System Development Corp.)

As the title indicates, this project will develop a simulation model for traffic flow through signals at the surface street terminals as well as at the freeway terminals of exit and entrance ramps. The object of the model will be to test various signal timing and phase-sequence schemes prior to trying them out on real traffic. Because of the painstaking care with which the model is being validated (by aerial movies), the ancillary objectives of this research could be just as important as the primary objective. Knowledge of intersection capacity could be greatly refined if the research is successful.

“Gap Acceptance in the Freeway Merging Process” (Donald R. Drew, Texas Transportation Institute)

This was a study of 32 ramps throughout the U.S. by aerial time-lapse photography. One of the principal findings was confirmation of the previously suspected fact that well-designed ramps have a higher capacity, and smoother flow at flow rates less than capacity, than stingy ramps. The study was thorough and well documented, and was a useful study for its findings applicable to geometric design. It showed, among other things, that the capacity of a well-designed merge is greater than the capacity of the downstream freeway, even when no controls are exerted.

However, the objective implied in the title of the project deserves further comment. This is one of a series of studies being pursued by theorists who believe that the process of merging into a freeway is difficult for a human being, but that the mathematics are simple if the location, size, and speed of gaps are sensed mechanically and assumptions are made regarding the acceleration ability of ramp vehicles, drivers' reaction time and aggressiveness, and if the assumptions are combined with forecasts of mainline drivers' lane-changing and proclivity for changing the size of the gap purposely (in either plus or minus direction) after the gap is measured and the ramp vehicle has been given the "go" sign, and if further assumptions are made of many other variables including ramp geometry which cannot be expressed numerically.

The difficult thing is not merging, as anyone who has spent five minutes observing traffic in Chicago, Detroit, or Los Angeles knows. The difficult thing is to understand why these theorists think that because the mathematics is simple, the merging process can be digitized into a mathematical procedure which can be solved determinately by inserting a machine between the driver's eyes and his task.

Many natural processes, such as a cat catching a mouse,
or a baseball player hitting a pitched ball, can be described mathematically, and good cats and good baseball players solve the laws of motion involved even though the task might appear impossible to a mathematician unless he had a high-speed computer. But it is guaranteed that no matter how much research he does or how fast a computer he uses, the mathematician will never be able to hit a home run if he takes his eyes off of the ball and looks at a computer output instead. He would do better to hire a coach to instruct him. Similarly, drivers who do not know how to used for improving driver judgment through education. to eliminate the need for driver judgment could be better up the learning. It is believed that the money being spent those who do; and, in fact, that is exactly why drivers in places like Detroit do know how: they have seen others do it. For a certain type of intelligence, a formalized in-struction process, including movies, would probably speed up the learning. It is believed that the money being spent to eliminate the need for driver judgment could be better used for improving driver judgment through education.

SESSION VII. Analysis and Control of Traffic Flow on Urban Freeways

This subject is discussed in considerable detail in Chapter Two and Appendix E, and the discussion is not repeated here.

SESSION VIII. Highway Communications

Three projects were reported in this session.

“The Stranded Motorist” (Martin A. Warskow, Airborne Instruments Laboratory)

NCHRP Report 6 showed that any automatic method of detecting disabled parked cars and of doing anything about them is expensive and therefore highly unlikely to be implemented on a large scale in the foreseeable future. On the other hand, the cooperative motorist method of locating disabled vehicles, both on the shoulder and on the traveled way, could be very effective and not very expensive.

Airborne Instruments Laboratory, which performed NCHRP Project 3-4, has contracted with the Bureau of Public Roads to do a study called “Reporting of Disabled Vehicles by Cooperative Motorists.” This is a natural outgrowth, or continuation, of Project 3-4 and is a very promising piece of research.

The main object of the study is to determine the extent to which motorists will cooperate (by flashing their headlights at a reporting point). Secondary objectives are to determine functional requirements of the detecting equipment, what kinds of messages to use to let motorists know where the reporting point is, how many false alarms are given and how to tell the difference between a false alarm and a real disabled motorist, and so on.

To the current researchers’ knowledge, research on the removal of disabled or wrecked vehicles from the highway has not been done. Freeway surveillance and control projects in Chicago, Detroit, Houston, and Los Angeles have all shown that disabled vehicles or accidents have a drastic effect on freeway throughput so frequently that they constitute one of the greatest causes of congestion on an annual basis. Every minute that can be shaved off of the time that is required to remove these disabled vehicles will have a huge payoff in reduced delay.

Whether the reduction is in the detecting-reporting time or in the handling-removal time, a minute is a minute. However, experience shows that the detecting-reporting time is a comparatively small proportion of the total time, and therefore there is a greater possibility of over-all improvement in tackling the removal problem.

“Radio Roadside Communications” (Donald O. Covault, Georgia Institute of Technology)

This was an excellent summary of work done during the past five or six years to test the practicality of induction radio to transmit local messages from a roadside transmitter to a driver who has appropriate receiving equipment. Reports have been published in Highway Research Record No. 49 (1963.) Although the system shows a lot of promise, there does not seem to be much impetus to develop it further, perhaps because a method of gradual implementation has not been thought of. Any system requiring equipment in automobiles must be capable of doing some good during the transitional stage when only a fraction of cars on the road are equipped.

“Automated Routing” (John Z. Grayum, Philco Corp.)

This report described a method of coding routes for individual trips throughout the United States. When fully implemented, people would no longer need maps or directional signs. It appears that the implementation of results of this research, if achieved, is very far in the future, and that it would not be very important even then. The effort would better be applied to either basic research or to problems capable of earlier solution.

SESSION IX. Optimization of Flow on Urban Networks

Three papers on signal timing were presented at this session. As pointed out in Chapters Two and Three, this work is probably the most important, from the standpoint of early and significant improvement in traffic operations, of any work going on in the United States in the field of traffic surveillance and control.

The three papers were:

2. Traffic Simulation Validation (James H. Kell).

In talking with other researchers in this field, the impression was gained that this kind of research would be greatly enhanced by public discussion and criticism in scientific journals and perhaps meetings or symposia, because there are so many ideas germinating in so many places that are not being tested simply because the researchers engaged in these projects did not think of them.
APPENDIX H

PROJECTS AND ORGANIZATIONS VISITED

A list of organizations, research agencies, and projects visited during the course of this study is included in this appendix. Discussions were held with project personnel as indicated. Acknowledgment should be made of the courtesy, patience, effort, and time freely offered by these people. Also they should be credited with many of the ideas that have been expressed in this report.

<table>
<thead>
<tr>
<th>Organization (and Project)</th>
<th>Persons Interviewed</th>
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<tr>
<td>Joint Vehicular Signal System Committee</td>
<td>Gordon Newell, R. B. Potts</td>
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<td>University of California, Institute of Transportation and Traffic Engineering</td>
<td>Edward Cleary, James Rudd, Wilbur Smith, R. S. Foote, Al Gomness, Lou Bender</td>
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<td>P. G. PakPoy Associates</td>
<td>Leonard Newman, Jack Eckhardt, Wm. E. Schaefer</td>
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<td>City of Los Angeles Traffic Department</td>
<td>A. Taragin, D. Solomon, Joseph Hess, A. Carter, W. Wolman</td>
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<tr>
<td>Traffic Research Corp.</td>
<td>J. Boring, E. Mahoney, O. Berman, M. Mason, P. Haddon, D. Brooks, D. Gazis</td>
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<td>Michigan Highway Department (John Lodge Freeway Surveillance Project)</td>
<td>Prof. R. J. Smeed, J. G. Wardrop, Mr. Allsop, D. J. Lyons, J. A. Hillier, Mr. Whiting, Dr. Holroyd, J. T. Duff</td>
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<tr>
<td>General Motors Technical Center (DAIR System)</td>
<td>B. M. Cobbe</td>
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<tr>
<td>Texas Transportation Institute and Texas Highway Department (Gulf Freeway Surveillance and Control Project)</td>
<td>B. A. Hunn, D. G. Hornby, H. A. Codd, Mr. Scott, Mr. Ridley, Mr. Huddart, Dr. E. W. Goerner, Mr. Kuhn and about 15 traffic engineers from Germany</td>
</tr>
<tr>
<td>Illinois Division of Highways (Chicago Expressway Surveillance Project)</td>
<td>Dr. von Stein, Dr. R. Lapierre</td>
</tr>
<tr>
<td>Illinois Division of Highways (Freeway Emergency Patrol in the Chicago Area)</td>
<td>The Ohio State University Transportation Research Center (NCHRP Project 3-3 and other projects)</td>
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APPENDIX I

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Houston


Port of New York Authority


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Under the terms of its Congressional charter, the Academy is also called upon to act as an official—yet independent—adviser to the Federal Government in any matter of science and technology. This provision accounts for the close ties that have always existed between the Academy and the Government, although the Academy is not a governmental agency and its activities are not limited to those on behalf of the Government.

THE NATIONAL ACADEMY OF ENGINEERING was established on December 5, 1964. On that date the Council of the National Academy of Sciences, under the authority of its Act of Incorporation, adopted Articles of Organization bringing the National Academy of Engineering into being, independent and autonomous in its organization and the election of its members, and closely coordinated with the National Academy of Sciences in its advisory activities. The two Academies join in the furtherance of science and engineering and share the responsibility of advising the Federal Government, upon request, on any subject of science or technology.

THE NATIONAL RESEARCH COUNCIL was organized as an agency of the National Academy of Sciences in 1916, at the request of President Wilson, to enable the broad community of U. S. scientists and engineers to associate their efforts with the limited membership of the Academy in service to science and the nation. Its members, who receive their appointments from the President of the National Academy of Sciences, are drawn from academic, industrial and government organizations throughout the country. The National Research Council serves both Academies in the discharge of their responsibilities.

Supported by private and public contributions, grants, and contracts, and voluntary contributions of time and effort by several thousand of the nation's leading scientists and engineers, the Academies and their Research Council thus work to serve the national interest, to foster the sound development of science and engineering, and to promote their effective application for the benefit of society.

THE DIVISION OF ENGINEERING is one of the eight major Divisions into which the National Research Council is organized for the conduct of its work. Its membership includes representatives of the nation's leading technical societies as well as a number of members-at-large. Its Chairman is appointed by the Council of the Academy of Sciences upon nomination by the Council of the Academy of Engineering.

THE HIGHWAY RESEARCH BOARD, organized November 11, 1920, as an agency of the Division of Engineering, is a cooperative organization of the highway technologists of America operating under the auspices of the National Research Council and with the support of the several highway departments, the Bureau of Public Roads, and many other organizations interested in the development of transportation. The purpose of the Board is to advance knowledge concerning the nature and performance of transportation systems, through the stimulation of research and dissemination of information derived therefrom.