NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT 9

TRAFFIC SURVEILLANCE AND MEANS OF COMMUNICATING WITH DRIVERS INTERIM REPORT

HIGHWAY RESEARCH BOARD NATIONAL ACADEMY OF SCIENCES - NATIONAL RESEARCH COUNCIL

AUTHOR'S CORRECTIONS

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

REPORT 5

EFFECTS OF DIFFERENT METHODS OF STOCKPILING AGGREGATES

(Interim Report)

Page 10, "Relative Costs."
In the table of equipment rental charges, the field laboratory item should read "$15.00 per day."

Page 17, Equation 3 should read

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} X_i^2 - \frac{\left[\sum_{i=1}^{n} X_i\right]^2}{n}}{n-1}} \qquad (3)$$

(In the squared (second) term of the numerator of the fraction under the radical, the brackets should not include the denominator, n.)

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT 9

TRAFFIC SURVEILLANCE AND MEANS OF COMMUNICATING WITH DRIVERS INTERIM REPORT

BY MORTON I. WEINBERG, CORNELL AERONAUTICAL LABORATORY, INC.
BUFFALO, NEW YORK

HIGHWAY RESEARCH BOARD OF THE DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH
NATIONAL ACADEMY OF SCIENCES - NATIONAL RESEARCH COUNCIL 1964

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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 Highway Planning and Research 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 Commerce.

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 is one of a series of reports issued from a continuing research program conducted under a three-way agreement entered into in June 1962 by and among the National Academy of Sciences-National Research Council, the American Association of State Highway Officials, and the U. S. Bureau of Public Roads. Individual fiscal agreements are executed annually by the Academy-Research Council, the Bureau of Public Roads, and participating state highway departments, members of the American Association of State Highway Officials.

This report was prepared by the contracting research agency. It has been reviewed by the appropriate Advisory Panel for clarity, documentation, and fulfillment of the contract. It has been accepted by the Highway Research Board and published in the interest of an effectual dissemination of findings and their application in the formulation of policies, procedures, and practices in the subject problem area.

NCHRP Project 3-2, FY '63
NAS-NRC Publication 1208
Library of Congress Catalog Card Number: 65-60012

FOREWORD

By Staff

Highway Research Board

This interim report will interest all traffic engineers and highway officials responsible for the operation of existing and future freeway and traffic systems. It describes the operation of major freeway surveillance systems in this country and develops logical methods to predict impending congesting conditions through the use of vehicle detection equipment. The information contained herein should aid in the development of surveillance and control networks for traffic systems.

Although the freeway concept was put in operation with the belief that it would operate without need of direct traffic controls, it has been found through experience that a freeway capability for transporting people and goods breaks down when the traffic demand exceeds the capacity of the facility. For this reason research projects have been initiated on heavily-traveled freeway sections to develop a workable surveillance system. The objective of the research is to determine the controls necessary to insure that the desired flow rate will not be inhibited by overcrowding.

The project of "Surveillance Methods and Ways and Means of Communicating with Drivers" was initiated to assist in the overall development of traffic surveillance and to fill gaps in research conducted by other organizations. This work does not duplicate other research work, but takes advantage of the information available from other major projects in this field. It uses the suitable components of other projects along with its own to fashion a more comprehensive and practicable monitoring system. This project is designed to provide application criteria, methodology, cost and expected results of such a surveillance system.

The major emphasis of this first interim report is on the operating characteristics of freeway systems. The recommended spacing of detection devices to measure speed, volume and/or occupancy data was developed to collect the required information for determining impending traffic congestion. The methodology was developed and tested to predict congestion about three minutes in advance of its actual development. Mathematical models were tried on both the Eisenhower Expressway in Chicago and the John Lodge Expressway in Detroit to test their application to real-life situations.

A control device was then developed to communicate freeway ramp operating conditions to motorists in advance of entrance ramps. This device indicates the free flow, metering or closure on the nearest three entrance ramps in each direction. It would also provide information to the driver which would allow him to choose an alternate route if the closest ramp were operating under limited flow conditions. Preliminary tests were conducted to measure acceptance of the device by drivers.

This report describes in detail the operation of an airborne observer in traffic

control. Communications were made to motorists through commercial radio of alternate route recommendations when incidents producing unexpected congestion occurred. Attempts were made to measure the actual time saved by the drivers in response to the information.

Research is continuing on this project by the Cornell Aeronautical Laboratory. The next phase will include a study of effectiveness of freeway surveillance, a study of digital-computer-controlled traffic signal networks, further study of the requirements of an airborne-observer surveillance and control system, and a study of driver communication by aural and visual messages.

CONTENTS

ACKNOWLEDGMENTS

Appreciation is expressed to the many individuals and companies who provided the project team with valuable additional assistance. Special acknowledgment is given to the following:

Edward F. Gervais, Frank DeRose, Jr., and Gordon Paesani, of the Michigan State Highway Department; Adolf D. May, Jr., of the Expressway Surveillance Project, Illinois Division of Highways; John R. Sharpe and David F. Leopold, of Radio Station WEBR, Buffalo, N.Y.; William H. Schneider and Chester B. Kern, of the Buffalo (N.Y.) Police Department; T. T. Hart, of the New York Central Railroad; Lloyd A. Maeder, of the New York State Traffic Commission; B. John Tutuska, of the Erie County (N.Y.) Sheriff's Department; Hugh Kendall and John H. Auer, Jr., of the General Railway Signal Company; Arthur Uhrlandt, of the Crouse-Hinds Company; Karl Moskowitz, of the California Division of Highways; Henry W. Osborne, of the Division of Safety, City of Buffalo, N.Y.; J. T. Hewton, of the Toronto Metro Traffic Commission; John L. Barker, of the Automatic Signal Division; Robert S. Foote, Leslie C. Edie, and John R. Shelton, of the Port of New York Authority; and Robert Brenner, of the Institute of Transportation and Traffic Engineering, University of California at Los Angeles.

TRAFFIC SURVEILLANCE AND MEANS OF COMMUNICATING WITH DRIVERS INTERIM REPORT

SUMMARY

This study is concerned with the development of a specification for a traffic control system for urban freeways. The specific problems investigated for purposes of this system are (a) methods of predicting congestion, (b) the effectiveness of an airborne observer, and (c) the design of a ramp access advisory signal.

The first section describes an attempt to formulate a mathematical model on which a method of anticipating traffic congestion can be based. Traffic data from two urban freeways were applied to two computational logics to determine whether a warning system is attainable at reasonable cost.

In one experiment, vehicle counts in and out of a study segment of the John C. Lodge Freeway, Detroit, were taken each minute through a three-hour period by means of acoustic detectors, while the speed and incident data were observed on closed-circuit TV monitors. Speeds of randomly selected vehicles were determined in each minute, and stoppages and significant slow-downs were noted and logged, giving numbers of lanes involved. The actual number of vehicles in the test section was determined at half-hour intervals by counting vehicles following a lead car until the latter emerged.

The computational logic called for a prediction of density for three minutes into the future when, in any minute, there was an increase in the average lane density in the test segment. The crude logic and the data that were used produced 32 warnings of "congestion," of which 25 were borne out. Brief stoppages, when they occurred, usually were at average lane densities of 80 or more vehicles per mile.

Another prediction experiment was performed with data recorded by the Expressway Surveillance Project on the Congress Street Expressway, Chicago. Generally, the prediction logic followed the same procedure as that described for the Detroit facility. The principal difference was in the availability of a historically derived curve of hourly volumes at the upstream end of the test segment. No such data existed for the Detroit test. Thus for any five-minute period of prediction, volume into the test segment began at the current value and followed the slope of the historic curve.

Results of the data processing for three hours of the peak period showed that computed densities varied from 0 to 125 vehicles per lane per mile. The excessive density variations are ascribed to cumulative errors from the data collection system. However, the test seemed to confirm a traffic characteristic—that density increased gradually enough to provide useful warning periods. The longest period of increasing density ("compression") was 10 minutes, while 4 minutes was typical.

It was concluded that the computational logic used was too demanding for the

accuracy of currently available instrumentation. It was also indicated that traffic behavior may be predictable to the point that a sufficient (and reasonable) amount of instrumentation may implement a compatible logic to provide for automatic control of access to an urban freeway and, in addition, for speed regulation to optimize service to the motorists. A continuing program will investigate this problem.

A second continuing program in traffic control was initiated to study the effectiveness of an airborne-observer surveillance and control system. A real-life situation was used for the purpose of evaluating the ability of an airborne observer to re-route traffic in a repeatedly congested situation, and to report impending emergency situations and issue advisories on alternate routes. In this experiment an observer in a helicopter broadcast information, via microwave link and a standard AM-FM radio station, to motorists concerning traffic situations in an urban (Buffalo, New York) area. Evaluation of the congested traffic situation was inconclusive because of the small response from motorists who were asked by the airborne observer, as part of his regular broadcasts, to furnish travel times.

A description of two emergency traffic situations is included. A crude evaluation of these emergencies showed a saving of 476 and 512 vehicle-hours, respectively, due to airborne-observer intercession. A plan for obtaining increasingly accurate data for analysis purposes is described.

The third facet of this study in traffic control was a program to devise and test, in real traffic, a format for a signal to advise motorists on the use of access ramps to an urban freeway. These signals, installed on approach streets leading to the ramp locations, would enable drivers to make decisions on alternate routes when necessary, and adopt them without reversing their direction of travel.

Three operating states are assumed: closed (flashing red), metered flow (amber), and open (green). The signal format devised displayed information for the ramp closest to the location of the signal and the three succeeding access ramps "downstream."

The signal was tested in real traffic at a site which simulated a city street with regard to both traffic signal spacing and approach speed limit. The participants, who took the part of a commuting public for whom the signals would be designed, were indoctrinated into their meaning and use by a two-page memorandum. The tests showed that the signal required no further explanation or lettering to identify its purpose or the ramp locations it served.

CHAPTER ONE

INTRODUCTION

It is generally known that a significant part of the American economy is concerned with the production, construction, maintenance, and control of the automobile and the associated highway transportation system. Increasingly heavy demands made on the highway system by growing numbers of motorists have risen to the point that the seemingly generous areas of paved surface allotted for highways become glutted with vehicles at least twice each weekday in heavily populated areas. Furthermore, great numbers of people take to the highways during holidays and vacation periods, causing traffic jams which induce discomfort, delay, exasperation and frustration.

It is apparent that these traffic situations cannot be accepted as normal operation because of excessive travel times.

The importance of operating the highway system at peak or near-peak efficiency is self-evident. Although some transportation requirements can be met in some areas by mass transit systems, the predominant consideration today is in expediting the movement of the private automobile. This cannot be done simply by "laying more concrete" because new roads or additional lanes make serious (and expensive) inroads on the land areas they are intended to serve. However, when the "optimal" movement of traffic has been attained there is no alternative to building new highways, if additional traffic is to be accommodated without a deterioration in the quality of service.

In the present study, the highway and street systems are accepted as they exist today. No attempt is made to suggest improvements to these systems. Furthermore, vehicles are dealt with as they are and not as they might be. Finally, the point of view of the traffic engineer is adopted in an effort to determine means for observing and quantifying traffic operations, establishing controls and control doctrines, and communicating with motorists so that the present highway system may best meet the demands of the users.

This point of view is reflected in the problem statement of this project, which expresses the view that ". . . traffic-carrying facilities of all types are subject to congestion. . . . Experiments have indicated that traffic operations . . . can be improved by surveillance . . . and communicating with drivers. . . . It is desired to test the hypothesis using real traffic on a real road system which includes an operating freeway network."

Personnel at Cornell Aeronautical Laboratory (CAL) assumed that a number of traffic facilities existed that would answer the description of a "closed loop" system, as suggested by the National Cooperative Highway Research Program. In this context, a closed loop system is one that provides for surveillance of traffic operations, acquiring data on those operations which can be processed by a computational logic in a real-time computer, testing observed conditions against a set of decision rules, selecting commands in light of the results of the tests, activating appropriate controls or communicating with drivers to improve traffic movement when necessary, and then re-assessing the traffic behavior to determine if further corrections are to be made. CAL expected that practice could be obtained in processing collected data, analyzing the data, making control decisions, and communicating these decisions to drivers. It was expected that traffic movement could then be evaluated to determine if the decisions and controls would lead to some "optimal" performance. Further, the assumption was made that some capability would be present for automated implementation of decisions and controls.

A review of the "advanced" control installations in the United States revealed that this is, in general, not the case. There are numbers of traffic signal control installations which depend on volume-occupancy or similar data to signify when certain fixed control programs should be placed into effect. The programs themselves are usually compromises to allow traffic to pass in some suboptimal manner determined subjectively by visual observation or by analysis of data from traffic counting devices. In general, these systems were selected by traffic engineers, or others responsible for traffic control, to answer the needs of normal traffic operations. They are found principally on surface arterials or in some specialized applications such as vehicular tunnels. Ostensibly, they are not intended to be used as part of the instrumentation on an experimental traffic research facility.

Turning to limited access highways, the Expressway Surveillance Project on the Eisenhower Expressway (formerly the Congress Street Expressway) in Chicago was found to have a large instrumentation installation for data collection, but no provisions for real-time data processing to implement controls and, in fact, no controls. Another facility, located on the John C. Lodge Freeway in Detroit, provided for some closed-loop operation, but with human observers doing the "data processing," evaluation and decision making, and then operating the controls.

CONGRESS STREET EXPRESSWAY SURVEILLANCE PROJECT

The pilot detection system operated by the Expressway Surveillance Project at the time it was first visited by CAL personnel was installed on a 5-mile length of the westbound lanes of the Congress Street Expressway. At the eastern end of this length (Cicero Avenue) there are four lanes, reducing to three lanes between Central and Austin Avenues. A layout of the Expressway and the adjacent arterials is shown in Figure 1. Pulse-type presence detectors, emitting acoustic energy, were located over each lane at Cicero, Central, Austin, East, Harlem, DesPlaines and First Avenues. Other detectors of the same type were located on entrance and exit ramps at these stations. In addition, Doppler-type, continuous-wave (CW), acoustic detectors were located over the center lane at Harlem Avenue and over the three lanes at DesPlaines.

The data furnished by the detectors was processed at the

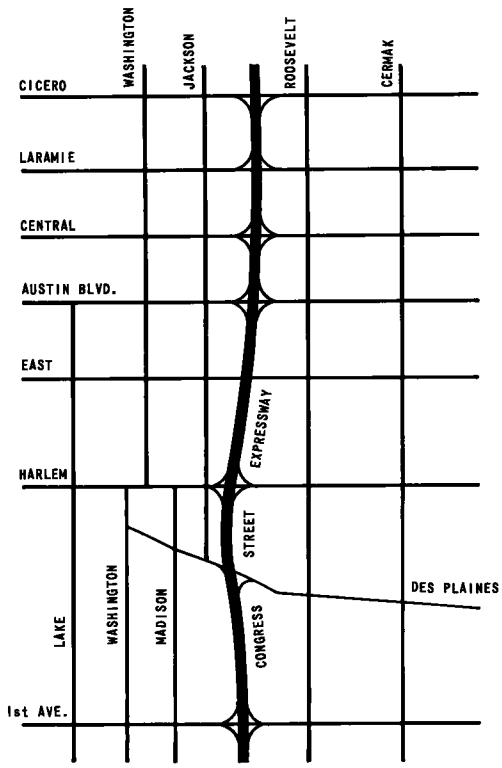


Figure 1. The Congress Street Expressway and adjacent streets within the Surveillance Project limits.

project office by pulse counters, analog averaging circuits, and frequency filter equipment. Results from the presence detectors were expressed as time occupancy and volume. The Doppler detectors gave individual vehicle speed, average speed over a predetermined period, and volume. Another detector provided an indication of the presence of precipitation on the Expressway pavement. Project personnel recorded pertinent meteorological data obtained from the local Weather Bureau office.

Full-time data processing was available for all lanes at East and DesPlaines Avenues and at all ramps. At the other stations provisions were made for accepting data from one lane only; the lane to be processed was selected by switching at the project office. Paper tape punching equipment was available for data recording. This data collection installation appeared to be the largest on any traffic facility in the United States. However, it failed to meet the description of the Project Statement in that it included no provision for exercising "control" over Expressway traffic.

JOHN C. LODGE FREEWAY TRAFFIC RESEARCH PROJECT

The only other facility found to have an information "feedback" capability was the Traffic Surveillance and Control Research Project on the John C. Lodge Freeway in Detroit. This project employed closed-circuit television as its primary source of information on Freeway operations. Fourteen cameras provided a direct view of all traffic on the Freeway from the intersection with the Edsel Ford Expressway, northwest for a distance of 3.2 miles, to the intersection with Davison Road. The 14 video monitors are in a control center located near the middle of the distance. Automatic data collection equipment was sparse. It consisted of six presence detectors and six motion detectors and compatible analog averaging and data recording equipment. However, cabling extended throughout the length of the surveillance area, making it possible to collect data at any point along the Freeway where an overhead structure could act as a suitable mounting for the detectors, which were of the type used on the Congress Street Expressway.

As noted previously, provisions are made for the control of traffic seeking access to and on the Freeway. Ramp closure signs are installed at the head of all access ramps in the length of the Freeway under TV surveillance. Signs giving three levels of recommended speeds are posted at nine stations in the southeast-bound lanes and at eleven stations in the northwest-bound lanes. Lane "closed" or "open" signals are located at five of the southeast-bound stations and at six of the northwest-bound stations. These signals, consisting of an illuminated red X for "closed" and an illuminated green arrow for "open," are of the "blank-out" type, so that only the arrow or the X is visible. All three of these types of controls are operated through remote manual actuation by project personnel at the control center. Decisions for the activation of controls are based on subjective judgments made by the personnel based on their observation of traffic operations on the video monitors. A flexible doctrine was followed by the operating personnel in making decisions concerning activation of controls.

Inasmuch as the major emphasis on instrumentation on the John C. Lodge Freeway appeared to be in its closed-circuit video, it was evident that no formalized and documented mathematical decision rules for the control of traffic could be implemented there. Furthermore, it does not seem likely at this time that any reasonable scheme exists for extracting and quantifying data from the video which would make it suitable for incorporation into an automated data processing, decision-making, and control system. Therefore, this system on the Freeway also fell short of the type of facility which was sought. However, it is important to note that the video system made it possible to apply the detection and discrimination capabilities of the human observer to an extensive length of real traffic facility, a vantage point previously available only to an airborne observer. Visual presentation allows for collection of traffic data in almost all sorts of weather. Accurate speed measurements may be made, average densities determined, accidents observed, speeding vehicles detected, infractions of regulations noted, volume counts made, relative lane movements and passenger and commercial vehicle distributions recorded. It appears that the TV surveillance, if not a candidate for an automated control system, is an extremely valuable adjunct to any instrumentation system which might be used for traffic research.

SELECTED TASKS

Because no real traffic-bearing facilities were found in the United States which answered the description in the Project Statement, it was necessary to re-orient the project. Instead of outlining in detail a program for implementing and

practicing control decisions and evaluation on one or two facilities, several tasks were set up which related to the overall objectives of the program but not directly to each other. Four of the tasks were experiments with real traffic or real traffic data. Results of two of these tasks are documented in Chapter Two and a third is presented briefly in Chapter Four. The fourth task, which was to have been a "before-and-after" study of the effects of the installation of a new traffic control system on Buffalo's Main Street, was eventually dropped in favor of the topic treated in Chapter Three. Other effort on the project was devoted to discussions with traffic engineers and a literature review of many past and current works in traffic theory and operations.

Several theoretical treatments on traffic characteristics have been written. The volume and headway resulting from a linear speed-density relationship is considered. The use of travel time to measure the efficiency of a road network is suggested and an electrical network is "developed" as an analog to the equations describing the traffic behavior. A model for traffic flow is postulated and then is disproved and replaced by a transmission function. Two studies of direct practical application were the statement of a statistical test for travel time data and an analysis of error possibilities with pulse-type presence detectors. The first year's work by the CAL project team is completely documented elsewhere (*1*).

A single digression from an approach to conventional automated traffic surveillance and control systems was made in the subject matter of Chapter Three. Here, apparently for the first time, an exploratory attempt was made to assess the potential value of an airborne-observer system in performing the functions of surveillance, decision making, and communicating control information to drivers. This particular observer service, known as the "Trafficopter 970," is located in Buffalo and is supported by a commercial radio broadcasting station, WEBR.

As far as is known, none of this work is a duplication or extension of any program or study, either current or completed. The decision to do experimental work on the facilities chosen was based on two reasons: one, there appeared to be no others from which the proper kinds of data would be available and, two, both Chicago and Detroit are close enough to Buffalo so that liaison with these projects was reasonable. Also, although the Project Statement provided for considering "city street systems," it seemed advisable to place the initial emphasis on urban freeways.

CHAPTER TWO

PREDICTION OF CONGESTION ON A FREEWAY

The Cornell Aeronautical Laboratory approach to the total problem of devising a traffic surveillance, evaluation, and control system and its operational doctrines is based on several assumptions.

First, it was assumed that the type of congestion which was to be predicted on the basis of surveillance of traffic operations occurs randomly, rather than in a cyclically repetitive pattern. Hampered traffic movement can be categorized in at least these two ways. But before the movement can be described as free, congested, or jammed, a standard movement must be established as a reference. Then a deterioration of traffic operations can be quantized. In general, the standard chosen is the most efficient movement the facility can accommodate in maximum number of vehicles moving at maximum average speed. This characteristic is discussed in detail later.

Deviations from the standard are caused by random events or emergencies such as vehicular accidents and fires. Traffic movements are reduced temporarily because of reduction in the size of channels through which the vehicles "flow." Other deviations are caused when a simultaneous demand for use of the highway (system) exceeds its standard capability to provide service. Usually the latter can be expected to occur with a high degree of regularity because they have been identified historically as clock-dependent. This second type of problem is subject to long-term planning and scheduled execution (control programs that can be activated by a clock). The random event calls for a quick reaction control once a threat of congestion has been detected and confirmed.

The second assumption is that an early warning system would permit prevention of traffic congestion in the least costly manner. It is assumed that if a clue to incipient congestion can be derived from a real-time assessment of the operating characteristics of traffic, it will be possible to put into effect controls which will alleviate or eliminate the difficulty (minimize delay time). When a control system is finally devised and implemented, the word "congestion" will be replaced by the more accurate term "control threshold density," because density will define the point at which a traffic complex should be switched from one operational mode to an alternate.

The purpose of this research is to discover whether or not congestion occurs in such a manner that ample warning time can be obtained, and also to determine what characteristics of traffic must be observed in order to detect the onset of congestion. The type of equipment needed for detection of the characteristics and processing of the information acquired is also a consideration.

The investigations were conducted with data taken on the John C. Lodge Freeway in Detroit and the Congress Street Expressway in Chicago. They are reported in detail in a more extensive report (*1*), which serves as background for this document.

APPROACH TO THE PROBLEM

It has been stated that one of the aims of the research task is to determine what traffic characteristics might be used to indicate the onset of congestion. Theoretical treatments and observations of traffic movement were reviewed. Because experimentation on this project was limited to that which could be performed on existing traffic facilities, with only minor modifications permitted, the documents examined were limited to those considered to have direct relevance to these experiments. At the outset it was known that the facilities of the John C. Lodge Freeway and the Congress Street Expressway would be used.

Several investigators have developed performance curves for the numbers of vehicles passing a point per unit of time (volume), and also spacing between vehicles, as a function of speed. The speed-volume curves are based on the results of many observations of real traffic systems and are envelopes of maximum performance for representative mixes of vehicles and drivers. As used here, "maximum performance" means the volume-speed relationship existing when, at a given speed, a certain minimum spacing between vehicles (lane density) will be accepted by the average driver. Although the numbers vary to reflect characteristics unique to each site, the general shape of the curves is the same for nearly all situations sampled. Figure 2 is typical.

The traffic performance parameters most available with the detection and data processing equipment currently in use by traffic recording facilities are volume, speed, lane occupancy, and lane density. Lane occupancy is defined as the percentage of time in a unit period that vehicles occupy the detector site. Lane density is computed by dividing current volume by current average speed of vehicles in passage in a lane. At the outset it seemed reasonable that one or more—preferably one—of these parameters might be used as an index of congestion. Therefore, their characteristics were examined with this end in view.

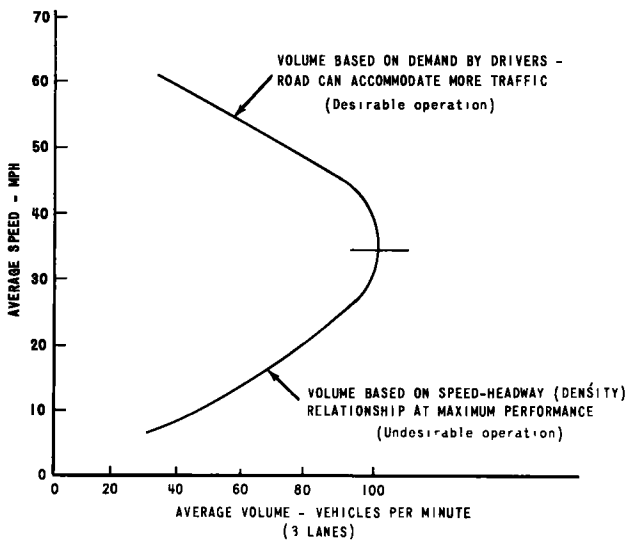


Figure 2. Typical speed-volume curve (derived from data on page 12, Ref. 2).

Volume

A set of curves taken on the Congress Street Expressway shows that peak volume occurs at about 38 to 40 mph and that volume degenerates significantly with speed variations on either side of the value for maximum volume (*2*, p. 12). Because the curves show that speed is a bi-valued function of volume, it is clear that volume alone (one of the measurements currently being made at the Detroit and Chicago facilities) is insufficient as a criterion for traffic movement. At the very least, an indication of speed associated with the volume is needed to show whether the highway is operating on the demand side or on the maximum performance side of the curve of Figure 2.

Speed

The use of speed alone as an indicator of traffic performance was considered. It, too, fails as an unambiguous characteristic on which to base a prediction of congestion. For, while congestion implies a condition of greatly reduced traffic speed, the converse is not strictly true—although it may be for all practical purposes. (The notion of drivers dawdling along on a sparsely occupied freeway is difficult to conceive.) However unlikely it would be for speed to be low at long headways, the chance of its happening in an automated (and unreasoning) system eliminates it as a sole indicator for control purposes.

Lane Occupancy

Lane occupancy is used in a number of traffic signal control systems as a basis for establishing cycle times and splits. On the Congress Street Expressway it is used as the measure of the operating condition of the traffic. The reason is that lane occupancy, in theory, specifies both speed and volume, thereby describing a unique condition of traffic movement at the point of data sensing. For this reason, and also because both facilities to be used in the experiment were instrumented to measure lane occupancy, it was felt that this parameter should be considered analytically for its suitability in a congestion prediction logic.

The computation of speed from the output of a presence detector, which is used for measuring lane occupancy, assumes that the length of the average vehicle, statistically derived, is divided by the time the vehicle is under the detector. This assumption is the first source of possible error. The measurement accuracy of lane occupancy introduces a second source of error. The detectors used in Chicago and Detroit are mounted over the roadway. They operate on the principle of measuring the time delay for the return of a pulsed signal when it is reflected either from the pavement or from a vehicle below the detector. These detectors use an acoustic signal and their pulse repetition frequency (prf) is limited to something less than 30 pulses per second. The effect that prf has on these measurement accuracies is discussed elsewhere (*1*, Appendix J). Statistically, the speed errors can be biased out of the system, but this would be applicable on a long-term basis and not suitable for a control system.

The point has been presented that the most efficient use of the roadway is obtained when the product of interde-

pendent speed and density is maximum, at a given site and for the existing environmental conditions. Therefore, it would be expected that a control logic for traffic would make use of the speed and density parameters. The volume-occupancy detector feeding its signals to an appropriate computer can furnish this information, but with an inherent systemic error and instrument error.

Lane Density

The last of the characteristics mentioned as possible indicators of impending congestion was lane density. It was noted that the value of lane density could be computed from data taken at a point by a speed and volume detection and data processing system; although the results would be, in reality, a "point density." Consideration of other relevant factors further supported the choice of density as an indicator of congestion. For one, speed and volume detectors were available at both facilities mentioned. Secondly, lane density is akin to lane occupancy, an accepted and valid criterion, in that it is a function of the headway between vehicles and can be calculated more accurately than occupancy from data taken at a point. Both density and occupancy may be extrapolated over a length of highway, but only if all vehicles operate at constant speed. Finally, average actual density over a length of roadway can be computed from a running count of vehicles into and out of the road segment if the initial content can be determined at some instant, and the volume detectors and totalizers for running counts are already installed at the Detroit and Chicago facilities. Thus, lane density, which is neither insufficient nor ambiguous and can be measured with adequate accuracy, was chosen as the best indicator for traffic performance.

TECHNICAL PROCEDURE

The material presented here is a digest of the technical portions of three memoranda (*1*, Appendices A, B and C) on the problem of predicting congestion. The first is a preliminary attempt to formulate a computational model for the prediction of congestion. The second and third are the results of the application of the computational process to traffic data taken at the Chicago and Detroit facilities, respectively. The formulation of the model first was planned from information gleaned from reports on the two projects (*2, 3*) and from brief visits to the two facilities.

There are several reasons why the experiment was planned for both cities, even though the two installations used the same type of detection and data processing equipment. For one, the test on the John Lodge Freeway originally was designed as a real-time operation, which called for data processing quite different from that for the computations that were made with Congress Street Expressway data. Because the television monitors permitted a view of the happenings in the test segment on the John Lodge Freeway, it was attractive to make predictions in real time, to check their accuracy, and also to correlate calculation with visible Freeway operation. (Eventually the test was performed with recorded data because of difficulties with two detector installations. This is discussed more fully in the background report (*1*).) However, although there was no provision for visual surveillance over traffic operations on the Congress Street Expressway, there were many more recorded data available. It was thought that a more elaborate prediction logic could be worked out to use these data, as compared to the procedure used for the John Lodge Freeway, where data were available only at the ends of the test section.

MATHEMATICAL MODELS

Detailed descriptions of the computational processes used for the Chicago and Detroit traffic data are given in the background report (*1*, Appendices B and C). The basic mathematical model from which these computational processes were formulated is discussed here, along with the variations in the computational logic used for the data from each facility.

Derivation of the Computational Model

The model for the behavior of traffic on the freeways was taken as the volume-density curve derived from a maximum speed vs volume curve (envelope) as shown in Figure 2. It was expected that critical traffic problems usually would develop during the two peak travel periods of the weekday, when the motorists mostly would be commuters. At these times the heavy demands made on the freeways impel the drivers, as a class, to maintain minimum headways at any given speed, so that the traffic movement relationship of volume vs density is along the maximum performance curve.

The logic used to predict a time when congestion might be expected to occur on a freeway is comparatively simple. Changes in density in a given length of freeway are computed from volume data acquired in real time. When the density at a given time is sufficiently high and a further increase in density is detected, the following type of computation is made:

$$\text{Time at stall} = \text{Present time} + \frac{\text{Required change in density to stall}}{\text{Time rate of change of density}} \quad (1a)$$

in which "stall" is some arbitrarily selected condition of unacceptable traffic movement. For a given road segment, this general statement is written as

$$t_s = t + \tau\, n\, l \frac{\rho_s - \rho_t}{v_1 - v_0} \quad (1b)$$

in which

$$\rho_t = \rho_{t-\tau} + \frac{v_1 - v_0}{n\, l} \quad (2)$$

t_s = time at stall;

t = present time;

τ = data processing interval;

n = number of lanes in highway;

l = length of highway segment;

ρ_s = density of stall, in vehicles per lane per unit length;

ρ_t = present density;

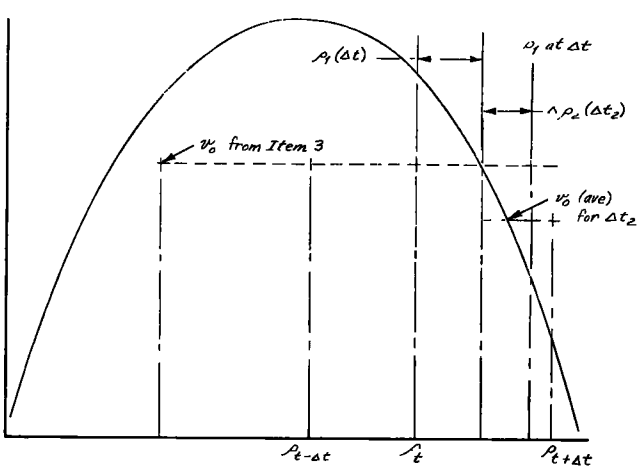
v_i = total vehicle count "in" during interval; and

v_o = total vehicle count "out" during interval.

For very preliminary experiments it seems reasonable to expect that the calculations might be made at 60-sec intervals, assuming hand computation with a small desk calculator, after the operations had been practiced for a short period of time.

One shortcoming in this method of computation is the assumption that the flow out of the highway segment, v_o, could remain constant during a linear increase in density. The assumption may be true only until peak volume rate is reached from the higher-than-at-peak-volume speed side of the speed-volume curve. After that it is characteristic for both speed and volume to decrease with increasing density, so it is reasonable to expect that the linearity will not hold for long. If the situation is one in which the influx of vehicles into the highway segment remains essentially constant at the value which caused the initial significant density rise, the flow out of the segment may be expected to decrease and the time to stall will be shortened materially. Thus, a more realistic logic to use to compute the time to stall would be based on a time rate of change of density which would assume a constant influx, at the rate determined for the computational period, and a deteriorating efflux once the density at peak volume is exceeded. (This last comment appears to indicate that the threshold value of density which warrants the computation of predicted time to stall is that found at the time of maximum volume.)

The "density at stall" is a value which must be determined for the particular facility or portion of the facility under consideration and for various conditions of environment. Where sufficiently continuous portions of a highway can be assumed similar to other highways for which the data had been developed, these data can be applied for initial computations and then verified or modified. Patently, stall conditions (density) on a slippery road will not be equal to densities achievable on clear dry pavement.



(a) Compute ρ_1 at $t + \Delta t$ as if v_o persisted at the constant level.
(b) Determine average v_o for the interval Δt_2.
(c) Use average v_o for the computation of actual $\Delta\rho$ during the period from Δt_1 to Δt

Figure 3. Volume-density curve.

In developing computational procedures for the two freeways under consideration, it appeared that the one for the John C. Lodge would have to be the simpler and less accurate because of the limited amount of instrumentation available. It was realized that the first shortcoming of the outlined procedure could be reduced considerably by allowing v_o to vary according to the volume-density curve deriving from Figure 2. This is shown in Figure 3. Volume, v_o, was to be permitted to remain constant until a density was reached at which the current value of v_o fell on the curve, after which it fell with increasing density. Inasmuch as the only information available on vehicles moving into the freeway segment being tested was from a set of volume detectors over all lanes at the upstream end, there was no way to estimate v_i for the "future" except to hold it constant at the current level. Thus, for the John C. Lodge Freeway, the procedure would be as follows:

Computation of Time at Stall, Constant v_i and $v_o = f(\rho)$

1. Determine stored value of present density, ρ_t.
2. Determine present v_i from counter.
3. Determine present $(v_o)_t$ from counter.
4. Compute change in density, $\Delta\rho$, for the period from $t + j\Delta t$ to $t + (j+1)\Delta t$ ($j = 0$ for the initial computation) from

$$\Delta\rho = \frac{\Delta_t[v_i - (v_o)_{t+j\Delta t}]}{\tau n l} \tag{3}$$

in which Δt is an arbitrary computational time increment.

5. Compute

$$\rho_{t+(j+1)\Delta t} = \rho_{t+j\Delta t} + \Delta\rho \tag{4}$$

6. Test if $5 \geqq \rho_s$; if yes, let

$$t_s = t + (j+1)\Delta t \tag{5}$$

if no, continue below.

7. Determine $dv/d\rho$ from equation of $v - \rho$ curve (input for various environmental conditions) at $\rho = \rho_{t+j\Delta t}$ from 5.
8. Compute $v = \left(\frac{dv}{d\rho}\right)\Delta\rho$ from 4 and 7.
9. Determine value of $(v_o)_{t+j\Delta t}$ in 4.
10. Increase j from its value at 4 by unity.
11. Compute new $(v_o)_{t+j\Delta t} = 9 + 8$ and return to 4.

When the computational procedure for the Congress Street Expressway data was first conceived it was supposed that much useful information could be derived from the volume-occupancy detectors located well upstream of the test segment. It was thought that the time of arrival of vehicles in the test segment from points upstream could be

calculated with sufficient accuracy from the occupancy data and also that total volume could be estimated from statistically derived lane volume distribution and the data from one lane. The latter assumption was prompted by already available curves of volume distributions for three lanes on the Congress Street Expressway (*2*). Figure 4, however, shows the distributions in these data to have a scatter that made the readings from one lane only completely inadequate for the purpose intended.

Still, it was expected that a refinement over the computational procedure for the John C. Lodge Freeway could be obtained because there were data on the Congress Street Expressway for the traffic flow as a function of time of day. Therefore, it was possible to insert in the logic a "look-up" to determine the flow expected over the period in the future for which the computation was being made. It is possible to introduce a significant error by this scheme, for any particular computation, because the actual flow into the system for the event can vary materially from the average (expected value). It may be that a more reasonable middle course to follow is to insert in the computation an expected traffic which follows the historical curve but has an initial value equal to the present flow. The validity of either approach might be determined by experiment.

Computation of Time at Stall, $v_t = f(t)$ and $v_o = f(\rho)$

The computational logic is essentially the same as for constant v_t, as shown previously, except that instruction 4 would include a readout from the computer memory. Assuming the scheme would be used in which historically expected values would be inserted into the computation, the instruction would read:

4. Compute change in density, $\Delta\rho$, for the period from $t + j\,\Delta t$ to $t + (j+1)\Delta t$ ($j = 0$ for the initial computation), from

$$\Delta\rho = \frac{v_t - \Delta t/\tau(v_o)_{t+j\Delta t}}{n\,l} \qquad (6)$$

in which Δt is an arbitrary computational time increment and v_t is the number of vehicles expected from time t to time $t + j\,\Delta t$ as determined from stored values.

THE CONGRESS STREET EXPRESSWAY EXPERIMENT

The prediction model is based on the use of average lane density as the descriptor of traffic behavior. The approach taken for processing of the data was, first, to determine at the beginning of the test period the number of vehicles in the segment of roadway selected for the experiment. On the Congress Street Expressway, determination of initial density in the 0.85-mile length of the test segment had to be done by an approximate computation. There were two choices for a method—the first, to use volume-occupancy data from detectors over each of the three lanes at the upstream end of the test segment; the second, to use data from speed-volume detectors over each of the three lanes at a station 0.55 mile beyond the downstream end of the segment. In either case, it had to be assumed that the density computed at the point of data collection could be

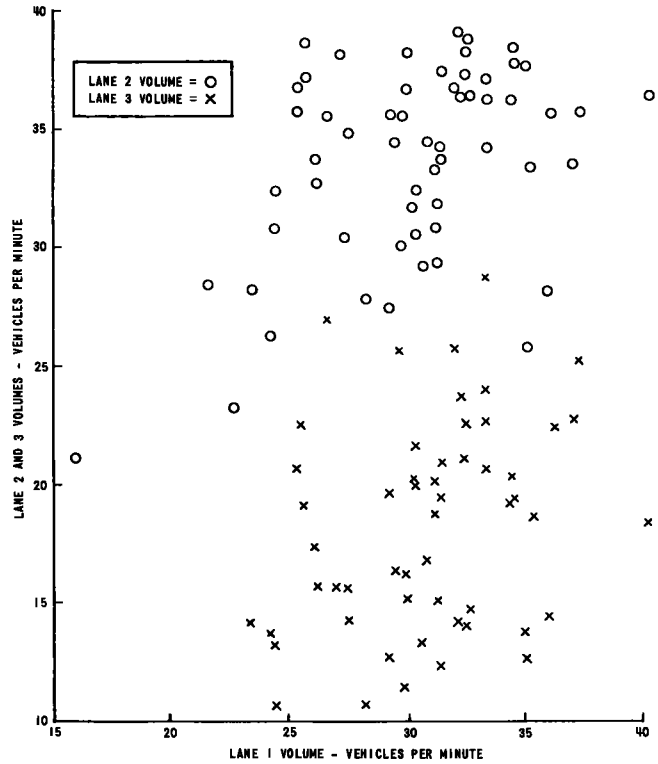


Figure 4. Distribution of Congress Street Expressway lane volumes at East Avenue, 3:00 pm to 4:00 pm.

extrapolated to cover the entire test segment, implying that all vehicles would be moving at the same speed. The error in the assumption would be the same no matter which procedure was used, but the error in speed would be less if this information were taken directly from a speed-volume detector than from a volume-occupancy detector, as was discussed previously. Therefore, even though the extrapolation distance was greater and a correction had to be made for vehicles using an on ramp and an off ramp at the downstream end of the test segment, the density was based on speed-volume data. (At a much later date it was determined that errors in speed readings from the motion detectors might easily have exceeded those based on a computation of speed and density from volume-occupancy data. This source of error became apparent when a comparison between densities computed from each type of detector, located at the same point, failed to show an acceptable correlation.) Figure 5 is a layout of the roadway under consideration, showing how initial density was computed.

Once the initial density had been computed by extrapolation a new density was computed at the end of each minute by summing the volume readings for the three lanes at East Avenue and subtracting from this total the volume at both the off ramp and the mainline at Harlem. This last volume is an approximation. Volume detectors were located over two lanes only at Harlem. A curve-fitting scheme was used to solve for factors to be applied to the two lane readings in order to get a total volume that would

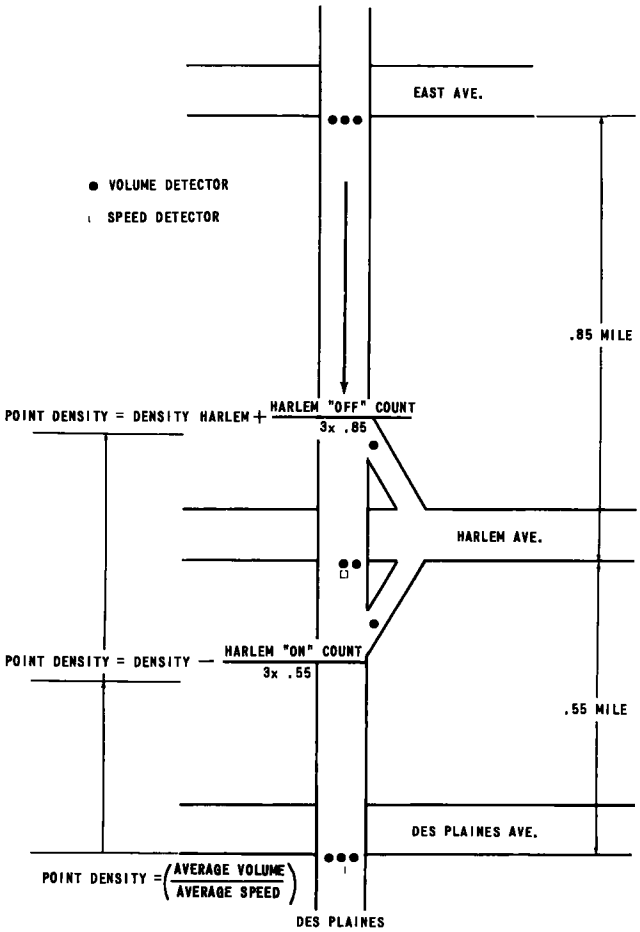


Figure 5. Route layout and instrumentation locations on test portion of Congress Street Expressway.

agree with the totals at East and DesPlaines Avenues, both of which have detectors on all three lanes.

Whenever the computation of density for a given minute showed a higher value than for the preceding minute, a prediction of density for the next 5 minutes was made. The anticipated volume flows with which the calculations were made were derived as follows:

1. Volume "in" at East Avenue at a given time was based on present volume as a starting point and either increased or decreased for each succeeding minute in accordance with the trend of the historical curve of Figure 6b, which covers the period for which the experimental computations were made.

2. Volume "out" at Harlem at the start of the prediction period was the sum of the last ramp volume and mainline volume, the latter approximated as previously discussed. This total volume was held constant through the prediction period unless density rose to the point where the volume fell on the maximum performance curve. Once the latter occurred, volume was reduced as density rose. This scheme is shown in Figure 3.

The information supplied to CAL by the Expressway Surveillance Project consisted of punched paper tape on which were recorded the outputs of 84 measurements on Congress Street Expressway westbound operations between 3:00 PM and 7:00 PM on May 8, 1963. From these data the density was computed to be 19 vehicles per lane per mile at 3:00 PM, after which it increased irregularly until, at 4:37 PM, a value of 80 vehicles per lane per mile was reached. The latter figure had been designated as "jam" density by arbitrary choice. As Figure 2 shows, this density should have forced the average speed on the Expressway to 18.7 mph, but did not; this failure will be discussed later.

At 5:22 PM the computed density reached its maximum value, 125, then declined fairly steadily to 79 at 6:00 PM and continued to decrease, but irregularly, to 12 vehicles per lane per mile at 7:00 PM. One computation of density was made that lacked credibility: density was zero at 3:06 PM. The peak value of 125 also appeared to be unreasonable so a check was made of the data at that time from each end of the test segment to see what discrepancies could be found.

The three volume-occupancy detectors at East Avenue ranged from 14.7 to 18.5 percent, with the average at about 17.5 percent, indicative of an average "point" density of 56 vehicles per lane per mile. A volume-occupancy detector reading at Harlem, converted to density, showed 76 and a speed-volume detector over another lane indicated 41 vehicles per lane per mile. As a matter of fact, a review of the data showed that maximum indicated density at any time, from a volume-occupancy detector at East Avenue, was 99 vehicles per lane per mile, considerably below the maximum of 125 from the running computation.

Because of these large inconsistencies between computed and measured values of density, the data received and the results of some processing were scrutinized further. It was apparent that the collecting and recording instrumentation included inaccuracies that made the data incompatible with the computational logic. For instance, a check of two successive hours of volume counts at East Avenue, Des Plaines, and the on and off ramps at Harlem showed that 126 vehicles more came out of the 1.4-mile length of roadway than went into it, an impossible condition. Because the total volumes were about 5,000 vehicles for each hour, the error was only about 2.5 percent, which indicates that the instrumentation is adequate for making traffic surveys but could not be used to implement the logic assembled by CAL for control purposes. Also, a check of probable density was made for 3:00 PM from the volume-occupancy detectors at East Avenue. The values for the three lanes were 44, 45 and 33, quite different from the 19 used as a result of extrapolation from DesPlaines. It was then concluded that if the initial density had been increased to 41, the average of the three lane readings, the computed peak density would have been higher than the already improbable 125, because the density profile for the entire period would have been raised by 22 vehicles per lane per mile. (It has been noted previously that the initial density of 41 probably would have been the more accurate value.)

Summarily, the density prediction logic as devised for the Congress Street Expressway failed to meet its objectives. The computational procedure demanded an accuracy of

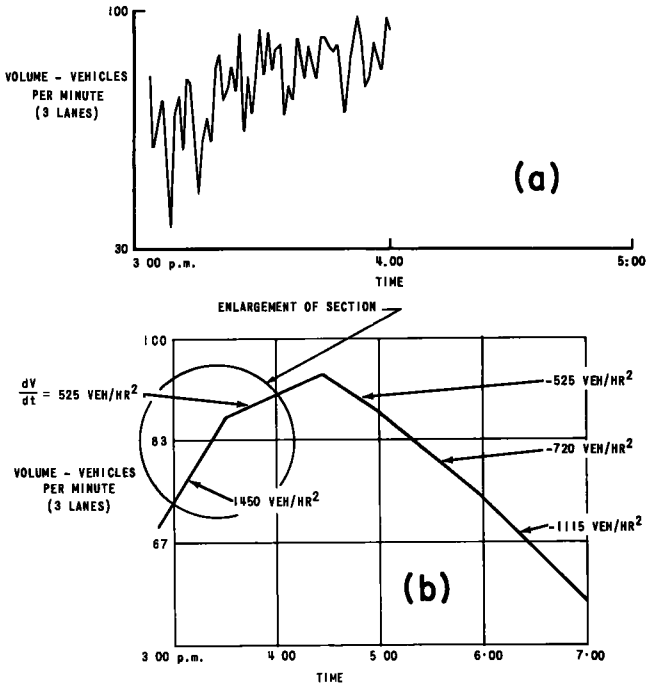


Figure 6. Volume counts on Congress Street Expressway at East Avenue (a) by minute and (b) as smoothed. Data are from Ref. 2.

data not available with the presently installed instrumentation; however, this requirement may be unrealistic. But the test did seem to confirm one characteristic of traffic which was suspected: compression to high density appeared to take place gradually enough so that some warning could be obtained. One compression at high volume persisted for a period of 10 minutes, but most of the time a 4-minute period was characteristic.

Another fault in the computational logic was in the use of the time-smoothed historic curve of volume at East Avenue to predict values of v_t for the period of prediction computation. This curve (Fig. 6b) actually has the minute-by-minute scintillation shown in Figure 6a. The latter is a plot of the volume counts for the individual minutes for the first hour, but its characteristic shape was not known to CAL until the data were received and analyzed. This knowledge, along with the variability of lane volumes, as shown in Figure 4, led to the conclusion that instrumentation on all lanes was required for a real-time prediction system.

THE JOHN C. LODGE FREEWAY EXPERIMENT

The data from the John C. Lodge Freeway were processed by using the computational logic, previously described, which maintained v_t constant during the prediction period but let v_0 be a function of density. The computational procedure had been translated into a series of graphs which were meant to be used as overlays in a real-time density prediction experiment.

The initial attempt was conducted with the intention of making predictions of density in real time, based on readings of the total volumes at Hamilton and Calvert Streets at 1-min intervals. The experiment failed due to a series of difficulties with the detectors and recording equipment.

After correction of the installation of two detectors at Hamilton, a second attempt was made, this time with the object of obtaining printed records of the total lane counts for each minute at the two stations. After a considerable period of data recording, it was noticed that one of the totalizers was recording false counts. The run was stopped and a check made of the approximate error in the totalizer by comparing its reading with the sum of the individual lane counts. Later, a correction for this error was applied during the processing of the data, but the error was found to be too variable so the run was lost.

Finally, two printer-counters were employed by Control Center personnel to collect individual lane counts at each station. These data, along with the ramp counts, speed timing and traffic condition observations, were collected on October 8, 1963. Again errors were found in the lane counts, but application of a correction factor appears to have made these data useful. Processing of the data is discussed in the following paragraphs.

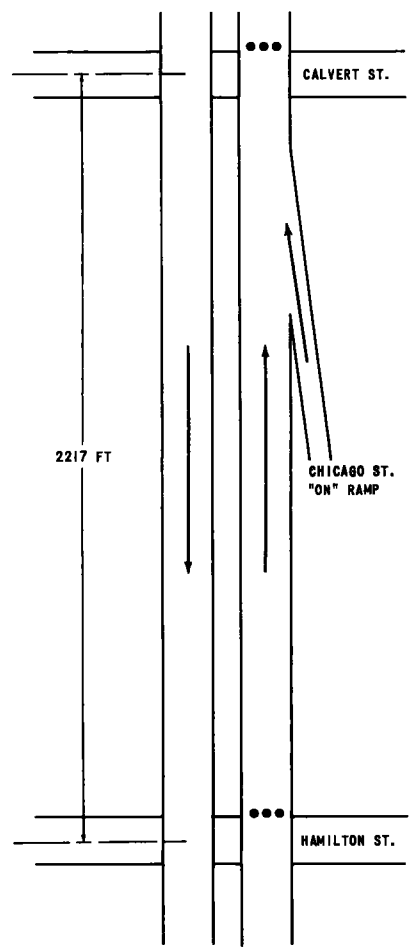


Figure 7. Test segment of John C. Lodge Freeway.

Volume in at Hamilton Street was summed each minute from the detector readings over each of the three lanes. Volume out at Calvert was computed similarly, but was corrected by subtracting from the sum the flow into the segment from an on ramp. This flow, which discharged onto the Freeway just short of the Calvert Street detectors, was measured by an observer through a TV monitor showing the ramp. The test section layout is shown in Figure 7. Minute-by-minute computations of density were made and, as for the Expressway experiment, predictions of density were computed whenever there was an increase in density during the preceding minute.

Although the data processing for the John Lodge Freeway was done after the fact, some of the properties of a real-time operation were preserved. Personnel of the TV Control Center recorded the time and nature of all significant traffic flow perturbations during the data logging period and also sampled speeds in one or two lanes chosen at random during each minute of the period.

Because the actual density was known at the beginning and end of five of the six half-hours of the data logging period, much of the difficulty arising from data recording inaccuracy could be reduced to what appeared to be negligible proportions. This is discussed in more detail in Appendix C of (*1*).

During the 3-hour period there were 32 predictions of "jam" density which, in the light of the experience with the Chicago data, had been increased to 95 vehicles per lane per mile. In 25 instances the predictions were borne out by observed and recorded interruptions to the movement of the traffic, varying from significant slowdowns to complete halts. This is a "false alarm" rate of about 25 percent. Two stoppages that occurred were missed by the prediction process, one at a density of 67 and the other at 75.

From the results it was concluded that some warning of congestion could be provided by a system which would predict density. Although the 3 hours of data processing constitute a small sample, it showed odds heavily in favor of a "fail-safe" system; that is, warnings of congestion brought congestion 25 times during the period but only on two occasions did a stoppage occur without warning. The amount of warning time provided left something to be desired in a number of cases, since only five predictions of congestion gave 3 min or more advance notice. Recalling that the instrumentation for this test provided no information on flow upstream of the test segment and that there was no historical flow versus time data, as there was for the Congress Street Expressway, it is felt that the warning time obtained was reasonable. Detectors located on all lanes at half-mile intervals would have contributed to much more reliable and accurate prediction.

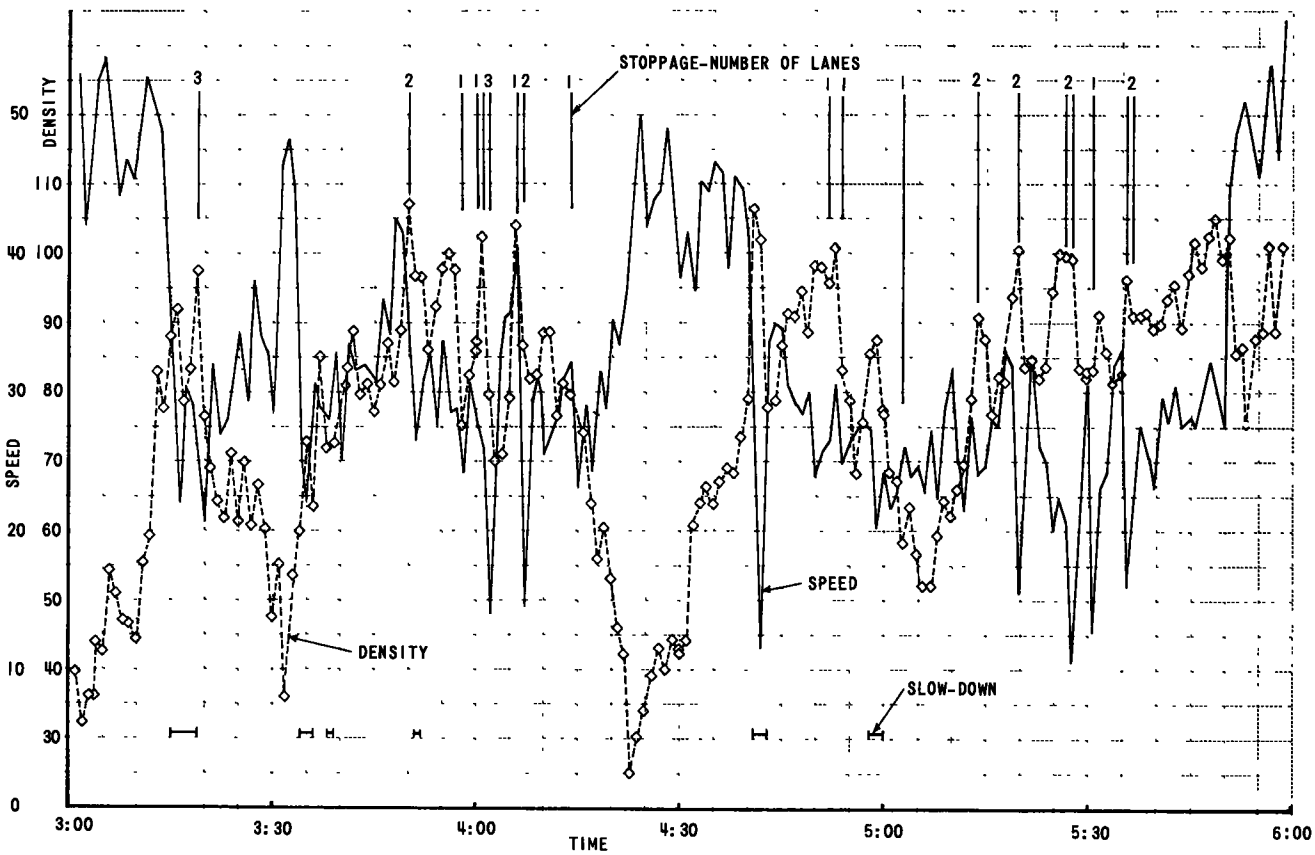


Figure 8. Speed and density variation, John C. Lodge Freeway.

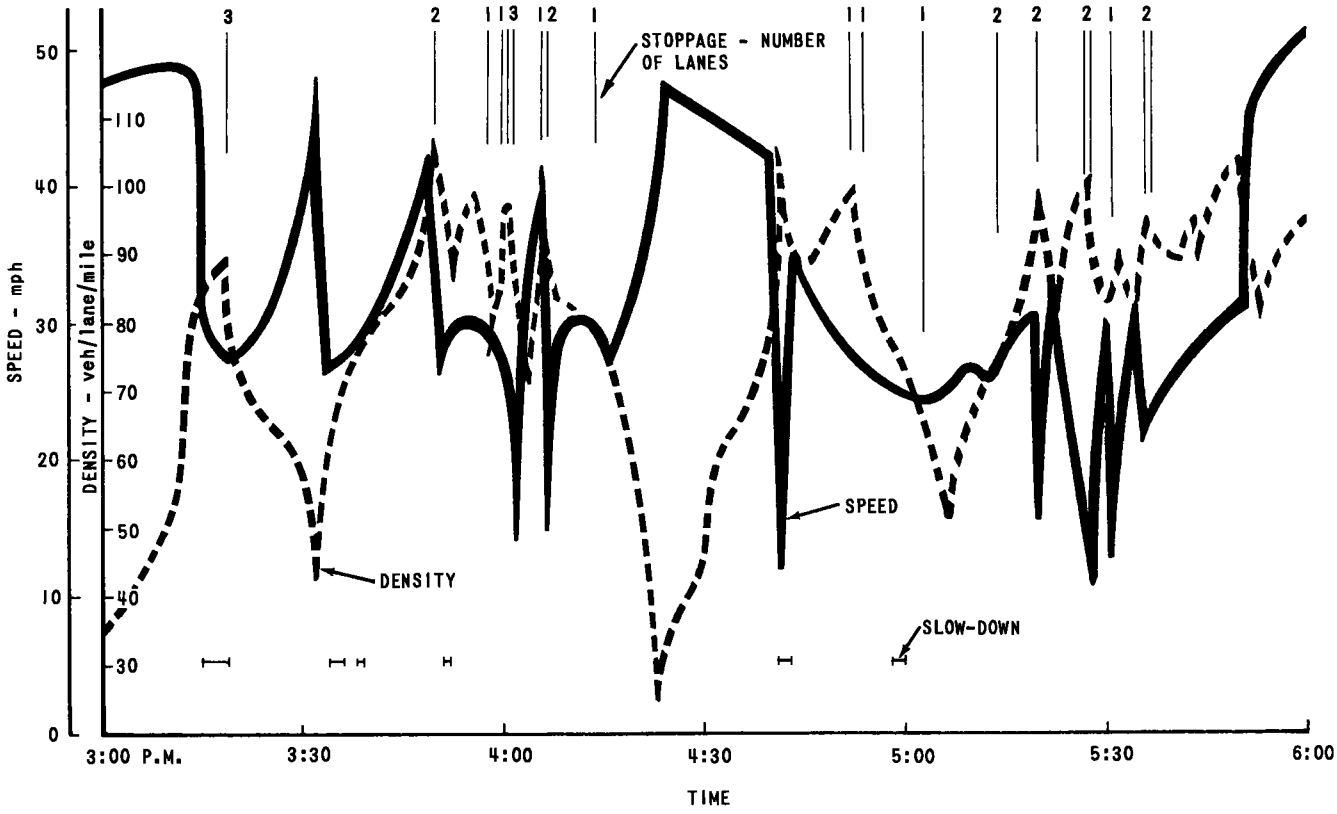


Figure 9. The curves of Figure 8 smoothed out.

Minute-by-minute density and speed variations (Fig. 8) are reproduced in smoothed curves (Fig. 9), which indicate that the correlation shown by the many investigators who have logged this type of data is valid. However, the unpredictability of the behavior of individual segments of the traffic stream is shown by the scatter of density-speed points in Figure 10. This variability will plague the best laid plans of traffic engineers, so long as individual motorists can drive as they please instead of having to conform to a doctrine. However, this variability also explains why the Freeway performed at a high level of both density and speed during the period from 3:40 PM to 3:46 PM, as shown in Figure 9.

DISCUSSION OF THE DATA

The point has been noted that the value of 80 vehicles per lane per mile had been selected as jam density from the data recorded on the Congress Street Expressway (*2*). The speed should have been about 19 mph for this value of density. From the volume-speed data received from detectors over Lane 1 at DesPlaines Avenue the maximum density was computed to be 175 vehicles per lane per mile and the speed was 13.4 mph at 5:53 PM, which is far different from 80 and 19. Lane density computed from occupancy, same place, same time, was 130 vehicles per lane per mile. In all cases the recorded information was

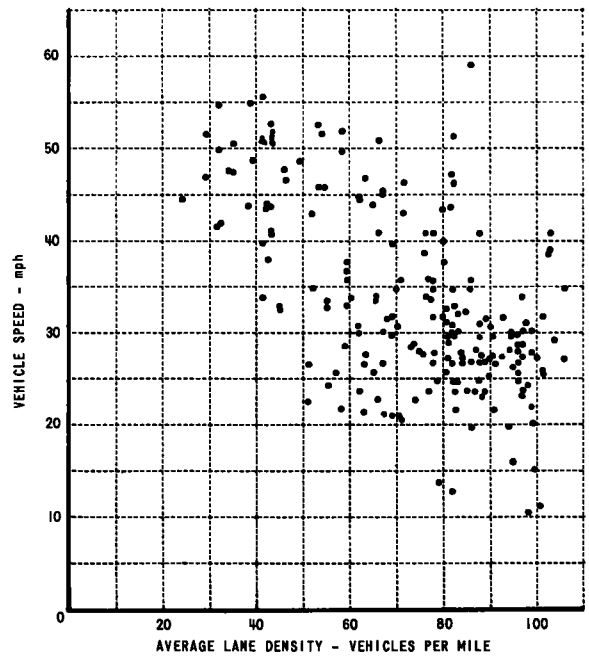


Figure 10. Speed vs density at 1-min intervals, John C. Lodge Freeway, 3:00 to 6:00 pm, October 8, 1963.

the analog averaged value for the 45-sec period just prior to the time of print-out. Similarly, at 5:52 PM a volume-speed computed density of 168 was accompanied by an occupancy computed density of 230 and the average speed was 18 mph. These data are inconsistent within themselves and also with those from the John Lodge Freeway. The latter information is felt to be more credible; there were much tighter controls on the data acquisition and, in addition, it was monitored by experienced observers who could attest to the normalcy of the traffic operation.

Densities calculated with the Detroit data showed values exceeding 100 on eight occasions during the period from 3:00 PM to 5:30 PM, the period during which the data could be corrected at each end of each half-hour. Of the eight occasions, seven produced stops or severe slowdowns. Maximum average density during the period was 107 vehicles per lane per mile.

An upward revision of "jam" density from 95 to 96 or 97 might have reduced the false alarm rate from 25 percent to negligible proportions. However, selection of a new value might be inappropriate for a much larger sample of speed-density data.

CONCLUSIONS

It has been noted previously that traffic facilities of an advanced nature were found to be controlled by signal systems designed specifically for operational rather than experimental and research purposes. The instrumentation installed on the two facilities on which research was being conducted was also of this operational type. The limited amount of work done in processing the data from these facilities shows that no surveillance, evaluation and control scheme which depends on serial computations with summed data can function with the types of equipment currently installed. The analog computers available are not accurate enough to be used to supply data for the computational procedure, although they are quite suitable for processing and recording the more usual traffic data such as volume, occupancy, and average speed. The detector installations were unable to discriminate individual vehicles without possible misses or ambiguities. With the present detector designs this discrimination capability would require 5 detectors for 3 lanes. However, it is felt that the tests, particularly the one on the John C. Lodge Freeway, indicated that the behavior of traffic would make the prediction logic valid if it could be implemented properly.

It is evident that the kinds of control logic and mathematical representation of traffic behavior which may be needed for a next generation surveillance and control system cannot be handled with analog computing equipment, although this hardware has served its purpose well in the past. Traffic volumes are growing rapidly, and increasing the urgency for more efficient use of existing pavement. It appears that the next logical step is to develop a detector capable of collecting from the highway information that can be fed to a high-speed, large-capacity digital computer which can be programed for great flexibility of control. Such computers are available.

Whereas the shortcomings in accuracy of analog types of computers may have been suspected before the experiments were performed, the degree to which they were in error, and the shortcomings of the detectors, particularly the Doppler motion detectors, were not known. This was discovered after the experiment was performed with the Chicago data. Because accurate volume detecting equipment may be very costly, the mathematical models of traffic behavior and computational prediction logics will be reformulated and based on reasonable requirements for volume accuracy. In view of the fact that the presence detectors may offer a computed speed at least as accurate as that derived from the motion detectors, these may be used in an interim effort to implement a new computational procedure. But a need still exists for an accurate and reasonably priced speed-volume detector which will take advantage of the capabilities of a high-speed digital machine.

In a new approach to this problem, concessions will be made to the accuracy of the detection equipment. The prediction will be dependent solely on current information gathered at a number of points along the roadway. Currently gathered data will be analyzed for the purpose of eliciting criteria for the performance which may be expected from the traffic on the roadway, taking into account highway geometry and the environmental conditions, rather than averaged historical data which may not apply to the situation at a particular time. A likely criterion is the volume-density envelope for maximum performance (minimum headway at each speed over the range).

Additional information which might be useful would be the flow conditions on surface arterials in the immediate vicinity of exit ramps; it is likely that during periods of high demand, stoppages occurring on the streets will be transmitted upstream quickly.

A deviation from normal traffic behavior was made apparent from the processing of the data. Stoppages can occur at relatively moderate densities if an accident or other unforeseen incident occurs.

In any future development of a data processing scheme, it may be desirable to examine more than the first derivative of the varying traffic behavior. This sort of computation may be necessary if warning time is not consistent or is too short. Additional data from detectors upstream may alleviate the latter difficulty.

In summary, a prediction logic appears possible which will determine travel time expected along a portion of the freeway under varying traffic conditions, especially when there is a threat of a slowdown. It is suggested that such a mathematical model and computational logic be devised and that the instrumentation required for its implementation be installed on the traffic surveillance and control portion of the John C. Lodge Freeway in Detroit. This facility, with its television surveillance, access ramp controls, speed controls, lane controls, and radio communications through six commercial channels, is known as the National Proving Ground for Freeway Surveillance, Control and Electronic Traffic Aids and is being supported by eleven states and the Bureau of Public Roads. It is a logical site for conducting the proposed experiments, by reason of both its research-oriented project management policy and its relative proximity to the location of CAL.

CHAPTER THREE

THE AIRBORNE OBSERVER IN TRAFFIC CONTROL

This section discusses a method of traffic control not usually considered by traffic engineers as a candidate system for full-time operation but which appears to have great power during periods of peak traffic flow. The idea of airborne observation and control is not at variance with the aims of the project, even though the principal emphasis is on the implementation of ground-based, fully-automated surveillance and control systems.

Although aircraft were used for observing and controlling traffic more than 25 years ago, the literature on traffic control contains only one report by the California State Highway Patrol (*4*), although another report on use of rotary-winged aircraft is in preparation by the same agency. The existence of the Radio Station WEBR "Trafficopter 970" airborne observer service in Buffalo made it convenient and economical for the project to evaluate this system. Project personnel were appointed to monitor the broadcasts and also to investigate some of the history of, and public reaction to, the service.

A traffic control system using an airborne observer for surveillance, detection, discrimination, evaluation, decision-making and communication of commands might be of special value to patrol a metropolitan area during the two peak traffic periods of the day. The application of television surveillance to 3.2 miles of the John C. Lodge Freeway (and similar installations in 13 cities in Germany) has proven that human observer-controllers, given a simultaneous view of a significant length of highway, can exercise beneficial control over traffic in order to expedite its movement with safety. Although the television equipment is not overly expensive, its area of effectiveness is very limited. Therefore, personnel who monitor the video presentation spend a large portion of their time observing a smoothly operating Freeway which does not require their intercession. The same observer, if airborne, would attain a degree of mobility that could make him almost immediately available to handle a traffic snarl resulting from some sort of emergency or accident that would occur in an urban complex of some 50 square miles in area. Whereas the cost of the aerial "platform" becomes a major item of expense in such an operation, the increased area of coverage is also significant, so it remains for an evaluation to show the cost versus effectiveness of the system. Preliminary considerations concerning such an evaluation are described later in this section.

In his present role, the WEBR "Trafficopter" is essentially an aerial traffic policeman. By contrast, the airborne-observer operations conducted by the Port of New York Authority as Project Skycount are directed toward research in traffic movement, their primary method of data acquisition being time-lapse vertical photography, although they also include estimates, made subjectively by the airborne observer, of relative traffic densities along heavily-traveled major routes.

GENERAL DESCRIPTION OF THE OPERATION

Aerial surveillance in Buffalo is carried out from a Bell Model 47 helicopter, carrying both a pilot and the traffic reporter. The area patrolled regularly is about 6 miles wide in an east-west direction, and about 12.5 miles long in a north-south direction. This primary route is shown in Figure 11 by the solid line. The area encloses a population of about 500,00 to 600,000, but the motorists served by the Trafficopter are primarily commuters originating over an area populated by more than 1 million. Weather permitting, the patrol flights usually are conducted at 400 ft above the surface and at a speed of 70 to 75 mph.

Flights are performed in accordance with Federal Aviation Agency regulations covering operation of rotary-winged aircraft. Therefore the only statutory limitation on flying operations is dense ground fog. The practical limitations are gale winds or severe icing conditions. Within these limits, generally less than six flights are missed each year.

Communication to motorists is usually made via a two-way microwave link between the helicopter and the radio station and then rebroadcast through WEBR on its regular frequency in the AM band. On occasion, the helicopter descends to the scene of a serious tie-up and issues advisory information through a powered megaphone. WEBR is one of five radio stations located in the Buffalo area which broadcast on the AM band. The others do not participate in the "Trafficopter" service.

Inasmuch as the route of the patrol is fairly well defined, having evolved through experience, the times at which broadcasts are made are fairly regular. A typical report will be of 2- to 3-min duration. In the event of a traffic tie-up or other emergency, the observer requests immediate time on the air for reporting and issuing advisory information. These broadcasts are accorded unlimited time and are used to help fulfill the Federal Communication Commission's requirements (not specifically defined at this time by the FCC) for service to the public by the radio station.

The normal flight schedule maintained during the summer vacation months (July and August) is from 7:45 to 8:30 AM on weekdays only. For the rest of the Daylight Saving Time period (May through October) the patrol is increased to the hour between 7:30 and 8:30 AM. During the remainder of the year an afternoon flight from 4:30 to 5:30 is added to the 1-hr flight in the morning.

Although the regular Trafficopter service is supported primarily by commercial sponsorship, Radio Station WEBR shares the cost of the helicopter for special holiday and sporting events or emergency situations and rescue missions such as are generally caused by weather, missing persons, and waterfront accidents. Much of the public service rendered by the airborne observer in this latter role cannot be readily evaluated in dollars.

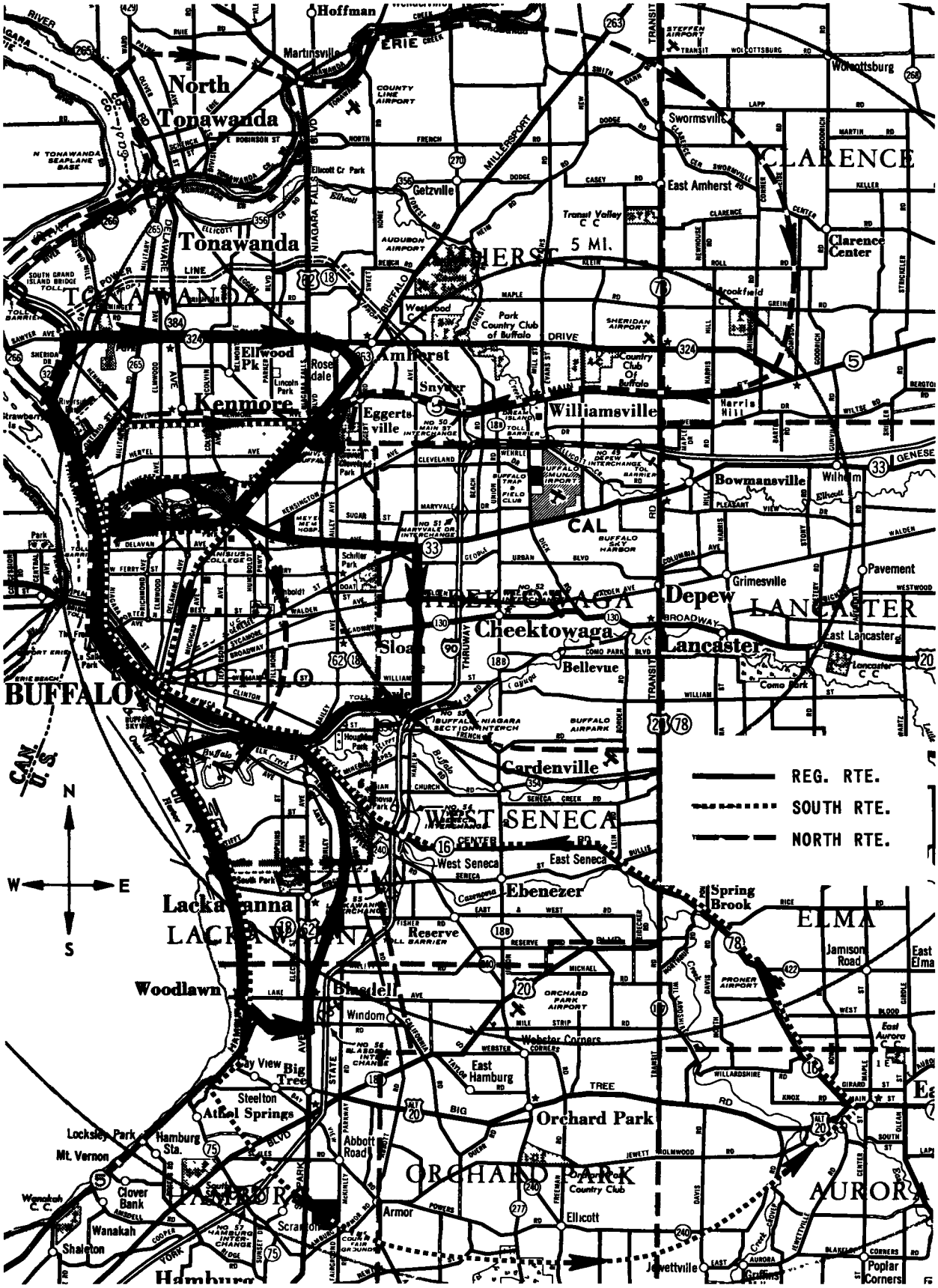


Figure 11. Buffalo's Trafficopter patrol routes.

TYPICAL AND EMERGENCY BROADCASTS

Typical reports of no significant traffic events are made four times during a 45-min flight and five times during a 60-min flight. They include a notation that traffic is heavy, moderate, or light and the names of the principal arterials and freeways concerned. Comments and reminders are offered on exact locations where bottleneck conditions might develop due to construction or parked repair or service vehicles, and any other general information that may help motorists to traverse the major routes with minimum difficulty.

When an emergency occurs the Trafficopter is accorded as much time on the air as he deems necessary to report and advise on the situation. An abridged account of one of these broadcasts is presented here. This city-wide situation was caused by bad weather during the afternoon of February 6, 1964. A heavy snow had started at about 2:00 PM. By Trafficopter flight time (4:45 PM) there was an accumulation of 2 to 3 in. on the ground and the snow was so wet that it had packed to an icy consistency on the streets. The aviation weather broadcast at 4:45 gave the ceiling as 100 to 200 ft, obscured, and the visibility as ⅜ mile. Conditions at the heliport were worse. Buffalo Airport was closed to all traffic. The Trafficopter remained airborne until 6:15 PM giving many reports on conditions on the ground both with respect to the conditions of the streets and the traffic situation. No difficulty was experienced with the radio transmission and reception.

The following broadcast was made at 5:40 PM:

> We are flying now over the Kensington Expressway and boy, it's really snowing! Visibility is about an eighth of a mile right now. Traffic is stacked up all over the place and we'll give it to you route by route. First, don't get on the Kensington Expressway. The traffic is backed up all the way from Humboldt and Utica into downtown Buffalo. They can't get up the incline leading to Humboldt Parkway. The exit ramps are impassable and there are ten cars pointing in every direction on the Best Street ramp. Motorists are all getting together and trying to push cars up the ramps. For those of you already in this jam there just isn't any alternate route, as you can't get off so you'll just have to bear with it. That incline and the ramps are just sheets of ice. A salt spreader could ease this whole jam in about ten minutes by merely coming down the other side of the Expressway, crossing the divider, and fixing this incline.
>
> The Thruway eastbound to South Ogden is backed up all the way from the toll barrier to the Genesee Street on-ramp. They're just packed in there solid and moving about five miles an hour and stopping many times. Take Clinton or William to the east. . . . The Skyway, Fuhrmann Boulevard, and the Father Baker Bridge, strangely enough, are not in bad shape . . . , so those of you who live along the lakeshore, keep coming. You'll be okay if you take it easy.
>
> Don't take the Thruway north out of downtown. . . . Take Seventh Street to Porter, then get back on the Niagara Section and you won't have much trouble going north.
>
> Delaware Avenue is impassable between. . . . Once again a salt spreader could ease this mess in minutes. One car at most gets through on a green signal and sometimes none. If you're coming up Delaware, get off at Gates Circle. . . . Elmwood Avenue is in bad shape too, but anything is an improvement over Delaware. The problem on Elmwood is northbound between Hertel and Kenmore. Once again, it is inclines causing all the trouble. You can turn on Hertel and duck through residential streets to Kenmore and then swing back. Actually, you can turn right on Amherst, go back to Delaware and proceed north. The jam on Delaware is all south of Amherst Street.
>
> Main Street is a mess. We always have that tangle at Main–Winspear which is bad enough in good weather. To compound it, two cars have collided right under the railroad overpass just north of Hertel. They are blocking the passing lane at the moment. As a result traffic is backed up just about solid all the way back to Fillmore. There is a little gap, and then it's stacked up again down to Michigan. There really aren't any alternate routes for Main as nothing else goes under the tracks. The only other route is to go 'way over to Starin and that means an illegal left turn off Main Street. Lots of blinkers down there and we thank you for your "hello" and are sorry we can't get you out of that mess you're in. There's a blinker coming up now. Turn right on Amherst sir, you'll do a lot better! Atta boy, there he goes!
>
> This is a long report but there is a tremendous tie-up eastbound on the Scajaquada Creek Expressway. They can't get up that slight incline at Parkside. Cars are taking a run at it one at a time and they are having a tough time. The jam begins right in front of the Parks Department and all someone would have to do is throw a few shovels of salt on the road and it would be okay, but I guess they've all gone home.
>
> That's just about it, Carroll. Stay off the Thruway north to Porter, Seventh Street the alternate; avoid Delaware between Delavan and Nottingham either north- or southbound, Elmwood the alternate. Main Street is just about blocked, get off at Amherst and take the back way. The Kensington Expressway is completely blocked, don't get on it. Scajaquada Creek Expressway eastbound is in the same shape. Thruway eastbound, five miles an hour at best. Usually the Expressways are the best routes in a snowstorm, but not today, they are a mess. These jams are all being caused by slippery inclines. Three or four salt spreaders in the right places would cure the reason in ten minutes, but we've been up here forty minutes and nothing has changed. Back to the ground and. . . .

Fortunately for traffic, broadcasts like this are relatively rare. A general deterioration of movement was indicated at a sufficient number of critical points to delay commuting motorists as much as 3 hr in getting to their destinations. In the more usual emergencies, delays may be suffered up to 25 to 30 min per vehicle, but on only one route, and diverting to alternate routes usually alleviates the tie-up.

EQUIPMENT AND COSTS

The principal equipment required for an airborne-observer operation is:

1. An aircraft or aircraft flight service (usually helicopter).

2. A radio broadcasting station in the 550–1600 kc band (AM). FM may do in some areas, but usually is subject to the line-of-sight restriction for high-frequency radio.

3. A two-way communications link, aircraft to radio station.

Helicopter services were priced ranging from $59 to $100 per hour for the same type Bell Model 47 three-place machines, based on a utilization of 500 hr per year. A two-place Hughes helicopter service was quoted at $56 per hour and the smallest machine that could serve to carry a pilot, an observer, and 50 lb of equipment was the Brantly, at $45 per hour. All prices included the cost of a pilot.

Light aircraft can be rented on a similar contract basis for less than $10 per hour, not including the services of a pilot. The simple operation of these machines would probably make it unnecessary to have a separate observer aboard, as the pilot could perform both functions with relative ease.

A commercial broadcasting radio station is not included in the cost. It is expected that traffic broadcasts from an airborne observer would be relayed through these radio stations as a public service in partial fulfillment of FCC requirements for public service.

Cost of a police radio system is not cited either, because it would be in operation anyway and an airborne observer coordinating with the various police branches would simply be identified as another "car." The Trafficopter has been deputized as "Car 506" of the Buffalo Police Department. A standard police frequency two-way radio is carried in the helicopter.

The airborne communications transceiver used in the Trafficopter operation is a Motorola T33 BAT-1102A. Simplex transmission and reception is at 163.6 megacycles. Transmitting power output is 7 w, maximum power input is 3.2 amp at 24 v. Cost of this equipment, which weighs 22 lb, is approximately $725.

A solid-state transceiver for the same frequency range is available from another manufacturer. It weighs only 3.25 lbs and has a 1-w output on the antenna. It carries its own battery pack, so is completely portable, but can be plugged into a 12-v direct-current system (standard for most light aircraft) with a cable of negligible weight. The cost of this unit is about $630. The 1-w radiating power would be adequate for transmission to the radio station for the radius of operation over most city complexes, especially if that station employed an elevated, rotatable, directional antenna, as does Radio Station WEBR. The cost of the antenna was less than $100, as it was a cut-down version of a standard "ham" antenna, a 13-element array.

An annual operating cost for an airborne-observer service might be assembled by assuming that a helicopter and pilot would cost $30,000 for 500 hr per year. The observer, who would be a member of a police or sheriff's department, would receive a flight pay of $5,000 for the year (including fringe benefits and overhead), bringing the total annual operating expense to $35,000. The initial cost of two transceivers, one for a traffic broadcast channel and one on police frequency, would be $1,500. Maintenance costs on the radio equipment are negligible.

EVALUATION PROGRAM

The program to evaluate the effectiveness of an airborne-observer traffic control system developed as a result of auditing the broadcasts made by the Radio Station WEBR "Trafficopter." The content of these broadcasts seemed to make up two classes of control information for:

1. Reduction of long-term (repetitive) traffic movement difficulties.

2. Reduction of spontaneous (accidental) traffic movement difficulties.

In each case "control" is effected only by the Trafficopter's issuing voice communication advisory messages through the Radio Station WEBR frequency of 970 kc. The service thus offered is available to all motorists who elect to receive this frequency during the period when the Trafficopter is on patrol.

The task of evaluating the effectiveness of the Trafficopter is doubly difficult. First, it is not known which drivers in a traffic complex are monitoring the broadcasts. Second, there is no assurance that the instructions contained in an advisory are being followed, assuming that they are received. For these reasons it would seem that the effectiveness of a properly implemented and authoritative airborne-observer control system should be greater than one dependent on the good office of a commercial broadcasting station and a voluntary obedience on the part of the drivers.

A properly implemented system might be one in which all vehicles operating in a "control zone" would be required to be equipped with a crystal-controlled command channel receiver. The receiver would be automatically switched on with the ignition system so that advisory broadcasts would be received whenever the vehicle was in operation. Both the broadcasting station and the airborne observer would be part of the local government so that ground patrols would be advised as to specific traffic control measures to be effected through the same command channel. It is thought that this combination of information on a situation and corrective action would have a desirable effect on the alacrity with which motorists would follow instructions and would prevent, rather than provoke, accident-inducing impatience.

The order of the program to measure the effectiveness of this type of control system was purely a matter of chance. The broadcasts were first audited during the month of May 1963, so that peak travel periods occurred in full daylight and general fair weather. At this time of year the Trafficopter service is offered in the morning only. It was a fortunate period for Buffalo motorists: there were no accidents or incidents of any great significance to traffic in the region under surveillance. However, some long-term construction was under way on a limited-access road that carries a heavy load of commuter traffic into the city. As a result, the broadcasts frequently carried advisories urging some motorists to leave this road at ramp locations prior to their normal exits and to follow surface arterials which were recommended because they were lightly loaded at the moment. It appeared that the construction was causing a continued difficulty but the motorists were accustomed to

the route and were enduring the resulting delay rather than explore an alternate route.

The first of the Trafficopter's capabilities of interest to this project was the possibility of reducing travel time by a redistribution of traffic over the available route structure. Discussions with the Trafficopter's principal observer, John R. Sharpe, on the nature of the operation led to the formulation of an alternate route travel study.

ALTERNATE ROUTE STUDY

It was agreed that the Trafficopter would broadcast an appeal to local motorists to assist in a study of commuter traffic. (This was thought to be for the first time anywhere.) No details concerning the nature of the test were to be given, simply a request that drivers willing to cooperate should state so in a card or letter addressed to Radio Staton WEBR. It was expected that CAL would supply a letter of reply giving instructions on the conduct of the study and also a card for recording the data desired. The first phase of the test was to acquire statistics on morning commuter trips in the Buffalo complex. Data were requested on travel times, trip distance, route of travel, and scheduled stops enroute for a two-week period (ten trips). The intent was to "thread" the routes on a map, which would show both the popular routes of travel and the relative amounts (assuming the data sample was large enough).

It was hoped that a control group and a test group could be designated for each of several well-traveled routes. Alternate routes would be selected by the Trafficopter, based on his experience and knowledge of the Buffalo traffic situation. The test groups would be requested to follow these routes for a period of two weeks, recording the same kind of data as previously. Both sets of data were to be processed and evaluated in accordance with the procedure shown in Appendix I of (*1*), which would indicate whether or not the selection of alternate routes by the Trafficopter resulted in a decrease in total travel time.

The number of volunteers who offered to act as test participants was disappointingly low—only 525 drivers. They were furnished the instructions and cards previously mentioned. Of the 525 cards sent out, 332 (63 percent) were returned in various stages of completion. When the routes were threaded on a map it was evident that only about ten or twelve surface streets, including three expressways, carried the large majority of the responding drivers into the central business district, which appeared to be the prime "target" for that part of the day.

About 260 cards of the 332 (50 percent of the total) returned to CAL carried data consistent enough to be processed. This means that at least nine trips were made over the same route with the same number of scheduled stops and at approximately the same time of the morning (same general traffic conditions). Processing consisted of computing, for each card, the average speed, average trip length, and time variance. Results of the calculations are discussed later.

An examination of the routes traveled by the participants seemed to indicate that the desired procedure of establishing control and test groups would not be feasible. For one thing, the only place where a number of drivers sufficiently large to split into two groups traveled a sufficiently long distance over the same route to give meaningful results was over an expressway. In a normal traffic situation there is no alternate to this route which can provide a decreased travel time. Therefore, in order to gain some indication of the Trafficopter's ability to redistribute traffic patterns, it was necessary for him to devise alternate routes for individual drivers, an unexpected task which imposed a considerable delay in initiating the second phase of testing. The original travel time reporting period was the two weeks beginning October 7, 1963. The second phase was begun on February 10, 1964 and may continue beyond the termination date of the contract period for this report.

CONTROL OF EMERGENCY SITUATIONS

Continued auditing of the Trafficopter's broadcasts finally resulted in recording his handling of a traffic situation which occurred as a result of a three-car accident on a major limited-access arterial leading into Buffalo. This incident indicated ways in which the airborne observer could most effectively perform the following functions:

1. Detect the occurrence of the accident.
2. Inform motorists of the accident and its location.
3. Note the number of lanes blocked and estimate the rate of growth of the waiting queue.
4. Advise motorists as to the expected delay time in the queue and the alternate routes available to those not having reached the last exit point before the queue.
5. Detect and locate police and tow vehicles heading toward the scene and estimate their time of arrival, broadcasting this information to motorists at the scene of the accident.
6. Observe clearing operations of disabled vehicles, estimate rate of dissipation of the queue, and then issue advisories on the time at which normal conditions would be restored.
7. Advise motorists using the route that if they were beyond a certain point (farther distant) and headed toward the affected area to continue on the route, rather than use an alternate, because the traffic would be moving freely by the time they arrived.

It is reasonably certain that existing technology falls far short of the ability of the human to accomplish these functions. Many of the accomplishments in detection, surveillance, data processing, recognition, discrimination, traffic control (in the general sense) and communications were considered. The fields of airborne and space operations (conceded to be the most advanced in these areas) were reviewed in this connection. It can be stated categorically that no complete inventory of equipment exists which could have accomplished the functions listed without human intercession.

Because the broadcast seemed to indicate the most significant role the airborne observer might play in controlling traffic, it was decided to maintain a record of his intercessions in behalf of the motorists. A tape recorder was used for this purpose. As some of these broadcasts were played back it became apparent that the information contained in them might make it possible to reconstruct the traffic

situation in order to evaluate the airborne observer's effectiveness in reducing delay time caused by the incident.

During the evening broadcasts on November 15, 1963, there were four accidents in the Buffalo area that had a serious effect on traffic. For three of these it was possible for the Trafficopter to reroute traffic by issuing alternate route advisories and in one case enough information was reported to permit a crude reconstruction for evaluation purposes.

This particular incident was caused when a bus caught fire on Main Street in Buffalo. An analysis of the situation was made to determine delay suffered by motorists caught in the tie-up and the delay avoided by those who followed the airborne observer's advisories on alternate routes.

The crudity of the analysis was enforced by the sparseness of data. It appeared that adequate data could never be supplied by means of surveillance of the vehicles in the traffic stream, except at a forbiddingly high cost. Even then there could not be a close accounting of the time delays experienced by drivers following the advisory broadcast instructions in the event of an incident. For several reasons, only the drivers themselves could supply this information.

Inasmuch as accidents cannot be foretold as to either time or location, accurate recording of delays would require that an airplane equipped to take time-lapse photographs in color be on patrol at all times when the Trafficopter was airborne. This conclusion came as a result of long consideration of the several ways in which a traffic tie-up could be observed and recorded for purposes of time delay evaluation. Then, assuming that photographs of the entire area affected could be taken, it would be possible to count the numbers of trapped cars and the lengths of time they were delayed. But the problem remained of discriminating the vehicles that used the recommended routes from vehicles that followed these routes, or portions of them, in their ordinary travel. It was apparent that the information needed for a complete reconstruction must come from the drivers themselves.

Accordingly, it is contemplated that a different technique, that of public relations, will be applied to the problem of acquiring traffic data. As of this writing the Buffalo Police Department and Erie County Sheriff's Department have been enlisted in the data collection effort. Also, a publicity campaign is being assembled that will be released through a Buffalo newspaper and Radio Station WEBR in an effort to evoke a high level of public interest and encourage motorists to become "deputy researchers."

It would be incorrect to view this effort as a publicity stunt, although it may have that general appearance. So long as the acquisition of certain types of traffic and travel information by surveillance external to the vehicles remains a difficult problem, it will be of great value to have the information presented in the form desired by the drivers. It is expected that this whole problem will be posed when it is desired to evaluate the effect of the implementation of controls on an urban freeway, when re-routing may be done by automated means. If the campaign is successful in Buffalo to the point that the public will cooperate to a satisfactory degree, it will point the way to achieving meaningful evaluations of traffic systems at a reasonable cost.

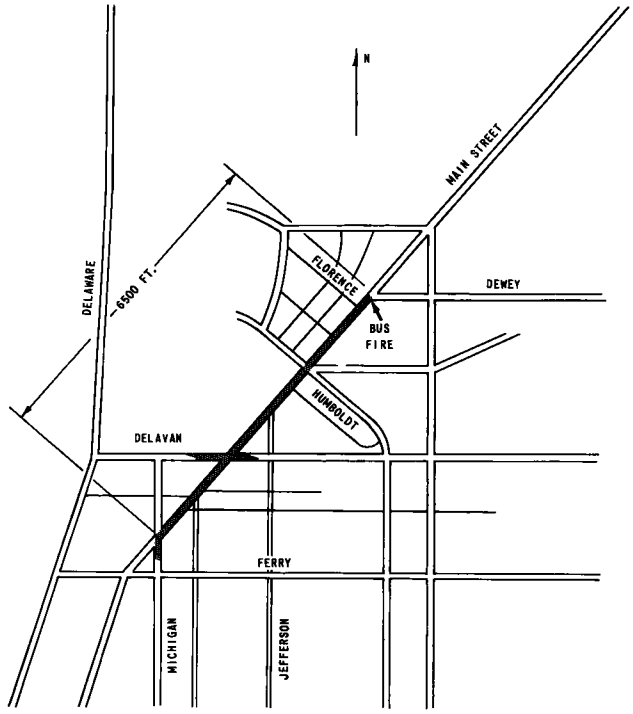


Figure 12. Effect of bus fire on traffic blockage, Main Street, Buffalo, N.Y.

DISCUSSION OF RESULTS

Results of the investigation into the airborne-observer operation are presented in two parts. The first has to do with handling of two accident situations and the second with the continuing alternate route study.

Accident Situations

One of the incidents analyzed was caused when a city bus caught fire on Buffalo's principal arterial street during the peak period on a Friday afternoon, and in the direction of travel of the lanes bearing the major traffic. A queue 6,500 ft long developed in three lanes, extending southward on Main Street from the scene of the fire nearly to Ferry Street. No data were available on the amount of traffic tied up on the streets crossing or emptying into Main Street. The area involved is shown in Figure 12.

Information elicited from the Fire Department, the Police Department, the Trafficopter, and the City Traffic Engineer led to an estimate that 750 vehicles in the queue suffered an average delay of 20 min each. Probably another 680 vehicles were re-routed by the Trafficopter, losing only about 5 min each over their normal travel time. The cost of the delay to those caught in the tie-up, using $1.25 per vehicle-hour as the penalty, was $312. The loss to those who were re-routed was about $71. However, had the re-routed vehicles remained in the queue, their loss would have been about 47 min each, at a cost of $665. It can be seen that the potential savings for all motorists would have been in the order of $850, had they been subject to full control by the airborne observer.

The second incident occurred on a limited-access expressway within the City of Buffalo. A three-car accident blocked the two lanes momentarily during the morning rush hour. A light snowfall during the night had made the roadways slippery. The accident was observed by the Trafficopter and a broadcast was made immediately, advising on alternate routes and describing the incident. Although one lane was opened almost immediately, 80 vehicles collected in a queue in 4 min, and then dissipated relatively rapidly. The volume flow was computed, from the rate of build-up of the queue, as 1,200 vehicles per hour. The Trafficopter noted that the blockage remained for an hour.

In this particular incident the cost of the delay to drivers caught in the queue is of secondary interest, because it was small. The important point is the likelihood that about 1,100 drivers may have avoided an average delay of about 28 min, for a total of 512 vehicle-hours or $640 of expense.

The two incidents described may be considered as typical of those in which the airborne observer has functioned in his most useful role, that of issuing advisories on traffic difficulties. Other incidents which occurred are not described because there was insufficient information on which to base an analysis. However, the frequency of such happenings is important because the cost-effectiveness of the airborne-observer function must be based on total delay time eliminated compared to the cost of the service. Other benefits deriving from the service may be much more difficult to cost, such as involvement of human life.

Table 1 gives incidents that called for advisories on alternate routes. The list must be considered incomplete, however, because all broadcasts were not monitored by CAL personnel and no other records have been kept. As can be seen from the dates, the only consistent monitoring of broadcasts took place through the month from October 16 to November 15. From a discussion with the Trafficopter it was determined that the frequency of traffic tie-ups due to all causes might be higher than indicated by this sample (more nearly 180 to 200 incidents per year). During the sample period twelve incidents occurred which required re-routing. No firm estimate of the time saved by the motorists through the Trafficopter's intervention can be made for these incidents. However, some evaluation may be made in the reverse order.

If a helicopter service at $30,000 per year is used and the observer is paid $5,000 per year ($10 per hour flight pay, including fringe benefits and overhead) the cost of the airborne-observer operation would be $35,000. (It is assumed that the observer is a member of a police or sheriff's department.) Based on 180 incidents per year the delay cost eliminated would have to be only $200 per incident for the service to "earn its keep." Results of the analyses of the two incidents for which costs were approximated indicate that the operation might justify its expense.

The incidents that took place on August 7 and November 7, 1963 (see Table 1) emphasize the point that direct dollar cost might be secondary in some instances. For one, during the flood it was necessary to transfer blood from a donor service bank to a hospital when it was needed urgently for an open-heart surgery case. In the November 7 incident a control system fully attended by all drivers would have made it a relatively easy matter to route the ambulance. At a time of peak traffic flow, when streets may become blocked quite easily by an accident of some sort, the value of the airborne observation point with communication to emergency vehicles is obvious.

TABLE 1

INCIDENTS OBSERVED BY BUFFALO "TRAFFICOPTER"

Aug. 7, 1963	A severe flooding situation over much of Buffalo resulted from an unusually heavy rain. The Trafficopter was airborne 8 hr.
Oct. 16, 1963	N.Y. State Thruway barricaded for construction. Traffic jam required issue of an alternate route advisory.
Oct. 17, 1963	Repeat of October 16. Estimated delay was 10 to 15 min.
Oct. 18, 1963	Repeat of October 16. Estimated delay was 12 to 15 min.
Oct. 21, 1963	Construction on Main Street at Bailey. Advisory issued.
Oct. 28, 1963	Fire at Main and Summer. Several advisories due to severe traffic load.
Oct. 30, 1963	Blocking of heavily-loaded boulevard. Issued advisory to avoid delay of 4 to 7 min.
Nov. 1, 1963	Bus-car accident, Main at Winspear. Alternate routes advised. Severe traffic jam, estimated 15-min delay if alternates not used. Stalled truck in jam added to tie-up.
Nov. 6, 1963	Heavy fog and smog. Barricades on Thruway for construction. Advisories issued to avoid bad tie-up.
Nov. 7, 1963	Child struck by car on heavily-traveled boulevard. Alternate routes advised. Noted difficulty of ambulance to find its way through the traffic jam.
Nov. 15, 1963	Four incidents. Bus fire on Main Street. Accident on entrance ramp to Thruway. Car broken down on heavily-loaded boulevard. Advisories issued on all three. Severe six-car accident on Thruway, no alternates available except to wait for clearing operation.
Jan. 31, 1964	Accident on suburban road. Advisories issued to avoid delay of 9 to 12 min.
Feb. 6, 1964	Severe snowstorm. Conducted a general patrol operation.
Feb. 19, 1964	Accident on urban expressway, advisories issued. Three-car accident on Thruway, no advisories.

Results of Alternate Route Study

Referring now to the previously described "Alternate Route Study," the data returned from the first travel time survey were processed for 266 of the 332 cases. Nominally, there are ten trips for each case, although in isolated instances

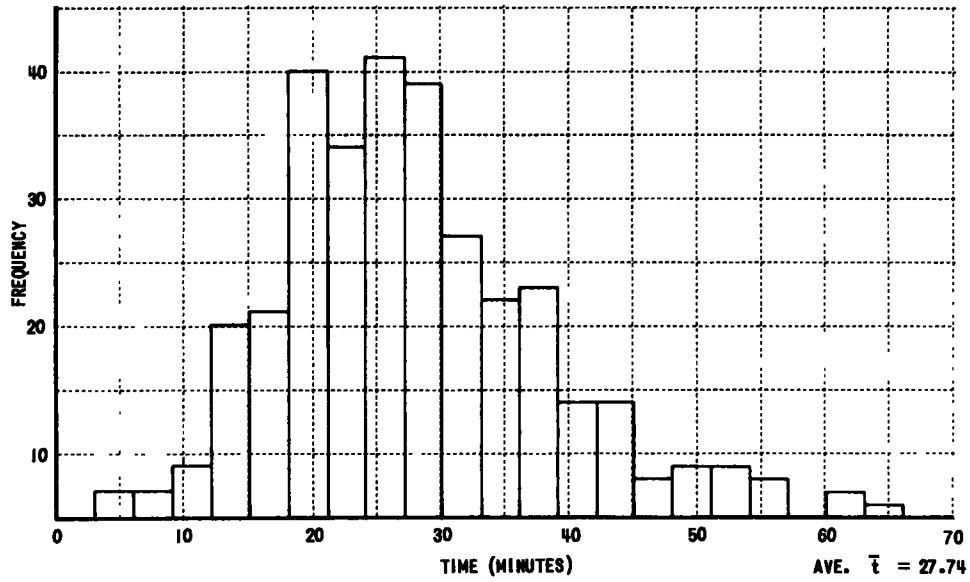


Figure 13. Distribution of average travel time of Buffalo commuters. Data for ten morning trips in two weeks beginning October 7, 1963.

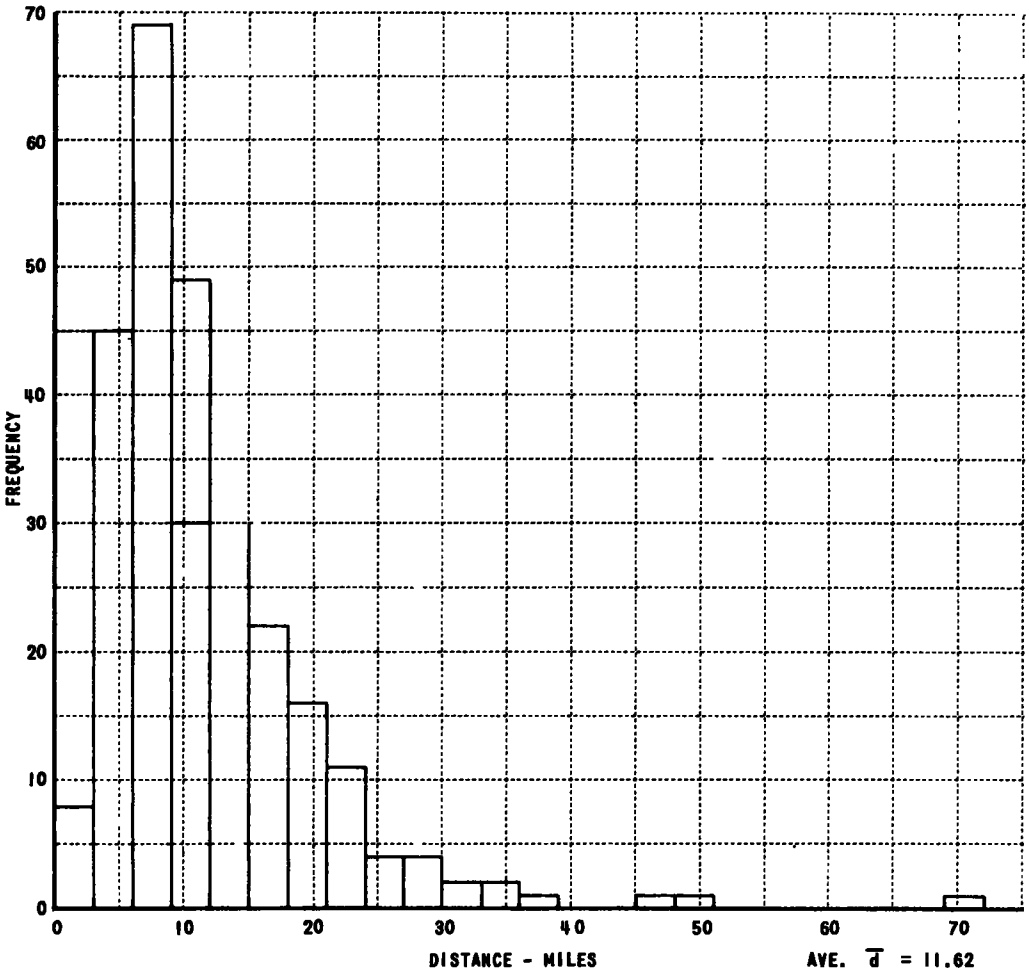


Figure 14. Distribution of average (one-way) travel distance of Buffalo commuters.

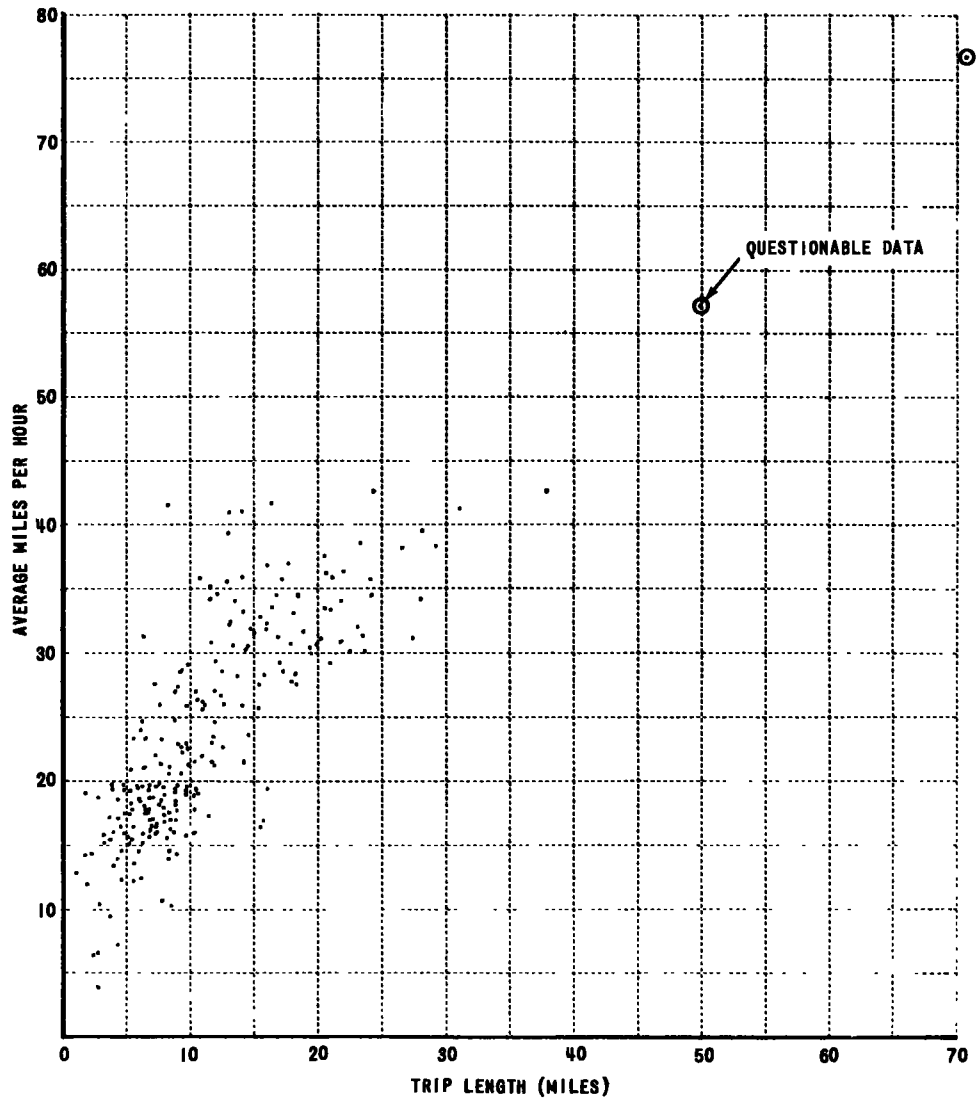


Figure 15. Trip length vs average speed, Buffalo commuters.

one trip may have been rejected from a case because of some radical departure from the usual travel pattern.

It has been noted that the recorded data were processed to furnish, for each case, average speed, average trip length, and time variance. These data are most meaningful when considered against the total background of this travel sample for the Buffalo area. Therefore, the distribution of travel times for the 266 cases is shown in Figure 13 and the distribution of travel distances in Figure 14. The difference in the appearance of these two profiles is caused by the fact that the longer trips are accomplished at higher average speeds, as shown in Figure 15. This is an indication that most commuters are concerned with holding their travel times to less than some value that is accepted as a maximum. Figure 13 suggests that 35 to 40 min is that maximum value for this area. All data were for morning commuter trips for the two weeks beginning October 7, 1963.

The distribution of average speeds is shown in Figure 16. The time variance, $\bar{\sigma}^2$, is plotted against trip length in Figure 17. This variance is computed as the average value of the squares of the differences between the time for each trip and the average travel time. For example, the values for one travel time card are: average trip length, $\bar{d} = 10.38$ miles; average trip time, $\bar{t} = 31.3$ min; time variance, $\bar{\sigma}^2 = 4.23$ min^2. One point made evident by Figure 17 is that the time variance is not dependent on trip time. From the viewpoint of the driver this means that a nominal schedule has been established and he will change the speed and urgency of his driving in order to maintain that schedule. Also, some drivers commuting long distances travel in a traffic environment which permits them some freedom in making up lost time due to unforeseen delays enroute.

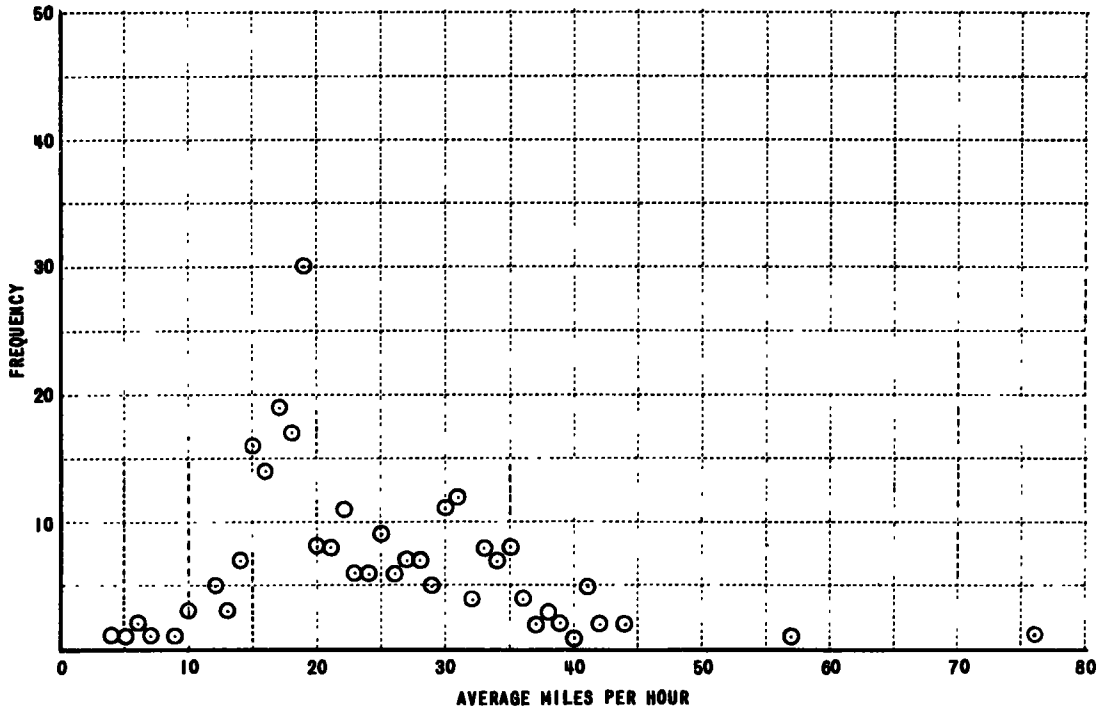


Figure 16. Distribution of average speed, Buffalo commuters.

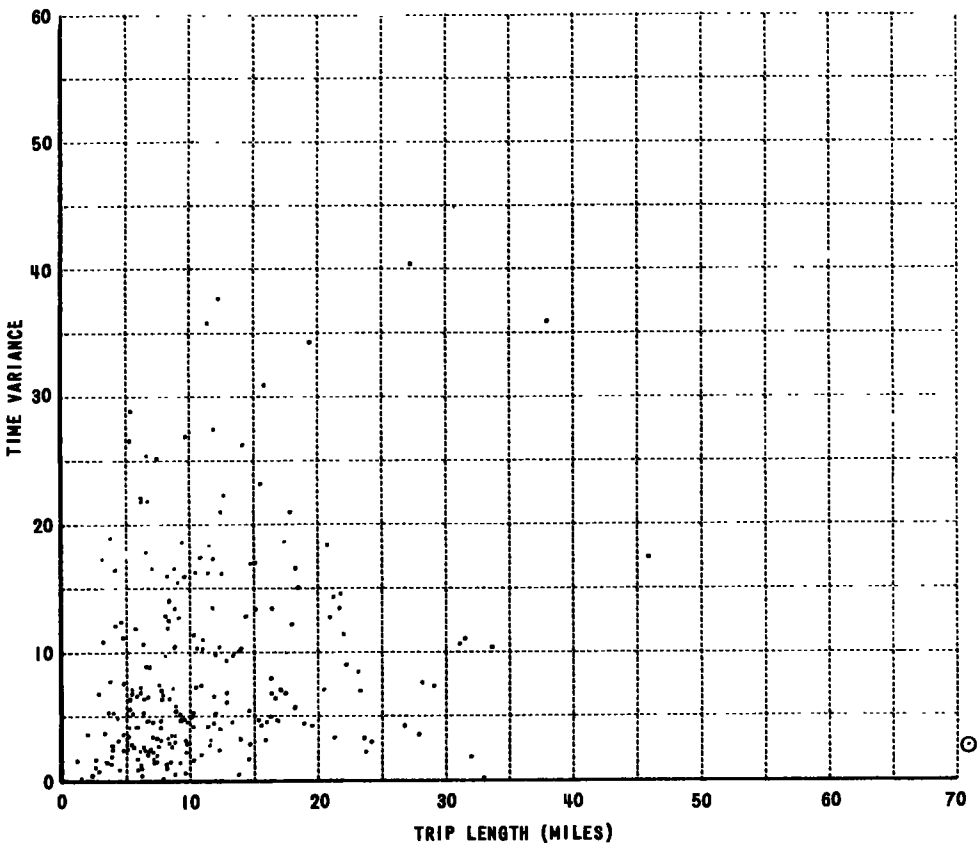


Figure 17. Time variance vs trip length, Buffalo commuters.

CONCLUSIONS

As the first part of this project draws to a close, the evaluation of the potential of an airborne observer in traffic control is, as yet, unfinished. First, a wider sample base for the alternate-route study is desired in order to determine if the Trafficopter can improve the customary flow pattern in Buffalo. Whether the technique can be applied elsewhere to better advantage must depend on the particular traffic complex and the capability of the person who acts as the airborne observer.

Second, it is desired to increase the accuracy of estimating the effectiveness of an airborne observer in reducing delay time to motorists as the result of some incident. This is being done by enlisting the aid of police and, eventually, the drivers themselves to furnish information for reconstruction and analysis of the traffic situation.

For maximum effectiveness of traffic control in a metropolitan area the airborne observer must function as a low-capacity, low-speed, highly flexible surveillance, detection, decision-making, command and control system. His abilities can complement those of a fully automated, high-speed, high-capacity, computer-controlled traffic signal system. The airborne observer, in such a role, can handle traffic situations caused by emergencies such as fires, accidents, and weather, and can also perform other functions permitted by his overview of the surface and speed of traverse over the surface.

As yet no surveillance equipment available for traffic operations can duplicate the singular capabilities of the human to detect, discriminate, and estimate the behavior of traffic on an area basis or in the event of an emergency. When such equipment becomes operational in conjunction with a high-speed computer-controlled signal and communication system, the airborne observer may no longer be warranted. However, inasmuch as the airborne service can be obtained quickly and at moderate cost, it would appear to be an interim solution for handling traffic emergencies in metropolitan areas. This service can be implemented with present equipment and its immediate success or failure is more a matter of public relations than a technical problem.

CHAPTER FOUR

DESIGN OF A RAMP ACCESS ADVISORY SIGNAL

APPROACH TO THE PROBLEM

Development of a ramp access advisory signal was considered an essential contribution to the project's final goal—formulation of a specification for a closed-loop traffic surveillance and control system.

Acting on a request by the Expressway Surveillance Project, CAL undertook an experimental investigation of design requirements for a signal or sign format to advise motorists of the operating conditions of ramps providing access to the Congress Street Expressway.

This use of ramp access advisory signals is believed to be unique in the history of traffic control. No mention of any such concept was found in any of the pertinent literature, including the "Manual on Uniform Traffic Control Devices" (*5*). Thus, there were no background data from which design criteria or performance requirements could be extracted. The guidelines used for this project were chosen for the following reasons.

First, it was expected that the displays would be made on city streets at points sufficiently in advance of the access ramps or intersections at alternate routes so that the drivers would not have to react immediately, in contrast to the case for normal traffic signals. Also, because the displays would be on city streets they would have to be distinct enough to compete with other distractions within the drivers' central vision angle and yet be small enough not to intercept a major portion of the solid angle of vision, the latter for reasons of safety as well as aesthetic treatment of the vista. Another point was that the display must be clearly distinguishable from other traffic information devices such as route signs and control signals. Finally, it was assumed that the displays were being addressed to commuters during peak travel conditions and that local news media were available to educate the drivers concerning the coding used in the displays.

The assumptions were a by-product of the reasoning followed in deciding on preferred signal formats. The stipulation that drivers would not have to react immediately to the information presented by the signal was made to permit the driver to make a decision on a route best suited to his needs, rather than to impose a one-sided control. The latter would be the case if a signal indicated only that the ramp served by the particular approach was "open" or "closed." Actually, an indication of ramp "open" is not a control. However, it does offer information that traffic is moving freely on the Expressway in the segment just downstream of the ramp. An indication of ramp "closed," a positive control, was felt to leave the driver with two choices—to avoid use of the Expressway altogether or to investigate successive ramps in the direction of his desired travel until he finds an open one or decides to abandon the attempt. Such a cut-and-try operation would hardly qualify as expediting traffic.

Figure 18. Simulation of signal in place on a street.

Figure 19. Test signal in place.

It was decided that the single ramp advisory was inadequate and that a broader band of information should be presented. Once this condition was established as a requirement it was obvious that the display would have to be assimilated by the driver sufficiently in advance of an intersection with an alternate route so that a decision could be made on a course of action and the vehicle maneuvered accordingly.

To minimize the size of a display intended to give a broad band of information it was evident that the use of some sort of "shorthand" (such as abbreviations, symbols, or a lighting code) would be necessary. This would enable the drivers to locate the advisory signal and begin to read the information it displayed in time to assimilate the message before the display passed from view.

Because the ramp advisory display was required to be clearly distinguishable from other traffic information and control devices, it was evident that not only would the appearance of each ramp signal have to be discernible from a distance sufficient to relay its information, and yet remain relatively small, but its format also would have to be distinctive and unambiguous.

The assumption regarding beforehand education of the local commuter public implies that the advisory system was not designed for the general driving public, who might desire to use the Expressway during off-peak hours, nor for transients. Almost at the outset of this task it was seen that a completely self-explanatory display, even for a single ramp, would be entirely impractical. Furthermore, because it was expected that the commuters would be fully initiated into the meaning of a coded display, it was possible to design a most obtrusive format for minimum size.

The format evolved as most desirable is the self-illuminated "chevron" design shown in Figure 18. Each chevron group would be made up of three incandescent gas tubes, emitting a green, amber, or red light. This design was arrived at by experimentation in real traffic, using 70 CAL employees as test subjects. The test signal set-up used is shown in Figure 19. The signal "window" dimensions were obtained by a convergence procedure, the triangular openings were decreased in size until their directional sense was not discernible, except at too short a range to be useful. Then they were changed to a chevron shape and increased in size until the directional sense was unmistakable to all test subjects. Final size of the chevrons was 3.75 in. long and 2.75 in. high, with 0.5-in. wide legs.

The color indications were green, amber, and red for ramp "open," "metered," and "closed," respectively. The red signal was "flashed" in order to make this denial-of-access condition most obtrusive, especially to color-blind drivers (7 percent of the male population is color-blind to some degree). In general, 40 w of incandescent lamp illumination was sufficient to provide adequate visual perception range on the test site used, except when the sunlight was reflected directly from the face of the signal.

The latter difficulty can be overcome by nesting color filters in such a way that only one is visible in the chevron "window." In this way only the color that is in effect will be seen, either by direct or reflected light.

No definite plans have been made for operational testing of this signal design. However, its use may be incorporated in a real-time surveillance and control system if the program planned for the continuation of Project 3-2 is followed.

CONTINUATION OF THE PROJECT

As the first year's effort on this project drew to a close, it was possible to formulate plans for a continuation of the work on a much firmer basis than was possible when the project was initiated. In the two foregoing sections of this report it has been concluded that additional effort should be spent on the subject matter of each of these.

Thus, the project will continue with heavy emphasis on the formulation of a computational logic for predicting travel time on an urban freeway in the event of seriously impeded traffic movement. This logic will be tested with data collected on the John C. Lodge Freeway (National Proving Ground) and processed at CAL on an IBM-7044 computer. When a successful and adequately reliable mathematical traffic model and computer logic have been obtained, appropriate computational equipment will be installed at the National Proving Ground and the logic will be tested in real time with real traffic. A successful culmination to this second part of the program would warrant the third step, the determination and implementation of control doctrines aimed toward minimizing overall travel time for all vehicles using the John C. Lodge Freeway and its adjacent arterial system. Finally, an effort would be made to evaluate the effectiveness of the control doctrines and the means of communication with and information dissemination to drivers.

A modest effort will be directed at a more complete evaluation of the cost-effectiveness of an airborne-observer system to be used for control of traffic in emergency situations. A light airplane will be tested as an alternate to the helicopter and system cost will be based on the least expensive combination that can be airborne the maximum number of days, on an annual basis.

Although it came too late to have any bearing on the project effort reported herein, the most ambitious and forward-looking concept for city street network control is being implemented in Toronto, Ontario. This unique system is to be fully supervised by a high-speed digital computer and is probably the most advanced system anywhere, having the greatest potential for flexibility, speed of response, and program storage capacity. If this attempt is successful it would be expected that the methodology used to develop the control programs and the computational logic, as well as the amount and cost of hardware in such a system, would be of interest to traffic engineers. CAL plans to conduct an analytical study, using as a traffic model the requirements for a typical city of 50,000 to 100,000 population.

Integrated with the three tasks described will be studies in means of sensing traffic movements, communications, message structures and formats, and a second-generation airborne observer using closed-circuit television.

CONCLUSIONS

During the first year, emphasis was placed on questions concerning a distribution of events, most of them ordered, some of them random. Although the general behavior of traffic has been viewed as an expected value based on a statistically derived distribution, the problems have been approached from an engineering viewpoint: the system may be permitted to strain under the load but it is not allowed to break.

The results of the first project period are not startling, but they are without precedent. The first prediction logic was unsupportable because of equipment limitations; the next time the two will be compatible. As a rule, the airborne observer has been viewed as a publicity agent; however, he may yet play an important part in traffic control. If so, his effectiveness will have been measured on an objective basis. At the very least, the airborne system may deserve consideration as an interim means for handling traffic emergencies in metropolitan areas, until such time as a comprehensive, automated, ground-based system can be found to perform the task. The ramp signal format may have been derived by a partially subjective analysis, but its applicability was proven objectively by statistics.

For the future, there is reason to believe that traffic can be prevented from bogging down to a virtual standstill, even with the increasing demands being made on the highway. The delayed motorist will be informed by an efficient surveillance, communication, and control system of the causes of congestion and, whenever possible, will be advised how to make the best progress toward his destination.

REFERENCES

1. WEINBERG, M. I., *et al.*, "Surveillance Methods and Ways and Means of Communicating with Drivers." Cornell Aeronautical Laboratory, Report No. VJ-1790-G-1, Apr. 15, 1964.
2. Expressway Surveillance Project, "Development and Evaluation of the Congress Street Expressway Pilot Detection System." Illinois Division of Highways, Jan. 1963.
3. DEROSE, FRANK, JR., "The Development and Evaluation of the John C. Lodge Freeway Traffic Surveillance and Control Research Project." Michigan State Highway Department, Jan. 1963.
4. California Highway Patrol, "Aircraft in Traffic Law Enforcement." Mar. 20, 1963.
5. U.S. Bureau of Public Roads, "Manual on Uniform Traffic Control Devices for Streets and Highways." U.S. Govt. Printing Office, Washington, D.C. (June 1961).

Previously published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Highway Research Board
National Academy of Sciences
2101 Constitution Avenue
Washington, D.C. 20418

Inquiries concerning prices and quantity purchases should be directed to this address.

NCHRP Report No.	*Title*
—*	A Critical Review of Literature Treating Methods of Identifying Aggregates Subject to Destructive Volume Change When Frozen in Concrete and a Proposed Program of Research—Intermediate Report
1	Evaluation of Methods of Replacement of Deteriorated Concrete in Structures
2	An Introduction to Guidelines for Satellite Studies of Pavement Performance
2A	Guidelines for Satellite Studies of Pavement Performance
3	Improved Criteria for Traffic Signals at Individual Intersections—Interim Report
4	Non-Chemical Methods of Snow and Ice Control on Highway Structures
5	Effects of Different Methods of Stockpiling Aggregates
6	Means of Locating and Communicating with Disabled Vehicles—Interim Report
7	Comparison of Different Methods of Measuring Pavement—Interim Report
8	Synthetic Aggregates for Highway Construction

* Highway Research Board Special Report 80.

THE NATIONAL ACADEMY OF SCIENCES — NATIONAL RESEARCH COUNCIL is a private, nonprofit organization of scientists, dedicated to the furtherance of science and to its use for the general welfare. The Academy itself was established in 1863 under a congressional charter signed by President Lincoln. Empowered to provide for all activities appropriate to academies of science, it was also required by its charter to act as an adviser to the federal government in scientific matters. 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.

The National Research Council was established by the Academy in 1916, at the request of President Wilson, to enable scientists generally to associate their efforts with those of the limited membership of the Academy in service to the nation, to society, and to science at home and abroad. Members of the National Research Council receive their appointments from the president of the Academy. They include representatives nominated by the major scientific and technical societies, representatives of the federal government, and a number of members at large. In addition, several thousand scientists and engineers take part in the activities of the research council through membership on its various boards and committees.

Receiving funds from both public and private sources, by contribution, grant, or contract, the Academy and its Research Council thus work to stimulate research and its applications, to survey the broad possibilities of science, to promote effective utilization of the scientific and technical resources of the country, to serve the government, and to further the general interests of science.

The Highway Research Board was organized November 11, 1920, as an agency of the Division of Engineering and Industrial Research, one of the eight functional divisions of the National Research Council. The Board is a cooperative organization of the highway technologists of America operating under the auspices of the Academy-Council and with the support of the several highway departments, the Bureau of Public Roads, and many other organizations interested in the development of highway transportation. The purposes of the Board are to encourage research and to provide a national clearinghouse and correlation service for research activities and information on highway administration and technology.