NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT **233**

SELECTING TRAFFIC SIGNAL CONTROL AT INDIVIDUAL INTERSECTIONS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT **233**

SELECTING TRAFFIC SIGNAL CONTROL AT INDIVIDUAL INTERSECTIONS

P. J. TARNOFF
Alan M. Voorhees & Associates
McLean, Va.
and
P. S. PARSONSON
Georgia Institute of Technology
Atlanta, Georgia

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AREAS OF INTEREST
OPERATIONS AND TRAFFIC CONTROL
TRAFFIC FLOW, CAPACITY, AND MEASUREMENTS
(HIGHWAY TRANSPORTATION)

TRANSPORTATION RESEARCH BOARD
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WASHINGTON, D C JUNE 1981

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

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The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. 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 and Transportation 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 Transportation Research Board.

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FOREWORD

By Staff
Transportation
Research Board

This report will be of particular interest to state, county, and local traffic engineers who are responsible for selecting traffic signal equipment. Operational characteristics and relative costs are described for pretimed, semi-actuated, full-actuated, and volume density controls. Individual intersection controls and coordination considerations between adjacent intersections are covered. Data from a nationwide survey of traffic engineering organizations, from field studies, and from traffic simulation analyses provide the basis for the research findings; this information will assist the traffic engineer in determining the most appropriate form of control for a particular location. Because of the wide selection of control equipment currently available and the different conditions existing at individual sites, this report provides basic information that can be used in the selection process and does not attempt to specify a rigid procedure.

Selection of the most appropriate form of traffic signal control for an individual intersection is a complicated process because of the many types of control that are available, the wide range of control equipment, and the varying site conditions. Each type of control (pretimed, semi-actuated, full-actuated, and volume-density) offers varying performance and cost characteristics depending upon the nature of the installation and existing traffic conditions. The proper choice of vehicle detector configuration and controller settings further complicates the selection and design process.

The available literature on this subject is extensive but provides little guidance on the complete set of costs and benefits associated with the selection of alternative forms of signal control at a specific site. Although traffic engineers recognize that each type of control has its appropriate use, selection of control type is generally determined without a comprehensive analysis because of the lack of specific guidance and supporting reference data. To assist in the evaluation of the best type of traffic signal control to use at an intersection, this report describes (1) maintenance requirements, (2) vehicle delays on the major and minor streets, (3) overall traffic safety, (4) coordination adaptability, and (5) cost effectiveness.

Controller performance was evaluated in terms of delay per vehicle (in seconds/vehicle) and percent stops per vehicle. These measures of effectiveness were selected because they are frequently used in traffic engineering studies and can be directly related to traffic flow at individual intersections. The approach used was to perform detailed analysis of controller effectiveness expressed in terms of stops and delays and then to develop additional relationships for vehicle emissions, fuel consumption, and accidents as a function of stops and delay.

Three complementary approaches were used to evaluate controller effectiveness: (1) field data collection using observers to manually measure vehicle volumes and vehicle stops and delay; (2) simulation using the NETSIM model, developed under the sponsorship of FHWA, to evaluate control system performance; and (3) analytical techniques developed by the research team and other agencies.

The research results demonstrated that the form of control which minimizes the vehicle stops and delays at an intersection also minimizes fuel consumption and emissions. Furthermore, the differences in the annualized costs for equipment acquisition, installation, operation, and maintenance between the control alternatives were significantly less than the differences between the benefits. For this reason, the control alternative that minimized stops and delays also proved to be the most cost-effective installation. Therefore, it is not considered necessary to develop individual estimates for all of the measures of system effectiveness and costs in order to select the best form of control.

Graphs are used to define regions in which each type of control is most effective; the regions defined are for pretimed, semi-actuated and basic full-actuated control. The applicability of volume-density control and detectorization requirements are also defined.

Although this report significantly advances the state of knowledge on this subject, the reader should understand that both the field data and simulation data used to develop the relationships were somewhat limited. Further refinement of these relationships through other research, as well as by traffic engineers for their specific situations, is desirable. Nonetheless, the comprehensive information presented herein should prove useful until the desired refinements are accomplished.

CONTENTS

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The research reported herein was performed under NCHRP Project 3–27 by Alan M Voorhees & Associates and the School of Civil Engineering at the Georgia Institute of Technology Alan M. Voorhees & Associates was the contractor for this study The work undertaken at the Georgia Institute of Technology was under a subcontract with Alan M. Voorhees & Associates. Mr Philip J. Tarnoff, Vice President, Alan M. Voorhees & Associates, was the principal investigator.

The work on this project was performed under the general supervision of Mr. Philip Tarnoff. Activities at the Georgia Institute of Technology were directed by Dr. Parsonson, Associate Professor of the School of Civil Engineering. Activities at Alan M. Voorhees & Associates were performed under the direction of Mr. Tarnoff with the assistance of Mr. E. Cleary, Mr W Kittelson, Mr S. Seeburger, Mr. S. Shapiro, Ms. M Johnson, and Ms S. Pappas.

SELECTING TRAFFIC SIGNAL CONTROL AT INDIVIDUAL INTERSECTIONS

SUMMARY

Because of the complexity of modern traffic signal control equipment, the selection of the most appropriate form of control for an individual intersection can be a difficult and confusing process. Four basic types of control are available: pretimed, semi-actuated, basic full-actuated, and volume-density. Each type of control offers varying performance and cost characteristics depending on the nature of the installation and existing traffic conditions. The performance of these control alternatives is further influenced by the configuration of vehicle detectors employed and the controller settings. NCHRP Project 3-27 was undertaken for the purpose of developing information that would permit the local traffic engineer to evaluate costs and benefits of the various control alternatives while taking roadway and traffic conditions into account.

A review of the extensive literature related to this subject revealed that much of the work performed to date either is of a theoretical nature or considers the operation of a specific intersection. In spite of these limitations, it was possible to arrive at some general conclusions:

1. Pretimed controllers operate most effectively when the shortest possible cycle length is used subject to the constraints of providing adequate intersection capacity and minimum green times for pedestrians and vehicle clearance intervals.
2. The delays produced by full-actuated controllers are extremely sensitive to the value of the extension that is used. In general, the shorter extensions reduce vehicle delays.
3. At low and moderate volumes when extensions of 2 or 3 sec are employed, and use of the full-actuated controller will produce reduced delays and stops over those which can be achieved using pretimed controllers. When high traffic volumes occur both on the main street and on the side street causing the controller to extend the green time to the maximum on all phases, the full-actuated controller will perform as a pretimed controller, producing comparable measures of vehicle flow.
4. The relative effectiveness of the various control alternatives depend on the quality of the signal timing employed. A poorly timed actuated controller will degrade traffic performance to as great an extent as a poorly timed pretimed controller.

The detailed evaluation of controller performance conducted on this project employed simulation techniques validated from field data collected at five intersections. In addition, the evaluation of both pretimed and full-actuated controller performance generally confirmed the relationships defined by the available literature.

It was also concluded that volume-density controllers provide the greatest benefit at intersections with high approach speeds where detector setbacks from the intersection in excess of 125 ft require a variable initial green time. The time-waiting extension-reduction option of the volume-density controller will not improve the controller's performance over that of a basic full-actuated controller

unless the option is used to reduce the vehicle extension to a value that is less than would be used with the full-actuated controller.

Evaluation of semi-actuated controller performance at individual intersections demonstrated that these controllers produce a higher level of stops and delays for all traffic conditions than do either the full-actuated or pretimed controllers. However, for side street traffic volumes that are less than 20 percent of main street volumes, there is an insignificant difference between semi-actuated and full-actuated controller effectiveness.

Basic full-actuated controller performance was evaluated for a variety of signal phasing and detectorization schemes. On the basis of these evaluations it was concluded that full-actuated controllers produce significant benefits when used in an 8-phase dual ring configuration. The 8-phase configuration also produces significant benefits in terms of both stops and delays, as well as capacity, over that which would be possible with a 4-phase pretimed controller. Further modest gains in performance are possible with the use of long loops and short (or zero) initial and extension settings using the basic full-actuated controller. This application was found to produce a performance similar to a 2-sec extension with a short loop.

Extensive cost data were also accumulated for each type of control. These were found to vary significantly with type of control. The variations in these costs were also sensitive to the number of phases, primarily because of the need for increased detectorization with additional phases. In addition, it was found that the microprocessors used in the newer controller designs tend to reduce annual controller maintenance costs.

The controller performance data and cost data were applied to the development of benefit-cost analysis procedures. The application of representative data to these procedures demonstrated that the annual benefits (expressed in terms of motorists costs) were five to ten times greater than the annualized controller costs. For this reason, it was concluded that the formalized benefit-cost procedure would be insensitive to the alternative controller costs. A more appropriate procedure would begin with the analysis of alternative forms of control to identify the one that provides the most effective operation. As a second step, the controller acquisition, installation, and maintenance costs of the selected control should be evaluated to ensure that local agency budgetary constraints are not violated. If the available budget is adequate to support the selected form of control, it should be implemented because the magnitude of the benefits will outweigh the cost differential to be borne by the local agency.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

Traffic signals have been used for the allocation of right-of-way at intersections for almost as long as the motor vehicle has been in existence. The original traffic signals were manually controlled. Subsequently a simple timer mechanism was used to allocate right-of-way on a regular schedule. More recently a variety of sophisticated equipment has become available for modifying signal timing based on time-of-day or vehicle arrivals at the intersection.

With increased-equipment complexity has come a requirement for a development of engineering procedures that will permit a selection based on the characteristics of the intersection being controlled. A comprehensive set of procedures must consider operational effectiveness, equipment reliability, and costs associated with installation, operation, and maintenance.

PROBLEM STATEMENT AND RESEARCH OBJECTIVE

A review of the procedures currently being used in the traffic control equipment selection process reveals an absence of uniformity and only a limited availability of analytical techniques to support the process. Surprisingly, the available traffic signal control literature (including the Transportation Engineering Handbook (*1*)), although voluminous, provides little guidance related to the complete set of costs and benefits associated with the selection of alternative forms of signal control at a specific site.

Without more comprehensive assistance, the traffic engineer's problems can be expected to increase as a result of the rapidly changing state of the art. These changes will probably result in reduced acquisition costs for microprocessor-based equipment and increased costs for other solid state and electromechanical equipment. Salaries for maintenance personnel could increase significantly as more sophisticated procedures are required to trouble shoot and repair the more complex equipment. In some cases, the need for higher maintenance salaries can be offset by the use of automated diagnostic hardware. However, it is likely that these equipment costs will also increase. Cost of spares is increasing with the use of large-scale integrated (LSI) circuits, but the possibility of decreased failure rates (increased mean times between failure—MTBF) should offset this increased cost These rapidly changing conditions serve to emphasize the current absence of any guidelines for selection of traffic control alternatives.

The absence of guidelines can be attributed to the complexity of the problem. This issue was discussed by Jacks (*2*), who commented on the relative complexity of establishing warrants for various types of interconnected signal control systems because of the wide variations in the conditions under which they must operate. He concluded that the ". . state-of-the-art of traffic signal system operations is such that establishment of warrants for utilization of specific types of signal systems is not presently feasible. However, for a given situation, an analysis which considers all qualitative factors, costs, and capabilities of various systems can provide a logical basis for system determination." These conclusions are directly related to the problems of individual intersection control.

The objective of NCHRP Project 3-27 was to develop information needed for selecting the most appropriate type of traffic signal control for an individual intersection in both urban and rural areas. Although the emphasis of this project was on traffic control at isolated intersections, adjacent intersections were considered insofar as the identification of the need for coordinated operation is concerned.

SCOPE OF STUDY

This research developed procedures for the computation of benefits and costs as a function of the following three dimensions: (1) roadway characteristics, (2) traffic characteristics, and (3) control characteristics.

The relationship among these three dimensions is shown schematically in Figure 1. As indicated by this figure, the final selection of a particular form of control is based on the comparison of the costs and benefits of the alternative control techniques.

The benefits used to compare the alternative forms of control include traffic flow, fuel consumption, vehicle emissions, and safety. The traffic flow variables are those associated with an individual intersection—stops and delays. They do not include the system measures of speed and travel time because these measures have no meaning for an individual intersection.

The costs used in the procedures are those associated with the design, installation, operation, and maintenance of the basic control equipment. These costs include both equipment and labor costs; they include both controller equipment and associated detectors. The cost of equipment that is common to all forms of control, such as signal displays and cabinets, is not included in the procedures. Differences in equipment reliability are accounted for through the maintenance costs.

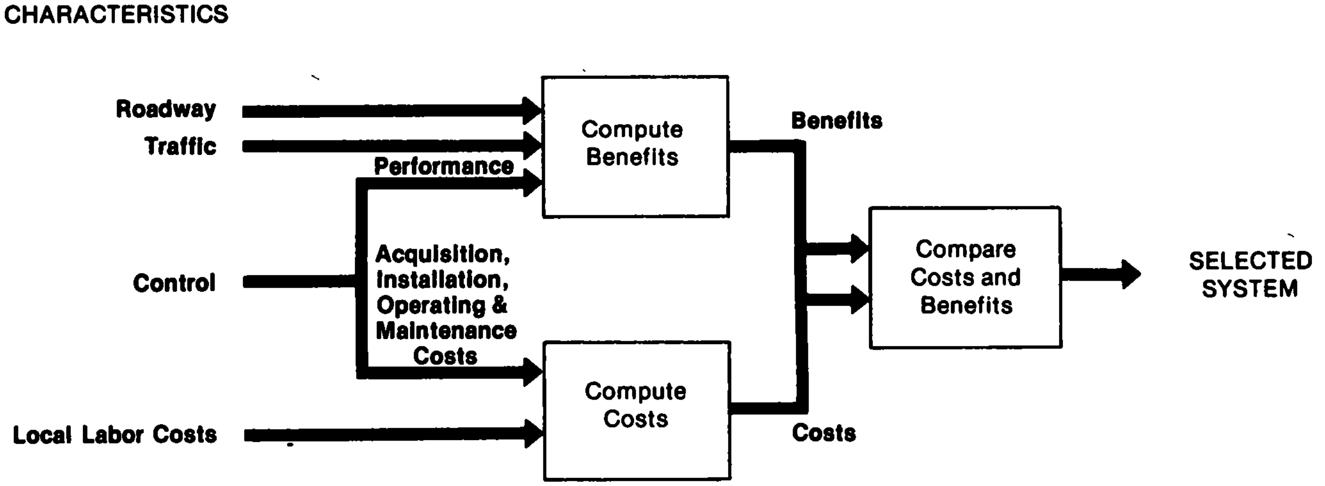


Figure 1. Control system selection process.

RESEARCH APPROACH

In order to accomplish the objective of NCHRP Project 3-27, activities were organized into the following four tasks:

- *Task 1—Review and summarize relevant literature and research findings* The purpose of this task is to review and summarize all publications and research related to the project This information is to serve as a reference for all future project activities.
- *Task 2—Identify and define the study variables.* The purpose of this task is to define roadway and traffic characteristics for which the various types of signal control are to be compared. During this task, alternative forms of signal control are also identified. One important element is the study of variables that may be used as surrogates for the roadway and traffic characteristics.
- *Task 3—Develop cost effectiveness methodology.* The purpose of this task is to define the measures of effectiveness, costs, and analytical techniques to be used for the comparison of alternative types of control.
- *Task 4—Obtain the data required to determine the relative effectiveness of each control type.* The purpose of this task is to combine the analytical framework developed in Tasks 2 and 3 with the available data identified in Task 1 and to collect any supplementary data needed.

CHAPTER TWO

FINDINGS

This chapter presents the findings from each of the research tasks. In several cases, detailed appendixes were prepared to provide a more comprehensive discussion of these findings. Specifically, the annotated bibliography prepared during Task 1 is contained in Appendix A. The detailed results of the study of traffic platoon behavior and the relationship between controller effectiveness and interconnection with upstream intersections are covered in Appendix B. Results of the validation of the simulation model is contained in Appendix C. The derivation of actuated controller characteristics used to calculate regions of controller effectiveness is presented in Appendix D.

STATE-OF-THE-ART SUMMARY

The state-of-the-art review conducted during Task 1 served the dual purpose of providing a general definition of the state of the art in signal control as well as identifying sources of data that might be used for the remainder of this project. Appendix A contains the annotated bibliography developed as a result of this review. References contained in this appendix are listed in alphabetical order.

Numerous references are available in the area of signal control. In order to keep the state-of-the-art review within reasonable proportions, it was restricted to those dealing with the installation, operations, maintenance, or performance of signals at individual intersections. Systems of coordinated signals have not been included.

During the state-of-the-art review over 100 references were reviewed and the following was concluded:

1. The vast majority of the available literature deals with performance characteristics of controllers at isolated intersections Within these references, vehicle delay is used almost exclusively as the measure of controller effectiveness.
2. A limited number of references offer criteria for the selection of control alternatives at individual intersections. These criteria are generally based on capacity considerations and do not include costs.
3. With the exception of manufacturers' literature, there are few documents identified that discuss installation, operations, or maintenance issues. All of the documents identified deal exclusively with procedures. None contain any data that would allow cost comparisons to be performed between alternative forms of control.
4. Numerous analytical studies have been performed that develop statistical relationships for various types of control. These studies often provide insight into operation of signal control alternatives. However, they have always been conducted under assumptions too restrictive to permit their application to a specific set of guidelines.

The following discussion summarizes some of the more significant references identified during the state-of-the-art review. This discussion is divided into two sections: Performance Characteristics and Theoretical Considerations. No attempt has been made to summarize the design, installation, operations, and maintenance information reviewed because the references reviewed failed to produce any information directly applicable to the project. The information required to support this aspect of the project activities was developed from information supplied directly by users and manufacturers.

Performance Characteristics

In 1975 Orcutt (*3*) mentioned three basic forms of control—pretimed, actuated, and semi-actuated. He indicated that pretimed control is "used primarily in CBD areas, especially where a network of signals must be coordinated. This is not a good strategy where more than three phases are required."

Orcutt (*3*) defines actuated signals as equipment that "responds to actual traffic demand of one or more movements as registered by detectors. If all movements are detected, the control is called fully actuated." He states that: "Fully actuated control should normally be used at isolated intersections."

These statements reflect the conventional wisdom of the traffic control community. They are a result of the well-known fact that an actuated controller will provide a more effective operation at individual intersections provided it is installed and timed properly, at least one phase is serviced by the controller, and the equipment is properly maintained such that a high degree of reliability is achieved for the duration of the installation and the cost of providing such maintenance is not a major concern to the local agency.

The NEMA standards (*4*) were used to define the basic controller types examined during this project. The four types considered include pretimed, semi-traffic-actuated, full-traffic-actuated without volume-density, and full-traffic-actuated with volume-density. For the remainder of this report, the latter three types of control will be designated semi-actuated, full-actuated, and volume-density control, respectively. NEMA provides the following definitions for the four types of control:

> Pretimed Controller Assembly—A controller assembly for the operation of traffic signals with predetermined:
> 1. Fixed cycle length(s).
> 2. Fixed internal duration(s)
> 3 Internal sequence(s)
>
> Semi-Traffic-Actuated Controller Assembly—A type of traffic-actuated controller assembly in which means are provided for traffic actuation on one or more but not all approaches to the intersection. [For the purpose of this definition, traffic actuation is defined as the supervision of] the operation of traffic control signals in accordance with the varying demands of traffic as registered with the controller by detectors
>
> Full-Traffic-Actuated Without Volume-Density Controller Assembly—A type of traffic-actuated controller assembly in which means are provided for traffic actuation on all approaches to the intersection Where traffic actuation is defined as before, the full-actuated controller without volume-density has three settings [for the determination of green timing on an actuated phase].
> 1. Initial—The first timed portion of the green interval which is set in consideration of the storage vehicles waiting between the sensing zone of the approach vehicle detector and the stopline.
> 2. Extension (gap) (vehicle interval, preset gap, passage time)—The timing of this portion of the green interval shall be reset with each vehicle actuation and shall not commence to time again until the vehicle actuation signal is removed from the input to the controller unit.
> 3 Maximum (extension limit)—This time setting shall determine the length of time that this phase may be held green in the presence of an opposing serviceable call.
>
> Full-Traffic-Actuated With Volume-Density—The volume-density operation shall include a form of variable initial timing and gap reduction timing. The effect on the initial timing shall be to increase the timing in a manner which is dependent upon the number of vehicle actuations stored on this phase while its signal is displaying the yellow or red. The effect on the extensible portion shall be to reduce the allowable gap between successive vehicle actuations in a manner which is related to the delay of the first vehicle arriving on a conflicting phase.

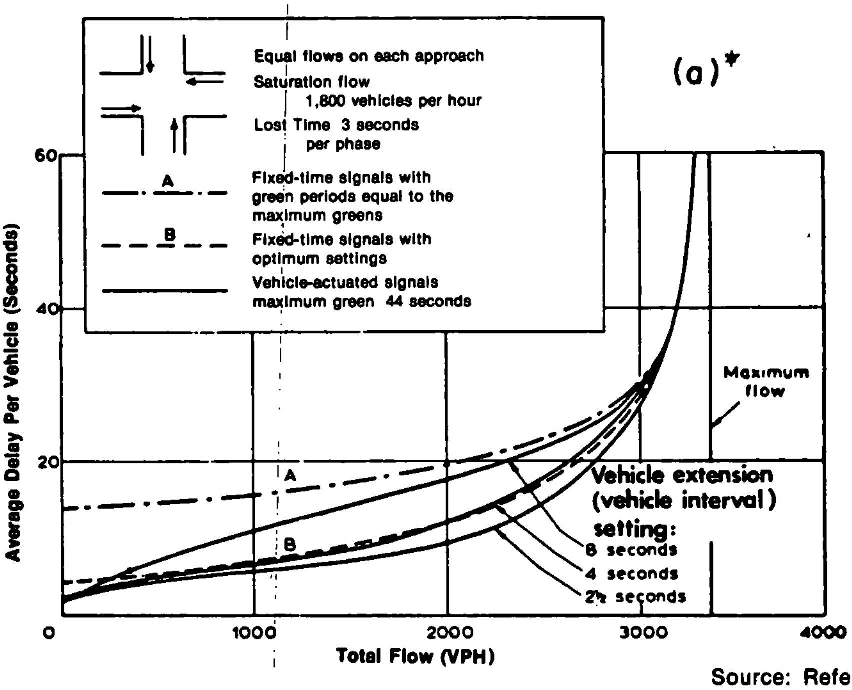
Although in the past, controllers such as the Automatic Signal Model 1022 and the Eagle Signal ET150 have employed additional extension reduction features that are a function of the number of cars waiting on the conflicting phase and density on the street currently being served, the NEMA specifications restrict the volume-density extension reduction feature exclusively to the vehicle delay on the conflicting phase.

Staunton (*5*), who has summarized the work of numerous signal control researchers, presents comparisons of the delays produced by fixed-time and actuated control as a function of vehicle volumes (see Figs. 2(a) and 2(b). Figure 2(a), which Staunton reproduced from Webster's early work at the Road Research Laboratory in Great Britain, is significant in that it demonstrates that full-actuated control with 2.5-sec extension will always be better than the best form of pretimed operation; that is, with optimum settings for all volumes. Also significant in this figure is the fact that longer values for the extension can easily degrade actuated controller performance to the point where it is significantly worse than pretimed control. It should be noted that these are simulation results. In actual practice 2.5-sec extensions can lead to the premature termination of an actuated phase due to fluctuations in queue discharge headways A final factor demonstrated by this figure is that heavier traffic flows on all approaches tend to cause the performance of these two types of control to be nearly equivalent.

These performance estimates are supported by Bang (*6*), who developed a new form of control for individual intersections. Designated Traffic Optimization Logic (TOL) control is based on the concept of calculating a control function that represents the net gain (or loss) in vehicle delays for vehicles on all phases of the intersection approach resulting from terminating the current phase In comparing TOL with other forms of control, Bang used a simulation along with field tests which produced comparisons between pretimed and full-actuated control. These comparisons, reproduced in Figures 3(a) and 3(b), show the results of the simulation and field experiments at a 2-phase urban intersection. Bang does not distinguish between the two forms of pretimed control (PT 1 and PT 3) shown in the figure However, it is significant that these curves generally agree with the data shown in Figure 2 and demonstrate that it is possible for full-actuated control to produce higher delays than the pretimed control alternative when the approach volumes are close to saturation.

It is interesting that these curves also demonstrate the potential of the TOL performance. However, in Bang's words, this form of control, which is not commercially available, "is among other things dependent on the accuracy of the detector information." For this reason, it did not receive further consideration in this project.

Gerlough and Wagner (*7*) compared pretimed controller effectiveness against the more complex volume-density control. Here again, degraded performance resulted for the actuated form of control at higher intersection volumes. The basic queue control refers to an actuated-control concept developed in Ref. 7. In this form of control, the duration of green for each phase is dependent on directly sensed queue lengths at the beginning of the phase. Subsequent



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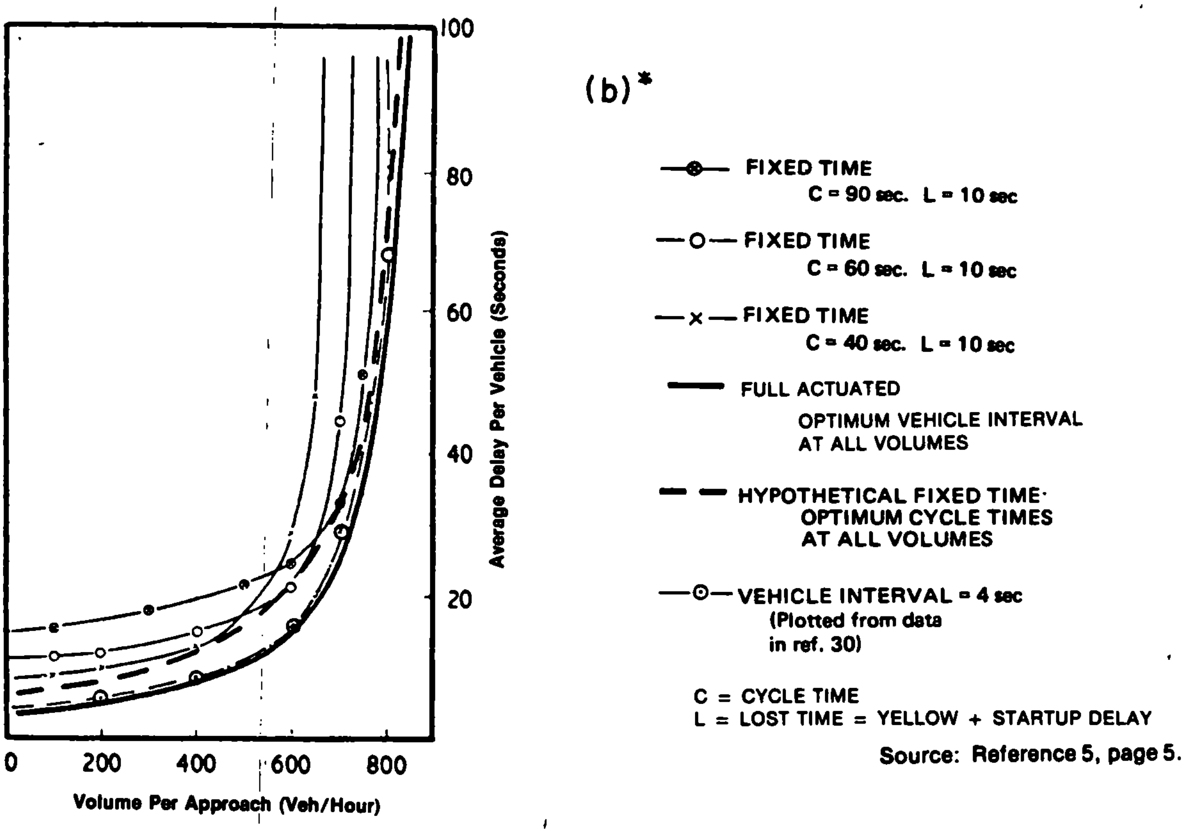

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* Note The terms fixed-time and vehicle-actuated are references to the standard terminology for pretimed and full-actuated control used in the remainder of this report The terminology in these figures has been used for consistency with the terminology in the original source document

Figure 2. (a) Comparison of fixed-time and vehicle-actuated signals with various vehicle interval settings on a vehicle-actuated controller, and (b) comparison of vehicle-actuated control with fixed-time signals.

research (*8*) has demonstrated the difficulty of measuring queue lengths accurately, with the result that this form of control is usually extremely difficult to implement. It should be emphasized that for all the results presented here, the authors did not provide a detailed description of the controller settings used. It is shown later in this report that controller performance is very sensitive to these settings.

Studies of delay at actuated signals have also been made for the purpose of evaluating warrants for this type of control on the basis of the information in the 1961 edition of the MUTCD. This information has been expanded by the Texas Highway Department into the series of curves shown in Figures 4 through 7. Figure 4 is plotted from the warrants contained in the 1961 edition of the MUTCD. Volume levels for fixed-time control, warrant 1 from the 1971 edition, are also indicated in this figure to show their similarity to the actuated warrant. Figures 5 through 7 represent 1.25, 1.50, and 1.75 times the levels shown in Figure 4. These factors are based on a study conducted by Texas which developed the relationship between the eight high hours, four high hours, and two high hours, respectively. Figure 8 was developed by extrapolating these data for the one high-hour case. These curves have been studied by Vodrazka, Lee, and Haenel (*9*) who concluded that they provide "good guidelines for selecting actuated equipment for locations where traffic volumes do not warrant pretimed signals. Delay studies at three locations that meet the suggested warrants for actuated control, but not for pretimed control, showed that actuated control consistently resulted in less delay than pretimed equipment up to total volumes of about 450 vehicles per 15 minutes." This conclusion implies that actuated control produces higher delays than pretimed equipment under high-volume conditions corresponding to approximately 2500 vph for a 4-legged 2-phase intersection with two lanes per approach. These volume levels correspond to a level of service of E or F. Here again, it must be emphasized that these conclusions will be sensitive to the controller settings employed

Theoretical Considerations

Numerous theoretical studies of pretimed control have been conducted. Two examples are the work of Miller (*10*) and Webster (*11*). This theoretical work has been applied to the computation of optimum cycle lengths as a function of vehicle arrival rates It has also been used for evaluating vehicle delays, intersection capacity, probability of stops, and so on. These results are also well validated through comparison with field data. However, the pretimed computations are of limited value for the development of guidelines because they do not provide an equivalent theoretical development for actuated control that will permit a comparison of the two.

More recently, Newell (*12*) and Newell and Osuma (*13*) have expanded the body of theory by developing relationships for mean vehicle delay with both pretimed and actuated control at the intersection of two 1-way streets and two 2-way streets, respectively. In Ref. 12, Newell demonstrates that the average delay per vehicle for an actuated signal is less than that of a pretimed signal by a factor of

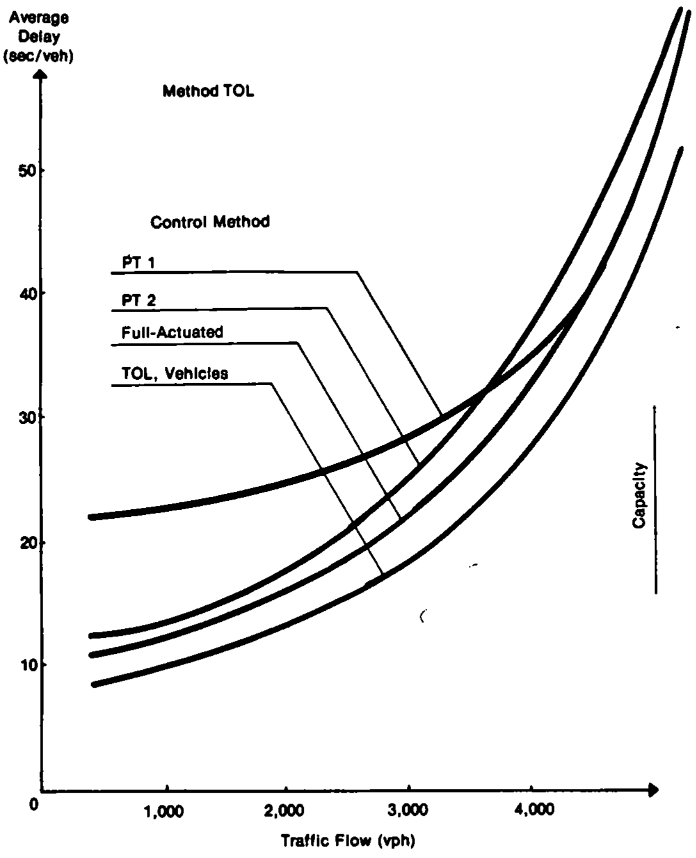

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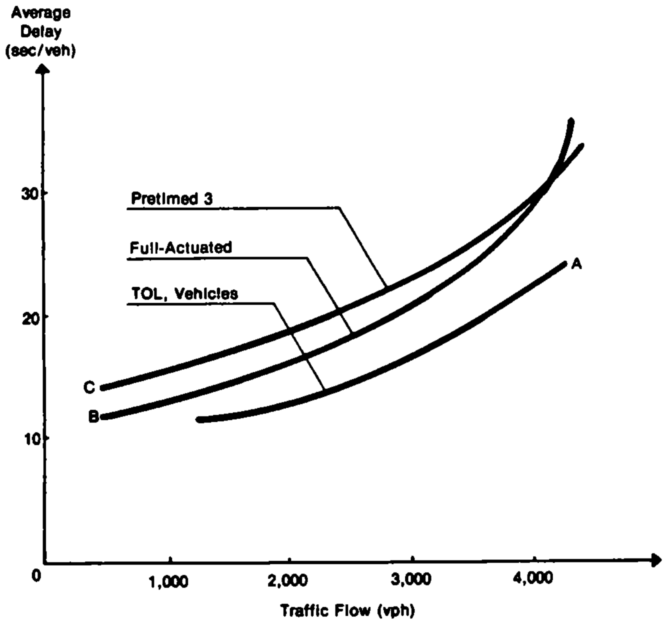
Figure 3(a). Comparison between different control methods; simulation results, two-phase four-way intersection.



Source Reference 6, page 291

Figure 3(b). Test results.

about 3. However, it must be emphasized that this result applies to the restricted case of intersecting 1-way streets.

Reference 13 considers a second situation—the intersection of 2-way streets at which there was no turning traffic. The main conclusion of this work is that the high efficiency indicated for vehicle-actuated control at the intersection of 1-way streets does not necessarily exist for 2-way streets. For the particular vehicle-actuated policy examined —that of holding the green until the queue has been discharged—the vehicle-actuated control will not perform as well as pretimed control when (1) flows are nearly equal on both approaches of a given phase, and (2) the intersection is nearly saturated.

This work confirms Bang's results, previously described, that for high levels of vehicle flows, vehicle-actuated control can degrade performance when compared with pretimed control. The degree to which this degradation occurs will be a result of the degree to which flows are balanced, the value of the extension, and the setting of the maximum green time.

CURRENT PRACTICES AND PROCEDURES

As part of the state-of-the-art survey, numerous traffic engineering organizations were contacted to identify current practices. The purpose of these contacts was to identify existing procedures that might be used in the comparison of controller effectiveness.

Approach

Contacts were made with a sample of 43 state, county, and city traffic engineering agencies selected to provide information for all regions of the United States. The 43 interviews are stratified as follows:

	Governmental Unit			
Region	State	County	City	Total
Northeast	4	1	2	7
Midwest and Mountain	5	0	8	13
South	4	2	7	13
West	3	4	3	10
	16	7	20	43

Summary of Survey

These findings indicate that in some jurisdictions, particularly in the northeast, there are certain barriers to the use of full-actuated control with large-area detection at isolated intersections. These barriers are the difficulties in maintaining the controllers and the detectors.

Controller maintenance has become difficult for many agencies throughout the country because of the multiplicity of makes and models that tend to be purchased under low-bid policies. Also, the continuing increase in sophistication of design of solid-state equipment dictates a transition in bench-repair staff from electrician to electronics technician. Limited budgets make this transition difficult. However, the controller industry is currently experiencing the same conversion to microprocessor technology that has revolutionized the calculator and wristwatch industries. The low cost and high reliability of microprocessors, coupled with their simple procedures for field troubleshooting, suggest that maintenance requirements may be eased in the future. There is a feeling in the traffic-signal industry that detection may be the next beneficiary of advances in microprocessor technology.

Detection at an intersection approach must often cover a large area (typically a length of 50 to 70 ft in the vicinity of the stopline) so that the green time allocated to each phase can be closely tailored to actual traffic demand. Although this can be done with magnetometer detectors, loop detection is generally less expensive and is the detection of choice for most agencies.

The early crystal-controlled loop-detector electronics of the late 1960's have been replaced with excellent units capable of tracking environmental drift and detecting small vehicles adequately. Several manufacturers produce high quality, reasonably priced loop detectors that are satisfactory to traffic engineers. Problems appear to exist only within those agencies with inadequate specifications.

Loop configuration has evolved over the years as a result of research performed by detector manufacturers and traffic engineering agencies throughout the world. Today, large-scale detection is frequently implemented, using techniques such as the "quadrupole" configurtion (Fig. 8) or by groups of interconnected, small-area loops.

EVALUATION OF CONTROLLER EFFECTIVENESS

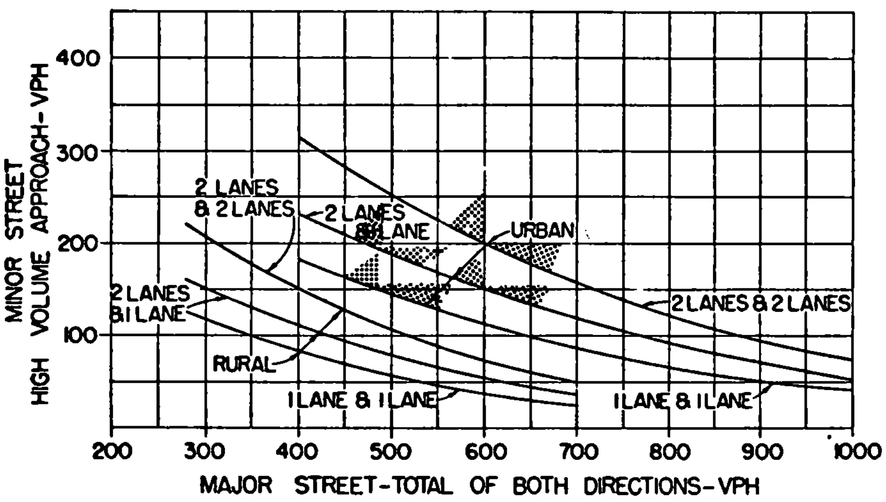
A key element in the selection between signal control alternatives is the evaluation of their effectiveness under a variety of operational conditions.

In the following discussion controller performance will be consistently expressed in terms of delay per vehicle (in seconds/vehicle) and percent stops per vehicle. These variables (measures of effectiveness) were selected because they are frequently used by the traffic engineering community and can be directly related to traffic flow at individual intersections. Subsequent sections discuss the relationships between the stops and delay and emissions, fuel consumption, and accident rate. Thus, the approach used herein has been to perform detailed analysis of controller effectiveness expressed in terms of stops and delays and to develop additional relationships from which the stops and delays can be translated into vehicle emissions, fuel consumption, and accidents.

Three complementary approaches have been used to evaluate controller effectiveness:

1. Field data collection using observers to measure vehicle volumes and to measure vehicle stops and delay.
2. Simulation using the NETSIM model (*14*) developed under the sponsorship of FHWA to evaluate control system performance.
3. Analytical techniques developed by the research team and other agencies.

It was originally intended that the field data collection would form the baseline data to provide a starting point from which future simulation studies would be performed.



Note Shaded area indicates region where actuated control is warranted but fixed time control is not warranted according to the 1971 MUTCD

WARRANT 1 FROM 1971 MUTCD

1 1 Lane and 1 Lane
2 2 Lanes and 1 Lane
3 2 Lanes and 2 Lanes
4 1 Lane and 2 Lanes

Figure 4. Texas warrant volumes for actuated signals eight high hours

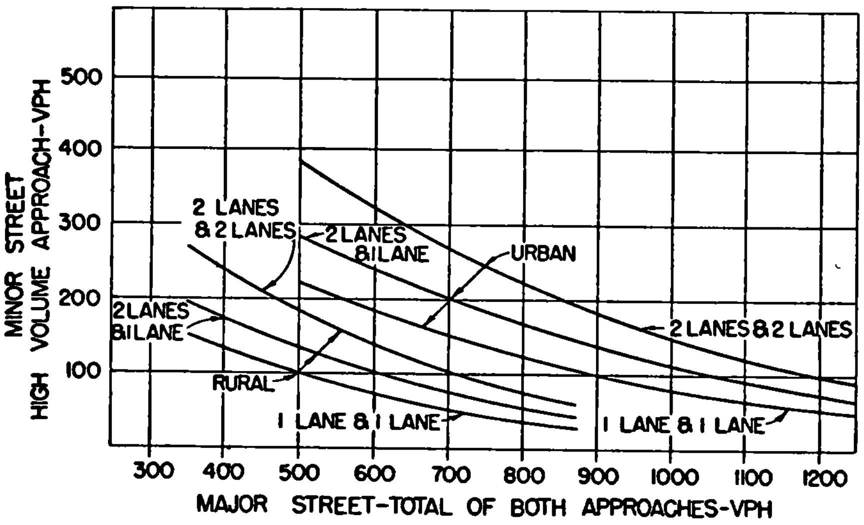


Figure 5. Texas warrant volumes for actuated signals four high hours.

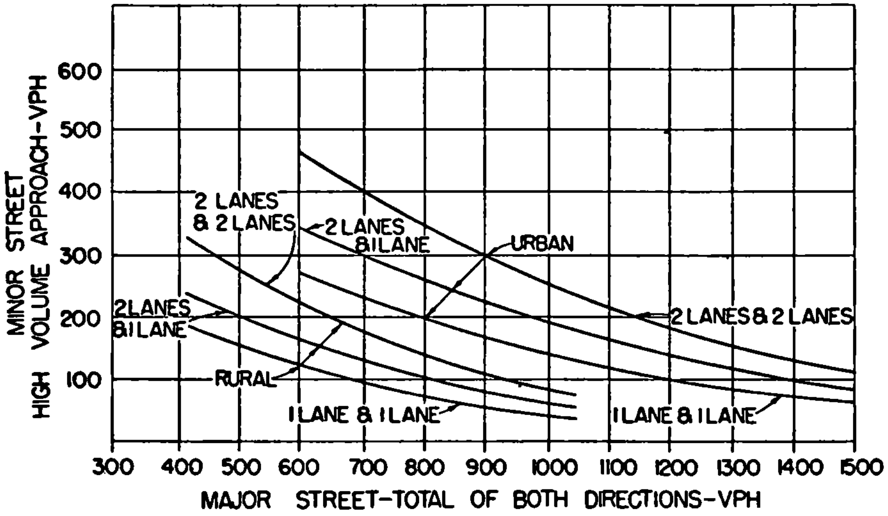


Figure 6. Texas warrant volumes for traffic signals two high hours.

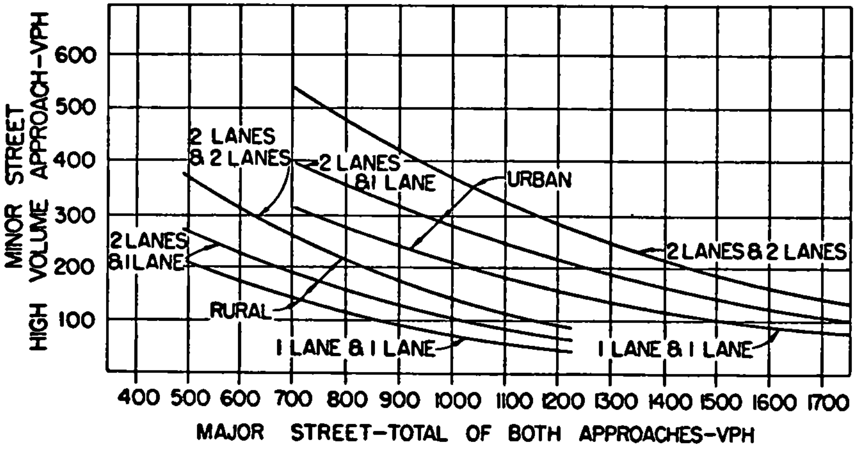


Figure 7. Texas warrant volumes for traffic signals one high hour.

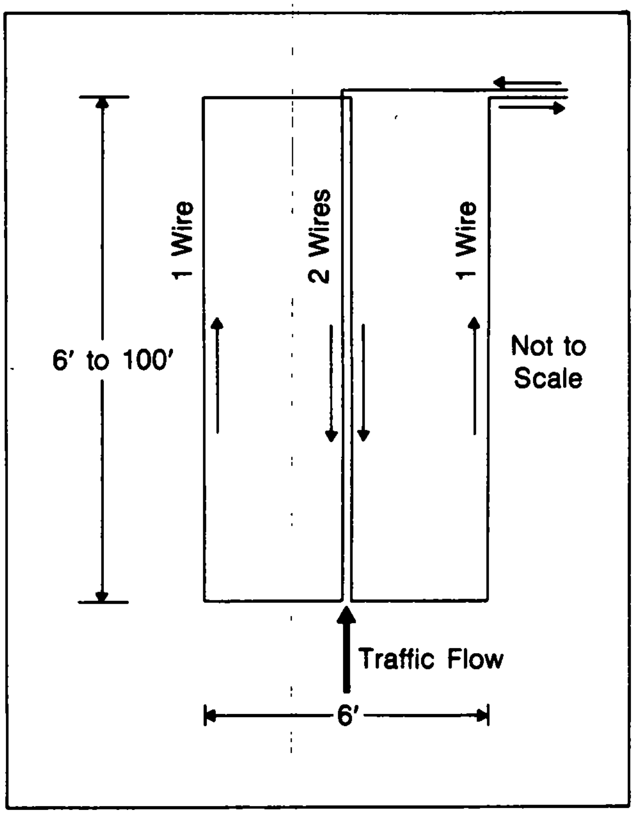


Figure 8. Quadrupole installation.

Then, in effect, the simulation would be used to both extrapolate and interpolate the field data base. This approach was subsequently modified to include a greater reliance on simulation for the following reasons:

1. Experience with the application of simulation for evaluation of the operational effectiveness of control devices showed that they would provide a highly reliable evaluation of changes in traffic flow behavior resulting from modifications in control or roadway characteristics. Thus, although the simulation results might not always be precisely accurate in absolute terms, the changes in flow resulting from an operational change would be very reliable.
2. Other research activities showed that simulation could not be used for a direct extrapolation of field data. The assumptions inherent in the simulation model were such that the use of two fundamentally different sources of data for the development of relationships between dependent and independent variables would result in serious inconsistencies and discontinuities in these relationships. Therefore, although the simulation provided an excellent basis for comparative studies, it should not be used in conjunction with a field data collection activity.
3. Problems were experienced early in the project in the identification of individual (isolated) intersections with the desired range of characteristics. In many cases, controller timing changes might be needed for the reevaluation of a particular set of conditions. This required the approval and assistance of local agency personnel on a continuing basis.
4. The large number of different conditions to be examined precluded the collection of a sample of data that was adequate for interpolation or extrapolation using the simulation.

Thus the basic approach on this project was to use the simulation to examine the performance of pretimed, semi-actuated, actuated, and volume-density controllers over a broad range of traffic and roadway conditions.

However, because excessive reliance on simulation can lead to unrealistic conclusions, the simulation activity was preceded by a field comparison with data measures at five intersections; and the simulation results were cross-checked with the results of other studies to ensure their validity. The results of the field comparison of data are presented in Appendix C; they indicate that the field measurements of delay and the simulation estimates for delay were consistently within 15 percent of each other. The agreement between percent stops was not as close, probably a result of small differences in the definition of stops within the simulation as opposed to the definitions used by the field observers. NETSIM did not count a slowly rolling vehicle as having stopped, whereas the field observers considered such a vehicle to be stopped. Thus, the field data produce a consistently higher value for this measure of effectiveness. However, inasmuch as performance comparisons are being made, the bias in the stops data should tend to be eliminated. On the basis of these field validation tests, it was concluded that the accuracy of the simulation results was better than 15 percent.

Unless otherwise indicated, the simulation results presented here were developed under the following conditions for the individual intersection:

1. Four 2-lane right-angle approaches.
2. Two-phase signals.
3. Approach speeds of 35 mph.
4. Traffic volume for each approach evenly divided between the approach lanes.

Results are presented for the change in traffic delays and stops that result from varying each of these conditions except for speed. The effects of variations in speed are presented only for a full-actuated controller with long-loop presence detection. No change in controller operations with vehicle speed was found for other types of control.

The following discussion of controller effectiveness considers the operation of individual controllers as a function of timing, roadway, and traffic conditions. The final section compares the effectiveness of these various controllers and contains the basic data for use in comparing their operation.

The results discussed throughout this section are presented in terms of the critical lane volume at the intersection. This volume is defined as the sum of the critical lane volume for each controller phase. The critical lane volume for a controller phase is the lane of traffic carrying the heaviest volume for all approaches serviced by that phase. Where turning movements are serviced concurrently with through movements, the critical lane volume is the largest volume represented by the through plus opposing left-turn volume.

Pretimed Control

As previously defined, a pretimed controller operates using a fixed cycle length and split during a predefined time period. Thus, the analysis of pretimed controller performance focused on the relationship between controller performance, cycle length, and split for a variety of roadway and traffic conditions. The basic intersection for which these relationships were examined has four right-angle 2-lane approaches. Where turning movements are studied, protected left-turn pockets are provided. Traffic volumes referred to in the discussion are the volume for both lanes of a single approach.

The relationship between delay, stops, and cycle lengths for equal volumes on all approaches at a 2-phase pretimed intersection was examined using simulation. These results are shown in Figure 9. Figure 9(a) indicates that for total critical lane volumes below approximately 1,200 vph the cycle length that produces the minimum delay is 50 sec or less. However, as volume increases beyond this level, the cycle length that produces the minimum delay becomes successively longer. These results are replotted in Figure 10 to demonstrate better the relationship between cycle length and delay. Also shown in this figure is a comparison with similar data developed by Webster (*11*) in his classic study of traffic signal settings at isolated intersections. The close agreement shown in Figure 10 with Webster's results, which have been validated in the field on numerous occasions, lends credence to the validity of the pretimed simulation results.

The relationship between stops and approach volume for a range of cycle lengths can be seen in Figure 9(b). Although stops increase with approach volume, they are insensitive to cycle length. This insensitivity can be explained on the basis that for random vehicle arrivals the percentage of vehicles stopped is related to the split, and not to the cycle length. Because a constant percent split has been maintained, stops will not be affected by cycle length. From this information it can be concluded that the most efficient signal operation for approach volumes of 600 vehicles per lane per hour or less will occur for signal cycles of less than 50 sec.

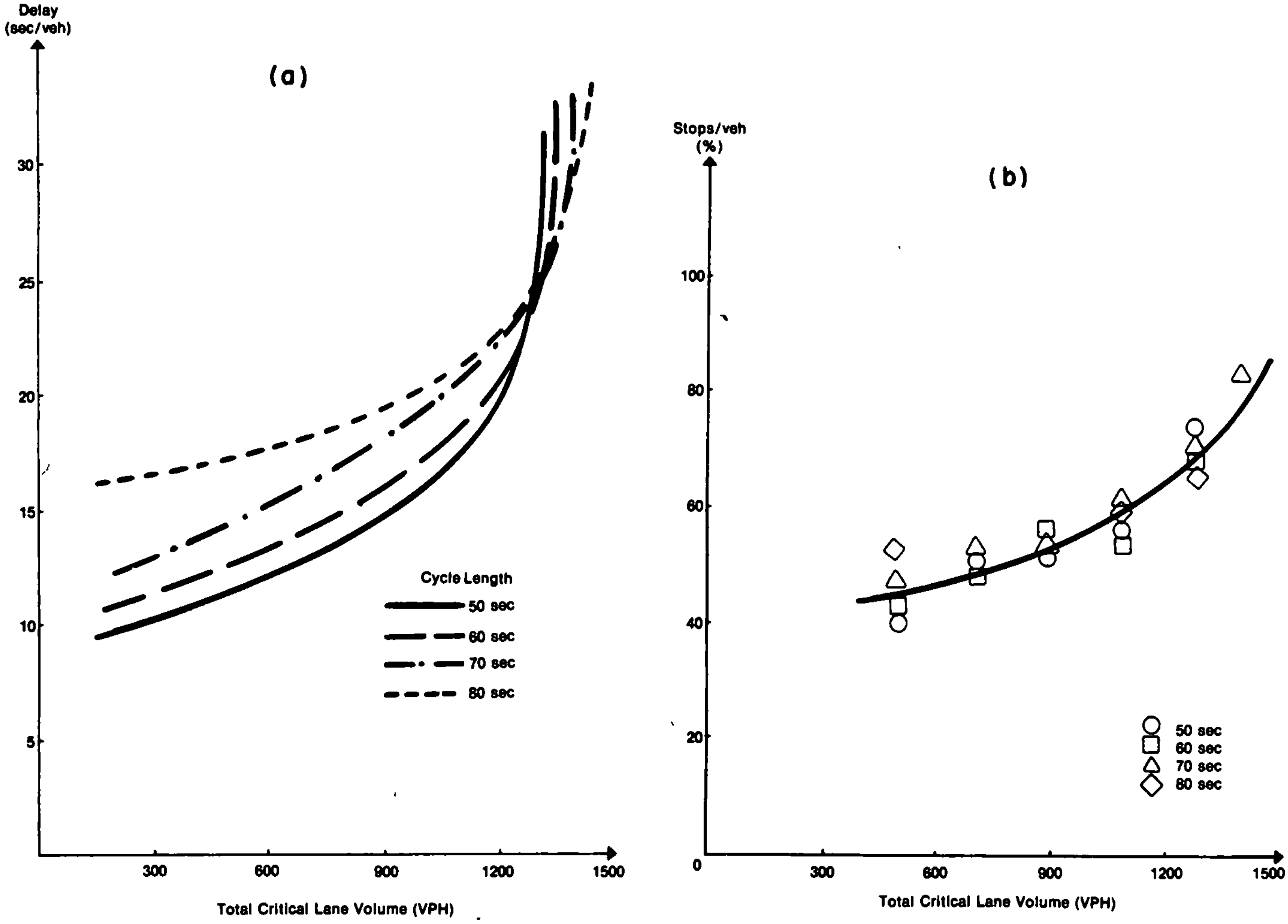


Figure 9. (a) Relationship between delay and cycle length for a pretimed controller, and (b) relationship between stops and cycle length for a pretimed controller.

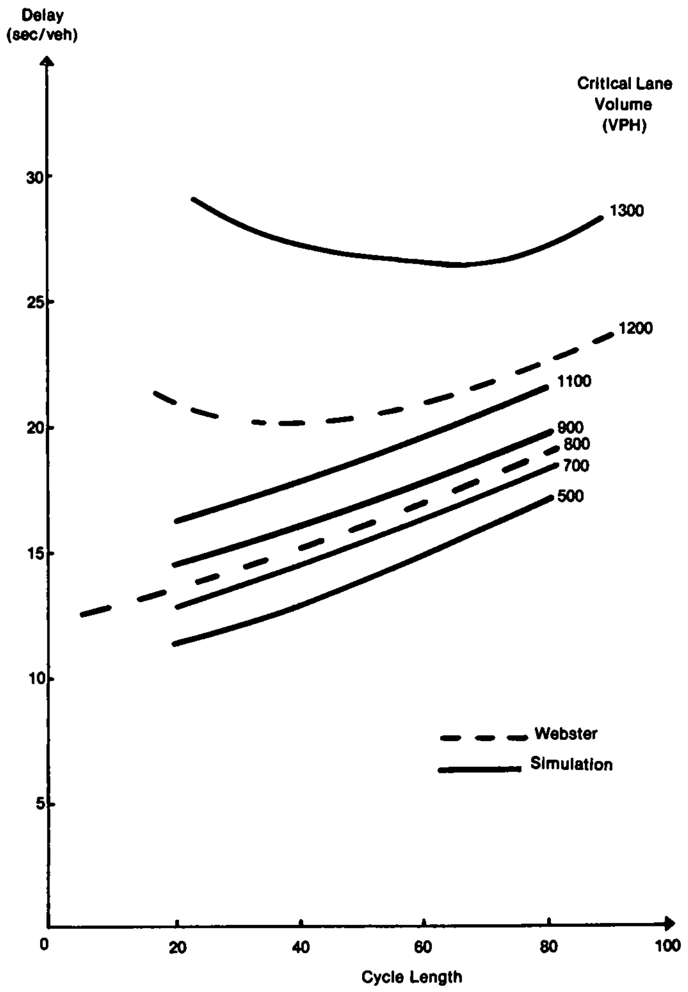


Figure 10. Comparison of Webster's equation and simulation results.

Other relationships examined for pretimed controllers include the relationship between stops, delay, and the error in split computation. These results are shown in Figure 11. Also examined was the relationship between controller operation, timing percentages, and phasing. These results are discussed in a subsequent section.

In general, it has been found that Webster's equations for computation of delay and the percent split can be used for determining delay and stops respectively.

Full-Actuated Controllers

The actuated controller has three basic timing adjustments that can be set for each approach: initial interval, extension, and maximum green. The analysis of the operation of actuated controllers considered the effect of the extension and maximum green times on controller performance. From the results presented here, it is possible to arrive at some conclusions regarding the use of the initial interval.

Staunton (*5*) presents the results of Webster and Pak-Poy, which consistently show that the longer the vehicle extension, the higher the delay. The data from this reference demonstrate that the percentage of vehicles stopped is reduced as the vehicle extension increases. (See Figs. 12(a) and 12(b).)

Unfortunately, this reference did not specifically define the conditions under which data were obtained. As a result, it was necessary to use NETSIM to obtain a definitive set of baseline performance data. The results of the simulation were derived using the same conditions as those applied to the fixed-time controller tests previously described; that is, 2-phase control with two 2-lane approaches per phase. The results of the simulation runs are shown in Figure 13(a) and 13(b). From these figures it can be seen that for the ranges of variables studied, the shorter vehicle extensions produce consistently lower values of both stops and delay up to an approach volume of approximately 1,050 vph. As the volume increases past this point, the number of stops is minimized using longer vehicle intervals. This effect is caused by the maximum green times of 60 sec per phase, which causes the controller to behave like a fixed-time controller with a 50/50 split at the higher traffic volumes. It should be noted that these simulation results do not properly account for the problem of premature termination of green resulting from the variations in queue discharge headways that occur under normal operating conditions. For this reason, extensions greater than 3 sec are often used.

The effect of the controller reaching the maximum green times is also shown in Figure 13. The longer extensions are shown to be approaching a curve corresponding to the case of the 120-sec pretimed controller.

Thus from this analysis two significant conclusions were developed:

1. Shorter vehicle extensions provide better performance at low-to-moderate vehicle volumes.
2. The maximum green times cause the full-actuated controller to behave as a pretimed controller under heavy traffic conditions. The point at which this behavior occurs is dependent on the value of extension used. If the controller is to be operated under these conditions, the maximum green times should be selected to correspond to the desired split and cycle at the intersection rather than the maximum green time generally selected which would correspond to the tolerance of the motorists waiting at the cross street red.

The conclusion that shorter vehicle intervals provide better performance is to be interpreted as a recommendation that such short intervals should always be used. The application of short intervals can lead to premature termination of the green during queue discharge because of variations in discharge headways.

Semi-Actuated Controllers

The semi-actuated controller is often applied to intersections with extremely light or variable cross traffic and moderate-to-heavy main street traffic. A typical installation controls traffic on a major arterial containing entrances to shopping centers or relatively minor cross streets. Because of their application to this type of installation, emphasis was placed on analyzing the effectiveness of semi-actuated

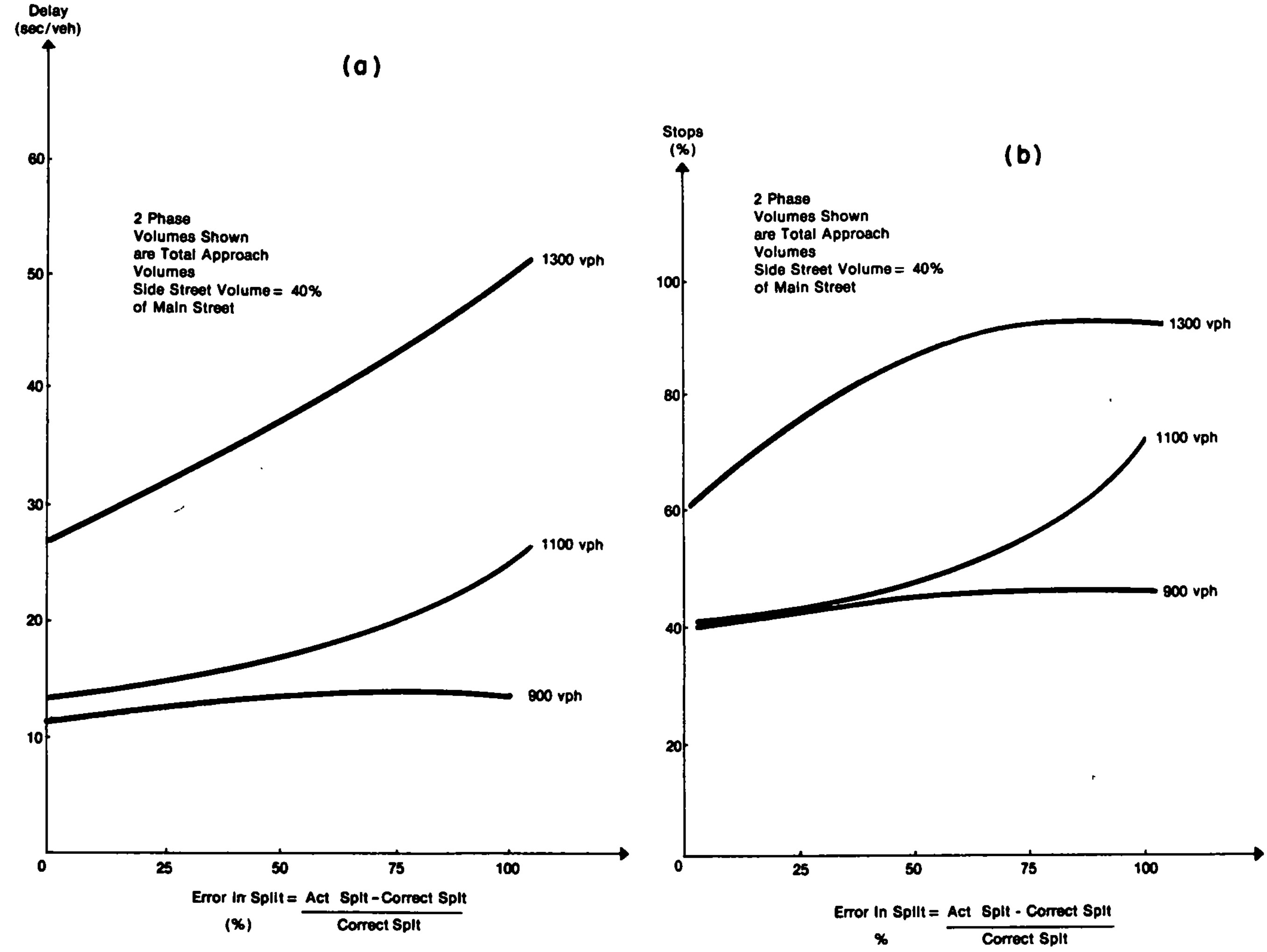


Figure 11. (a) Relationship between split error and delay-pretimed controller, and (b) relationship between split error and stops-pretimed controller.

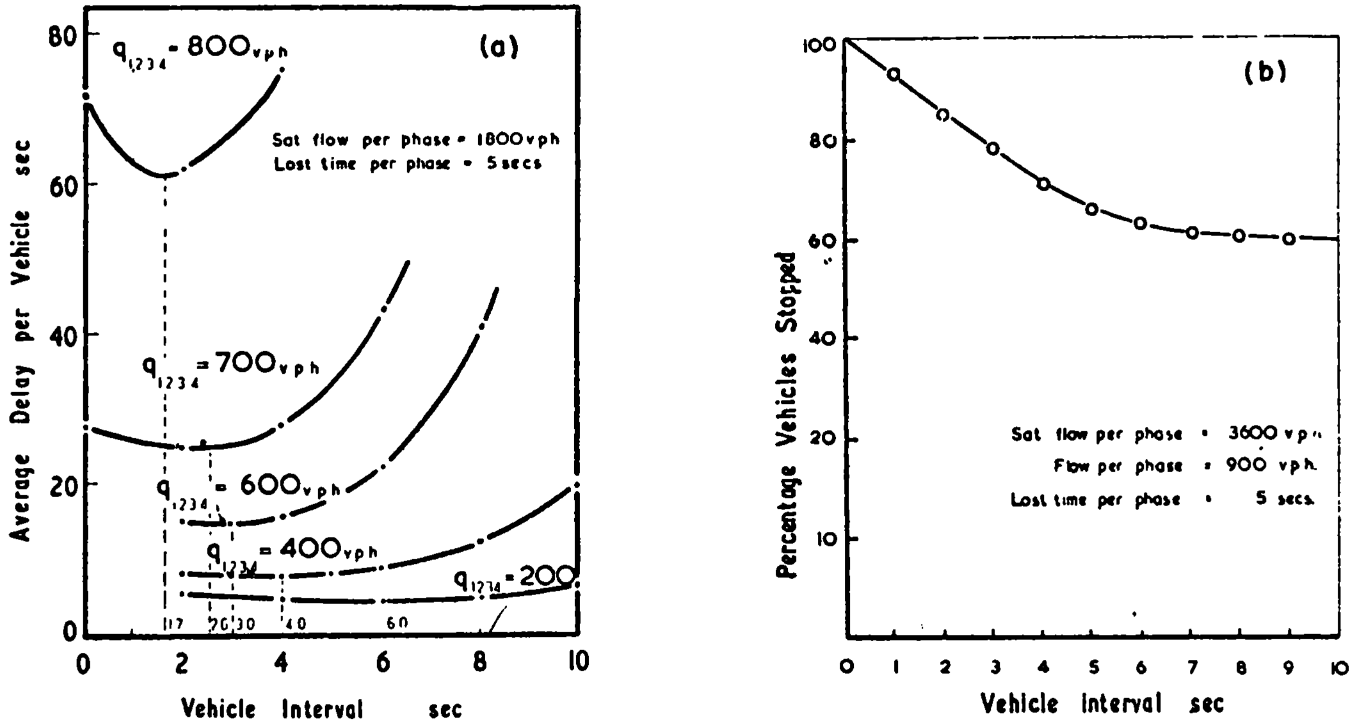


Figure 12. (a) Variation of delay with extension (vehicle interval) setting at a two-phase crossroad, and (b) variation in the proportion of vehicles stopped with extension (vehicle interval) setting on a simple two-phase controller

controllers as a function of the ratio of main street to side street traffic volumes.

Figures 14(a) and 14(b) demonstrate the effectiveness of the semi-actuated controller as a function of the relative level of side street volume as a percent of main street volume. All of these curves were developed assuming a 2-phase 4-legged intersection with a total critical lane volume of 900 vph.

From Figure 14(a) it can be seen that the intersection delay generally increases as the relative volume on the side street increases. As the fixed main street green time is reduced, the delay decreases. This effect is caused by the fact that reduced main street green is equivalent to providing the controller with increased flexibility to allocate green time to the side street. It is interesting to note that the full-actuated controller produces lower delays for the complete range of side street volumes.

Comparison of stops for various side street volumes is shown in Figure 14(b). This curve is insensitive to the main street green time and shows only a slight reduction in stops through the use of the actuated controller.

A detailed analysis of the relationship between the full-actuated and semi-actuated controllers revealed that for side street volumes that are less than 20 percent of main street volumes there is no significant difference between the two forms of control. However, at higher percent side street volumes, the full-actuated control is significantly better.

Volume-Density Controllers

The volume-density controller is a form of actuated control in which the initial green time and the extension interval are varied as a function of traffic conditions and time. The NEMA standards recognize three types of variation of the initial interval:

1. Added initial in which there is a minimum value assigned to the initial interval. Subsequent vehicle arrivals during red past some minimum number cause additional time to be added to the initial interval for each vehicle arrival.
2. Computed initial in which a maximum and minimum initial interval value are set on the controller along with the number of actuations required to reach maximum initial.
3. Extensible initial in which minimum and maximum initial interval values are set on the controller along with the added initial time per actuation.

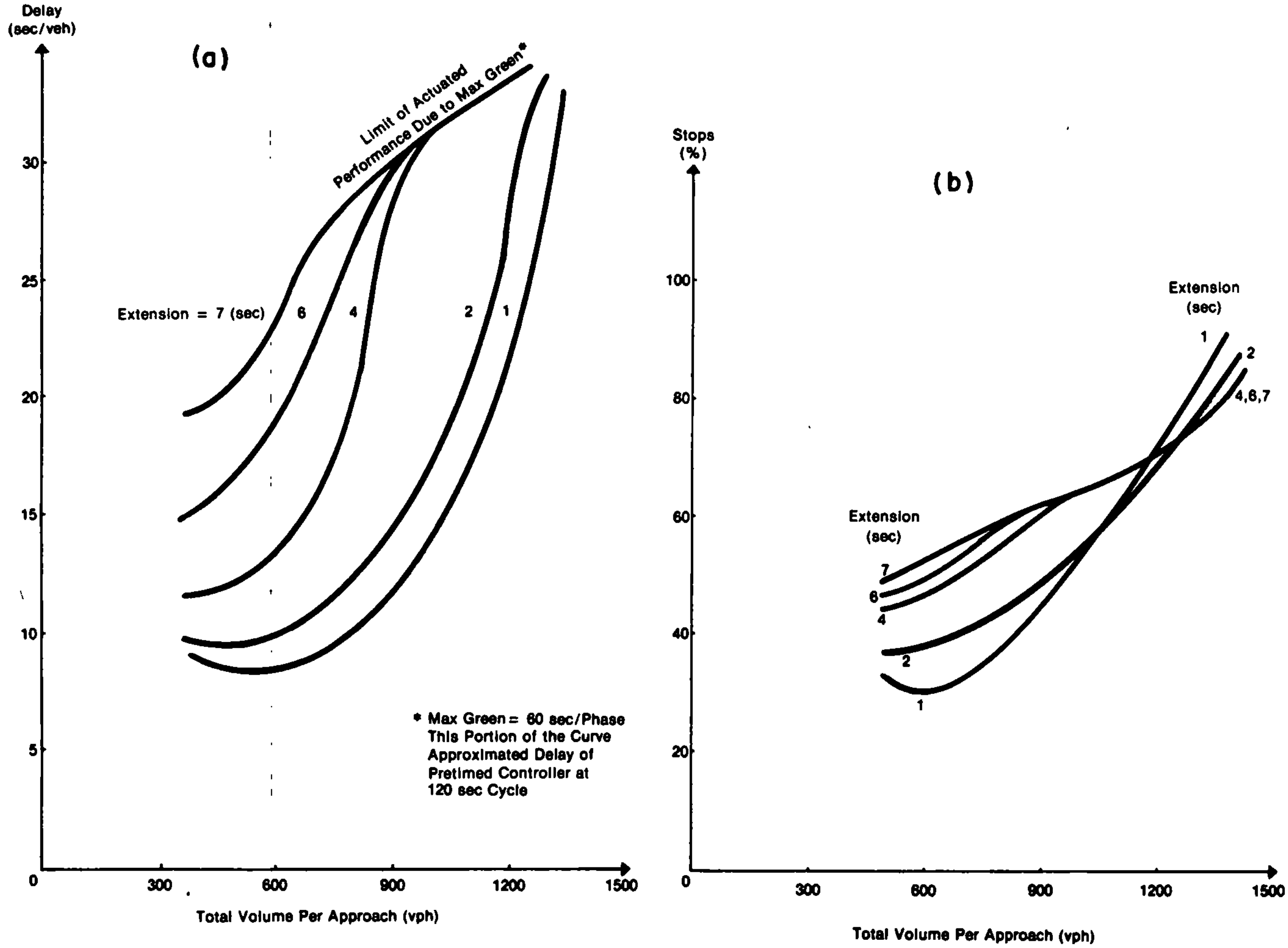


Figure 13. (a) Relationship between extension and delay—full-actuated control, and (b) relationship between extension and stops—full-actuated control.

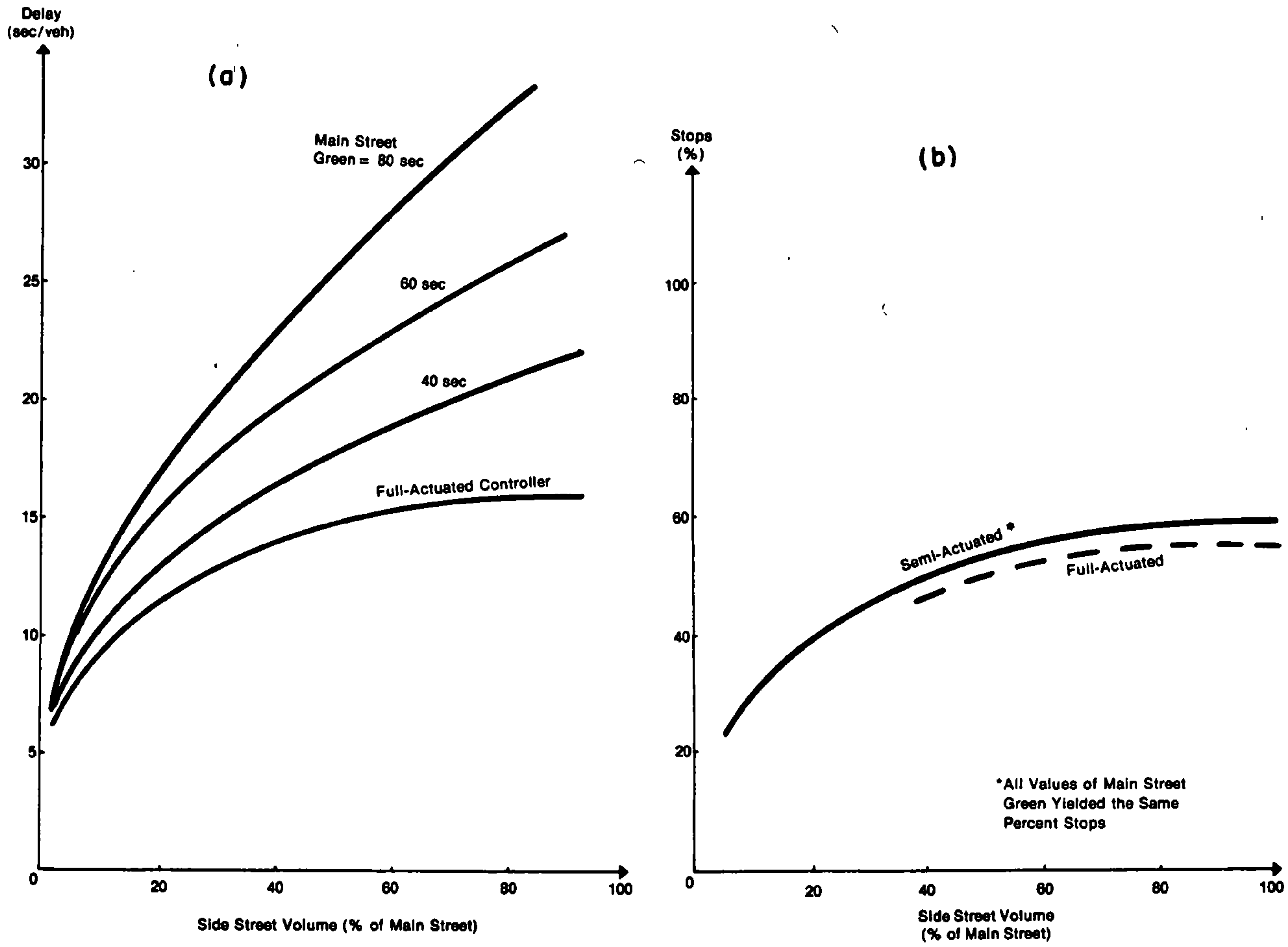


Figure 14. (a) Relationship between side street traffic and delay—semi-actuated controller, and (b) relationship between side street traffic and stops—semi-actuated controller.

Controllers currently being manufactured offer only a single form of initial interval variation. For example, the Multisonics 901 uses the extensible initial feature and has a maximum initial that is programmable from 0 to 63 sec, while the Automatic Signal Division Series 118 controller uses the added initial features and has a maximum initial interval that is fixed at 30 sec. All three types of initial interval variation are designed to accomplish the same purpose of adjusting initial green to ensure that the waiting queue is discharged prior to terminating a given phase. This difficulty is overcome by a feature used in the State of California Type 170 traffic signal equipment. When more than one detector is used for a phase, this controller calculates the variable initial based on the detector with the highest count.

Errors may also be introduced into the calculation of initial interval if a significant number of vehicles are turning right on red.

Variation of the extension on controllers manufactured to the NEMA standards can be implemented using a variety of techniques. The starting value of the extension is established by the passage time setting on the controller. The final value of the extension is defined by the minimum extension setting. The rate at which the extension will be reduced is established using one of three possible approaches:

1. Providing a time to reduce to minimum extension. This setting will provide a rate of extension reduction defined by the equation:

$$\text{Rate} = \frac{\text{Passage time} - \text{Minimum extension}}{\text{Time to reduce}}$$

2. Reduce extension every second by—this setting specifies the rate of extension reduction by defining the increment of extension reduction that will occur for every second of green time past the end of the initial interval. The time to reduce is related to the "Reduce gap every second by" (RGES) by the equation:

$$\text{Time to reduce} = \frac{\text{Passage time} - \text{Minimum extension}}{\text{RGES}}$$

3. Reduce extension every/Reduce extension by—this combination of settings specifies the interval between extension reductions and the amount by which it is to be reduced each interval. In effect, the two settings combined are equivalent to the specification of the extension reduction rate. This is:

$$\text{Reduce extension every second by} \approx \frac{\text{Reduce extension by}}{\text{Reduce extension every}}$$

As with the computation of initial interval, the alternative forms of implementation for the reduction in extension (or gap) all provide the equivalent effect.

The combination of features that have been described for the volume-density controller is shown in Figure 15. This figure is representative of the Automatic Signal Model 114 and 118 controllers that use the added initial and time to reduce features.

In studying the effectiveness of volume-density controllers, two aspects of this operation must be considered: the effect of varying the initial interval time, and the effect of varying the extension Figure 16 shows the relationship between the delay and stops produced by the extensible initial as a function of the distance between the detector and the stop line In these runs, the passage time was 6 sec and the minimum extension was 2 sec with a time to reduce of 40 sec. From these results it can be seen that slight increases in delay result as the detector is moved further from the stop line, while stops remain relatively constant.

The following section compares the operation of the volume-density controller using the extensible initial with a fixed initial interval of 8 sec This comparison shows that the extensible initial produces a reduction in stops and delay for detector setbacks in excess of 60 ft. This feature is therefore of value when the detector is located at a distance from the stop line.

The second aspect of volume-density controller performance studied was the effect of time to reduce and passage time. (A constant value of 2 sec was used for the minimum extension time.) The results, shown in Figures 16(a) and 16(b), indicate that delay increases as the time to reduce and passage time values are increased, while stops are relatively insensitive to the value of these parameters. These results are consistent with the results previously presented for the full-actuated controller which indicate that delay and stops will be minimized when shorter values of extension are employed. For comparison purpose, Figures 16(a) and 16(b) present the values of delay and stops for the full-actuated controller evaluated under the same conditions. These delays appear as a straight line, because the time to reduce has no impact on the constant value of extension employed with full-actuated control. The stops and delays resulting from volume-density control can always be made less than, or equal to, those produced by a full-actuated controller providing the passage time and minimum extension are less than, or equal to, the extension interval of the full-actuated controller. The intent of Figure 16(a) is to demonstrate the sensitivity of controller performance to the passage time setting and to indicate that long values of passage time will cause the volume-density controller performance to approximate the less efficient operation of a full-actuated controller with longer extension intervals.

Although the volume-density controller does not necessarily improve traffic flow, its extension reduction features permit the use of a shorter minimum extension than would be possible with the full-actuated controller. In other words, it is usually impractical to use a 2-sec extension on a full-actuated controller, because a rapid response to short extensions will frequently lead to premature termination of green during queue discharge because of fluctuations in discharge headways. Thus, if the volume density controller is timed to provide a 3-sec passage time and a 2-sec minimum extension, its performance will be superior to that of a full-actuated controller with a constant 3-sec extension.

On the basis of the results presented in this section, it can be concluded that the volume-density controller provides improved performance for circumstances in which the variation of the initial interval and a short extension interval are required. The volume density controller also has application at intersections with high vehicle approach speeds at which the detectors can be set back far enough to provide dilemma zone protection.

Detector Location

It is not possible to perform a comprehensive evaluation of controller effectiveness without also considering its relationship to detector location. As indicated in the state-of-the-art review contained in Appendix A, numerous researchers have studied this relationship. Unfortunately, as with evaluations of overall controller effectiveness, the parameters of their investigations are not adequately described, nor do their studies investigate an adequately varied set of conditions to arrive at any general conclusions. Thus, it was necessary to perform a comprehensive investigation of the relationship between detector location and controller effectiveness relying upon the existing literature for verification of the results.

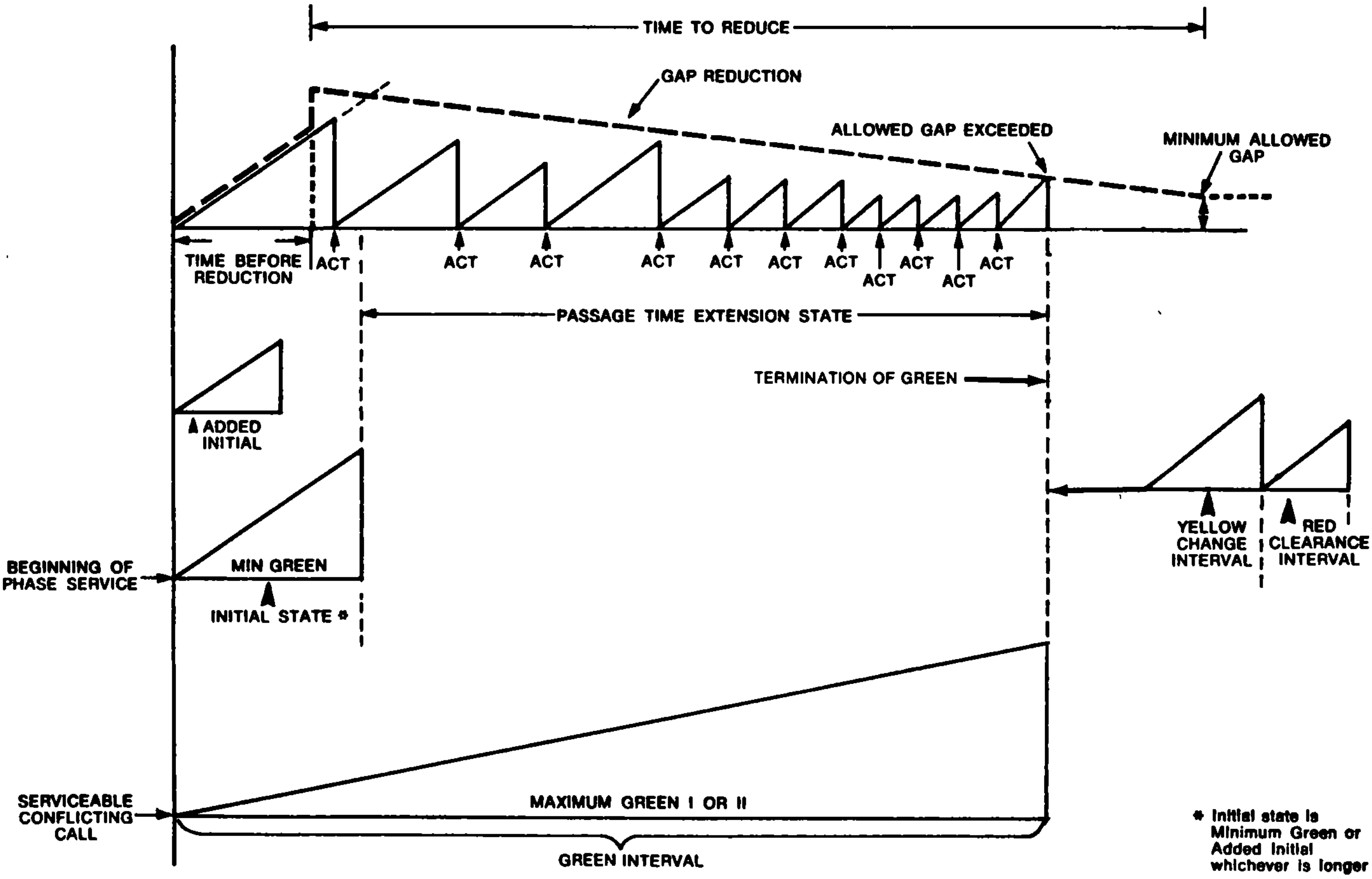
Detectorization can be classified into three basic types:

1. Location of small area detectors for basic actuated controllers (full-actuated controllers according to the terminology of this report).
2. Location of small area detectors for actuated controllers of advanced design. (Volume-density controllers according to the terminology of this report.) This category of detectorization includes location of detectors to minimize dilemma zone problems.
3. Use of long-loop presence detectors. This latter category of operation has become known as either lane-occupancy control or loop-occupancy control which will be referred to as LOC in the following discussion.

Each of these three types of detectorization has been examined using the simulation model to develop an understanding of its relationship to varying traffic conditions. The results of this investigation are presented in the following.

Location of Small Area Detectors for Full-Actuated Controllers

References 15 and 16 emphasize the importance of setting the vehicle interval on the full-actuated controller equal to the travel time from the detector to the stop line. Placing the detector nearer to the intersection results in an exension of the green time past that which is required by the detected vehicle. Locating the detector at a greater distance from the intersection can cause the green to ter-



* Initial state is Minimum Green or Added Initial whichever is longer

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Figure 15. Typical volume-density timing diagram.

minate before the detected vehicle can reach the intersection. Reference 15 also contains a table that relates detector location to approach speed for various values of vehicle interval. This table is reproduced as Table 1.

References 15 and 16 emphasize that the location of the detector should determine the values of the initial interval. In order to reduce the possibility of vehicles being trapped between the detector and stop line, this setting should be computed such that the minimum green time permits discharging all of the vehicles in the longest queue that can potentially form between the detector and the stop line. Assuming a start-up delay of 4 sec and an average headway between discharging vehicles of 2 sec, the minimum green time must be at least $(4 + 2n)$ where n is the number of vehicles between the detector and the stop line. Usually n is computed by dividing this distance by 20. For detectors located in excess of approximately 120 ft (36.6 m) from the stop line, the minimum green time will be 18 sec or longer. This length of minimum green time will reduce the controller's ability to respond to changes in traffic demand resulting in a sluggish operation. Therefore, 120 ft is often selected as an upper limit for the location of the detector. The minimum green time may be equal to the initial interval or the initial interval plus one vehicle extension, depending on the controller model being timed.

For a vehicle interval of 3 sec, the 150-ft restriction corresponds to an upper limit on approach speed of 35 mph (56 km/hr). For higher approach speeds, it is necessary to employ a volume-density controller with the capability of varying the initial interval in proportion to the actual number of vehicles waiting.

These concepts were evaluated using the simulation both in order to verify their reliability and to develop adjustment factors for the guidelines that could be used for cases of imperfect detector location. Figures 17(a) and 17(b) show the relationship between detector location and controller effectiveness for distances of 0, 50, and 150 ft from the stop line. A detector location of 100 ft was also evaluated, but is not shown because it closely resembles the 50-ft case. From these figures, it is clear that the correct location (in view of the approach speeds of 35 mph) of 150 ft produces a level of performance far superior to that of the closer detectors. These results are for basic full-actuated control.

These figures contrast the effectiveness of a basic full-actuated controller with detectors located at 0, 50, and 150 ft with a volume-density controller using the added

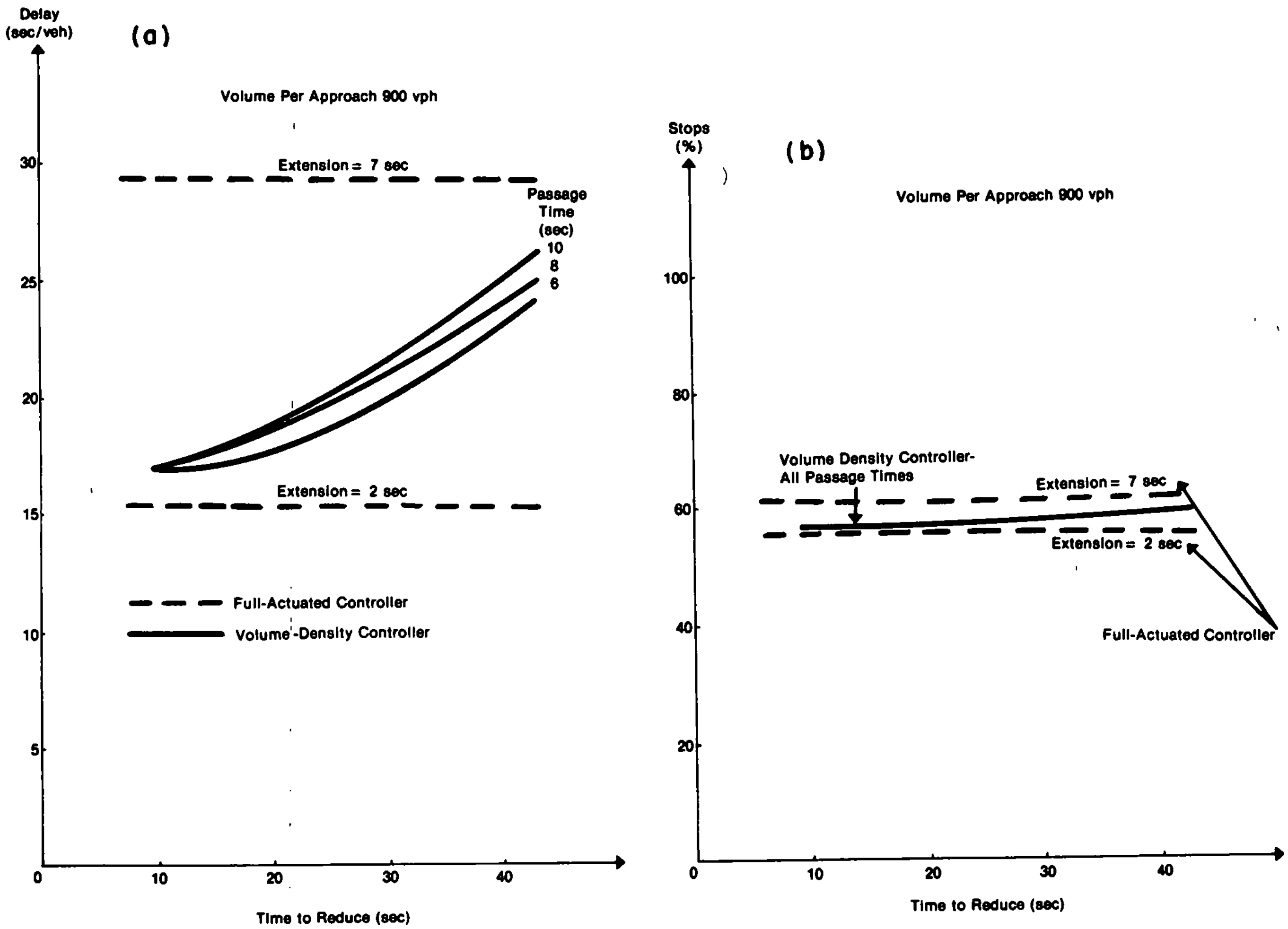


Figure 16. (a) Relationship between extension time to reduce and delay—volume-density controller, and (b) relationship between extension time to reduce and stops—volume-density controller

initial feature and no extension reduction From these figures, it can be seen that controller performance is relatively insensitive to detector location for light traffic volumes. In actual practice, detectors are located close to the intersection because of a possible actuation during the yellow change interval that may cause the controller to return to service an approach on which there is no demand. Controller performance is most sensitive to detector location at moderate volumes. At high volumes, the worst performance is registered by the full-actuated controller.

On the basis of these results, it is concluded that it is appropriate to locate the detector such that the travel time is equal to the extension. It is also concluded that for volumes in excess of 450 veh per lane (900 vph) additional improvement can be realized through the use of the added initial feature of the volume-density controller for approach speeds of 35 mph or higher.

Location of Small Area Detectors for Volume-Density Controllers

The ability of volume-density controllers to adjust their initial interval in response to the number of vehicles waiting gives them a significant advantage over the basic full-actuated controller. This is particularly true for approach speeds in excess of 35 mph for which great distances exist between the detector and the intersection. This relationship was discussed in the previous section.

In order to determine the change in performance with the addition of extension reduction, the tests performed to obtain the data for Figures 18(a) and 18(b) were repeated with a passage time of 6 sec, a time to reduce of 40 sec, and an extension of 2 sec. The results of this study are shown in Figures 18(a) and 18(b). From these figures, it can be seen that the addition of extension reduction again degrades the performance of the volume-density controller as it did for the results presented in the comparison of volume-density and full-actuated controllers.

Thus, it can be concluded that the primary benefit derived from the use of the volume-density controller is in the variability of the initial interval The use of the extension-reduction features degrades operation for all conditions examined. This result can be explained by the previously observed characteristic that actuated controllers operate most effectively when a short (2 sec) extension is used.

TABLE 1

DETECTOR LOCATION FOR SMALL-AREA OR "POINT" DETECTORS SUCH AS A 6′ x 6′ LOOP FOR ACTUATED CONTROLLERS

Approach Speed, Miles per Hour	Passage Time in Seconds from Detector to Stop Bar														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
20	29	58	87	116	145	174	196	232	261	290	319	348	377	406	435
25	36	78	108	144	180	216	252	288	324	360	396	438	468	504	540
30	44	88	132	176	220	264	308	352	396	440	484	528	572	616	660
35	51	102	153	204	255	306	357	408	459	510	561	612	663	714	765
40	59	118	177	236	295	354	413	472	531	590	649	708	767	826	885
45	66	132	198	264	330	396	462	528	594	660	726	792	858	924	990
50	73	146	219	292	365	438	511	584	657	730	803	876	949	1022	1095
55	81	162	243	324	405	486	567	648	729	810	891	972	1053	1134	1215
60	88	176	264	352	440	528	616	704	792	880	968	1056	1144	1232	1320
65	95	190	285	380	475	570	665	760	855	950	1045	1140	1235	1330	1425

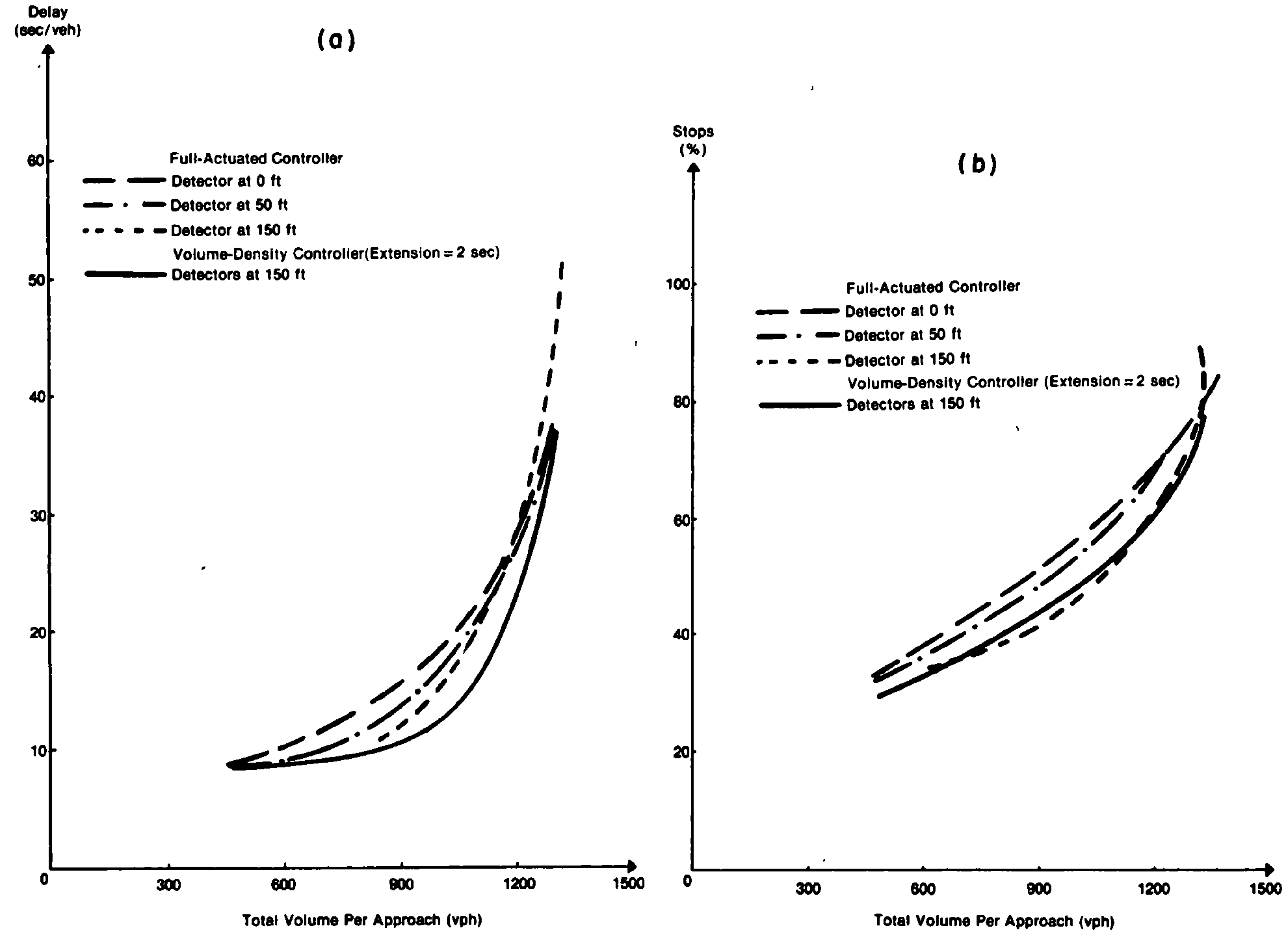


Figure 17. (a) Relationship between detector location and delay—basic full-actuated controller, and (b), relationship between detector location and stops—basic full-actuated controller.

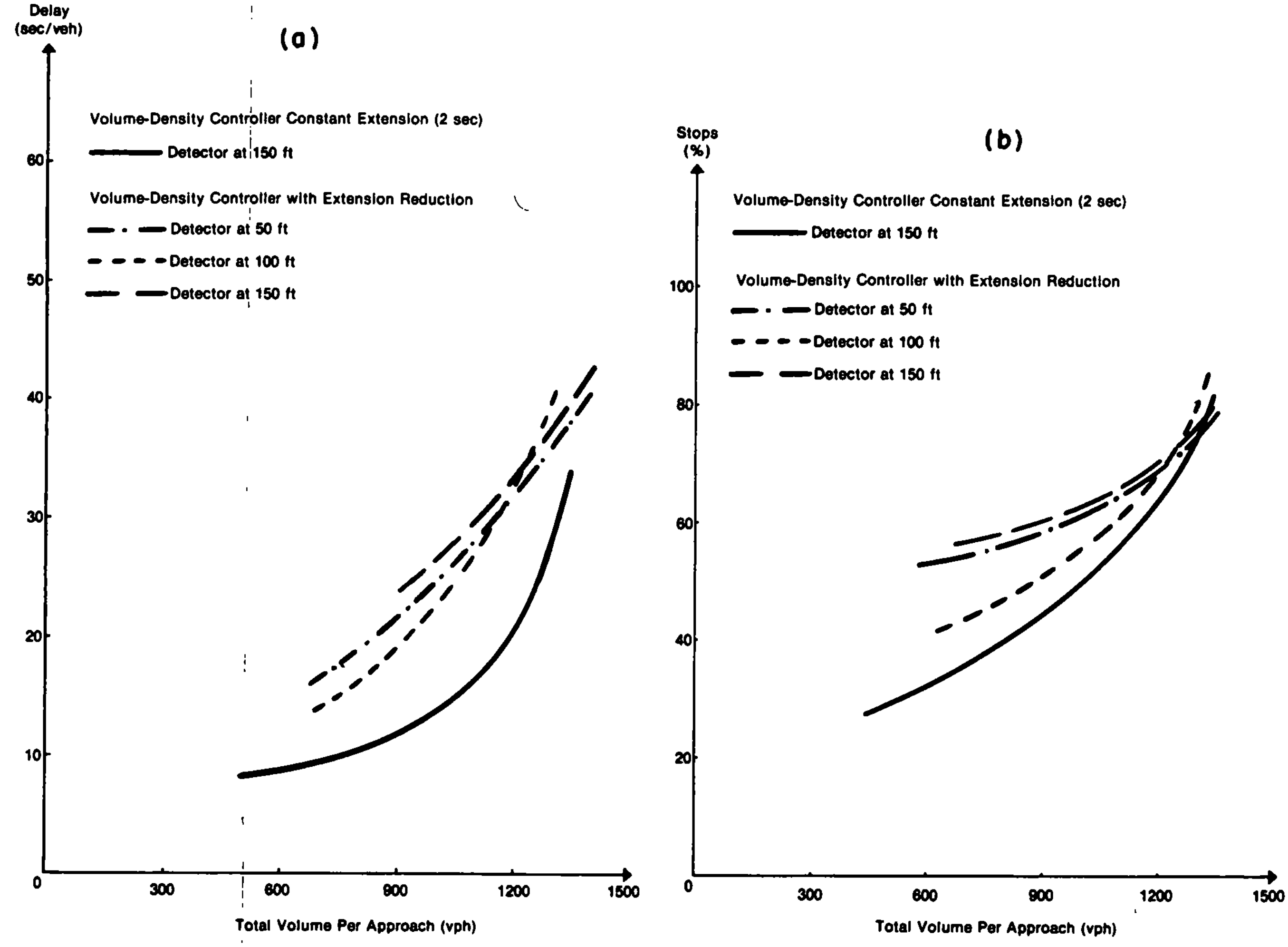


Figure 18. (a) Relationship between detector location and delay—volume-density controller, and (b) relationship between detector location and stops—volume-density controller.

The increased flexibility provided by the volume-density controller can permit detector setbacks of several hundred feet. These setbacks can result in the presence of a dilemma zone for high-speed vehicles using the intersection approach. A dilemma zone is that region of an intersection approach in which a driver will be forced to make a quick decision either to stop or to proceed through the intersection if the light changes to yellow. If he stops, the speed-distance relationship is such that his decision to stop can at worst result in a rear-end accident; at best, it will result in an uncomfortable rate of deceleration. If the driver proceeds through the intersection, he will have difficulty clearing the intersection before the end of the clearance interval

The procedure generally followed to minimize the probability of a vehicle being caught in the dilemma zone at the onset of the yellow change interval is to place the detector further from the intersection than will be required if only vehicle delays are considered. When this is done, the longer passage times of the volume-density controller are used to maintain compatibility with the increased detector setback.

There is evidence from field experience that properly designed installations offering dilemma zone protection will significantly improve the safety of intersection operation. However, it should be noted that the preceding discussion indicated that the use of volume-density controllers with extension reduction can increase the number of vehicle stops at the intersection, which can degrade intersection safety.

For this reason, it can be concluded that volume-density control should be used at intersections with high-speed approaches at which accident experience or physical design indicates the need for dilemma zone protection and the variable initial interval.

Long-Loop Presence Detection

Long-loop presence detection operates by producing a vehicle call for the duration of time that the vehicle is over the detector. This is as opposed to the modes of detector operation previously discussed in which the detector outputs a pulse (of less than 0.1 sec) when the vehicle is first detected. This latter mode of operation is known as either pulse or count detection.

When presence detection is used, the duration of the pulse produced is proportional to the sum of the vehicle length and the detector length. Thus, the detector length plays an important role in the operation of the combination of the detector and controller.

The expression that defines this relationship is:

$$PD = \frac{(LL + Lv)\,K}{S}$$

where:

PD = the duration of the vehicle presence indication from the detector;

LL = loop length, ft;

Lv = vehicle length, ft;

K = an adjustment constant to compensate for the fact that the sensitivity of the loop does not cause the detector to trigger as soon as the front bumper crosses the loop; and

S = vehicle speed (ft/sec) which equals vehicle speed (mph) × 1.47.

The significance of this equation is that when presence detection is used with a full-actuated controller, the effective extension is equal to the sum of the presence duration plus the extension setting on the controller. This relationship is plotted in Figure 19.

The long-loop presence detector is currently being used with full-actuated controllers in a mode known as lane-occupancy control or loop-occupancy control (LOC) *(17)*. LOC operation occurs when the controller is programmed for initial green interval of zero. Extensions are set either to zero or to a very low value. There is no need for a nonzero initial interval or minimum green time because the long loops continuously register the presence of any vehicles that are waiting, causing the controller to extend the green until the entire queue is discharged. The result is a signal operation that responds rapidly to changes in traffic flow.

Pedestrian WALK and pedestrian clearance intervals must be considered in the timing of all types of controllers. This aspect of signal timing becomes even more important with LOC because the minimum green time for vehicles is the sum of time for the vehicles to leave the loop area plus the extension time (if any) setting on the controller. Therefore, the minimum green time with LOC and light traffic conditions may be very short.

A second possible disadvantage is the expense and constraints represented by the longer loop. Because loop installation costs are based on the linear feet of sawcut and wire used, the longer loops will be more expensive to maintain and result in a less reliable operation. As previously indicated, the extension is partially determined by the length of the loop Thus, the vehicle interval cannot always be easily reduced unless the loop is physically shortened; in other words, replaced.

In spite of these disadvantages, LOC has received popular acceptance in areas of light pedestrian traffic because of its responsive operation. In order to quantify the benefits of LOC, a review of the literature was conducted followed by a series of simulation tests.

References 17 and 18 each compared small area detection with presence detection under real-life conditions. Bang and Nilsson *(17)* compared LOC operation with pulse detector operation in March 1970. They concluded that delay was reduced 10 percent and stops by 6 percent under the same traffic conditions with LOC.

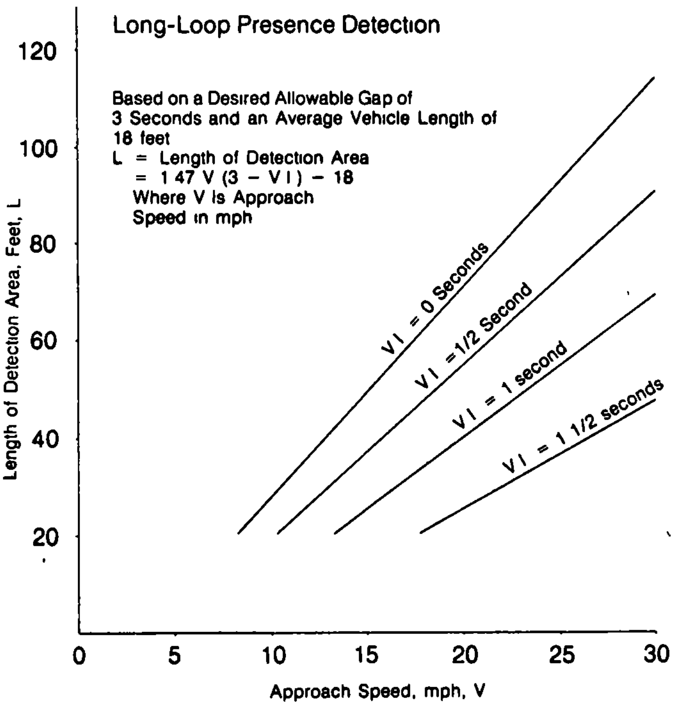


Figure 19 Long-loop presence detection for actuated controller in nonlocking mode chart for determining loop length

Cribbins and Meyer *(18)* compared pulse and presence detectors. They concluded that the longer the length of the presence detector on the major approach to the intersection, the longer the delay. They also concluded that the highest intersection travel time values occurred when either long-loop presence or pulse detectors were used on both major and minor approaches.

It is difficult to interpret these results because the vehicle speeds and controller settings used were not specified by either reference. It is likely that the improved operation with presence detectors over pulse detectors in both references was the result of the extensions used with the pulse mode.

In an effort to further test these theories, simulation runs were made for LOC using zero initial intervals and extensions. These runs were made to detector lengths of 30, 60, and 90 ft. These detector lengths correspond to extensions of 0.6, 1.2, and 1.8 sec for the 35-mph approach speeds simulated. Here again, it must be emphasized that the simulation results do not properly account for premature termination of the phase because of variations in queue discharge headways For this reason extensions shorter than 3 sec are not commonly used. These results were compared with a controller operated under the same conditions but a pulse detector with a 2-sec extension. The results of these comparisons are shown in Figures 20(a) and 20(b). From these figures it can be seen that as the effective extension approaches the 2-sec (optimum) vehicle interval of the pulse detector, the stops and delay are equivalent. However, at high vehicle volumes, the performance of the

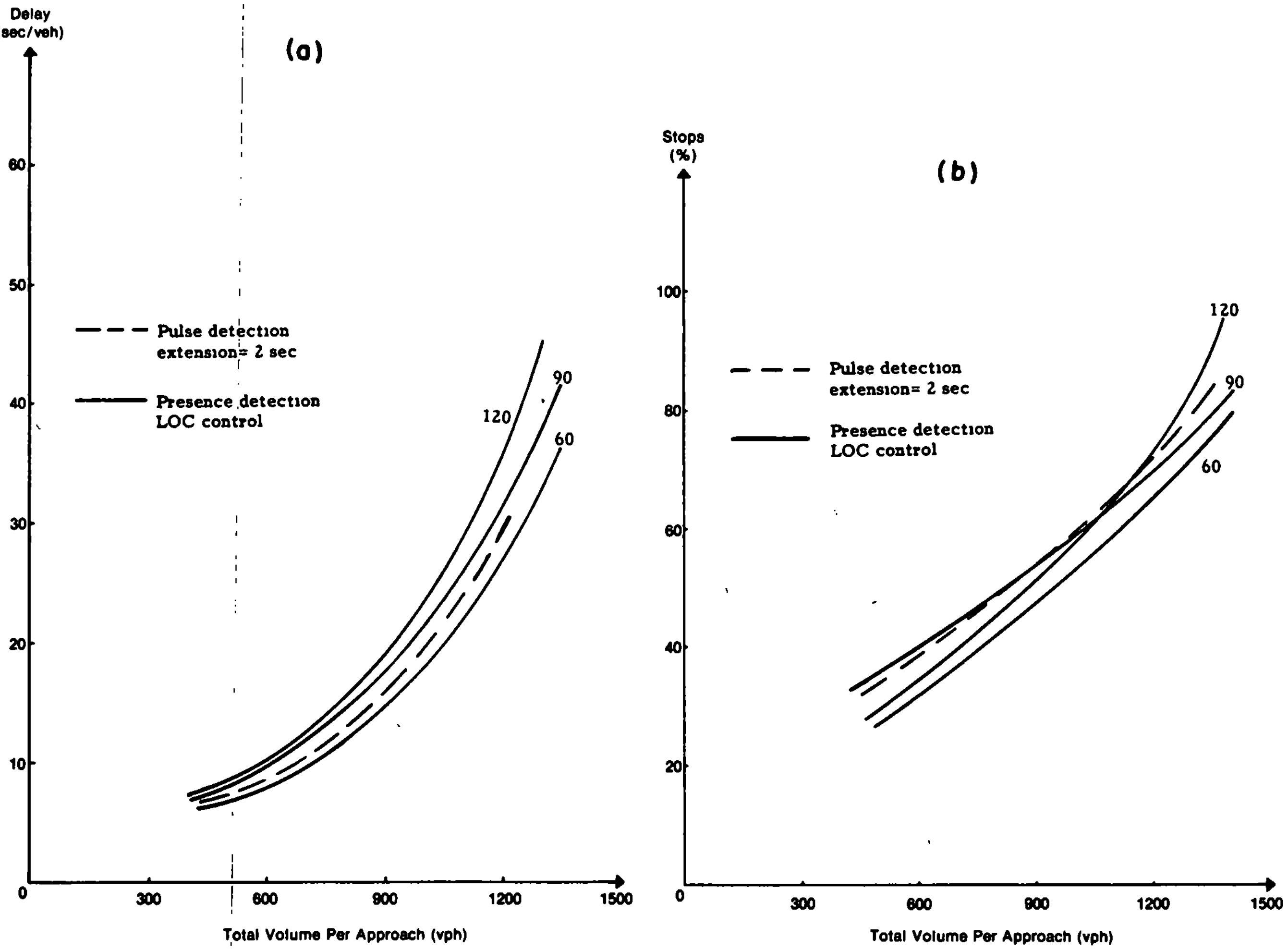


Figure 20 (a) Relationship between detector length and delay—LOC control, and (b) relationship between detector length and stops—LOC control.

LOC is somewhat degraded. This degradation in performance is a result of the slower vehicle speeds that occur in the presence of heavy traffic.

These results indicate that LOC will be more effective than pulse detection over a wide range of traffic volumes. It offers the further advantage not reflected by the simulation results of screening out false calls caused by vehicles approaching but not traveling through the intersection.

Comparison of Controller Effectiveness

On the basis of the discussion of the preceding sections, it is clear that unless long detector setbacks are used at relatively high-speed approaches, only pretimed or full-actuated controllers with either short loops or wide area loops (LOC) should receive serious consideration for installation at an individual intersection. In comparing the effectiveness of these forms of control, it is useful to combine the information presented in Figures 9 and 13 into the single curve of Figures 21(a) and 21(b).

From these figures it is clear that the relative benefits of full-actuated and pretimed control are heavily dependent on the signal timing to be used and the existing approach volumes. Therefore, the final selection of a particular type of control cannot be based on a particular rule of thumb, but must be developed using the specific circumstances of the installation.

In order to determine the effect of various sets of roadway and traffic conditions, a number of different relationships were examined. Figures 22(a) and 22(b) show the delay and stops for both pretimed and actuated controllers as a function of the percent of left-turning vehicles on the main street. Side street traffic was assumed to equal main street traffic and to have no turning movements. These figures show that for the 2-phase control, the actuated controller becomes less effective than the pretimed controller at an approach volume of 900 vph. This is a somewhat lower crossover in effectiveness than the case of Figure 21 (which has a crossover of 1,100 vph) because the turning vehicles degraded the operation of the actuated controller which tended to give a higher percent of green time to the left-turning vehicles than the pretimed controller which penalized the heavier cross-street volumes. The actuated controller operation could have been improved by reducing the extension for the left-turn movement.

The improvement in performance with the 8-phase dual-

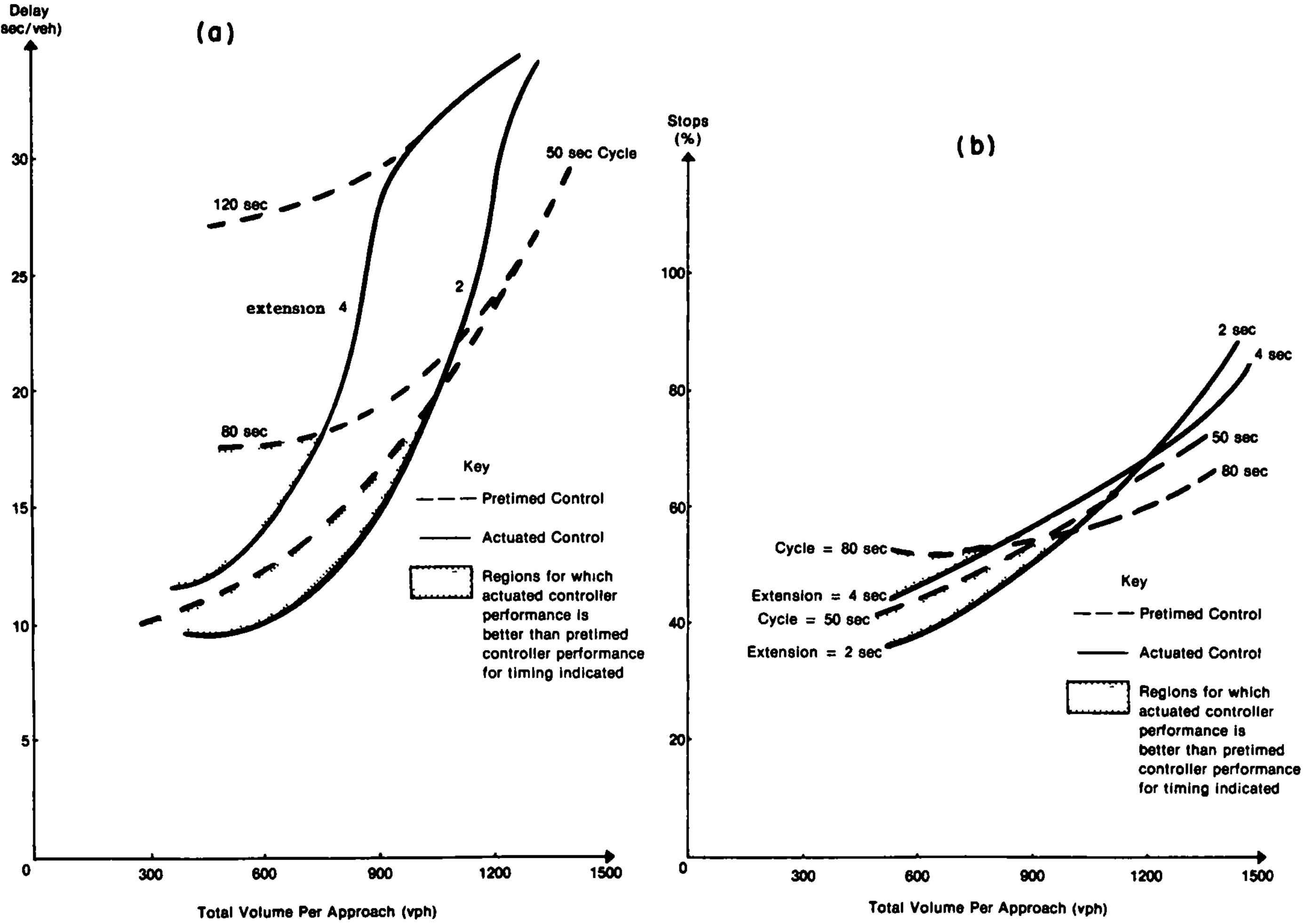
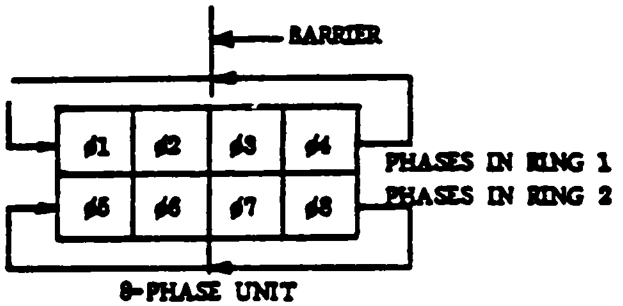


Figure 21. (a) Comparison of pretimed and full-actuated controller delay, and (b) comparison of pretimed and full-actuated controller stops

ring controller demonstrates the value of employing flexible turning phases when significant turning traffic is present. A dual-ring controller is a controller containing two interlocked rings that are arranged to time in a preferred sequence and to allow concurrent timing of both rings, subject to the restraint of the barrier (compatibility line). The phases within the two timing rings are numbered as illustrated in the following.



The advantages of multiple phases become even more evident in the presence of both cross street and main street left-turning traffic, as shown in Figures 23(a) and 23(b) for 10 percent left turns and in Figures 24(a) and 24(b) for 20 percent left turns. These figures compare both 4-phase and 8-phase (dual-ring) actuated controllers with a 4-phase pretimed controller. They show that reductions in delay as high as 50 percent are possible when the 8-phase controller is employed in favor of the pretimed controller

It is interesting to note that the benefits of 8-phase actuated control are not as great in comparison with the 4-phase actuated control for the case of 20 percent left turns as they are for the 10 percent left turns. This is because the high turning percentages restrict the dual-ring controller's flexibility of concurrently timing various non-conflicting phases. Thus, the controller's performance tends to resemble closely the performance of the 4-phase controller.

Figures 24(a) and 24(b) also show the effect of operating the intersection with left turns permitted during green through movements (permissive instead of exclusive left turns). As might be expected, the permissive operation provides its greatest benefits at the lowest traffic volumes.

However, even these benefits are not great (approximately 7 percent at 500 vph) As a result, permissive operation has not received additional consideration

In addition to studying the relationship between stops and delay, the ratio of main street to side street volume was studied for both pretimed and full-actuated controllers Stops and delay for pretimed controllers were found to be relatively constant as long as the degree of saturation for each phase is held constant, where the degree of saturation is the ratio of demand volume to effective green time That is:

$$DOS = \frac{V_d}{G_E}$$

where

V_d = lane volume of lane with greatest demand, and
G_E = (Green + yellow time) — (loss time due to start up delay, and portion of yellow not used by vehicles).

The actuated controller performance as a function of changing ratios of side street traffic has been shown in an earlier section in Figure 14

In concluding this section, it must be emphasized that the comparisons presented consider only vehicle stops and delays The relationship between these measures and other benefits involves several additional factors that are discussed in the following sections

Analytic Expressions for Comparing Controller Effectiveness

The preceding data demonstrate the importance of considering signal timing and roadway and traffic conditions when comparing alternative forms of control. The complex interaction of these variables precludes the development of a procedure for comparing control alternatives in a step-by-step nomograph form. For this reason, an analytical procedure was developed that permits a direct comparison of control alternatives taking all of these variables into account

The analytical relationship was developed using the results of simulation runs made to compare pretimed, semi-actuated, and full-actuated controller performance as a function of total critical lane volume and percent side street volume The relationship between delay and percent main street volume produced by the simulation is shown in

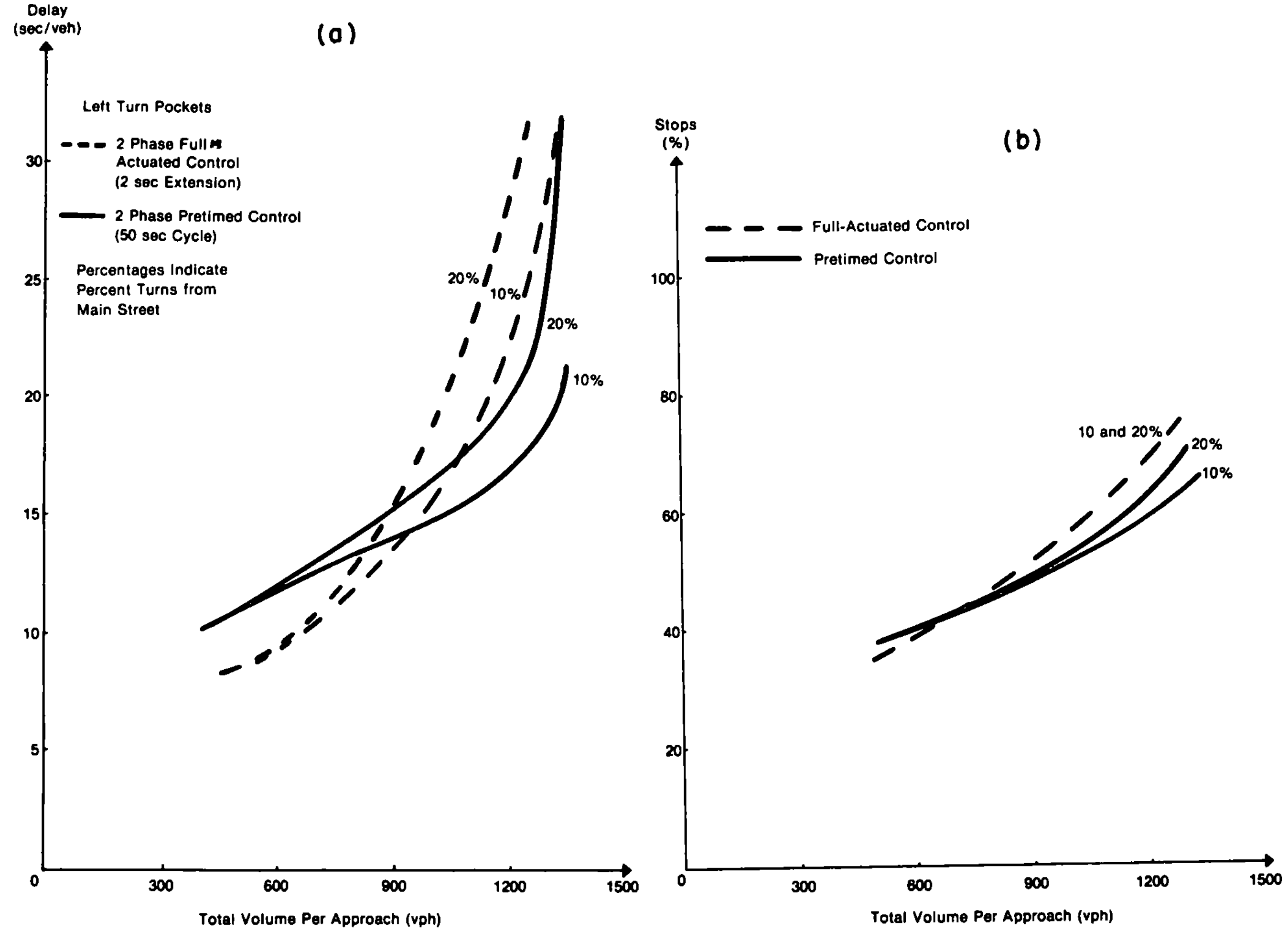


Figure 22 (a) Relationship between percent main street turns, type of control, and delay, and (b) relationship between percent main street turns, type of control, and stops

Figure 25. This figure assumes that the pretimed controller split has been adjusted to equal the relative critical lane demand on each phase. It further assumes that the pretimed controller is constrained to a minimum green time required by pedestrian walking speeds of 4.0 fps. Detailed analysis of these results indicated that for side street volumes that are less than 20 percent of the total critical lane approach volume, there is an insignificant difference in controller performance between the semi-actuated and full-actuated alternatives. At higher percentages of side street volume, the semi-actuated controller delay is consistently higher than those produced by the full-actuated and pretimed alternatives.

These curves also indicated that for higher volumes the full-actuated controller effectiveness will be degraded at the volume levels for which one of the full-actuated controller phases is extended to the maximum green. When this occurs, the delay becomes significantly higher because the split is inappropriate for the existing approach demand.

As the percent side street traffic increases, the delay produced by the full-actuated controller is reduced because the split determined by the effects of actuation and the maximum green times more nearly approximate the split required by the relative traffic demands on each approach. The curves shown in Figure 25 are representative of the delays produced by a full-actuated controller with equal maximum green times for both approaches. If the maximum green times were not equal, the full-actuated controller operation would approximate pretimed operation at different percent side street traffic.

To develop the mathematical relationship that defines the boundary between full-actuated and pretimed controller performance indicated in Figure 25, it is necessary to identify the side street and main street volumes for which the full actuated controller is operating at the optimum pretimed cycle length and the correct split, for a given set of maximum green times. At volumes that are lower than the calculated values, the full-actuated controller will be operating more effectively than the pretimed controller. At higher volumes, the pretimed controller will operate more effectively. These relationships can be derived using the equations for a pretimed controller that have been developed by Webster (*11*).

The relationships derived are based on the equations for the optimum cycle length, *C*, and the optimum green time, S_n, in seconds for approach *n*·

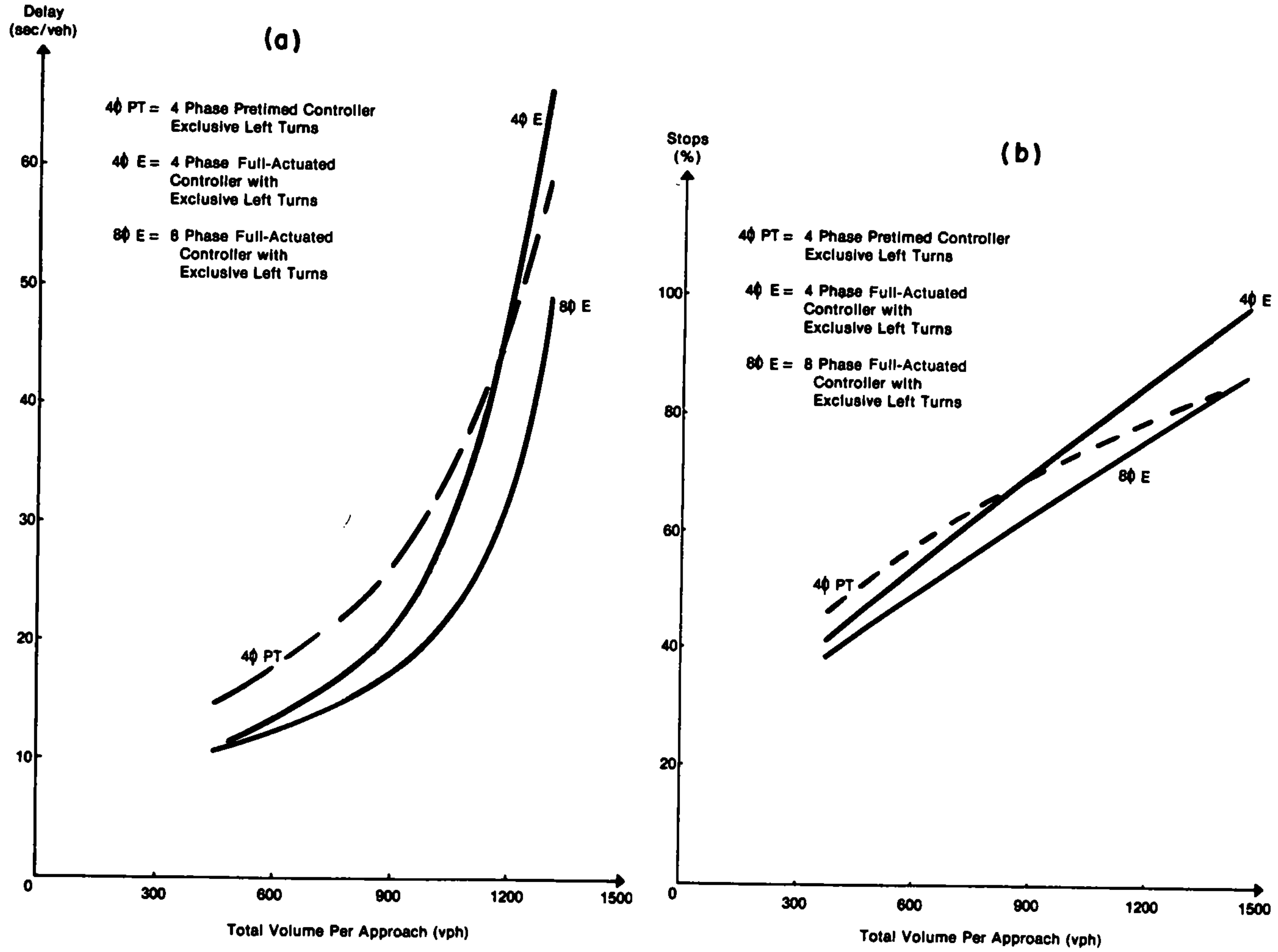


Figure 23. (a) Relationship between number of phases, type of control, and delay, 10% left turns, and (b) relationship between number of phases, type of control, and stops, 10% left turns

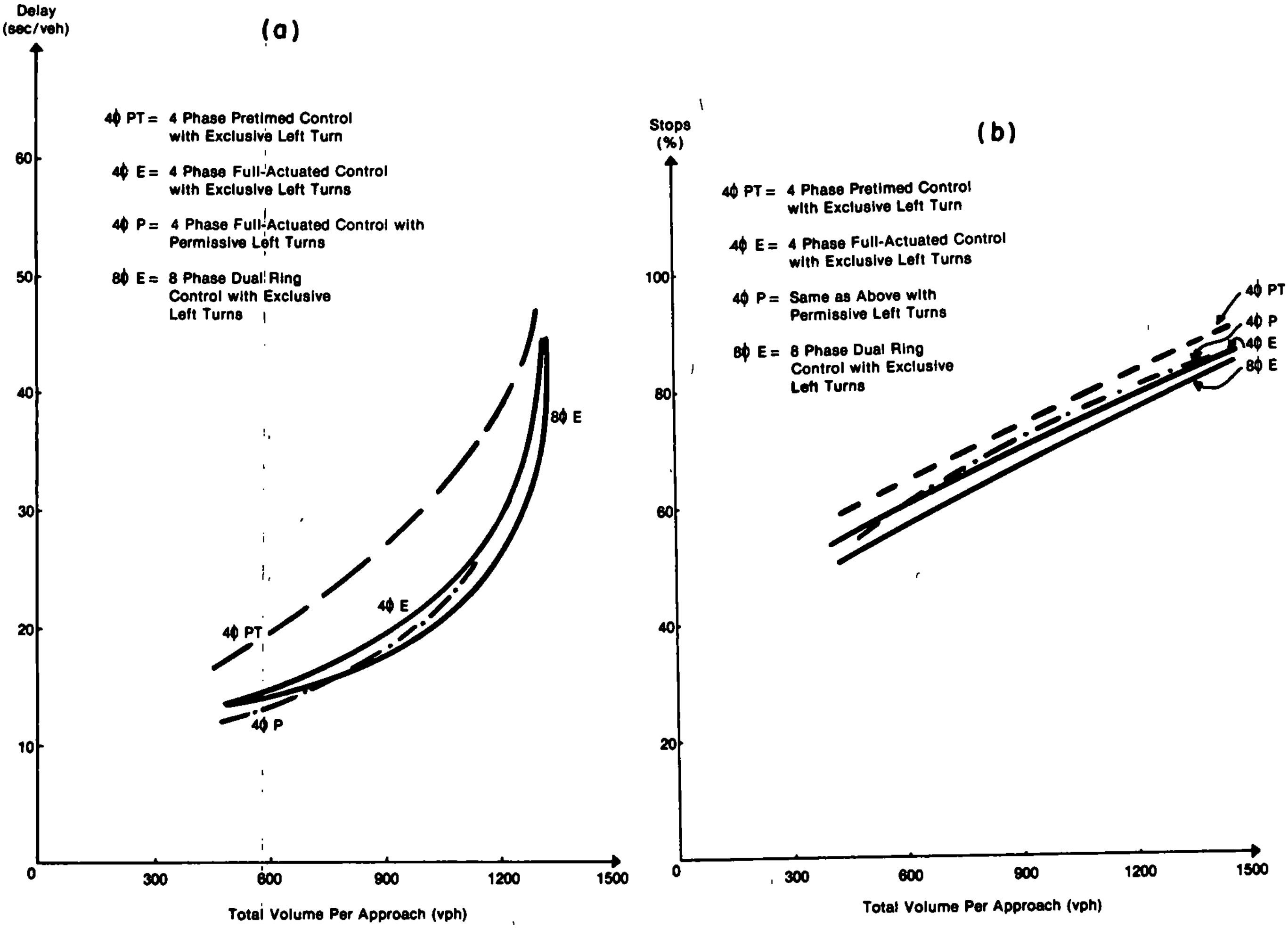


Figure 24 (a) Relationship between number of phases, type of control, and delay, 20% left turns, and (b) relationship between number of phases, type of control, and stops, 20% left turns.

$$C = \frac{1.5L + 5}{1 - Y} \qquad (1)$$

where:

Y = the sum of the ratios of actual flow to saturation flow, y_n, over all intersection approaches;

L = the lost time for each cycle due to startup delays and red clearance interval times; and

$$S_n = \frac{y_n}{Y} \times (C - L) \qquad (2)$$

in which

y_n = the ratio of the actual flow to the saturation flow on the approach n. Where the saturation flow rate is the capacity of the approach, a value of 1,200 vehicles per lane per hour is frequently used.

For actuated controller with given maximum green times, the maximum cycle length has already been determined as the sum of the maximum greens plus change intervals plus the red clearance intervals. The problem is then to determine the approach volumes corresponding to the predetermined cycle length. This can be calculated by solving for Y in Eq. 1 giving the results:

$$Y = 1 - \frac{1.5L + 5}{C} \qquad (3)$$

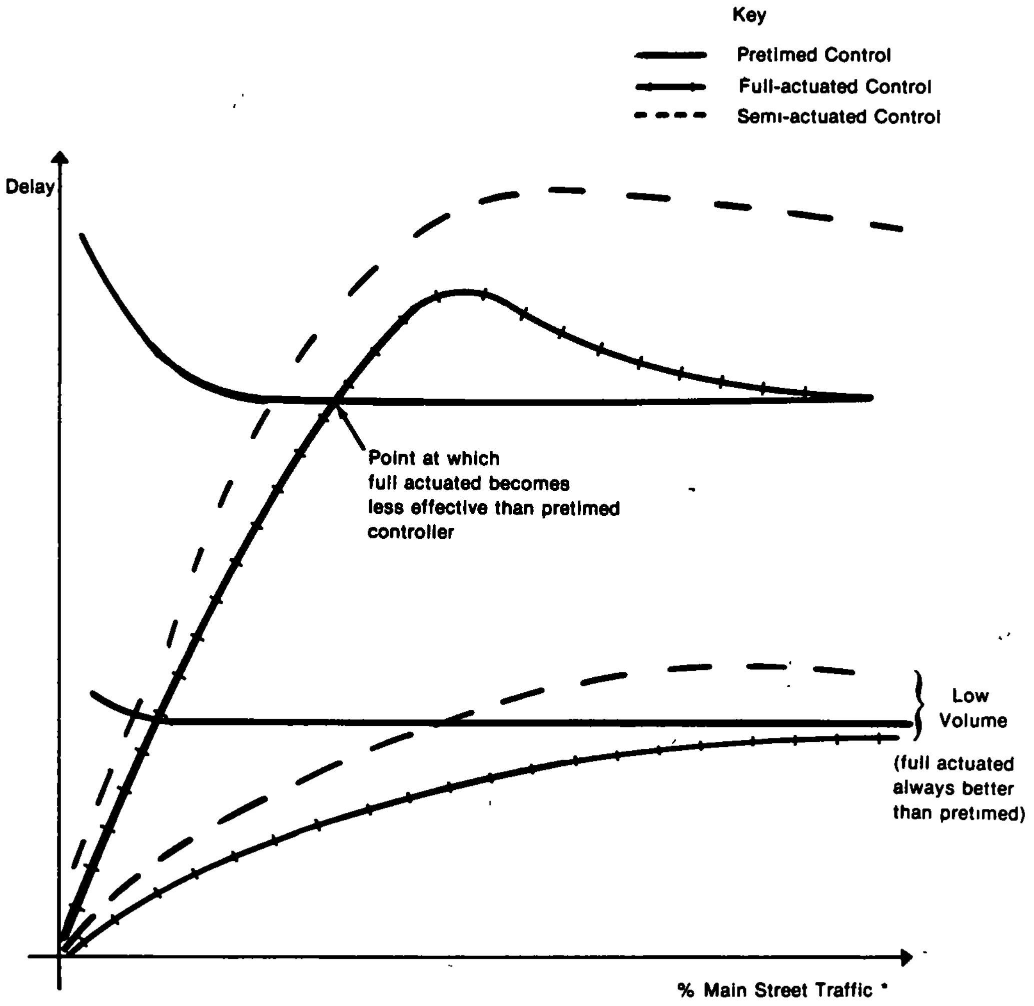
The flow ratio, y_n, for each approach can be calculated from Eq 2 using the value of Y calculated in Eq. 3:

$$y_n = \frac{G_n \times Y}{(C - L)} \qquad (4)$$

where G_n is the maximum green time for approach n.

The approach volumes corresponding to the boundary between full-actuated and pretimed control can be determined for each approach, n, by solving Eq 4 for each approach and multiplying the calculated value of y_n by the saturation flow rate for that approach. This calculation produces a unique set of approach volumes corresponding to the case for which all controller phases are extended to their maximum values. If only two phases are being considered, the result will be plotted as a single data point on the curve of main street and side street volumes (see Fig. 26).

A more complex procedure must be used to calculate the boundaries of pretimed and full-actuated control for the case when only one phase has reached its maximum time.



* Critical Lane Volume on Main Street
Total Critical Lane Volume for all Phases

Figure 25. Relationship between control alternatives as a function of traffic volume.

It is necessary to calculate the volume on the phases that have not reached the maximum which will cause the vehicle delays at the intersection to exceed those produced by a *well-timed* pretimed controller. This will occur when the green time on the phases that have not been extended to the maximum do not leave adequate green time for the phase that has already reached the maximum.

Equations 1 and 2 can also be used as the basis for this computation. To simplify the derivation of the equations and subsequent calculations, the notation has been changed to indicate that two volumes are being considered—a main street volume, V_m, and a side street volume, V_s. Each of these volumes has a ratio of actual flow to saturation flow designated y_m and y_s, respectively. In addition, there is a maximum green time for each appropriate designated G_m and G_s. For controllers with more than two phases, the side street volumes, ratios, and maximum green times become the sum of these times for all phases other than the main street phase.

Using this notation, Eqs. 2 and 3 can be rewritten as Eqs. 5 and 6, respectively:

$$\frac{G_s}{G_m} = \frac{Y_s}{Y_m} \tag{5}$$

$$Y_s + Y_m = 1 - \frac{1.5L + 5}{(G_s + G_m + L)} \tag{6}$$

In Eq. 6, L is much less than $G_s + G_m$. For this reason, Eq. 6 is simplified as:

$$Y_s + Y_m = 1 - \frac{1.5L + 5}{G_s + G_m} \tag{7}$$

Solving Eq. 5 for G_s and substituting the result in Eq. 7 gives:

$$Y_s + Y_m = 1 - \frac{1.5L + 5}{G_m + G_m\left(\frac{Y_s}{Y_m}\right)} \tag{8}$$

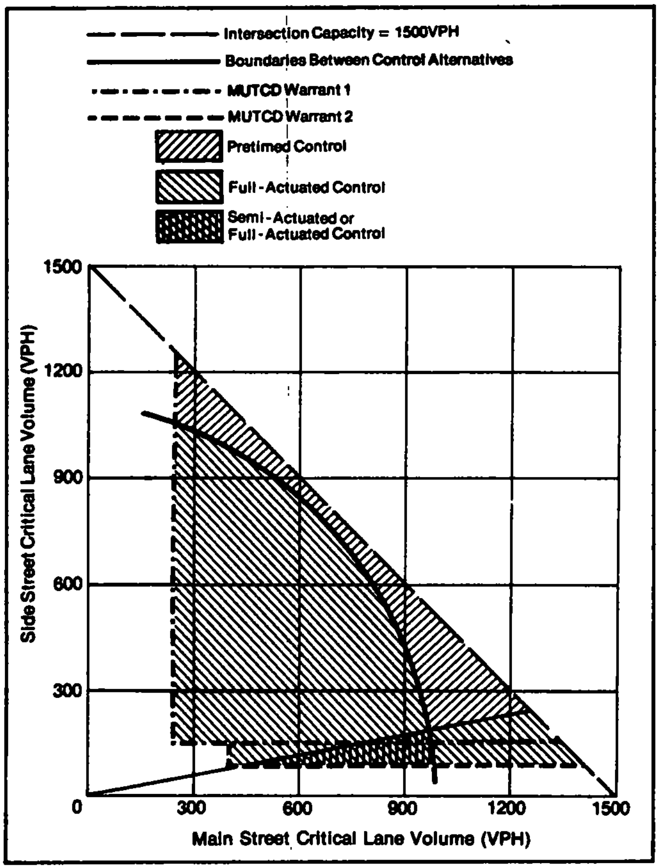


Figure 26. Sample graph of control boundaries.

Equation 8 can be expanded into a quadratic form for Y_s:

$$Y_s^2 + (2Y_m - 1)Y_s + Y_m\left(\frac{5}{G_m} \quad \frac{1.5L}{G_m} + Y_m - 1\right) = 0 \qquad (9)$$

The value of Y_s produced by Eq. 9 is determined by solving for the positive root of the quadratic which gives:

$$Y_s = (0.5 - Y_m) + \left[0.25 - \frac{Y_m}{G_m}(5 + 1.5L)\right]^{1/2} \qquad (10)$$

For a saturation flow rate of 1500 vph,

$$Y_m = \frac{V_m}{1500} \qquad (11)$$

$$Y_s = \frac{V_s}{1500} \qquad (12)$$

Substituting V_m and V_s for Y_m and Y_s in Eq. 10 gives:

$$V_s = (750 - V_m) + 1500 \left[0.25 - \frac{V_m}{G_m}(0.0033 + 0.001L)\right]^{1/2} \qquad (13)$$

Plotting V_s as a function of V_m for Eq. 13 produces the boundary conditions shown in Figure 26.

This curve is sensitive to the value of saturation flow rate used in Eq. 13. Changing values of saturation flow tend to shift the curve of Figure 26 upward and downward in the same direction as the change in the value of saturation flow.

The value lost time, L, in Eq. 13 will also affect the values calculated for the boundaries between actuated and pretimed control. Lost time is a function of the vehicle startup and stopping delays at the beginning and end of green. It is also a function of time lost during the actuated portion of the cycle because of an extension time that is longer than 2 sec. An expression for the relationship between the lost time and the extension is derived in Appendix D. The results of this calculation were also found to vary with approach volume. The effect of this variation on the side street volume was within the accuracy of the calculation and, as a result, the effects of volume were ignored.

RELATIONSHIP BETWEEN ACCIDENT RATE AND TYPE OF CONTROL

Numerous investigators have found that the installation of a traffic signal at a given intersection can have a significant impact on its accident rate. For this reason, it is logical to expect that the accident rate at an intersection is related to the type of signal control employed. In an attempt to determine whether such a relationship might exist, an analysis was conducted of questionnaire data collected by KLD and Associates, Inc., as a part of NCHRP Project 3-20, "Traffic Signal Warrants." In parallel with this analysis an extensive review was conducted of the existing literature to develop supplementary information.

Analysis of Questionnaire Data

The data collected by KLD and Associates, Inc., included 262 study intersections with the following attributes:

1. Type of control—unsignalized, pretimed, semi-actuated, full-actuated, or volume-density.
2. The yearly average of accidents per intersection based on a 2-year period.
3. Adjacent land use.
4. Average speed on the facility.
5. State in which each intersection is located.

The data were stratified in a number of ways in an attempt to negate the influence of variations in roadway and traffic characteristics on the analysis. The stratification produced two acceptable sample sets on which statistical tests were performed. The results of the tests are described in the following.

The first test was an analysis of variance using the complete set of yearly accidents per intersection stratified by control type only and ignoring the conditions existing at the intersection. The data satisfied the requirements of an analysis of variance (ANOVA); namely, normal distribution and homogeneity of variances. Table 2 gives the results of the ANOVA.

As can be seen from Table 2, there is a significant difference in the sample means between control types. Table 3 indicates that there is a significant difference between unsignalized and signalized intersections. Table 3 also shows the high variability of the data with the standard deviations equaling approximately 90 percent of the respective sample means for unsignalized, pretimed, semi-actuated, and full-actuated control types. This high variability suggests that inferences based on accidents stratified solely by control type will be questionable. However, a general trend can be observed in the sample means shown in Table 3. Pretimed and volume-density controllers tend to have lower accident occurrences than the actuated types. This unexpected result may be explained by the variations in conditions existing at these various types of control. For example, it is possible that actuated controllers may be more frequently installed at higher volume intersections with higher speed approaches than the fixed-time controllers. Therefore, they will be more likely to exhibit a higher accident rate.

The accidents per intersection for volume-density controllers are lower than for any of the other forms of control. This result supports the conclusion of the earlier discussion of volume-density controllers which indicated that the dilemma zone protection and variable initial features offered by this equipment can potentially improve intersection safety. However, these data are of only limited reliability because of the extremely small number of intersections that make up the sample for this type of control. Perhaps the most significant information contained in Table 3 is the change in the type of accidents between signalized and nonsignalized intersections with the percentage of rear-end accidents significantly increasing when a signal is present.

TABLE 2

ANALYSIS OF VARIANCE FOR ACCIDENT DATA STRATIFIED BY CONTROL TYPE ONLY

Source of Variation	d.f.	s.s.	m.s.	
Control Types	4	6411.84	1602.96	F=7.12
Duplication within Control Types	257	57,854.80	225.12	$F_{(.05,4,257)}=2.40$
Total	261	64,266.64		

Since $7.12 > F_{(0.05,4,257)}$ hypothesis of equal sample mean is rejected.

TABLE 3

SAMPLE STATISTICS FOR DATA STRATIFIED BY CONTROL TYPE

Type of Control	Number of Intersections	Number of Accidents/yr	Mean Accidents/yr per Intersection[1]	Percent Rear End	Percent Right Angle	Standard Deviation	Confidence Interval at $\alpha=0.05$
Not Signalized	65	571	8.78	26	74	7.78	6.85, 10.71
Pretimed	126	2,054	16.30	54	46	14.27	13.81, 18.79
Semi-Actuated	37	862	23.30	62	38	21.46	16.15, 30.45
Full-Actuated	29	638	22.00	69	31	19.28	14.68, 29.32
Volume-Density	5	84	16.80	66	24	4.44	11.70, 21.90
Total	262	4,209	16.06				

1. Inferences about certain control types having better or worse accident rates should not be made from this table because of the large variability in the data (standard deviations equaling approximately 90 percent of the sample means).

In an attempt to reduce the effects of roadway and traffic characteristics on the sampling error accident rate per 1,000 ADT was stratified by adjacent land use and average intersection speed. Various levels of stratification were identified; however, mixed commercial and residential adjacent land use together with average speed ranging from 25 to 35 mph (40 to 56 km/hr) were the only levels providing sufficient sample sizes for statistical analyses.

The resulting cell sizes from the foregoing stratification were sufficient only for the pretimed and full-actuated control types. The sample sizes were 60 and 14 for the pretimed and full-actuated cases, respectively. Because only two samples were available for statistical analysis, a t-test was performed. Table 4 gives the results of this test. As can be seen, the means of these two sample sets were not significantly different at a 90 percent level of confidence. In fact, a significant difference was first shown at the unacceptable low level of confidence of 63 percent ($\alpha = 0.37$).

A comparison of Tables 3 and 4 confirms the sensitivity of accident rate to traffic volume, land use, and approach speed. Table 3 indicates that the pretimed controller has a lower accident rate per intersection than does the full-actuated. Table 4 indicates that the opposite is true for accident rate when the traffic volume, land use, and approach speeds are held constant. Table 4 takes roadway and traffic conditions into account, while the Table 3 analysis does not.

Table 5 defines the data required to obtain a more defini-

TABLE 4

STATISTICS AND T-TEST RESULTS FOR ACCIDENT PER 1,000 ADT STRATIFIED BY COMMERCIAL/RESIDENTIAL LAND USE AND AVERAGE SPEEDS OF 25-35 MPH

Signal Type	Number of Intersections	Mean Yearly Accidents 1,000 ADT	Standard Deviation	Confidence Interval at α=.05
Pretimed	60	0.66	0.50	(.53, .79)
Full-Actuated	14	0.52	0.26	(.38, .66)

$$S_{pooled} = .22$$

$$S_{\bar{X}_P - \bar{X}_F} = -\sqrt{.22\left(\frac{60+14}{60(14)}\right)} = .144$$

$$t_{\bar{X}_P - \bar{X}_F} = \frac{.66-.52}{.144} = .974$$

$$d.f. = 60+14-2 = 72$$

$$t_{(.05,72)} = 1.993$$

$$t_{(.10,72)} = 1.667$$

$\therefore$ difference significant at $\alpha = .37$ level

tive relationship between accident rate and type of control. Sample sizes of between 140 and 290 intersections are needed for each particular set of roadway and traffic conditions being examined. For example, if it is desired to examine these relationships for two types of land use, two traffic speeds, and three levels of traffic volumes (2 × 2 × 3 or 12 sets of characteristics), it will be necessary to collect data at between 1,680 and 3,480 intersections. This level of data collection was not feasible within the limitations of the project.

Review of Existing Literature

To supplement the conclusions of the data analysis, a review of the literature dealing with accident rates at signalized intersections was undertaken. The results from this review generally confirm the results of the data analysis.

From the data analysis, it was shown that approach volume and roadway characteristics would have an impact on accident rate. Yet, when these variables were controlled, the type of signal control producing the fewest stops was shown to have a slightly lower accident rate. Thus, it can be deduced that the number of rear-end accidents are proportional to the number of intersection stops.

The literature corroborated this finding with the Automotive Safety Foundation reporting "several studies have shown that rear-end accidents are proportional to the number of vehicles required to stop" (*19*). The following illustrate the relationship of the number of rear-end accident occurrences to both signal controller and number of vehicle stops.

1. Schoene (*20*, p. 142) has shown that 11 out of 12 Indiana intersections converted from two-way stop to traffic-actuated control had significant increases in rear-end accidents. Also, 8 of 20 intersections upgraded from two-way stop to pretimed signal control had significant increases in rear-end accidents.
2. Texas A&M University (*21*) has indicated that there is some relationship between the number of involuntary stops and signal type based on coordinated signal systems in Toronto. Though an intersection in a coordinated system may have different flow characteristics from an isolated intersection, the trends in the Toronto experience are

TABLE 5

DATA REQUIREMENTS FOR ACCIDENT ANALYSIS

Significance Level, Type I Error (α)[a]	Significance Level, Type II Error (β)[b]	Sample Size								
		δ[c] = 0.09	0.14	0.19	0.24	0.28	0.33	0.38	0.42	0.47
		D[d] = 0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
0.05	0.05	651	290	164	106	74	55	42	34	27
	0.10	526	235	133	86	60	44	34	27	22
	0.20	396	177	100	64	45	34	26	21	17
0.10	0.05	541	241	136	88	61	45	35	28	23
	0.10	431	192	108	78	49	36	28	22	18
	0.20	311	139	78	51	36	26	21	16	14

Case most likely to represent accident data. ↑

[a] α = significance level of accepting an insignificant difference in the means when actually the difference is significant.

[b] β = significance level of rejecting a significant difference in the means when actually the difference is insignificant.

[c] δ = difference in sample means.

[d] D = proportion of difference in means to the pooled standard deviation of the samples.

worthy of note. Pretimed, full-actuated, and semi-actuated systems had rates of 0.9, 1.0, and 1.1 involuntary stops per mile of coordinated facility.

3. Shindler (*19*) has reported that there may be a relationship between volume-density and semi-actuated control types in regard to the number of rear-end accidents. This is based on the 62 percent reduction in rear-end accidents due to the change from semi-actuated to volume density control at an Oregon intersection.

4. The work of Schoene and Michael (*20*, p. 146) in Indiana has determined that 66 percent of the study intersections experienced a significant increase in rear-end collisions from before signal installation to after. Of significance is the conclusion that installation of a signal at low-volume intersections will usually not result in increased accidents. This conclusion was based on volume consideration.

From the foregoing reports, the following can be concluded:

1. There is a definite positive trend between rear-end accidents and volume at signalized intersections. Going one step further, increased volume produces increased stopping and, thus, vehicle stops are positively correlated with rear-end accidents.

2. There is some relation between pretimed, semi-actuated, full-actuated, and volume-density signals and stops. It is expected that there will also be a relation between type of control and accident rate.

3. It is apparent that the most significant contributing factor to the increase in accidents following the installation of a signal is the signal itself. Presence of other factors may have a far more significant influence on accident rates than the type of signal installed. These factors are discussed in the following.

Type and Extent of Accidents

Installation of a signal tends to have the effect of decreasing right-angle accidents and increasing other type accidents such as rear-end. This is not always the case, particularly in situations where there are few right-angle accidents or many other type accidents. The work of Schoene and Michael (*20*, p. 146) indicates that right-angle accidents can be expected to decrease after installing a signal if five or more right-angle accidents per year occurred previously. The Automotive Safety Foundation (*19*, p. 57) has determined that intersections with few accidents before installation can be expected to have increased rates following installation, and intersection accidents involving vehicles on the same street (head-on, rear-end, sideswipe) can be expected to increase after installation. It has also been determined that these type of "same street" accidents can be reduced with such measures as turn prohibitions, channelization, and special phasing.

Volume

There appears to be a definite trend between increased accidents with increased intersection volume. This was reported true in both Skokie, Ill. (*22*, p. 14) and Los Angeles (see Tables 6 and 7). Schoene and Michael suggest that intersections with large disparities in volumes between the major and minor approaches will have higher accident rates than those intersections without. It was reported (*20*, p. 145) that increased accidents could be expected at signalized intersections meeting the signal warrants with ratios of major approach volume to maximum minor approach volume greater than 4:1. This was also true at those signalized intersections not meeting the warrants and with ratios greater than 6:1.

Previous Control

The literature shows a difference in accident rates at signalized intersections previously controlled by 2- and 4-way stops. Box and Alroth (*22*) suggest that accidents can be expected to decrease at signalized intersections previously controlled by 4-way stop signs; also, intersections previously controlled by 2-way stop signs can be expected to experience an increase in accidents.

It is doubtful whether these tendencies are significantly related to the difference in volumes at 2- and 4-way stop intersections, although it may have an effect. It is more probable that they are related to the differences in operational characteristics of these two sign control types.

Conclusions of Accident Analysis

Analysis of the available accident reveals that there is little consistency in the relationships between type of intersection control and accident rate. It is likely that the in-

TABLE 6

ACCIDENT RATES PER YEAR FOR SIGNALIZED INTERSECTIONS IN SKOKIE, ILL.

	Entering ADT					
	11,000-16,000	16,000-21,000	21,000-26,000	26,000-31,000	31,000-36,000	36,000-41,000
Average Accidents/year	7.5	10.3	18.1	20.6	30.6	33.8
Number of Intersections	8	13	35	41	41	10
Range of Frquencies	3-13	3-18	5-30	3-73	12-60	14-61

Source: Reference (27).

TABLE 7

ACCIDENT RATES FOR SIGNALIZED INTERSECTIONS IN LOS ANGELES, CALIF.

ADT		Number of Intersections	Average Annual Accident Rate per Intersection	Standard Deviation
Major	Minor			
0-32,000	0-6,000	170	0.55	0.38
6,000-32,000	6,000-10,000	56	0.74	0.39
10,000-32,000	10,000-14,000	25	0.95	0.44
14,000-32,000	14,000-26,000	17	1.20	0.31

Source: Reference (27).

ability to arrive at specific conclusions regarding these relationships is a result of the effect of numerous external influences on intersection safety, such as intersection design, signal installation design, vehicle volumes and speeds, land use, and signal operation. The development of definitive conclusions in this area would require an extensive nationwide survey to accumulate a large enough data base to isolate the effects of signal control on intersection safety.

ESTIMATE OF VEHICLE EMISSIONS AND FUEL CONSUMPTION

The derivation of vehicle emissions and fuel consumption for this project was to be based originally on the models contained in NETSIM. However, this approach was abandoned in favor of the use of equivalent data available from the Environmental Protection Agency (EPA) (*23*) for the following reasons:

1. The estimate of emissions and fuel consumption produced by the simulation is dependent on vehicle speeds and travel distances on the approach link to the signal. As such, it will not produce estimates for these data that are related solely to the effect of signal performance on traffic flow.
2. The simulation results cannot be readily updated as more current vehicle emissions and fuel consumption data become available. This will be especially true during the next 5 years as the automobile manufacturers strive to meet new government requirements.

The relationships developed here are based on emissions and fuel consumption resulting from vehicle stops and delays caused by the traffic signal. The methodology for estimating stops and delay has been presented elsewhere in this report. Thus the data presented for each of the factors developed in this section are related to those previously computed quantities.

All data developed by Ref. 23 have been represented as a function of model year for the years 1967 through 1974. Data are also presented in this reference that provide for an estimate of the percentage of vehicles from each model year existing at the time these studies were performed (*24*). This percentage, as given in Table 8, and the subsequent data presented in this section must be updated as more up-to-date data become available from EPA.

TABLE 8

SUMMARY OF VEHICLES BY MODEL YEAR

Year	Percentage of Vehicles
1967	9.4
1968	10.0
1969	11.7
1970	12.2
1971	15.0
1972	16.7
1973	19.4
1974	5.6
	100.0

By using this percentage of vehicles for each model year, it is possible to develop the relationship between each of these factors: delay and stops. The approach used in developing this relationship is based on the concept of speed change and stop cycles and is described by Winfrey (*25*). The application of this concept depends on the assumption that the cost of a vehicle stop and delay, and a resumption of normal travel speed, can be estimated as the sum of the cost of two independent costs. The first of these is the incremental cost of the deceleration from the initial travel speed to zero and acceleration back to the initial travel speed. This is the incremental cost over and above the cost of traveling the same distance at a constant speed. This cost is designated a speed change cycle and is incurred for each vehicle. The second cost is the idling cost that is directly proportional to the idling time or delay. Using this approach, the cost per vehicle, C_{TV}, for a particular type of signal control is:

$$C_{TV} = N_{SV} \times C_{SC} + T_{DV} \times C_I$$

where:

N_{SV} = number of stops per vehicle;
C_{SC} = cost of a speed change cycle;
T_{DV} = average time delay per vehicle, sec; and
C_I = cost of idling, units of cost/sec.

The total cost, C_T, for a particular intersection is computed using the total approach volume, V, as:

$$C_T = V \times C_{TV}$$

In these equations, cost is expressed in pounds (grams) of pollutants and gallons (liters) of gasoline.

The data required to implement these equations were derived from the data of Ref. 24, and are shown in Figures 27 and 28 and Table 9.

Thus, for example, if, for an intersection with a total approach volume of 1,800 vph and an approach speed of 30 mph, the delay and stops have been determined to be 15 sec/veh and 0.3 stops/veh, respectively, the average emissions and fuel consumption costs per vehicle would be:

C_{HC} = 0.3 stops/veh (0.18 gm/stop) + 15 sec/veh (0.015 gm/sec) = 0.28 gm/veh
Total HC = (0.28 gm/veh) × (1000 vph) = 280 gm/hr
C_{CO} = 0.3 stops/veh (3.2 gm/stop) + 15 sec/veh (0.262 gm/sec) = 4.89 gm/veh
Total CO = (4.89 gm/veh) × (1000 vph) = 4,890 gm/hr
C_{CO_2} = 0.3 stops/veh (11.1 gm/stop) + 15 sec/veh (1.57 gm/sec) = 26.91 gm/veh
Total = (26.91 gm/veh) × (1000 vph) = 26,910 gm/hr
C_{NO_x} = 0.3 stops/veh (1.0 gm/stop) + 15 sec/veh (0.004 gm/sec) = 0.36 gm/veh
Total = (0.36 gm/veh) × (1000 veh/hr) = 360 gm/hr

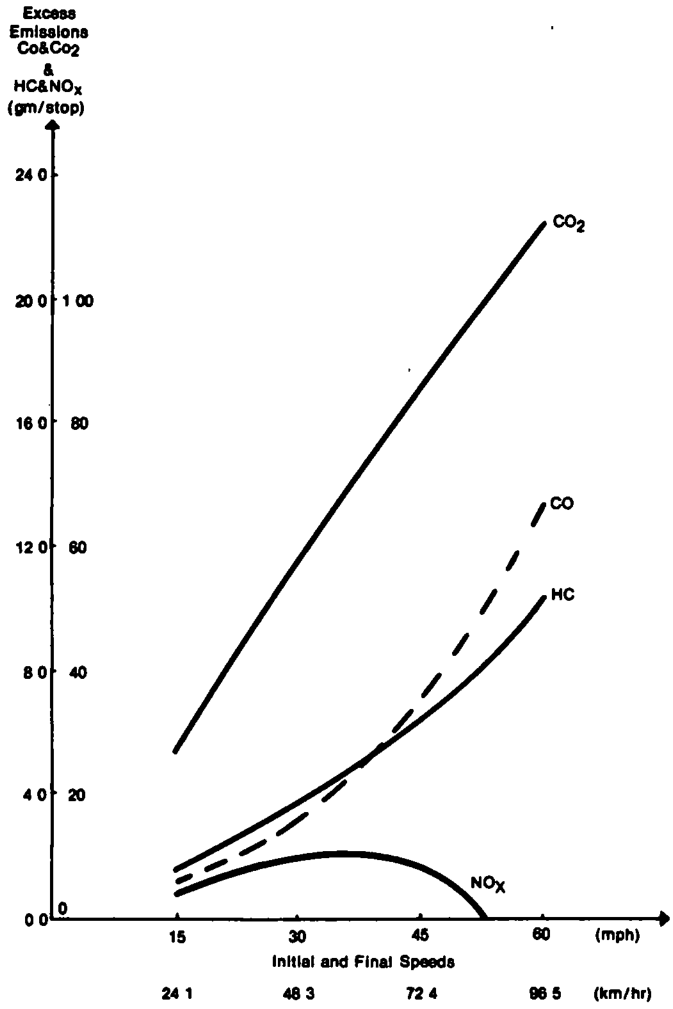


Figure 27. Emissions resulting from speed change cycle.

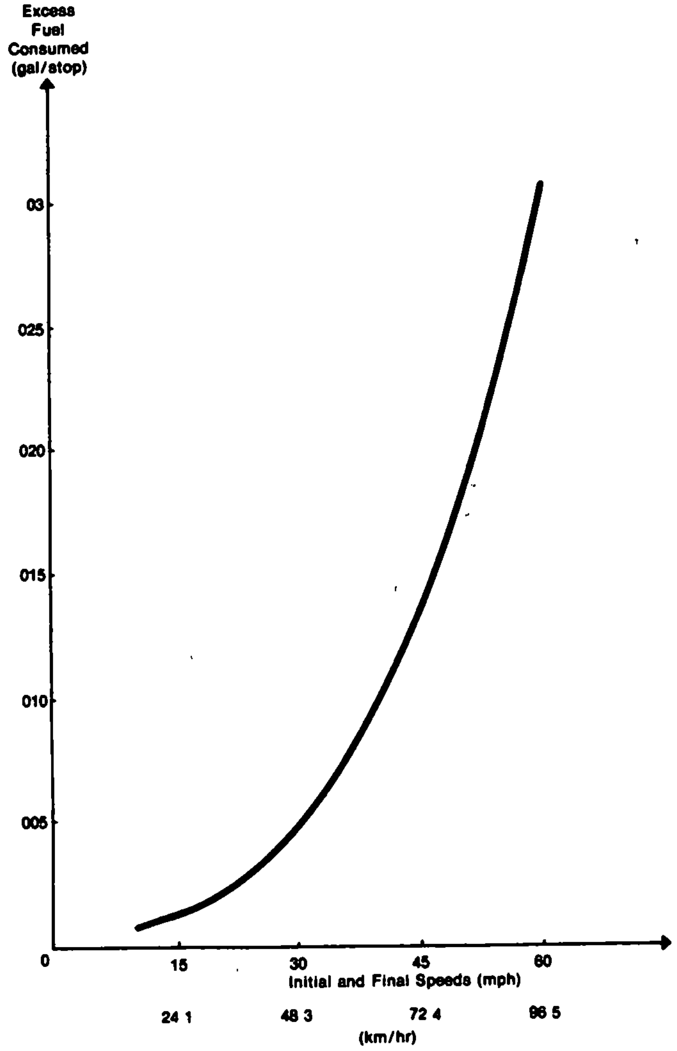


Figure 28. Fuel consumption resulting from speed change cycle.

$$C_{\text{Fuel}} = 0.3 \text{ stops/veh } (0.0045 \text{ gal/stop}) + 15 \text{ sec/veh } (0.00022 \text{ gal/sec}) = 0.0047 \text{ gal/veh}$$

$$\text{Total} = (0.0047 \text{ gal/veh}) \times (1000 \text{ vph}) = 4.7 \text{ gal/hr}$$

In this manner the stops and delays estimated for a particular type of control can be translated directly into measures of emissions and fuel consumption.

As previously indicated, these parameters change with future vehicle model years. Therefore, there is a need to update these data on a continuing basis if they are to remain current.

From this discussion it is clear that both fuel consumption and emissions can be derived directly from vehicle stops and delays. It can further be concluded that minimizing stops and delays will minimize these measures as well.

REQUIREMENTS FOR COORDINATION

The potential benefits to be derived from coordinated operation at an intersection are directly related to the platoon characteristics of vehicle arrivals at that intersection. If a well-defined compact platoon of vehicles exists, coordinated operation can provide a significant reduction in the stops and delays experienced by the vehicles being serviced at the intersection. One popular rule of thumb is that signals spaced more than ½-mile apart should be operated independently because the cohesion of the platoon cannot be maintained for such a long distance (*26*). However,

TABLE 9

EMISSIONS AND FUEL CONSUMED PER SECOND OF IDLE TIME

Parameter	Rate
HC	.015 gr/sec
CO	.262 gr/sec
CO_2	1.570 gr/sec
NO_X	.004 gr/sec
Fuel Consumed	.00022 gal/sec

although this guideline may be applicable to average conditions, it is of little value for specific installations because the characteristics of a platoon can be affected by a variety of factors. Traffic flowing on a well-designed facility without driveways with opportunities for passing and provisions for left turns can maintain a cohesive platoon structure for distances in excess of ½ mile. Conversely, if the design of a facility is such that traffic cannot flow in an unimpeded manner, it will not be possible to identify a platoon at the downstream intersection for signal spacings that are significantly less than ½ mile. This latter case will be designated uniform flow conditions in the following discussion because there is an equal (uniform) probability of vehicles arriving at the intersection at any point in the signal cycle.

Because of the high correlation between the platooning characteristics of traffic flow and the need for a coordinated signal system, a decision was made to develop a model of the characteristics as a function of traffic and roadway conditions. This model is based on an extended version of the approach used by Robertson (*27*) in the TRANSYT computer program used for the off-line optimization of traffic signal timing.

Robertson's model assumes that traffic platoons are created when a queue is discharged from an upstream traffic signal at the start of green. The queue discharge rate is assumed to occur at a constant saturation flow rate that is defined as the maximum rate of flow that will occur on the facility being analyzed. As the platoon of vehicles progresses along the link, the flow rate becomes modified by the dispersion effects of driver car-following behavior, midblock impedances to the traffic flow, and differences in desired travel speeds. This effect is shown in Figure 29. Note in this figure that, in addition to the slope of the platoon changing, its position in time changes which corresponds to the travel time of the vehicles along the street.

More complex platoon structures are produced when additional effects are taken into account. In his model, Robertson accounted for secondary flows produced by turning vehicles from the side street when the upstream signal displays main street red and additional platoon flows on the main street from the next signal upstream. He does not, however, consider the case of a major midblock source of vehicles from an unsignalized intersection such as a shopping center driveway or the equivalent effect of right-turning vehicles at a location where right turn on red is permitted.

During this phase of the research, a manual method for estimating the platooned arrival pattern at the downstream intersection was developed by adapting Robertson's model to a manual computational procedure. The additional ef-

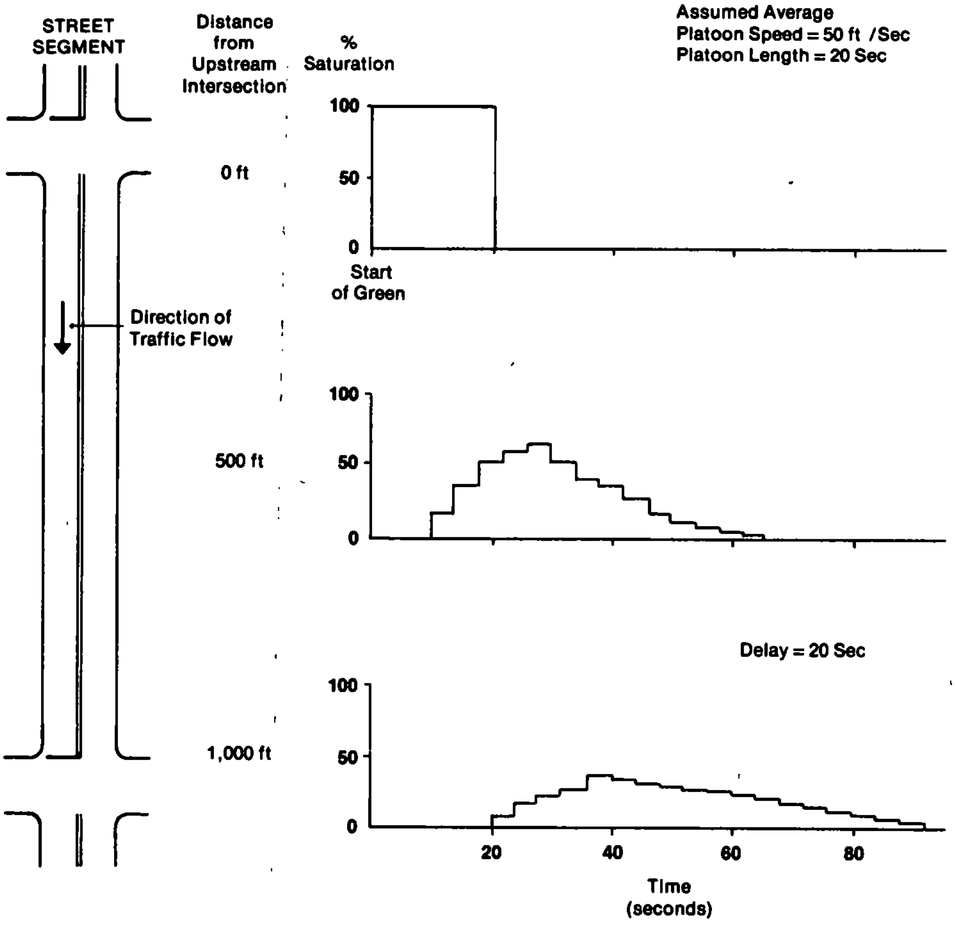


Figure 29. Platoon dispersion patterns.

fects of midblock sources of vehicles and right-turn-on-red were considered but were found to have a negligible effect on the overall platoon characteristics. This procedure was further developed to permit the estimation of the incremental benefit in terms of stops and delays that would be realized from coordinating the signal installation. The results presented here have been validated at three sites in Northern Virginia They are also based in part on the work of Lam (*28*) and Gartner (*29*).

Estimation of Platooned Arrivals

As previously indicated, the estimation of the arriving platoon pattern relies on the use of a model developed by Robertson for computing platoon dispersion as it travels from an upstream intersection. The implementation of this model as a manual procedure requires extensive computations for the user. Therefore, the model was simplified by decomposing vehicle flow from the upstream intersection into three components:

1 Discharge of the waiting queue from the upstream intersection.

2. Processing of through-vehicles passing through the upstream intersection during green but following the queue discharge.

3. Turning-vehicles arriving from the upstream intersection during main street red at that intersection.

Each of these three components of traffic flow is assumed to occur at a constant average rate. The queue discharge occurs at a likely rate of 2.4 veh/sec, and the remaining two sources of vehicles have flow rates equal to the number of vehicles divided by the duration of their flow. For example, if an average of 12 through-vehicles arrived at the upstream intersection during a main street green time of 24 sec, an average through-vehicle rate of 0.5 veh/sec would be assumed (see Fig. 30).

Appendix B demonstrates that each of these three sources of vehicles can be considered an independent platoon that disperses as it travels along the link. At the downstream intersection (being considered for potential coordination) a composite platoon arrival pattern can be constructed from the sum of the individual patterns. Thus, once the three vehicle flows from the upstream intersection are known, it is possible to estimate the arrival pattern at the downstream intersection for each approach.

TABLE 10

RELATIONSHIP BETWEEN ROADWAY CHARACTERISTICS AND K FACTORS

K	Roadway Characteristics	Description of Conditions
.5	Heavy friction	Combination of parking, moderate to heavy turns, moderate to heavy pedestrian traffic, narrow lane width. Traffic flow typical of urban CBD.
.37	Moderate friction	Light turning traffic, light pedestrian traffic, 11- to 12-foot (3.4- to 3.6-meter) lanes, possibly divided. Typical of well-designed CBD arterial.
.24	Low friction	No parking, divided, turning provisions, 12-foot (3.6-meter) lane width. Suburban high-type arterial.

The computation of arrival patterns for the simple case of a uniform upstream discharge rate is still a difficult task, because it employs a recursion equation that requires extensive arithmetic manipulation. To simplify this task, tables can be developed of arrival patterns as a function of a platoon dispersion factor, *K*, travel time, *TT*, and the initial platoon duration *PD*. Recommended *K* factors are given in Table 10. A sample is given in Table 11.

Thus the platoon arrival patterns are computed and aggregated in the following manner:

1. For upstream signalized intersections, compute the three discharge rates and determine their arrival patterns using Table 11.

2. Aggregate the three arriving platoons from each upstream intersection.

3. Determine the arrival rate for approaches that do not leave a signalized upstream intersection assuming a constant flow rate.

4. Develop the platoon arrival patterns for each signal phase by adding all arrival patterns occurring during the same phase.

Estimating Benefits of Coordinated Operation

Once the arrival patterns have been determined for each

TABLE 11

SAMPLE PLATOON DISPERSION TABLE

A= 2

	PLATOON LENGTH											
T	8	16	24	32	40	48	56	64	72	80	88	96
4.	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
8.	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
12.	0.37	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
16.	0.25	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
20.	0.16	0.53	0.87	0.97	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
24.	0.11	0.36	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
28.	0.07	0.24	0.61	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94
32.	0.05	0.16	0.41	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
36.	0.03	0.11	0.27	0.64	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
40.	0.02	0.07	0.18	0.43	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
44.	0.01	0.05	0.12	0.28	0.66	0.99	0.99	0.99	0.99	0.99	0.99	0.99
48.	0.01	0.03	0.08	0.19	0.44	0.99	0.99	0.99	0.99	0.99	0.99	0.99
52.	0.01	0.02	0.05	0.13	0.29	0.66	0.99	0.99	0.99	0.99	0.99	0.99
56.	0.00	0.01	0.04	0.08	0.19	0.44	1.00	1.00	1.00	1.00	1.00	1.00
60.	0.00	0.01	0.02	0.06	0.13	0.29	0.66	1.00	1.00	1.00	1.00	1.00
64.	0.00	0.01	0.02	0.04	0.09	0.20	0.44	1.00	1.00	1.00	1.00	1.00
68.	0.00	0.00	0.01	0.02	0.06	0.13	0.30	0.67	1.00	1.00	1.00	1.00
72.	0.00	0.00	0.01	0.02	0.04	0.09	0.20	0.44	1.00	1.00	1.00	1.00
76.	0.00	0.00	0.00	0.01	0.03	0.06	0.13	0.30	0.67	1.00	1.00	1.00
80.	0.00	0.00	0.00	0.01	0.02	0.04	0.09	0.20	0.44	1.00	1.00	1.00
84.	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.13	0.30	0.67	1.00	1.00
88.	0.00	0.00	0.00	0.00	0.01	0.02	0.04	0.09	0.20	0.44	1.00	1.00
92.	0.00	0.00	0.00	0.00	0.01	0.01	0.03	0.06	0.13	0.30	0.67	1.00
96.	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.04	0.09	0.20	0.44	1.00
100.	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.03	0.06	0.13	0.30	0.67
104.	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.04	0.09	0.20	0.44
108.	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.03	0.06	0.13	0.30
112.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.04	0.09	0.20
116.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.03	0.06	0.13
120.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.04	0.09
124.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.03	0.06
128.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.04
132.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.03
136.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02
140.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
144.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
148.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
152.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
156.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
160.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

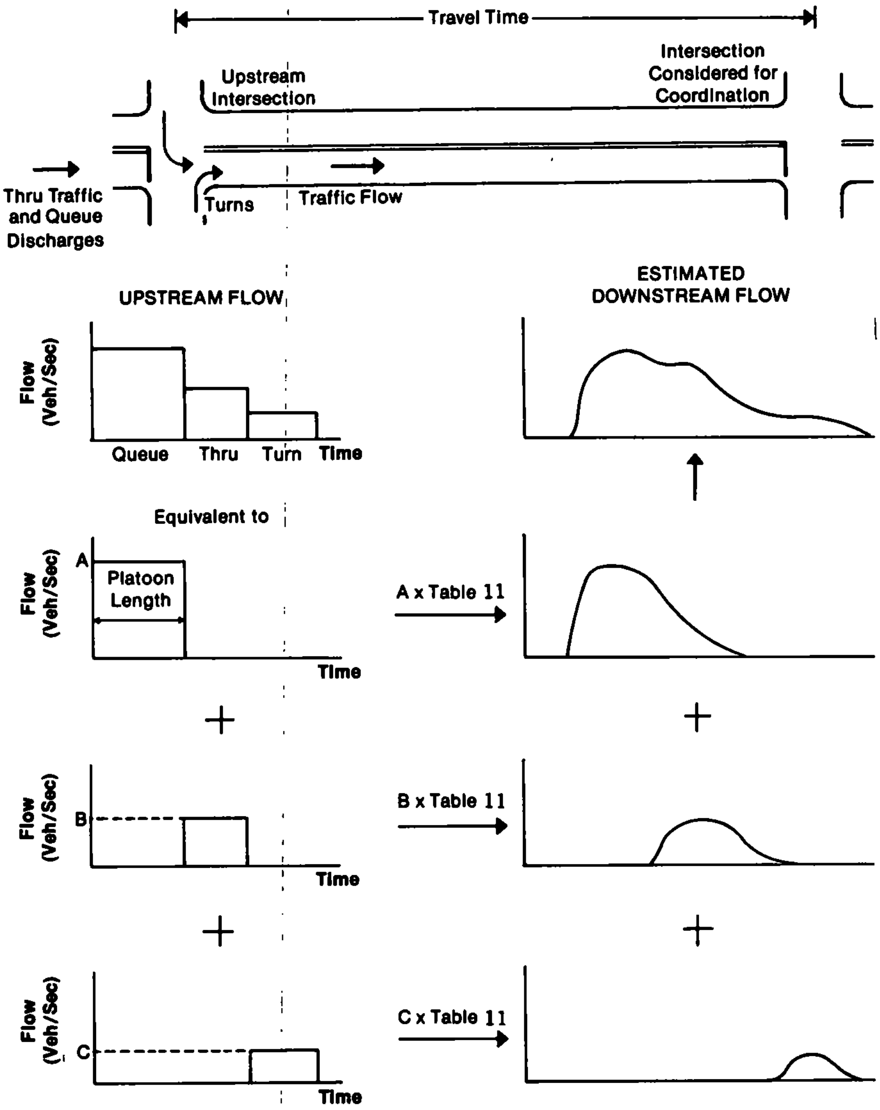


Figure 30. Traffic flow components

phase, it is possible to estimate the relative benefits associated with coordinated operation. These benefits are estimated in terms of vehicle stops and delays existing both with and without coordination. The resulting delay and stops can be translated into pollution and fuel consumption benefits using the methodology presented in previous sections.

Appendix B develops the expressions for delay, d, and stops, S, resulting from a given arrival pattern, q_a, as:

$$d = T^2 \sum_{m=r}^{t_o} \sum_{m=n}^{t_o} q_a(m) - \frac{1}{2} t_o^2 s_o \qquad (14)$$

$$S = T \sum_{m=r}^{t_o} q_a(m) \qquad (15)$$

where:

$T =$ the resolution of the flow pattern (4 sec);

$q_a(m) =$ the arriving flow pattern at 4-sec increments;

$s_o =$ saturation flow rate (2.4 sec recommended); and

$t_o =$ the time from start of green until the queue is completely discharged.

The equation for stops represents the cumulative number of vehicle arrivals from start of red, r, until the queue is completely discharged, t_o. This formulation assumes both a constant arrival pattern and a coordinated operation. The equation for delay uses a double summation to account for the accumulation of vehicle arrivals. In other words, these arrivals are summed a second time in order to account for the time they must wait until the queue is discharged. The second term in the equation for delay represents the decrease in delay that results from vehicles being discharged from the queue prior to the overall queue discharge.

These equations have been developed as summations to simplify the computations that must be performed. The traffic arrival pattern, q_a, computed according to the procedures described in the previous section is plotted on graph paper. The signal timing is also plotted on this paper. The cumulative vehicle arrivals at start of red are then plotted by summing the profiles from previous points in time. Then t_o can be determined by subtracting vehicles discharged at start of green from the cumulative vehicle arrivals. The point at which this difference equals zero is t_o

Stops can be directly computed by summing the area under the q_a curve and multiplying by T (4 sec). The process of summation is as simple as counting the number of squares under the curve on graph paper. Delay can be directly computed by summing the area under the cumulative vehicle arrival curve and multiplying by T. It should be noted that in the process of developing the cumulative curve, the remaining terms in this equation have been taken into account.

The manner in which these calculations are performed is shown in Figures 31(a) and 31(b). In the figures, the units of flow q_a have been selected to eliminate the need for the factor T in the delay expression.

The computations described assume a constant relationship between the signal timing and the pattern of arriving vehicles, q_a. The consistency of this operation is equivalent to coordinated signal operation. As the next step in the comparison process, it is necessary to estimate the stops and delays resulting from uncoördinated operation. Because it can be assumed that for this type of operation the platoons of vehicles can arrive at any point in the signal cycle, uncoordinated operation has been assumed equivalent to the case of uniform vehicle arrivals at the intersection. That is:

$$q_a\,(m) = \text{Vol (vph)}\;\frac{\text{Signal cycle length}}{3600} \qquad (16)$$

Then the expressions for delays and stops become:

$$d = \frac{1}{2}\,\overline{q_a}\,(t_o + r)\,(t_o + r)^2 - \frac{1}{2}\,t_o^2\,s_o \qquad (17)$$

$$s = \overline{q_a}\,(t_o + r) \qquad (18)$$

where

$$t_o = \overline{qr}/\,(s_o - \overline{q_a}) \qquad (19)$$

These relationships are shown graphically in Figure 32.

Thus the computation of delay and stops for the uncoordinated case requires the solution of Eqs. 17, 18, and 19. Once these equations have been solved, these results can be compared with the results obtained for the coordinated case to determine the benefits that will be realized from implementation of a coordinated system.

Summary of Analysis Procedure

The procedure developed is applicable to any number of signalized intersections upstream from the intersection being considered for coordination. Obviously the fewer number of upstream intersections, the easier the procedure is to implement. However, as review of the manual procedure will reveal, the case of two upstream intersections does not pose any computational difficulties.

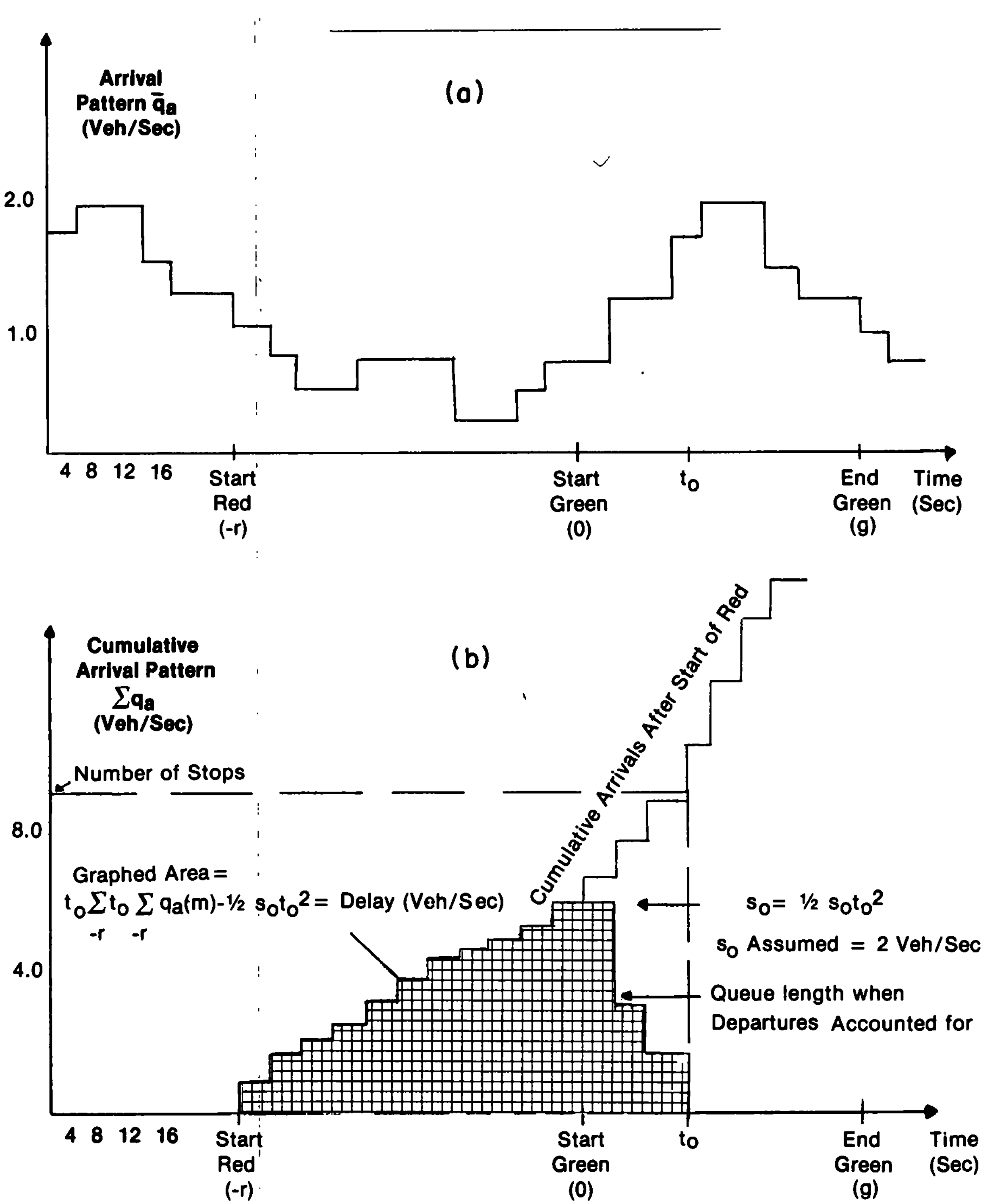
The following steps should be followed:

1. Develop signal timing.
    a. Compute the optimum intersection cycle length using data previously presented for a fixed-time signal. If upstream signal cycle length has already been determined, use the same cycle length for the signal being studied.
    b. Compute the split proportional to the critical approach volumes on each phase.
    c. Determine the offset using time-space diagrams or other, similar techniques.
2 Collect field data.
    a. Determine street lengths and travel times for all upstream signalized intersections.
    b. Count vehicle volumes on all approaches from unsignalized intersections. Counts should be made for at least 15 min.
    c. Count queue length at signalized intersections, through-vehicles not included in queue, and turning vehicles. Counts should be made for at least 15 signal cycles.
    d. Record upstream signal timing.
3. Compute flow profiles.
    a. Determine flow rate and platoon length for all upstream vehicle sources including three sources from each signalized intersection.
    b. Use tabular data to compute arriving platoon characteristics for each of the platoons arriving from upstream intersections.
    c. Combine arriving platoons into a single platoon pattern for each approach.
    d. Combine platoons on all approaches served by a single phase into a single platoon for each phase.
4. Compute stops and delays
    a. Compute stops and delays for each phase using signal timing from (1) and platoon pattern from (3). For phases with constant arrival rates (no upstream intersections), Eqs. 14, 15, and 16 can be used. For phases with at least one upstream intersection it is necessary to use the graphical procedure outlined by Figure 31.
    b. Recompute stops and delays for uncoordinated case using Eqs. 17, 18, and 19.
    c. Compare the results of the previous steps to determine the lengths (in terms of stops and delays) resulting from implementation of coordination.

The foregoing steps will provide a relatively reliable estimate of the lengths of coordination taking both traffic flow and roadway characteristics into account. The procedure eliminates the need for reliance on the relatively arbitrary threshold of ½ mile for the implementation of coordinated operation.

SYSTEM COSTS

Two types of costs were investigated: one-time costs (cost of acquisition and installation) and recurring costs (cost of operations and maintenance). The findings of an



Cumulative arrival pattern plotted to ¼ scale of arrival pattern.

Figure 31. Computation of stops and delay from arrival pattern: (a) vehicle arrival pattern, and (b) cumulative arrival pattern.

extensive data collection activity undertaken to determine these costs are presented in the following sections.

Acquisition and Installation Costs

This section compares the initial costs of pretimed, semi-actuated, basic full-actuated, and volume-density control at individual intersections. These are the costs to acquire and install the controller and any detection used by that type of control. Costs common to all types, such as the expense of signal heads and poles, are omitted as irrelevant to the comparison. The total initial cost for each type of control is converted at the end of the section to an equivalent uniform annual cost to permit the addition of annual maintenance costs discussed in the following section.

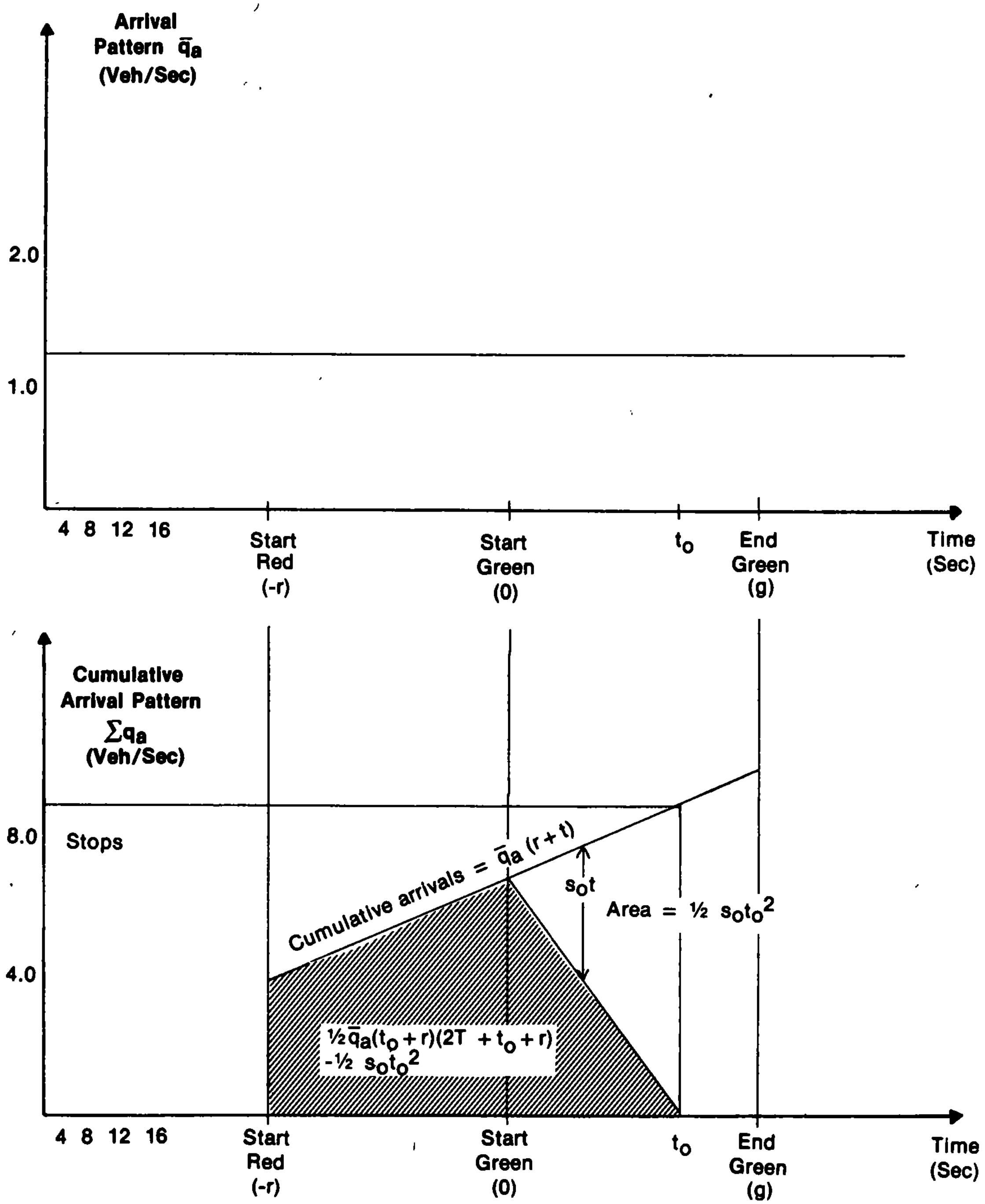


Figure 32. Computation of stops and delays for constant arrival pattern

The following typical controller/detector configurations were selected as representative of current practice:

1. *Pretimed*—A 2-phase 3-dial electromechanical controller with two time switches.

2. *Semi-Actuated*—A minimum design and a high-type design were identified as follows:

a. Minimum design: A 2-phase electromechanical semi-actuated controller, with a 6′ x 30′ loop at the stopline of each of the two cross-street approaches.

b. High-type design. A 2-phase solid-state semi-actuated controller, with a 6′ x 70′ quadrupole loop at the stopline of each of the two cross-street approaches.

3. *Basic Full-Actuated*—A minimum design and a high-type design were identified as follows:
   a. Minimum design: A 2-phase electromechanical full-actuated controller, with a 6′ x 6′ loop installed 120 ft from the stopline of each approach.
   b High-type design: A 2-phase solid-state full-actuated controller, with a 6′ x 70′ quadrupole loop installed at the stopline of each approach. The controller costs associated with this design could be either microprocessor or conventional solid state.
4. *Volume-Density Full-Actuated*—A 2-phase solid-state controller with density modules. A 6′ x 6′ loop is installed on each approach, 400 ft from the intersection. A 6′ x 6′ loop is installed near each stopline as a calling detector.

Many engineers would elect to use a 4-phase (or even an 8-phase) controller mainframe for the 2-phase full-actuated designs described above. The larger frames anticipate the future addition of phases and are, of course, more expensive than 2-phase frames. Inasmuch as pretimed control is inappropriate for multiphase control, the larger frames were not used for this cost comparison. All of the foregoing designs adhere strictly to 2-phase control.

Cost data were obtained in May 1978 from the low bids most recently submitted to the DOT's of North Carolina and Georgia and from the records of the Gwinnett County, Georgia, Traffic Engineering Department.

Table 12 gives the dollar cost of the six selected designs, broken down into components. For all of the actuated designs, the labor to install the loop detectors was calculated at $9 per hour, which includes fringe benefits and overhead. For example, the minimum semi-actuated design was calculated using ½ day for a four-man crew at $9 per hour, or $144. The XHHW loop wire and the Belden 8720 lead-in were estimated at $0.04 and $0.12 per foot, respectively The ¼-in. messenger cable and the 1-in. PVC conduit, both for running the Belden, were calculated using $0.08 and $0.18 per foot.

For the semi-actuated designs, the detector unit for the high-type design is $45 more than that of the minimum design because it is of delayed-call design. In the case of the basic full-actuated designs, the $90 extra cost of the detector units of the high-type design is due to the selection of a two-channel digital detector rather than two analog detectors. The density design uses one 4-channel digital detector.

TABLE 12

INITIAL COST COMPARISON OF VARIOUS TYPES OF CONTROL

		Semi-Actuated		Basic Full-Actuated		
	Pretimed	Minimum	High Type	Minimum	High Type	Density Full-Actuated
Controller	1,360	1,275	2,060	1,275	2,060	2,520
Detectors	0	80	125	160	270	320
Labor	0	144	288	216	432	432
Loop wire	0	14	32	24	64	48
Lead-in	0	34	34	91	67	226
Messenger	0	0	0	60	0	160
Conduit	0	10	10	80	20	80
Sealant	0	10	20	10	40	20
Saw, blade	0	25	25	25	50	25
TOTAL	1,360	1,592	2,594	1,941	3,003	3,831

The total costs of Table 12 can be converted to equivalent uniform annual costs by multiplying them by the appropriate capital recovery factor, or CRF. The CRF is obtained from tables of compound interest found in all texts on engineering economy. For a 10-year analysis period and an interest rate of 8 percent, the CRF is obtained by table lookup as 0.149. Therefore, the equivalent uniform annual costs to acquire and install the six control types are as follows:

Pretimed	$1,360 × 0.149 = $203
Semi-Actuated, Minimum Design	$1,592 × 0.149 = $237
Semi-Actuated, High-Type Design	$2,594 × 0.149 = $386
Basic Full-Actuated, Minimum Design	$1,941 × 0.149 = $290
Basic Full-Actuated, High-Type Design	$3,003 × 0.149 = $447
Density Full-Actuated	$3,831 × 0.149 = $570

Maintenance Costs

This research project places special emphasis on the incremental maintenance requirements associated with the more sophisticated types of traffic signal control. To obtain the needed data, telephone contacts were made with many state and local traffic engineering agencies throughout the United States in an effort to obtain maintenance data. Most of the agencies responded that their data were in raw form—handwritten malfunction reports—which could not be summarized at reasonable cost. However, a few were found to have manual tabulation, computerized summaries, or raw data in a form susceptible to tabulation at reasonable expense. These were as follows:

1. *State of California DOT*—The CALTRANS Maintenance Management System (MMS) includes data for 16 recent months on the total cost to maintain 121 actuated controllers of various designs.
2. *New York State DOT*—New York maintains a computerized file of the man-hours required for the field maintenance of the approximately 2,500 pretimed and actuated traffic signals in its jurisdiction. Two years of data were obtained.
3. *Ohio DOT*—Ohio furnished approximate data for 1976 on the frequency of repair of their 558 actuated controllers, divided into three levels of sophistication.
4. *State of Minnesota Department of Highways*—The Minneapolis District furnished data covering several years for the frequency of repair of 135 actuated controllers and several hundred detectors of various types.
5. *City of Cincinnati, Ohio*—Two and one-half years of computerized maintenance summaries were obtained for the frequency of repair of over 700 controllers and their detectors of various types and ages.
6. *City of Tampa, Florida*—A computerized record of frequency of repair was obtained for almost 400 controllers of various types and ages for the year 1974.

7. *City of Charlotte, North Carolina*—In 1977, Charlotte purchased 72 microprocessor controllers of Type 190 design. Therefore, the project staff felt it would be cost effective to summarize and tabulate the frequency of repair of their total of 414 controllers of various types for the 6 months the microprocessors had been in service.
8. *City of Springfield, Illinois*—Data on the frequency of repair of Springfield's 144 pretimed and actuated controllers were obtained for 1976.
9. *City of Winston-Salem, North Carolina*—Four years of detailed maintenance cost data were obtained for one example each of pretimed and full-actuated controllers.
10. *Washington, D.C.*—A total of 497 loop detectors were installed in connection with the UTCS Research Project. One year of maintenance data was obtained.
11. *City of Grand Rapids, Michigan*—Maintenance data for 1976-1977 are scheduled to be put on the City's computer by consultants by the end of 1978.
12. *City of Seattle, Washington*—Consultants to the City have hand-tabulated recent maintenance records.

Adequacy of Data

The data were gathered to assist in the future selection of type of control—pretimed, semi-actuated, basic full-actuated, and density full-actuated. As such, data on microprocessor controllers were needed to be included. In this context, there are two fundamental inadequacies in the available data. One is that none of the data sets provides the total maintenance costs for each of the four types of control. The California data quote total cost—field and bench labor, travel and materials—but do not include pretimed control or the new Type 170 microprocessor. The New York data include pretimed equipment, but the cost of only the field man-hours can be obtained; bench labor, travel, and materials are not covered. Most of the other sources quote only frequency of repair, not dollar cost.

Another difficulty with these data is that future consideration of actuated control—at least for the future as can be seen now—focus on the microprocessor controller and the digital loop detector. Almost all of the available maintenance data predate microprocessor designs.

Respondents in California, New York State, and Charlotte, N.C., for example, make it clear that microprocessor designs of Type 170 (user programmed) and Type 190 (factory programmed) are showing a longer mean time between failure (MTBF) and a shorter mean time to repair (MTTR) than have the controllers reported herein. (However, hard data on this superiority are skimpy as of this writing.) Presumably other designs of microprocessors will show similar benefits when their records are tabulated

Moreover, the digital loop detector is proving to be much more effective than its analog counterpart. New York State, for example, found in 1978 that digital loop electronics operated loops in such poor condition that the locations had been scheduled for reinstallation of new loops. A number of other respondents indicated that they are extremely impressed with the digital unit's sensitivity and ability to operate under adverse conditions of loop condition, temperature, and the like.

It should be noted that the present research project was conceived at a point in time when some states—particularly those in the northeast and upper midwest—were experiencing great difficulty in maintaining actuated controllers and loop detectors of conventional design. In 1977 and 1978, the microprocessor and the digital loop detector began to change this situation completely for some agencies. New York State, for example, now is able to look much more positively toward the selection of full-actuated control at individual intersections. It seems clear that this research project has been overtaken by technological breakthroughs that greatly diminish the potential attraction of pretimed or semi-actuated control at individual intersections. This reality needs to be kept in mind by the reader of the following maintenance data, which for the most part predate these breakthroughs.

State of California DOT Data

Traffic signal maintenance expense records for 121 selected locations are stored on the CALTRANS computer. These costs include the dollar expense of all scheduled and nonscheduled, field and bench maintenance of all electrical equipment at the location, including lampouts, detector malfunctions, knockdowns, and so on. (California has a group relamping program, therefore lampouts should be negligible in these statistics.) Table 13 gives data for the 16 months from July 1, 1976, to October 30, 1977, adjusted to 12 months by multiplying the raw data by 12/16 = 0.75.

For 2-phase controllers, Table 13 suggests an average annual maintenance cost of $516. Three- and four-phase machines average $717 for solid-state designs and somewhat more for the electromechanical models. The microprocessor controller is lowest, at $488 (although only one location is included). Controllers of five to eight phases vary widely in maintenance ocst, with an average of $1,300 for solid-state models. Electromechanical models are comparable. Again, the microprocessor controllers are well below average, at $749.

TABLE 13

CALIFORNIA DOT ANNUAL MAINTENANCE COSTS FOR SELECTED LOCATIONS

Controller Type	Cost ($) Per Signal for Various Phasings			
	2Ø	3 - 4Ø	5 - 8Ø	All
Electro-Mechanical, Actuated				
Full Volume-Density	--	$1,162(1)	$1,506(5)	$1,448
Three Phase, Non-Density	--	746(6)	1,187[a](4)	923
Solid State, Actuated				
Analog Timing, Transistors	--	664(4)	2,061(8)	1,595
Digital Timing, Non-Computer				
Brand A	$ 359(1)	776(4)	852(9)	795
Brand B	--	1,070(5)	3,136(5)	2,103
Brand C, 2Ø	503(6)	--	--	503
Brand C, 2 - 4Ø	1,549(3)	575(11)	--	784
Brand C, 5 - 8Ø	296	--	1,509(10)	1,399
Digital, Minicomputer	--	--	964(33)	964
Digital, Microprocessor (Not the Type 170)	--	488(1)	749(4)	696

NOTE The number of controllers of each type is shown in parentheses

[a] Using two minor movement controllers

CALTRANS presently (1978) has a program underway to replace all 800 of its electromechanical traffic-actuated controllers over a 3-year period. During that time, the State plans to install nearly 3,000 microprocessor controllers of Type 170 design. (These are purchased without factory software and the programs are loaded by the State.) As of early 1978, 50 Type 170 controllers had been installed as CALTRANS' standard unit for intersection or ramp metering signal control on all safety or operational improvement projects. Inasmuch as the first unit was installed in the field in September 1977, there were no maintenance data available as of April 1978. However, CALTRANS expects that the fewer connection points and the lower component parts count, as compared to other controllers, will produce an improved MTBF. The Type 170's design should also result in a shorter MTTR, because it is electrically organized in a more logical manner than earlier designs It contains several self-test features intended to expedite bench repair.

Although the available California data do not include the pretimed controller data needed for this project, they do furnish total cost benchmarks for other types. These benchmarks are incorporated into comprehensive conclusions later

New York State DOT

New York maintains a computerized inventory of its more than 2,500 stop-and-go signals, flashers, and beacons. The man-hours for the field portion of the maintenance of all of these signals are similarly catalogued. Table 14 is a summary furnished by the State for a recent 12-month period for all of the regions except one. Table 14 indicates that although the man-hours per call are relatively independent of the type of controller, the man-hours per signal increase with greater sophistication of controller Table 15 reduces the data of Table 14 to a dollar cost of field maintenance for the three types of controller of interest to this project The costs were calculated using rates furnished by NYSDOT. (The rate of $5 per hour is an average of the $6 paid to the electrician and the $4 paid to the helper who accompanies him on the repair truck.) Table 15 indicates an increase in dollars per year from $86 to $118 to $258 for the field maintenance of pretimed, semi-actuated, and full-actuated equipment, respectively.

The NYSDOT furnished a detailed computer printout of the controller and detector maintenance experience for the 12-month period of October 1, 1976, to September 30, 1977 (Table 15) Selected data from the printout were tabulated by the project staff and are given in Table 16. The heading "Mixed E–M and SS" refers to the New York practice of combining the data of controllers similar in function but perhaps of different electrical design. Table 16 is much more detailed in its breakdown of controller type than is its counterpart (Table 14) for the previous year. Table 17 reduces the data of Table 16 to a dollar cost of field maintenance for each type of controller. Table 17 shows that there is not much difference in the annual field maintenance costs of pretimed, semi-actuated, and 2-phase full-actuated (nondensity) control. Costs jump for actuated controllers of more than four phases.

Table 15 showed that full-actuated control is three times as costly in field maintenance than is pretimed control. Table 17, however, suggests a ratio closer to 2:1. The difference may be that the data of Table 17 were selected from the computer output on the basis of number of controllers in the State. That is, only those models installed at four or more locations in the State were included. It is possible that the more widely used models enjoy a better maintenance experience than those that are one or two of a kind.

State of Ohio DOT

Ohio furnished maintenance data for their 558 controllers (Table 18). The table shows primarily that electromechanical volume-density controllers require significantly greater maintenance than do their basic counterparts, and much more than modern solid-state controllers.

State of Minnesota Department of Highways

One of the goals of this portion of the project was to be sure to have sufficient data from the "Snow Belt" of the United States. Accordingly, it was considered cost-effective to develop from raw data the maintenance experience for the Minneapolis District of the Minnesota Department of Highways. The frequency of repair of 135 controllers is given in Table 19. The table indicates a distinct advantage of solid state over electromechanical design in this climate. As expected, the greater the number of phases the more frequent the repair. The bottom of the table indicates that the frequency of repair of solid-state controllers does not increase with the age of the unit.

TABLE 14

CONTROLLER FIELD MAINTENANCE DATA FOR A PORTION OF NYSDOT's JURISDICTION FOR THE PERIOD OF OCT 1, 1975, TO SEPT. 30, 1976

Controller Type	No of Signals	No. of Calls	Calls per Signal	Regular Man-Hours	Overtime Man-Hours	Total Man-Hours	Man-Hours Per Call	Man-Hours Per Signal
Pretimed	168	479	2.85	704	605	1,309	2 73	7.79
Semi-Actuated	1,243	5,500	4 42	8,201	5,442	13,643	2.48	10 98
Full-Actuated	557	3,960	7 11	6,577	6,277	12,854	3.25	23 08
Flashing	506	537	1.06	950	744	1,694	3.15	3 35
Beacon	43	36	0.84	63	36	99	2.74	2.30
TOTALS	2,517	10,512	4 18	16,495	13,104	29,599	2 82	11.76

The data included the frequency of repair of the 811 loop detectors and 12 magnetic detectors with the 112 controllers of Table 19. It was found that the loop detectors averaged 0.24 failures per detector per year and the magnetic models averaged 0.26.

City of Cincinnati, Ohio

Cincinnati has used a computerized Traffic Control Equipment Maintenance Summary for 5 years. These summaries have been used to reduce the number of chronically malfunctioning intersections from 17 in 1973 to only 2 today. The City has a total of over 700 traffic signals.

Table 20 is a summary of 2½ years of computerized record-keeping from March 1975 to August 1977. The project staff removed all "normal cycle" reports (indicating no malfunction found by the repair crew). The staff also removed all failure reports associated with system features, such as coordination units, because the emphasis in this project is on individual intersections.

TABLE 15

COST OF CONTROLLER FIELD MAINTENANCE FOR A PORTION OF NYSDOT's JURISDICTION FOR THE PERIOD OF OCT. 1, 1975, TO SEPT. 30, 1976

(Calculated using wages of $5.00 per man-hour plus fringe benefits and overhead of 80%, for a total of $9.00; overtime is time and one-half, or $13.50/hr.)

Controller Type	Cost Per Signal, $
Pretimed	86
Semi-Actuated	118
Full-Actuated	258

TABLE 16

SELECTED CONTROLLER MAINTENANCE DATA FROM NYSDOT's JURISDICTION FOR THE PERIOD OCT. 1, 1975, TO SEPT. 30, 1976

Controller Type	No. of Signals	No. of Calls	Calls per Signal	Regular Man-Hours	Overtime Man-Hours	Total Man-Hours	Man-Hours Per Call	Man-Hours Per Signal
Electromechanical								
Pretimed	84	154	1.83	412	234	646	4.19	7.69
Semi-Actuated	583	1,520	2.61	3,918	1,345	5,263	3.46	9.03
Full-Actuated	251	994	3.96	2,692	1,142	3,834	3.86	15.27
Volume-Density	24	115	4.79	246	139	385	3.35	16.04
Mixed E/M and SS								
Semi-Actuated	473	1,037	2.19	3,666	1,501	5,167	4.98	10.92
Full-Actuated	194	626	3.23	1,772	826	2,598	4.15	13.39
Solid State, Analog Timing								
Semi-Actuated	28	27	0.96	178	36	214	7.93	7.64
Full-Actuated								
2 - 4φ	72	260	3.61	713	376	1,089	4.19	15.12
5 - 8φ	22	162	7.36	305	274	579	3.57	26.32
Solid State, Digital Timing								
Full-Actuated								
2 - 4φ	37	54	1.46	155	154	309	5.72	8.35
5 - 8φ	14	58	4.14	145	155	300	5.17	21.43

TABLE 17

COST OF CONTROLLER FIELD MAINTENANCE FOR SELECTED NYSDOT CONTROLLERS FOR THE PERIOD OCT. 1, 1976, TO SEPT. 30, 1977 (Calculated using $9/hr. for regular time and $13.50/hr. for overtime.)

Controller Type	Cost ($) Per Signal for Various Phasings			
	2φ	3 - 4φ	5 - 8φ	All
Electromechanical				
Pretimed	--	--	--	82
Semi-Actuated	92	--	--	92
Full-Actuated	134	197	--	158
Volume-Density	208	109	--	170
Mixed E/M and SS				
Semi-Actuated	113	--	--	113
Full-Actuated	113	155	--	140
Solid State Analog Timing				
Semi-Actuated	75	--	--	75
Full-Actuated	166	154	293	191
Solid State, Digital Timing				
Full-Actuated	70	144	243	135

TABLE 18

FREQUENCY OF CONTROLLER REPAIR BY OHIO DOT IN 1976

Controller Type	No. of Signals	No. of Calls	Calls/Signal Per Year
Electromechanical			
Actuated (Basic)	296	412	1.39
Volume-Density	84	169	2.01
Solid State			
Analog Timing	178	237	1.33
Digital Timing	Few	Unknown	--

TABLE 19

FREQUENCY OF CONTROLLER REPAIR BY THE MINNEAPOLIS DISTRICT, MINNESOTA DEPARTMENT OF HIGHWAYS

Controller Type	Age, Years	Years of Data	No. of Signals	Calls/Signal Per Year
Electromechanical				
Full-Actuated, 2ø	0- 5	5.0	8	2 40
Full-Actuated, 3-5ø	0- 5	3.0	4	4.70
All E/M	0- 5	--	12	2.92
Solid State, Analog Timing				
Semi-Actuated	0- 5	5.0	2	1 10
Full-Actuated				
3ø	0- 5	4.9	11	1.84
5ø	0- 5	5.0	27	3.19
5ø	6-10	2.5	23	2 40
Solid State, Digital Timing				
Full-Actuated				
3ø	0- 5	3.45	13	1.34
5-8ø	0- 5	3 0	24	2 05
All Solid State	0- 5	--	100	2.37
	6-10	2.5	23	2.4

Table 20 does not indicate any significant increase in maintenance load with an increase in sophistication from pretimed to semi-actuated to full-actuated. Rather, the evidence is that the solid-state actuated equipment is more reliable than the pretimed. Table 20 also shows that the frequency of repair of electromechanical equipment increases with age to approximately the 10th year and then decreases with greater age. This same phenomenon is evident also in the data presented for Tampa, Florida.

Detector maintenance over 2 years in Cincinnati is given in Table 21. The data indicate that the pressure detector is significantly more reliable than the other types listed. The data for magnetic and loop detectors are strikingly similar to the Minneapolis data previously reported.

City of Tampa, Florida

A computerized record of frequency of repair was obtained for almost 400 controllers for the year 1974. The record is summarized in Table 22. Except for the pretimed controllers at 2.26 calls per signal per year and the most recently purchased solid-state controllers operated semi-actuated (at 1.75), the maintenance load is extremely heavy as compared with the agencies reported previously. The well-known reason for this problem is the severe lightning storms experienced frequently in Florida. The data are so atypical as to be of little use to this project, but are nevertheless retained herein for their general interest.

City of Charlotte, North Carolina

Charlotte has a variety of actuated equipment of both electromechanical and solid-state design. Their total of 414 controllers includes 72 Type 190 microprocessors received in 1977. Table 23 summarizes 6 months of 1977 data, including their initial experience with the first 24 microprocessors installed. The table shows that the typical solid-state actuated controller is averaging one failure every 2 years. Initial experience with the microprocessors is at this same level. These rates are very low and may reflect the fact that Charlotte has for many years provided adequate funding for traffic engineering operations.

TABLE 20

FREQUENCY OF CONTROLLER REPAIR BY THE CITY OF CINCINNATI FOR THE PERIOD MARCH 1975 TO AUGUST 1977

Controller Type	Age, Years	No. of Signals	Calls/Signal Per Year
Electromechanical			
Pretimed	0- 5	31	1.81
	6-10	35	2.17
	11-15	--	--
	16-20	139	1.99
	>20	72	1.74
	All ages	277	1.92
Semi-Actuated	0- 5	2	1.50
	6-10	48	2.58[a]
	11-15	80	1.70
	16-20	54	1 65
	>20	38	1.68
	All ages	222	1.87
Full Operated Semi	0- 5	16	1 13
	6-10	45	2.76[b]
	All ages	61	2.33
Solid State			
Semi-Actuated	0- 5	2	1.50
Full Operated Semi	0- 5	12	1.00
	6-10	7	1.14
	All	19	1.05

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[a] High because of a single model.

[b] High because of 20 units of an early design of phase-modular controller that experienced 3.85 calls/signal/year.

TABLE 21

FREQUENCY OF DETECTOR REPAIR BY THE CITY OF CINCINNATI FOR THE PERIOD MARCH 1976 TO AUGUST 1977

Detector Type	No. of Detector	Failures/Detector Per Year
Pressure	23	0.17
Magnetic	81	0.26
Loop	151	0.29
Sonic	37	0.32

City of Springfield, Illinois

Springfield furnished maintenance data for a 12-month period in 1976-77. These data for 144 signals are summarized in Table 24 which shows an unusually high failure rate for semi-actuated controllers. The City Traffic Engineer explained that the City had had excellent operational results with the 2-phase semi-actuated controller for many years. Their maintenance problems began in 1975 when multiphase full-actuated controllers were purchased and operated semi-actuated in an arterial system.

City of Winston-Salem, North Carolina

Four years of detailed maintenance cost data were obtained for one pretimed and one full-actuated controller. These locations were selected by the City as fairly typical. The data, summarized in Table 25, show a very low cost to maintain the controllers. However, the record of the loop-detector maintenance shows 33 trips in 4 years to retune, replace, and cut new loops.

Washington, D.C.

A total of 497 loop detectors were installed as a part of the UTCS Research Project sponsored by the Federal High-

TABLE 22

FREQUENCY OF CONTROLLER REPAIR BY THE CITY OF TAMPA, FLA. FOR THE YEAR 1974

Controller Type	Age, Years	No. of Signals	Calls/Signal Per Year
Electromechanical			
Pretimed	0- 5	32	1.69
	6-10	93	2.33
	11-15	5	0.40
	16-20	1	1.00
	>20	45	2 76
	All ages	176	2.26
Semi-Actuated	0- 5	1	0
	6-10	11	6 82
	11-15	38	8.71
	16-20	11	4.45
	>20	12	9.08
	All ages	73	7.73
Full-Actuated	0- 5	1	1.00
	6-10	3	4.33
	11-15	5	11.80
	16-20	4	7.50
	>20	1	5.0
	All ages	14	7.71
Semi Operated Fixed	0- 5	1	2.00
	11-15	1	11.00
	All ages	2	6.5
Full Operated Semi	11-15	1	3.0
	16-20	2	5.0
	All ages	3	4.33
ALL ELECTROMECHANICAL			4 09
Solid State			
Semi-Actuated	0- 5	--	--
	6-10	29	5.48
	11-15	4	6.00
	All ages	33	5.55
Full-Actuated	0- 5	35	6.17
	6-10	33	9.09
	11-15	2	30.0
	All ages	70	8.23
Full Operated Semi	0- 5	8	1.75
	6-10	8	5 00
	11-15	2	23 0
	All ages	18	5.56
ALL SOLID STATE			7.04

TABLE 24

FREQUENCY OF CONTROLLER REPAIR BY THE CITY OF SPRINGFIELD, ILL., FOR THE PERIOD OF MARCH 1976 TO FEBRUARY 1977

Controller Type	No. of Signals	Calls/Signal Per Year
Pretimed	117	2.37
Semi-Actuated	21	3.95
Full-Actuated	6	1.67

TABLE 25

EXAMPLE COSTS OF CONTROLLER MAINTENANCE BY THE CITY OF WINSTON-SALEM, N.C., FOR THE PERIOD 1973-1977

Controller Type	Calls/Year	Maintenance Cost[a] Per Year, $
Pretimed	2.16[b]	17
Full-Actuated, 3ϕ, solid state, digital	2.05	18
Loop detection for above controller	8.46	340

[a] Project staff increased city costs by 80 percent to account for fringe benefits and overhead. City costs include labor at $5.00/hour, truck, supplies.

[b] Six of the eight calls over 3.7 years were for preventive maintenance.

TABLE 23

FREQUENCY OF CONTROLLER REPAIR BY THE CITY OF CHARLOTTE, N.C., FOR THE PERIOD APRIL TO SEPTEMBER 1977

Controller Type	Age, Years	No. of Signals	Calls/Signal Per Year
Electromechanical			
Semi-Actuated	>20	75	1.95
Semi-Actuated (PR)	16-20	37	2.49
Full-Actuated	0- 5	3	0.67
Mostly 3ϕ	11-15	63	1.43
	>20	13	0 91
	All ages	79	1.29
ALL ELECTROMECHANICAL			1.83
Solid State			
Semi-Actuated	0- 5	1	2.00
	6-10	3	0.00
	All ages	4	0.50
Semi-Actuated (TPR)	6-10	11	1.82
	11-15	6	0.00
Full-Actuated			
Digital, non-computer	0- 5	4	0.00
Microprocessor	0- 5	24	0.42
Digital, non-computer	6-10	167	0.54
Analog, non-computer	11-15	7	0.57
ALL SOLID STATE			0.56

way Administration (*30*). The installations were made only after a thorough study by the contractor of the available (crystal) electronics units and the procedures and materials for installing the loop wire and lead-in. In the first year, there were 33 failures of the electronics units, for a rate of 0.07 failures per detector per year. During that period, 26 loops failed because of utility excavations; if these failures are added, the total rate becomes 0.13 failures per detector per year.

Conclusions

Table 26 gives a summary of the data described in this section. The California Maintenance Management System offers the only available data base of total maintenance costs. For this reason, the summary results are based on this data base. Table 26 shows a suffix (C) for those values directly from the California data in Table 13. In drawing conclusions from Table 13, the Brand B digitally timed controller was ignored because this model has to be modified by CALTRANS personnel to keep it running acceptably. Other values were obtained by weighted averaging; for example, the $1,198 for solid-state digitally timed full-actuated controllers of five to eight phases were obtained by averaging Brands A and C according to the number of each such controller.

The data from New York State, Charlotte, Cincinnati, and Minneapolis were also referenced to fill in the remaining gaps in Table 26. The New York State data (Table 17) were given preference because man-hours were available.

For electromechanical equipment, the coordination point between the California and New York State data sets was selected to be the full-actuated controllers of three and four phases. The ratio of California total cost to NYS field cost at that cell in the matrix is 746 — 197 = 3.79. This factor was multiplied by the values in the cells of Table 17 to yield values for the corresponding cells of Table 26.

For solid-state equipment with analog timing, the coordination point between California and New York data was again taken at the full-actuated controllers of three and

TABLE 26

PROJECT STAFF CONCLUSIONS FOR THE TOTAL ANNUAL COST TO MAINTAIN VARIOUS TYPES OF TRAFFIC SIGNAL CONTROLLERS

Controller Type	Cost ($) Per Signal for Various Phasings 2ϕ	 3 - 4ϕ	 5 - 8ϕ	 All
Electromechanical				
Pretimed	--	--	--	311(D)
Semi-Actuated	349(D)	--	--	--
Full-Actuated	508(D)	746(C)	1,187(C)	--
Volume-Density	788(D)	1,162(C)	1,506(C)	--
Solid State, Analog Timing				
Semi-Actuated	306(D)	--	--	--
Full-Actuated	461(D)	664(C)	2,061(C)	--
Solid State, Digital Timing				
Full-Actuated	503(C)	629(C)	1,198(C)	--
Microprocessor				
Type 190	--	490(D)	934(D)	--
Other[1]	--	488(C)[1]	749(C)[1]	--

NOTE· The suffix (C) means that this cost was taken directly from the California DOT Maintenance Management System data of Table 13. The suffix (D) means derived as described in the text.

[1] These data are for a few controllers from a single manufacturer Other microprocessor controllers may have different maintenance requirements.

four phases. The ratio of the two cells is 629 — 154 = 4.08, which is reassuringly close to the 3.70 calculated for electromechanical equipment This factor of 4.08 was multiplied by the values in the cells of Table 17 to yield values for the corresponding cells of Table 26. However, for two-phase full-actuated control, the Table 17 value used was $113, not $166. The result in Table 26 is the following cost progression· $306 for semi-actuated, $461 for two-phase full-actuated, and $664 for three- and four-phase full-actuated.

The remaining brands in Table 26 were for the Type 190 microprocessor The Charlotte data of Table 23 show that for the column headed "Calls/Signal Per Year," the ratio of "microprocessor" to "digital non-computer" is 0.42 — 0.54 = 0.78. This factor was multiplied by the California cost of $629 for digital controllers of three to four phases to give $490 for Type 190 microprocessor controllers. The $490 is very close to the $488 below it, and so appears reasonable. The same factor was multiplied by the California cost of $1,198 for digital controllers of five to eight phases, to give $934 for the Type 190 microprocessor.

The resulting Table 26 is an estimate of the incremental maintenance requirements associated with the more sophisticated types of traffic signal control.

BENEFIT-COST ANALYSIS

The identification of the type of control for a particular intersection should be based on the use of a formal benefit-cost or utility-cost analysis. The cost comparisons of the preceding section indicate that the annual costs of the controller installation, operations, and maintenance ranged from $1,611 to $4,425 per year, depending on the type of control employed. These costs appear to be significantly less than the annual benefits at an intersection when delay time and vehicle operating costs are taken into account.

To compare the potential annual benefits with annual costs, it is necessary to assume levels of traffic volumes and to calculate the dollars of benefits resulting per second of reduced delay and per reduced stop.

Assuming a relatively low level of annual average daily traffic (AADT) of 5,000 vehicles per day on each of two intersecting roadways, the combined AADT through the intersection would be 10,000 vehicles per day. If the roadways entering the intersection each carried two lanes of traffic, this would correspond to a lane volume of only 125 vph

Further, assuming approach speeds of 35 mph, the cost of stops from Winfrey (*25*) would be $12.24 per 1,000 stops in 1969. Assuming inflation has increased these costs by 10 percent per year, the cost would be $28.86 per 1,000 stops in 1979.

Similarly, the delay cost was estimated to be $1,00 per hour in 1970 (*9*). Assuming the same rate of inflation, this cost would be $2.12 per hour in 1979. Adding the fuel consumed during idling to the delay cost using the fuel consumption rate of 0.00022 gal/sec and an average cost of $0.90 per gal yields an idling fuel cost of $0.80 per hour. Thus, the total delay cost is $2.92 per hour.

Using the traffic volumes and stops and delay costs, it is then possible to estimate the average hourly benefits for each percent reduction in stops per vehicle. These savings would correspond to the product of the cost, the saving per vehicle, and the number of vehicles, or·

$$\text{Daily cost per percent stops} = \left(10{,}000\ \frac{\text{veh}}{\text{day}}\right)$$

$$\times\ (\$0.029 \text{ per stop}) \times \left(0.01\frac{\text{stops}}{\text{veh}}\right) = \$2\ 90 \text{ per hour}$$

$$\text{Daily cost per second delay} = \left(10{,}000\ \frac{\text{veh}}{\text{day}}\right)$$

$$\times\ (\$2.92 \text{ per hour delay}) \times \left(\frac{1}{3600}\ \frac{\text{sec}}{\text{hour}}\right)$$

$$= \$8\ 11 \text{ per hour}$$

The annual cost of these savings would be:

Annual cost per percent stops = $1,059
Annual cost per second delay = $2,960

Therefore the annual benefits (expressed as motorist costs) far exceed the annualized equipment costs for low traffic volumes and for extremely small changes in stops and delay.

More typical changes in stops and delay would be five to ten times the values used in these calculations. For this reason, it is concluded that the guidelines should contain calculations that directly indicate the traffic conditions for which each type of control operates most effectively, and should not rely on the use of a formal benefit-cost analysis.

This discussion is not intended to imply that equipment costs are not important In spite of the fact that the annual costs are relatively small, they vary by a factor of three between the lowest cost and the highest cost. This variation in cost can be significant to an agency that is responsible for the operation of a large number of controllers.

CHAPTER THREE

INTERPRETATION, APPRAISAL, APPLICATIONS

GENERAL RECOMMENDATIONS

On the basis of the findings of this research project it is concluded that only three types of controllers should receive consideration for installation at the majority of individual intersections; pretimed, full-actuated, and volume-density. Semi-actuated control should be considered only for cases with light cross-street traffic. Of these three, the volume-density controller should be installed at locations where high approach speeds and restricted signal visibility impose safety considerations on intersection operation that cannot be satisfied by the other two types of control.

Pretimed or full-actuated control will be the most appropriate form of control for the majority of individual intersections. Identification of the one best suited to a particular intersection requires the computation of the effectiveness of each form of control for the prevailing traffic and roadway conditions that exist at the intersection. This finding is not a new one. It was supported by Gerlough and Wagner (*31*) when they wrote in 1967·

> The findings of the research on signal operation characteristics permit a fresh interpretation of some old philosophies about traffic-responsive versus fixed-time control. It is often stated that under traffic conditions of low and medium volume, existing forms of actuated controllers yield substantial improvements in traffic performance as compared with fixed-time control. The authors believe that this reflects not so much on the value of the existing responsive modes as it does on the poor utilization of fixed-time controllers Very short fixed cycle lengths (on the order of 40 seconds or even shorter) would yield performance which would be nearly as effective as that possible with traffic-responsive controllers under these conditions

The findings presented in this report demonstrate the importance of considering *all* of the factors associated with the operation of a particular controller before arriving at a final conclusion. In a number of cases (particularly where relatively stable traffic conditions exist), the pretimed controller performance will equal or exceed the performance of the actuated forms of control. Because the pretimed controllers will be less expensive to install and maintain, the effort associated with the comparison of the alternatives is well justified.

NEED FOR COORDINATION

The analysis of platoon structures as a function of various roadway conditions has shown the sensitivity of these structures to various roadway conditions. This sensitivity demonstrates the importance of considering the factors influencing the platoon characteristics before arriving at a final determination regarding the need for coordination. The procedure developed is relatively straightforward, although it can lead to time-consuming computations if more than one approach has a nearby signalized intersection. For a detailed analysis of the benefits of coordination in the presence of more than two nearby upstream signals, a more sophisticated approach is recommended such as the use of one of the available computer programs for optimizing and evaluating signal timing

However, in any case, the current rule of thumb that a signal separation of less than ½ mile should be coordinated and more than ½ mile does not require coordination is inadequate. Following this criterion can lead to either poor operation or unnecessary expenditures, depending on the particular circumstances of the intersection being studied.

FUEL CONSUMPTION AND EMISSIONS

The data employed in developing the procedures for estimation of fuel consumption and emissions from vehicle delays and stops is based on a particular distribution of vehicle model years. With the annual change in Federal regulations regarding these vehicle characteristics, these data may become outdated. Therefore, if reliance is to be placed on this information, it will be necessary to update it as additional information becomes available from the Environmental Protection Agency Several research projects are currently underway in this area, so it can be anticipated that more up-to-date data will become available within the next few years.

EVALUATION OF COSTS

Although it is possible to conclude from the cost data in this report that the cost of a particular type of control will have a relatively minor impact on the overall activities of that agency's budget, it must be emphasized that, over time, these costs can be applied to hundreds of installations with a resulting budgetary impact that is significant.

It should also be emphasized that many agencies experience particularly severe problems associated with detector loop failures that may not be reflected in these average figures. Most of these problems are due to either poor pavement condition or deficient installation procedures. A low loop reliability can further increase the cost of actuated controller maintenance or degrade traffic performance.

For these reasons, the costs of alternative forms of control should receive serious consideration in the controller selection process.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

The effectiveness of alternative types of signal control has been studied by numerous agencies throughout the world. Most of these studies have examined limited sets of traffic and roadway conditions, and have only considered relative delay as a measure of effectiveness.

This study was conducted for the purpose of evaluating a wide range of benefits and costs associated with alternative forms of control for a broad range of conditions. It is concluded that in most cases either pretimed or basic full-actuated will provide the most effective form of traffic control for individual intersections. It is further concluded that the selection between these two alternatives requires consideration of the specific roadway and traffic characteristics of the intersection being considered.

With agencies currently operating with restricted budgets and with only limited opportunities for new construction, it has become important for the traffic engineering community to operate existing facilities efficiently and economically. As a result, it is necessary to abandon the old rules of thumb and move toward the more sophisticated analytical procedures capable of providing more reliable results.

SUGGESTED RESEARCH

The research conducted under this project has answered many questions. However, it has also uncovered several areas that warrant additional investigation. These areas include:

1. An analysis of current signal control deficiencies. This research would include a survey of existing controller malfunctions, deficient signal timing practices, the reasons for those problems, their impact on traffic flow, and possible solutions.

2. Continuing examination of microprocessor controller maintenance costs. A revolution is underway in the design of modern control equipment. The traditional electromechanical and solid state equipment is being replaced using a solid state microprocessor implementation. The impact of this revolution is a significant improvement in controller reliability and changes in maintenance procedures and equipment. At the time of this research insufficient data were available to reliably assess the effect of the new equipment.

3. Refinements to the platoon dispersion model. This research has demonstrated the utility of the platoon dispersion model for assessing the benefits of signal coordination. It would also be useful in the estimation of intersection capacity and traffic flow performance for a variety of other applications However, because this aspect of the project activities was not within the mainstream of the project, it was not possible to expend the resources required to fully validate the parameters of the model for the complete range of roadway conditions. Further research in this area could produce many benefits for the analysis of traffic flow on various types of facilities.

4. Extensive survey of the relationship between type of control and accident rates. It would appear desirable to develop a data base of adequate size to determine the relationship between accident rate, number of stops, approach volumes, approach speeds, and existence of a dilemma zone. These data must be based on a single consistent approach or a well-defined set of approaches to accident reporting.

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APPENDIX A

ANNOTATED BIBLIOGRAPHY

Table 1. Classification of references.

Signal Type	Data Type	Highway Types																							
		Rural						Urban Arterial/Network						Other						Nonspecific					
		Factors Analyzed						Factors Analyzed						Factors Analyzed						Factors Analyzed					
		Traffic Flow	Timing	Installation/ Maintenance	Emissions/ Fuel/ Geometrics	Other	Nonspecific	Traffic Flow	Timing	Installation/ Maintenance	Emissions/ Fuel/ Geometrics	Other	Nonspecific	Traffic Flow	Timing	Installation/ Maintenance	Emissions/ Fuel/ Geometrics	Other	Nonspecific	Traffic Flow	Timing	Installation/ Maintenance	Emissions/ Fuel/ Geometrics	Other	Nonspecific
Fixed Time	Chase Car/ Floating Car																			132					
	Freeway Surveillance											44								132					
	Arterial Surveillance							14	14																
	Photographic							51	51		51														
	Simulation							34																	141
	Other			118				4,13,14,34, 98,116	4,14,36, 98,116	89,98,116,118, 122	4,36,98	116		3,54	3,90					60	60,142			5,10	117
	Nonspecific	17,126		17,134		17	135	17,76, 133	35,107, 133	17,134	35	17,35, 107	127,135,136	17,38, 126	22	17,22		17	81,136		1,2,99, 114	25,64,69, 82		1,3,48, 123	39,40,56, 84,92
Semi-Actuated	Chase Car/ Floating Car																								
	Freeway Surveillance																								
	Arterial Surveillance																								
	Photographic																								
	Simulation																								
	Other			118				98,116	98,116,	98,116,118	98	116												5,10, 120	117
	Nonspecific	17		17,134		17		17,76	35,104	17,104,134	35	17,35, 104	43,127,136	17	22	17,22		17	136		114,119	25,64,69, 82		123	84,92
Fully Actuated	Chase Car/ Floating Car							24				24													
	Freeway Surveillance							33	33	33		33													
	Arterial Surveillance							14,30, 31	14	30															
	Photographic							30,51	51	30	51														
	Simulation							8,46	8,46			8									66	66			
	Other	87		118				14,36,77, 87,98,116	14,36,77, 98,116	98,116,118	36,98	77,116		29,94	94									5,10, 120	74,117
	Nonspecific	17,126	78	17,134		17	135	2,17,33,59, 76,95,143	35,37,95, 109,143	17,50,69,104, 134,143	35,95	2,17,35, 58,104	135,136	17,126	22	17,22		17	19,136	85	73,114, 119	25,52,62,63,64, 69,82,118,110,115		99,113, 115,122, 123	41,56,84,92
Other	Chase Car/ Floating Car																			132					
	Freeway Surveillance																			132					
	Arterial Surveillance								14	14															
	Photographic																								
	Simulation																				108				
	Other						32		19,116	116		116		54,94	94										117
	Nonspecific				134				37	134		57								144	144	25,64,83		11	112
Nonspecific	Chase Car/ Floating Car								23			93								42			42		101,138,139
	Freeway Surveillance							45	45											72,137	91				
	Arterial Surveillance																								121
	Photographic																				53			103	139
	Simulation							47	26,47, 88		27	88								71	28		28		67,101,129, 138
	Other					16	15					16	20						106		79			102	138,139
	Nonspecific							105, 147	100,105, 145,147	100		97,109								21,65, 128	61,65, 146	5,10,21,61,65,68, 70,75,80,85,126, 130,131,140	12,96	21,86, 111,128	55

Reference 1

Allsop, R. E. "A Diagram Showing Practicable Settings for a Fixed-Time Traffic Signal and Their Effect on Delay." Transportation Research, April 1971, pp. 59-65.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
X Signal Timing
__ Effects of Geometrics
X Other

Signal Types

X Fixed Time
__ Semi Actuated
__ Fully Actuated
__ Other

Summary/Abstract

A method is presented for the graphical determination of satisfactory timing values for a two-phase, fixed-time traffic signal. The method is based on an equilateral triangle. The variation with the signal settings of the estimated delay per unit time at the intersection can be illustrated by drawing contours of equal delay. Two examples are given.

Reference 2

Allsop, R. E. "Delay at a Fixed Time Traffic Signal - I: Theoretical Analysis," Transportation Science,, August 1972, pp. 260-285.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
X Signal Timing
__ Effects of Geometrics
X Other

Signal Types

X Fixed Time
__ Semi Actuated
__ Fully Actuated
__ Other

Summary/Abstract

The various theoretical analyses that have been made on delay to traffic at a fixed time traffic signal are critically reviewed. The more practicably applicable expressions for the average delay per vehicle, especially those derived by Webster, Miller, and Newell, are examined in some detail, and this paper provides an introduction to numerical comparisons to be reported by Hutchinson in the sequel.

Reference 3

Allsop, R. E. "Sensitivity of Delay at a Fixed-Time Traffic Signal to Small Errors in the Observations Used for Calculating the Signal Settings." Traffic Flow and Transportation, pp. 253-267.

This Literature Contains Information in the Following Categories:

Highway Types

☐ Rural
☐ Urban Arterial
☐ Urban Network
☒ Other

Data Types

☐ Chase Car or Floating Car
☐ Freeway Surveillance System
☐ Arterial Surveillance System
☐ Photographic
☐ Simulation
☒ Other

Factors Analyzed

☒ Traffic Flow Characteristics
☐ Vehicle Emissions
☐ Fuel Consumption
☐ Maintenance
☐ Installation
☒ Signal Timing
☐ Effects of Geometrics
☐ Other

Signal Types

☒ Fixed Time
☐ Semi Actuated
☐ Fully Actuated
☐ Other

Summary/Abstract

The cycle time and green times at a road junction controlled by fixed-time traffic signals can be calculated so as to minimize, subject to certain constraints, Webster's simplified estimate of the delay per unit time to all traffic passing though the junction. The signal settings are determined by a vector whose components are the proportion of the cycle for which each group of approaching traffic streans has right of way and the proportion of the cycle taken up by lost time. This paper shows how the vector determining the signal settings is affected by small errors in the observed arrival rates and saturation flows. It goes on to obtain an estimate of the difference between delay per unit time that would occur if the signal settings were calculated from the true arrival rates and saturation flows. The delay per unit time at the example junction is found not to be very sensitive to errors in just one arrival rate or saturation flow, except when the function is heavily loaded with traffic, but it is shown that the combined effect of several erros can be quite large. The method developed in this paper should enable engineers to identify situations in which particularly accurate measurements of arrival rates and saturation flows are necessary, and to estimate the range of conditions for which particular signal settings are likely to be suitable.

Reference 4

Australian Road Research Board. Australian Road Capacity Guide - Introduction and Signalized Intersections. Melbourne: 1968.

This Literature Contains Information in the Following Categories:

Highway Types

☐ Rural
☒ Urban Arterial
☐ Urban Network
☐ Other

Data Types

☐ Chase Car or Floating Car
☐ Freeway Surveillance System
☐ Arterial Surveillance System
☐ Photographic
☐ Simulation
☒ Other

Factors Analyzed

☒ Traffic Flow Characteristics
☐ Vehicle Emissions
☐ Fuel Consumption
☐ Maintenance
☐ Installation
☒ Signal Timing
☒ Effects of Geometrics
☐ Other

Signal Types

☒ Fixed Time
☐ Semi Actuated
☐ Fully Actuated
☐ Other

Summary/Abstract

Methods are given for estimating the capacities and operating characteristics of signalized intersections. Calculations are presented for determining vehicle delay and for timing fixed-time controllers.

Reference 5

Automotive Safety Foundation. "Chapter VII. Intersections," Traffic Control and Roadway Elements - Their Relationship to Highway Safety. (1963) pp. 57-59.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
_X_ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
_X_ Other

Signal Types

_X_ Fixed Time
_X_ Semi Actuated
_X_ Fully Actuated
__ Other

Summary/Abstract

A comparison of accident rates at intersections using fixed-time, semi-actuated, and fully actuated volume-density controllers. Rear-end accidents were found to decrease as controller sophistication increased.

Reference 6

Baltayan, A. M. "Troubleshooting Solid State Traffic Control Equipment." IMSA Signal Magazine. May 1972, pp. 12-13.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
_X_ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

__ Fixed Time
__ Semi Actuated
__ Fully Actuated
__ Other

Summary/Abstract

The author presents a guide to the troubleshooting of solid-state equipment. The most efficient way of troubleshooting is by methodically eliminating properly functioning sections of equipment until the faulty circuit is found.

Reference 7

Bang, Karl L. and Nilsson, Lars E. "Traffic Signal Control With Long-Loop Detectors." Traffic Engineering and Control, March 1970, pp. 525-527.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
X Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

X Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
X Other

Signal Types

__ Fixed Time
__ Semi Actuated
X Fully Actuated
__ Other

Summary/Abstract

This paper presents the results of an experiment to test the usefulness of long-loop detectors, as opposed to inductive loop passage detectors. The long-loop detectors were installed at an ordinary right-angle, four-way crossing between two arterials in a suburban residential area in Sweden. Minimum delay and the number of stopped vehicles were used as criteria of optimum traffic flow conditions. The results showed that the long-loop detector was very promising.

Reference 8

Bang, Karl-Lennart. "Optimal Control of Isolated Traffic Signals." Traffic Engineering and Control., July 1976, pp. 288-292.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
X Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
X Simulation
__ Other

Factors Analyzed

X Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
X Signal Timing
__ Effects of Geometrics
X Other

Signal Types

__ Fixed Time
__ Semi Actuated
X Fully Actuated
__ Other

Summary/Abstract

The author examines the properties of conventional fixed-time and vehicle-actuated control of isolated, signalized intersections and develops a self-optimizing control strategy which minimizes vehicle delay and gives special consideration to buses and pedestrians. The project was carried out in five stages:

1. Signal control criteria
2. Literature inventory of control strategies
3. Development of control strategies
4. Simulation
5. Field tests

Details of cost/benefit analysis are shown.

Reference 9

Bang, Karl L. and Nilsson, Lars E. "Traffic Signal Control Wih Long-Loop Detectors," Traffic Enigneering and Control, March 1970, pp. 525-527.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☒ Other

Data Types

- ☐ Chase Car or Floating Car
- ☒ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☒ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

This paper compares the efficiencies of loop-occupancy control with conventional, small-area loop detectors. Studies made at a test intersection show that LOC reduces the probability of stop, delay per vehicle, and number of stopped vehicles.

The possibility of using analog signals from a long-loop detector to separate bus calls from passenger car calls.

Reference 10

Barney, Alan F. "Communications System Technology and Its Use in Traffic Control Systems." Traffic Engineering, August 1971.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☒ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☒ Other

Signal Types

- ☒ Fixed Time
- ☒ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

The spectrum of accumulated knowledge in the communications systems field was sampled. Information and design concepts favorably related to traffic control techniques and principles and singled out and highlighted. These facts, teamed with marketing requirements, provide recommendations for the effective utilization of communications knowledge and techniques in traffic control.

This paper provides a good overview of communications information rleated to traffic control systems.

Reference 11

Barrow, B. L. and Bailey, J. A. "Microcomputers Applied to Traffic Control," Traffic Engineering Control. August/September 1974, pp. 773-774.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
X Other

Signal Types

__ Fixed Time
__ Semi Actuated
__ Fully Actuated
X Other

Summary/Abstract

This paper gives a general overview of the uses of microcomputers in traffic control systems. It includes a historical summary of the uses of electronic controllers, the components of microcomputer systems, the types of control strategies, and the communications network.

Reference 12

Bauer, C. S. "Some Energy Considerations in Tradffic Signal." Traffic Engineering, February 1975, pp. 19, 22-25.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
X Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

__ Fixed Time
__ Semi Actuated
__ Fully Actuated
__ Other

Summary/Abstract

An energy-based analysis scheme was studied for isolated pretimed intersections using Webster's equations. As with many engineering design activities, increased operating efficiencies in one area will often cause decreased efficiencies in others. This was the case with the minimum energy control scheme studied in this paper where it was shown that total vehicle delay must be allowed to increase in order to reduce the total fuel consumption of vehicles passing through an intersection.

Reference 13

Bellis, W. R. "Capacity of Traffic Signals and Traffic Signal Timing," Highway Research Board Bulletin 271. (1960) pp. 45-67.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☒ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☒ Other

Factors Analyzed

- ☒ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

This report contains the results of a detailed analysis of vehicle arrival rates and discharge headways at several isolated intersections. This data was used to determine the capacity of signalized intersections as a function of cycle length and green time.

Reference 14

Berry, D. S. "Field Measurement of Delay at Signalized Intersections." Highway Research Board Proceedings, Vol. 35, pp. 505-522.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☒ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☒ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☒ Other

Factors Analyzed

- ☒ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☒ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☐ Semi Actuated
- ☒ Fully Actuated
- ☒ Other

Summary/Abstract

Methods for field measurement of intersection delay and the effects of different signal timing plans on stopped-time delay during daylight hours at signalized intersections in the San Francisco Bay Area were studied. Three methods for measuring stopped-time delay were compared: (1) the ITTE Delay Meter, which accumulates vehicle-seconds of stopped time; (2) a sampling method for estimating vehicle seconds of stopped time; and (3) use of spaced serial photos to obtain stopped time and travel time for each vehicle. All three methods were satisfactory for obtaining stopped-time delay at signalized intersections. "Unnecessary" delay was substantially lower with actuated than with fixed-time control. Stopped-time delays were substantially lower for full-actuated control than for semi-actuated control. Stopped-time delay was also studied at two signalized intersections 1,185 feet apart to ascertain the effect on delay of coordinating the timing of two fixed-time signals. The delay to the Main Street traffic in both peak and off-peak hours was less than half the delay experienced when using actuate traffic signal control without coordination of the timing of the two signals. /Author/

Reference 15

Bleyl, R. L. "Speed Profiles Approaching a Traffic Signal," HRR 384. (1972) pp. 17-32.

This Literature Contains Information in the Following Categories:

Highway Types

- ☒ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☒ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

The objective of this study was to examine and compare the speed profiles of traffic approaching a traffic signal under six different signal displays. Detector loops were installed along one approach to a rural traffic signal installation. Detector actuations, signal indications, and timing information were recorded at a remote observation point by using a 20-pen operation recorder. Observations were made of lone vehicles approaching the traffic signal location. The speed profiles observed under each signal display were summarized and compared with the speed profiles under the other signal displays. Drivers at the study location entered the intersection more cautiously with a green traffic signal indication or a flashing yellow indication than they did with no signal installed. They did not speed up when signal control was changed from regular stop-and-go operation to flashing operation. Approaching a red signal indication, drivers did not begin to slow down until they were approximately 500 ft. from the signal. Under all other signal displays, drivers generally maintained their speed as they approached the signal location and entered the intersection./Author/

Reference 16

Box, P. C. Intersections. Highway Users Foundation for Safety and Mobility, Washington, D.C. (1970).

This Literature Contains Information in the Following Categories:

Highway Types

- ☒ Rural
- ☒ Urban Arterial
- ☒ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☒ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☒ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

Statistics show that intersectional accidents are a national problem in highway safety. About 24 percent of fatal accidents listed in a national tabulation were classified as occurring at intersections. In urban areas, approximately 41 percent of total accidents, and 39 percent of fatal accidents, were reported as intersectional. In rural areas, the data showed that 27 percent of total accidents, but only 17 percent of fatal accidents, were at intersections. An important design element involves provision for vehicles to make left turns off major routes. Left-turn channelization was installed at 48 unsignalized urban and rural intersections along California highways, and accidents were found to be reduced significantly. The types of intersectional controls included in the discussion are yield, two-way stop, four-way stop, and the traffic signal. The yield sign is used to regulate traffic flow at low volume intersections and at intersections where the accident rate is above the average of other intersections of the same type. Yield signs were found to be an effective measure at previously uncontrolled, isolated, urban, low-volume intersections. The findings of various researchers indicate that yield signs can be an effective control under many low-volume conditions. Several studies are reported on two-way stop control. The studies indicate for two-way stops that (1) accident rates increased as cross-street volume increased, and (2) accident rate decreased as main street volume increased. For four-way stops, St. Paul and California studies support a conclusion that accident reduction can be effective if the installation is warranted by accident frequency and the volumes are moderate and balanced. Many studies are reported on the effect of traffic signals on traffic operations. Studies on flashing beacons and directional signing are described.

Reference 17

Box, Paul C., and Alroth, Willard A. "Warrants for Traffic Control Signals, Parts 1, 2, and 3." Traffic Engineering, November 1967; January 1968, pp. 3-4.

This Literature Contains Information in the Following Categories:

Highway Types

X Rural
X Urban Arterial
X Urban Network
_ Other

Data Types

_ Chase Car or Floating Car
_ Freeway Surveillance System
_ Arterial Surveillance System
_ Photographic
_ Simulation
_ Other

Factors Analyzed

X Traffic Flow Characteristics
_ Vehicle Emissions
_ Fuel Consumption
_ Maintenance
X Installation
_ Signal Timing
_ Effects of Geometrics
X Other

Signal Types

X Fixed Time
X Semi Actuated
X Fully Actuated
_ Other

Summary/Abstract

This paper is the result of a review of the existing signal warrants. Part I covers introduction, summary of work performed, and the factors of volume, gap availability, and gap acceptance characteristics. Part II covers delay and pedestrians; and Part III covers accidents, suggested warrants, and bibliography.

Reference 18

Brammer, Donald D. "Economic Consequences of Traffic Signal Upgrading." Prepared for the Annual Conference of Southern Section, Institute of Traffic Enigneers. April 1973.

This Literature Contains Information in the Following Categories:

Highway Types

_ Rural
_ Urban Arterial
_ Urban Network
_ Other

Data Types

_ Chase Car or Floating Car
_ Freeway Surveillance System
_ Arterial Surveillance System
_ Photographic
_ Simulation
_ Other

Factors Analyzed

_ Traffic Flow Characteristics
_ Vehicle Emissions
_ Fuel Consumption
_ Maintenance
X Installation
_ Signal Timing
_ Effects of Geometrics
_ Other

Signal Types

_ Fixed Time
_ Semi Actuated
_ Fully Actuated
_ Other

Summary/Abstract

This paper presents a step-by-step procedure for evaluating the economics of upgrading traffic signal installations within urban areas. User benefits resulting from the reduction of stops and delays are compared with equipment and installation costs, and computed as a benefit/cost ratio. A case study of the replacement of a pertimed controller with an eight-phase, fully-actuated, loop-occupancy controller is presented in detail.

Reference 19

Brass, J. R., and Gitelson, D. "Shifting Presence Zone Detection." Reprinted in unpublished course notes "Fundamentals of Traffic Signal Design and Operation." (October 28, 1968). Berkeley: University of California, 1972.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☒ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

This paper proposes a possible solution to the dilemma-zone problem, based on a "shifting presence zone." The zone has hypothetical "speed detectors" in the dilemma zone and a 50-foot long presence detector at the stop line.

(Note: This paper's proposal has never been implemented.)

Reference 20

Buffington, Jesse L., and McFarland, W. F. "Benefit-Cost Analysis: Updated Unit Costs and Procedures." Texas Transportation Institute Research Report 202-2. August 1975.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☒ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☒ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

This report contains highway user costs that are based on 1975 conditions in the urban areas of Texas. The unit costs reported here are vehicle running costs, travel time costs, and accident costs. Also, data on air and noise pollution, as well as other highway impact data, are included in this report.

The report contains an analysis of the impact of the energy shortage on the relative costs that are used in the conventional benefit-cost or cost-effectiveness analyses.

Finally, the report contains a recommended analytical procedure that uses the benefit-cost or cost-effectiveness approach to determine whether a project is economically feasible or cost-effective. Also, the procedure can be used to select from among alternative projects the one that fulfills a particular goal or set of goals.

Reference 21

Cass, S. "Toronto's Digital Computer Signal System." Traffic Engineering and Control, January 1981, pp. 460-463.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☒ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☒ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☒ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

This paper presents the status of Toronto's system and includes the results of a before-and-after study. Topics discussed include a historical summary, reliability, traffic data, performance, critical intersection control, turning movement control, accident control, and economic benefits.

Reference 22

Cass, Samuel. "Traffic Signals, Chapter 17." Transportation and Traffic Engineering Handbook. Institute of Traffic Engineers, (1976) pp. 782-852.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☒ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☒ Maintenance
- ☐ Installation
- ☒ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☒ Semi Actuated
- ☒ Fully Actuated
- ☒ Other

Summary/Abstract

This chapter presents an overview of the subject of traffic signals covering all facets in some detail. Topics discussed include signal warrants and their application; signal equipment including controllers, signal heads, detectors, and associated hardware; signal timing for isolated and network situations; special signals including lane-use, railroad and beacons; maintenance and modification of signals.

Reference 23

Chapman, H. R., and Clark, J. E. "Application of RUNCOST for Evaluation of a Hybrid Traffic Control System." Traffic Engineering, April 1975, pp. 36-44.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
X Urban Network
__ Other

Data Types

X Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

X Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

__ Fixed Time
__ Semi Actuated
__ Fully Actuated
__ Other

Summary/Abstract

The RUNCOST computer programs developed by FHWA were used to analyze travel times before and after the installation of a computerized traffic control system in Charleston, S.C. The programs determine vehicle operating costs and time costs as a result of speed and delays.

Reference 24

Chapman, Howard R., and Raynor, Harold M. Jr. "MOE's of a Centralized Traffic Control System." Traffic Engineering. March 1972.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
X Urban Network
__ Other

Data Types

X Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

X Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
X Other

Signal Types

__ Fixed Time
__ Semi Actuated
X Fully Actuated
__ Other

Summary/Abstract

Measures of effectiveness (MOE's) were developed for the Charleston, S.C. Hybrid Traffic Control System (HTCS). The MOE's utilized were network speeds, stops, and delay times. A description of the traffic control system and the analyis results are included.

Reference 25

Cobbe, B. M., and Ridley, G. "Traffic Signals." Inst. Hwy Engineers Journal, London: May 1970, pp. 81-87.

This Literature Contains Information in the Following Categories:

Highway Types

☐ Rural
☐ Urban Arterial
☐ Urban Network
☐ Other

Data Types

☐ Chase Car or Floating Car
☐ Freeway Surveillance System
☐ Arterial Surveillance System
☐ Photographic
☐ Simulation
☐ Other

Factors Analyzed

☐ Traffic Flow Characteristics
☐ Vehicle Emissions
☐ Fuel Consumption
☒ Maintenance
☐ Installation
☐ Signal Timing
☐ Effects of Geometrics
☐ Other

Signal Types

☒ Fixed Time
☒ Semi Actuated
☒ Fully Actuated
☒ Other

Summary/Abstract

Part I looks at the maintenance of traffic signals from a national point of view. Satisfactory maintenance of signals depends not only on the reliability of the equipment and the speed of fault clearance, but also on the early detection of faults. Factors affecting these requirements are discussed and suggestions made for the reorganization of the whole maintenance service both for the existing equipment and for equipment likely to be available in the future. Part II looks at the maintenance of traffic signals from the local authority's viewpoint. Faults in signal installations are too frequent and the methods of dealing with them are unsatisfactory. A proposed new form of maintenance contract and the possible inspection organization necessary to make it effective in a large urban authority are discussed.

Reference 26

Cohen, S. L. Application of Network Simulation Models to the Analysis of Urban Intersection Performance. Final Report: FHWA-RD-74-25. September 1973.

This Literature Contains Information in the Following Categories:

Highway Types

☐ Rural
☒ Urban Arterial
☐ Urban Network
☐ Other

Data Types

☐ Chase Car or Floating Car
☐ Freeway Surveillance System
☐ Arterial Surveillance System
☐ Photographic
☒ Simulation
☐ Other

Factors Analyzed

☒ Traffic Flow Characteristics
☐ Vehicle Emissions
☐ Fuel Consumption
☐ Maintenance
☐ Installation
☐ Signal Timing
☐ Effects of Geometrics
☐ Other

Signal Types

☐ Fixed Time
☐ Semi Actuated
☐ Fully Actuated
☐ Other

Summary/Abstract

It was the objective of this study to adapt and validate the UTCS-1 Network Simulation Model for use in the analysis of traffic performance of single urban intersections. Modifications to UTCS-1 in order for it to be applicable to a single intersection are described. The modifie model which is hereafter referred to as UTCS-1s, was tested for reasonableness and compared to two other single intersection simulation models described in a report from Traffic Research Corporation. The model was then validated by simulaitng isolated intersections in Oakland, California, and Arlington, Virginia. As a demonstration of the model, two examples of applications were made. In the first example, the effectiveness of allowing right turns against a red signal indication was examined. In the second, a sampling procedure for estimating stopped delay at intersections was analyzed. It is concluded that UTCS-1s is an accurate and flexible model suitable for use in the analysis of the performance of individual intersections.

Reference 27

Cohen, Stephen L. "Analysis of Carbon Monoxide Pollution Using Traffic Simulation." Presented at the 56th Annual Meeting of the Transportation Research Board, Washington, D. C. 1977.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☒ Urban Arterial
- ☒ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☒ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☒ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

The method presently used to estimate CO pollution concentration caused by traffic facilities is shown to be inadequate for urban traffic because it assumes a constant emission profile, which is not in fact found in urban traffic. The UTCS-1 traffic simulation model is described along with its recently added fuel and vehicle emissions capability. This paper demonstrates, by using before and after studies for an arterial in Washington, D.C., the non-constant emissions profiles computed by UTCS-1 along the arterial.

Reference 28

Courage, K. E., and Parapar, S. M. "Delay and Fuel Consumption at Traffic Signals." Traffic Engineering, November 1975, pp. 23-27.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☒ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☒ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☒ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

A study carried out in Gainesville, Florida examines the tradeoffs between fuel consumption and delay at signalized intersections. The results showed that fuel consumption could be lowered to 44 gallons/hour if signals were timed with fuel consumption rather than delay in mind.

Reference 29

Cowan, Richard. "An Improved Model for Signalized Intersections With Vehicle-Actuated Control." To appear in the Journal of Applied Probability. (1978).

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☒ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☒ Other

Factors Analyzed

- ☒ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

This report uses statistical analysis to develop an optimal control policy for an actuated signal controller at the intersection of two one-way roads. The control technique is based upon the policy that the green phase for a given road is terminated at the earliest time that there had been no departures over a given time interval.

Reference 30

Cribbins, P. D., and Meyer, C. A. "Choosing Detectors—And Placing Them Right," Traffic Engineering, January 1975, pp. 15-18.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☒ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☒ Arterial Surveillance System
- ☒ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☒ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☒ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

This article describes a study undertaken in Raleigh, North Carolina on the locations at signalized intersections of the inductive loop detector, classified as either pulse or presence mode. With the exception of the detectors directly behind the stop lines, all were installed as pulse detectors. All data collected in the study were compiled with the aid of time-lapse photography. Travel time through an intersection was used in determining the optimum detector type and location. The article contains a description of the method of analysis employed and a summary of the results of the study.

Reference 31

Cribbins, P. D. and Meyer, C. A. Comparison of Presence and Pulse Loop Detectors for Actuated Traffic Signals. N. C. State University, December 1974.

This Literature Contains Information In the Following Categories:

Highway Types

_ Rural
X Urban Arterial
_ Urban Network
_ Other

Data Types

_ Chase Car or Floating Car
_ Freeway Surveillance System
X Arterial Surveillance System
_ Photographic
_ Simulation
_ Other

Factors Analyzed

X Traffic Flow Characteristics
_ Vehicle Emissions
_ Fuel Consumption
_ Maintenance
_ Installation
_ Signal Timing
_ Effects of Geometrics
_ Other

Signal Types

_ Fixed Time
_ Semi Actuated
X Fully Actuated
_ Other

Summary/Abstract

This research effort attempts to compare the effectiveness of various combinations of presence and pulse-type induction loop detectors in reducing intersection delay at a fully-actuated signalized intersection. Various combinations and lengths of detectors were utilized on both the major and minor approaches during a peak and off-peak period. Amounts of intersection delay were recorded by multiple time-lapse cameras operating simultaneously above the intersection area. It was ascertained that the use of presence-type detectors results in significantly lower average intersection delays during both peak and off-peak periods. In addition, it was determined that the use of presence-type detectors greater than 38 feet in length on the minor approaches to the intersection, in conjunction with presence detectors of approximately 38 feet on the major approaches, yielded the most favorable average intersection delay values. /FHWA/

Reference 32

Cribbins, P. D. and Walton, C. M. "Traffic Signals and Overhead Flashers at Rural Intersections: Their Effectiveness in Reducing Accidents," Highway Research Board.

This Literature Contains Information In the Following Categories:

Highway Types

X Rural
_ Urban Arterial
_ Urban Network
_ Other

Data Types

_ Chase Car or Floating Car
_ Freeway Surveillance System
_ Arterial Surveillance System
_ Photographic
_ Simulation
X Other

Factors Analyzed

_ Traffic Flow Characteristics
_ Vehicle Emissions
_ Fuel Consumption
_ Maintenance
_ Installation
_ Signal Timing
_ Effects of Geometrics
X Other

Signal Types

_ Fixed Time
_ Semi Actuated
_ Fully Actuated
X Other

Summary/Abstract

Two specific types of operational improvements—overhead flashers and traffic signals installed at low-volume, high-speed rural intersections—were selected for investigation. The effectiveness of the devices in reducing traffic accidents was earmarked as the primary objective of the analysis. Initially, all flashers and signal devices installed in North Carolina since 1965 were considered, but subsequent investigation and a more restrictive definition of a test site reduced the original inventory from 72 flashers and 153 signals to 14 flashers and 19 signals. A before-and-after study was made encompassing minimum time frames of one year prior to and immediately after installation of the device. Accident exposure during the two periods was compared on the basis of exposure rates, severity indexes, and equivalent property damage only accidents and rates. It was determined that the equivalent property damage only rate, rather than the normally used accident rate, was the most reliable and significant indicator of accident consequences. If all other factors were constant, any significant change in rate after installation of the control device could be attributed to the presence of the device. The relationship between the installation of signals and equivalent property damage only rate reduction was not statistically significant except for undivided highway intersections. The relationship between the installation of a flashing beacon and rate reduction was found to be statisticlaly significant at the 1 percent confidence level. /Author/

Reference 33

Dare, Charles E. and Jomini, Pierre-Andre. "Benefit-Cost Analysis of a Speed Signal Funnel" HRB Record. 445, (1973) pp. 1-11.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☒ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☒ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☒ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☒ Installation
- ☒ Signal Timing
- ☐ Effects of Geometrics
- ☒ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

The object of this research was to establish an estimate of the economic feasibility of modifying an intersection traffic control system to incorporate a speed signal funnel. Data on traffic volumes, delays, approach speed profiles, and accident experience were gathered for the study site so future costs of retaining the present control system could be estimated. Estimates specifying equipment costs, maintenance costs, vehicle operating costs, time costs, and accident costs were developed for the proposed speed funnel. The economic desirability of the speed signal funnel was determined by means of an incremental benefit/cost ratio. It was found that the speed signal funnel yielded benefit/cost ratios ranging from 1.5:1.0 to as high as 12.0:1.0 depending on the underlying assumptions/Author/

Reference 34

Davies, G. W. Optimization of a Traffic Signal Through Computer Simulation. Final Report, JHRP #8, June 1972.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☒ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☒ Simulation
- ☐ Other

Factors Analyzed

- ☒ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

The objective of this study was to develop a simulation program which would be suitable for use in the design of traffic signal systems. In keeping with this, it was desired to develop, program, and test a conceptual model that would simulate the flow of vehicles on a street network controlled by traffic signals. Secondary goals were that the model be general enough to apply to any moderate-sized network, and that the final program be such that the inputs and outputs could be easily understood by a non-computer oriented traffic engineer. A simulation model, SIGNET, was developed to reproduce traffic under laboratory conditions. The use of the SIGNET model is not restricted to signal timing studies. In fact, the effects of many other traffic engineering measures may be evaluated by varying the program inputs. Such measures could include turning movement prohibitions, parking restrictions, unbalanced lane operation, and one-way street operation.

Reference 35

Dickey, Dr. John W. Traffic Control Systems for Urban Areas: Exchange Bibliography 81, Council of Planning Librarians. Virginia Polytechnic Institute. May 1969.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
X Urban Arterial
X Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
X Signal Timing
X Effects of Geometrics
X Other

Signal Types

X Fixed Time
X Semi Actuated
X Fully Actuated
X Other

Summary/Abstract

This non-annotated bibliography contains nearly 300 references to articles related to urban traffic control systems. Of particular interest to this study are the fifty articles identified which deal with the characteristics of vehicle and geometric design related to traffic signal operation. The papers referenced within this bibliography were published between 1947 and 1969, with most of them dating later than 1960.

Reference 36

Drew, Donald R. and Pinnell, Charles. "A Study of Peaking Characteristicsof Signalized Urban Intersections as Related to Capacity and Design." HRB Bulletin 352.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
X Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
X Other

Factors Analyzed

X Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
X Signal Timing
X Effects of Geometrics
__ Other

Signal Types

X Fixed Time
__ Semi Actuated
X Fully Actuated
__ Other

Summary/Abstract

This report contains a detailed analysis of the distribution of vehicle arrivals during the peak period.

The distribution of vehicle arrivals during the peak period and peak hour were analyzed by the x^2test under the hypothesis of a Poisson distribution. It was shown that (a) arrivals during the peak period did conform to a Poisson distribution, and (b) arrivals throughout the entire peak hour did not conform to a Poisson distribution.

Finally, some of the aspects of the capacity-design analysis of an intersection are considered in light of these findings. New design and signalization procedures are developed based on vehicle arrivals during the peak period.

Reference 37

Duemmel, R. A. "Operation and Theory of Timing Two-Phase Volume Density Controllers Part 1." Traffic Engineering, November 1966, pp. 26-29.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☒ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☒ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☒ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☒ Fully Actuated
- ☒ Other

Summary/Abstract

The two-phase fully actuated volume controller is capable of moving large volumes of traffic with minimum delay. The controller, however, must be properly timed to operate at its peak efficiency. The timing of volume density equipment should not be thought of in terms of definite cycle lengths as applied to fixed time controllers. When cycle lengths are considered they should be thought of as being elastic, stretching and contracting with traffic demand.

Reference 38

Dunne, M. C. "Traffic Delays at a Signalized Intersection with Binominal Arrivals." Transportation Science, February 1967, pp. 24-31.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☒ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☒ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

Delay formulas are derived for vehicles at an isolated intersection at which the vehicle arrivals are supposed generated by a binomialprocess, the departure rates are assumed constant, the the control strategy is to switch the lights when the favored queue empties. The mean delay is calculated using a discrete analog of the method used by Darroch, Morris, and Newell for the case of random arrivals. Later a probability generating function for delay is developed yielding, in particular, the variance of the delay. /Author/

Reference 39

Eagle Signal Division, Gulf and Western Industries, Inc. The Subject of Pretimed Intersection Control. No Date.

This Literature Contains Information In the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

This pamphlet provides basic information about the features and characteristics of electro-mechanical pre-timed controllers. A glossary of terms is included.

Reference 40

Econolite, Division of Altec Electronics. Traffic Control Application Information Manual #1, No Date.

This Literature Contains Information In the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

This manual, prepared by a signal equipment manufacturer, provides basic information concerning pretimed equipment. It also presents the fundamentals of coordination of pretimed signal systems.

Reference 41

Estep, A. C. "A Mini Computer Traffic Signal Controller," American Highways, October 1971, p. 8.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

This article presents general information concerning the installation of a general-purpose minicomputer for use as an intersection signal controller.

Reference 42

Evans, Leonard; Herman, R.; and Lam, Tenny. "Multivariate Analysis of Traffic Factors Related to Fuel Consumption in Urban Driving," Transportation Science, May 1976, pp. 205-215.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☒ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☒ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☒ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

The influence of various urban driving conditions on automobile fuel consumption was studied in an experiment involving 383 km of driving in the Detroit metropolitan area. The detailed speed, acceleration, and fuel consumption records were analyzed by multivariate statistical techniques. The objective of the study was to identify pertinent measures of traffic-related speed-time characteristics that influence fuel consumption in urban driving. The results showed that average trip time per unit distance was the single most important factor in explaining the variability of fuel consumption. The results could be explained in terms of the physical properties of the engine-vehicle system and the interrelationships among the traffic-related variables. /Author/

Reference 43

Ficklin, N. C. "For and Against Semi-Actuated Traffic Signal Control", Traffic Engineering, March 1973, pp. 20-25.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☒ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☒ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

The choice between a semi-actuated type arterial signal control system and other types must be made with full realization of the advantages and disadvantages of each. The advantage provided major street traffic flow in maximum green time by the semi-actuated system must be weighed against the resultant irregular signal progression and the increased cost of actuated control equipment.

Reference 44

Garnett, G. B. "L.A. County Study of 24-Hour Operation of Pretimed Signals." Traffic Engineering, May 1972, pp. 42-43.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☒ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☒ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☒ Other

Signal Types

- ☒ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

The study demonstrates that operating pretimed signals 24-hours a day, instead of using a flashing period during light traffic hours, may reduce accident and injury experience, particularly right-angle collisions, at locations where a high incidence has been found during the flashing period. It also suggests that locations with low accident experience during flashing operation will not have increased accident experience during the same time period if signals are placed on 24-hour operation.

Reference 45

Gartner, Nathan, "Microscopic Analysis of Traffic Flow Patterns for Minimizing Delay on Signal Controlled Links," Highway Research Record 445, (1973) pp. 12-23.

This Literature Contains Information In the Following Categories:

Highway Types

☐ Rural
☒ Urban Arterial
☒ Urban Network
☐ Other

Data Types

☐ Chase Car or Floating Car
☒ Freeway Surveillance System
☐ Arterial Surveillance System
☐ Photographic
☐ Simulation
☐ Other

Factors Analyzed

☒ Traffic Flow Characteristics
☐ Vehicle Emissions
☐ Fuel Consumption
☐ Maintenance
☐ Installation
☒ Signal Timing
☐ Effects of Geometrics
☐ Other

Signal Types

☐ Fixed Time
☐ Semi Actuated
☐ Fully Actuated
☐ Other

Summary/Abstract

This paper reports results from a microscopic analysis of traffic flow patterns of two-way links on a major Toronto artery. "Accurate platoon profiles were obtained via the digital computer system controlling traffic lights throughout the metropolitan area and its associated vehicle-detector system. Individual link delay functions were calculated subject to the particular characteristics of each signalized traffic link. These functions were then combined in parallel according to the principles of the British TRRL combination method. The optimal settings derived are shown to deviate substantially from those established by conventional coordination methods. The resultant improvement in delay to traffic was confirmed by direct field observations./Author/

Reference 46

Gerlough, D. L. and Wagner, F. A. "Improved Criteria for Traffic Signals at Individual Intersections." Highway Research NCHRP Report 67.

This Literature Contains Information In the Following Categories:

Highway Types

☐ Rural
☒ Urban Arterial
☐ Urban Network
☐ Other

Data Types

☐ Chase Car or Floating Car
☐ Freeway Surveillance System
☐ Arterial Surveillance System
☐ Photographic
☒ Simulation
☐ Other

Factors Analyzed

☒ Traffic Flow Characteristics
☐ Vehicle Emissions
☐ Fuel Consumption
☐ Maintenance
☐ Installation
☒ Signal Timing
☐ Effects of Geometrics
☐ Other

Signal Types

☐ Fixed Time
☐ Semi Actuated
☒ Fully Actuated
☐ Other

Summary/Abstract

The signalized intersection is the cardinal element of a roadway system. To improve the operational quality of the system, it is necessary to develop traffic signalization to its highest level of efficiency. A state-of-the-art summary resulted in an extensive bibliography. A multiple purpose, microscopic, digital simulation model of traffic performance and control at an individual intersection was successfully formulated, programmed, tested, and refined. By applying the intersection simulation model, data were derived that led to an increased understanding of a variety of measures of effectiveness of performance, their dependency on the mode of traffic-signal control utilized, and their interdependency. The model was exercised comprehensively for fixed-time modes of intersection control in order to derive a controlled data base from which to judge objectively the relative effectiveness of experimental traffic-responsive philosophies of control. A new philosophy of intersection control, the basic queue-control scheme, appeared promising and was selected for pilot field implementation.

Reference 47

Green, D. H. "Control of Oversaturated Intersections," Operational Research Quarterly, Vol. 18, No. 2, (June 1967), pp. 161-173.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☒ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☒ Simulation
- ☐ Other

Factors Analyzed

- ☒ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☒ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

Simulation experiments are reported in which the control policies developed in an earlier paper for stable regimes are compared with other suggested procedures when employed during oversaturated periods. It is shown that the policies remain effective with respect to mean delay per vehicle. The problem of reducing the maximum individual delay may be tackled by means of a tradeoff of mean delay by imposing a maximum phase duration during extreme congestion. /Author/

Reference 48

Green, H. "The Effect on Accidents of Installing Traffic Lights on Trunk Road 4.4 at London Road/Upton Court Road, Slough." Road Research Laboratory Notes, Noln/839, (May 1965).

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☒ Other

Signal Types

- ☒ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

Casualties at the junction of A.4 at London Road/Upton Court Road, Slough, for 32 corresponding months before and after the installation of traffic lights/The junction was modified slightly and street lighting improved/ were compared with those in the rest of the Borough of Slough. They showed a decrease of 71 per cent and the number of casualties per year went down from 13 to 4 and it has remained at this figure for 4 years. The economic value of the saving in injury accidents neglecting damage-only accidents and the saving of suffering or bereavement/ was estimated to be 13,640 British pounds for 32 months, which represented more than 70 per cent of the total cost of works and land.

Reference 49

Grimm, R. Paul. "Traffic Signal Operational Design," Technical Notes, Vol. 1, Institute of Traffic Engineers. (1975) pp. 1-4.

This Literature Contains Information in the Following Categories:

Highway Types

- __ Rural
- __ Urban Arterial
- __ Urban Network
- __ Other

Data Types

- __ Chase Car or Floating Car
- __ Freeway Surveillance System
- __ Arterial Surveillance System
- __ Photographic
- __ Simulation
- __ Other

Factors Analyzed

- __ Traffic Flow Characteristics
- __ Vehicle Emissions
- __ Fuel Consumption
- __ Maintenance
- __ Installation
- __ Signal Timing
- __ Effects of Geometrics
- X Other

Signal Types

- __ Fixed Time
- __ Semi Actuated
- X Fully Actuated
- __ Other

Summary/Abstract

The application of loop-occupancy-control concepts with density controllers is presented, with emphasis on high-speed approaches. Extended call ("stretch") detectors for dilemma-zone protection are supplemented by presence detectors near the stop line. The author's designs are based on relatively high rates of deceleration; therefore the required detectorization is reduced in cost, but at the expense of full dilemma-zone protection.

Reference 50

Ham, R. "Area Traffic Control in West London: Vehicle Counting Detectors." Traffic Engineering & Control, August 1969, pp. 172-176.

This Literature Contains Information in the Following Categories:

Highway Types

- __ Rural
- X Urban Arterial
- X Urban Network
- __ Other

Data Types

- __ Chase Car or Floating Car
- __ Freeway Surveillance System
- X Arterial Surveillance System
- __ Photographic
- __ Simulation
- __ Other

Factors Analyzed

- __ Traffic Flow Characteristics
- __ Vehicle Emissions
- __ Fuel Consumption
- __ Maintenance
- X Installation
- __ Signal Timing
- __ Effects of Geometrics
- __ Other

Signal Types

- __ Fixed Time
- __ Semi Actuated
- X Fully Actuated
- __ Other

Summary/Abstract

This article discribes the principles of use, locations, dimensions, installation, and design considerations for detectors used in the traffic control system in West London.

Reference 51

Harland, Bartholomew & Associates, Memphis, Tennessee. "Three Timing Control Strategies for Signalized Diamond Interchanges." Federal Highway Administration, January 1977.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
X Urban Arterial
__ Urban Network
X Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
X Photographic
__ Simulation
__ Other

Factors Analyzed

X Traffic Flow Characteristics
__ Vehicle Emissions
X Fuel Consumption
__ Maintenance
__ Installation
X Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

X Fixed Time
__ Semi Actuated
X Fully Actuated
__ Other

Summary/Abstract

Before-and-after evaluations of five different timing plans—two fixed time, one actuated, and two using a micro-processor—were performed at the interchange of I-95 and Golfair Boulevard in Jacksonville, Florida. It was found that during the p.m. peak period (when volumes were highest) the micro-processor operation (pretimed, using table look-up and lagging left turns) was the most efficient (considering both stops and delay). During other periods, the actuated control was more efficient. Fuel consumption efficiency (FCE) was calculated from regression equations utilizing average network speed as the independent variable (developed by FHWA-RD-76-81). It was found that the actuated operation gave a much higher FCE than any of the other four timing plans.

Reference 52

Head, J. R. "The Operation of The Inductive Loop Vehicle Detector." Traffic Engineering & Control, July 1970, pp. 135-138.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
X Installation
__ Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

__ Fixed Time
__ Semi Actuated
X Fully Actuated
__ Other

Summary/Abstract

This article describes the principle of operation of the inductive loop vehicle detector and discusses factors which affect its use.

Reference 53

Herman, R.; Olson, P.; and Rothery, R. "Problem of The Amber Signal Light." Traffic Engineering and Control, September 1963, pp. 298-304.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
X Photographic
__ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
X Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

__ Fixed Time
__ Semi Actuated
__ Fully Actuated
__ Other

Summary/Abstract

This is a discussion of the "dilemma zone" associated with the yellow change interval. Factors such as approach speed, deceleration, length of yellow, and cross street width were used in the computation of probabilities of stopping. The importance of an adequate change interval is stressed.

Reference 54

Highway Research Board Proceedings. "Effect of Type of Control on Intersection Delay." 56th Annual Meeting, Vol. 35, pp. 523-533.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
X Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
X Other

Factors Analyzed

X Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

X Fixed Time
__ Semi Actuated
__ Fully Actuated
X Other

Summary/Abstract

A study of stopped-time delay was undertaken to provide data to support warrants for certain types of traffic control devices, and a simple method of recording this delay was adapted from a previously reported method. It was found that stopped-time delay to any vehicle which is required to stop is much greater with fixed-time control than with any other form, and average delay to all vehicles was less at two-way stops than with other forms of control under the moderate traffic volume conditions observed. There appears to be a positive relationship between stopped-time delay on a minor highway and the volume of traffic on the major highway. But the data available do not permit determination of the degree of relationship. /Author/

Reference 55

Hill, Morris. "A Method for The Evaluation of Transportation Plans." Highway Research Record 180, (1967), pp. 21-34.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☒ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

The paper questions the efficacy of traditional cost-benefit analysis for the evaluation of transportation plans designed to serve a broad set of objectives. An alternative method of evaluation, known as goal-achievement analysis, is proposed and described. Plans are examined in terms of the entire set of objectives in a single system. The relative effectiveness of alternative plans in achieving the set of desired objectives is determined by applying a weighting system to objectives and to the subgroups, sectors, locations, and activities affected./Author/

Reference 56

Huddart, K. W. "Area Traffic Control." Traffic Engineering & Control, July 1972,

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☐ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

This article reports the results of an IEE Colloquium on Area Traffic Control which was held in London on May 24, 1972. It includes an interesting discussion on the relative merits of fixed-time versus vehicle-actuated signal plans.

Reference 57

Huddart, K. W. The Use of Traffic Signals as a Means of Achieving Compromise Between Traffic Requirements and Environmental Constraints. Planning and Transport Research and Computation Company, Ltd. 1974.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
X Urban Arterial
X Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

X Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
X Other

Signal Types

__ Fixed Time
__ Semi Actuated
__ Fully Actuated
X Other

Summary/Abstract

The paper starts by describing the new awareness of the adverse impact of traffic on the environment. Objectives are set for keeping traffic on a limited number of defined routes, of protect residential and shopping areas and of giving priority to buses. A difficult urban problem is that the provision of traffic signals to provide access to an area can cause through routes to develop and increase in importance, and impact on the environment. Furthermore, the extra signals make the existing main routes less efficient and attractive. The problem has been present for many years even though traffic signal provision was limited by the need to meet numerical traffic criteria circulated by the Department of the Environment effectively removed this restriction, so that local authorities are left alone in balancing the pressure for signals against the less well-appreciated, long-term effects. In cases where signals are introduced to solve a safety problem, there is usually a range of solutions available, and it is important that the opportunity should be taken to improve protection of the environment. Examples of the various situations are presented in the paper. Signals cannot, however, solve all problems and attempts to use them to control vehicle speeds may well produce dangerous situations.

Reference 58

Hulscher, F. R. "Selection of Vehicle Detectors for Traffic Management." Traffic Engineering & Control, December 1974, pp. 915-919, 925.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
X Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
X Other

Signal Types

__ Fixed Time
__ Semi Actuated
X Fully Actuated
__ Other

Summary/Abstract

This article examines the practical requirements for vehicle detectors for use in traffic signal systems. It is shown that only the inductive loop and flux-gate magnetometer detectors are capable of meeting the authors criteria.

Reference 59

Hulscher, F. R., and Sims, A. J. "Use of Vehicle Detectors For Traffic Control." Traffic Engineering & Control, November 1974, pp. 866-869.

This Literature Contains Information in the Following Categories:

Highway Types

- __ Rural
- X Urban Arterial
- __ Urban Network
- __ Other

Data Types

- __ Chase Car or Floating Car
- __ Freeway Surveillance System
- __ Arterial Surveillance System
- __ Photographic
- __ Simulation
- __ Other

Factors Analyzed

- X Traffic Flow Characteristics
- __ Vehicle Emissions
- __ Fuel Consumption
- __ Maintenance
- X Installation
- __ Signal Timing
- __ Effects of Geometrics
- __ Other

Signal Types

- __ Fixed Time
- __ Semi Actuated
- X Fully Actuated
- __ Other

Summary/Abstract

This paper examines the type of vehicle detection and placement of detectors for use with traffic control signals. The theoretical requirements for placement of detectors are demonstrated to be at variance with past practice, and it is shown that advance detection has an adverse effect on efficiency. Use of presence detectors located at the stop line enables traffic parameters to be measured in terms of passenger-car-units (pcu) equivalents necessary for the implementation of efficient control.

Reference 60

Hutchinson, T. P. "Delay At A Fixed Time Traffic Signal—2 Numerical Comparisons of Some Theoretical Expressions." Transportation Science, August 1972, pp. 286-305.

This Literature Contains Information in the Following Categories:

Highway Types

- __ Rural
- __ Urban Arterial
- __ Urban Network
- __ Other

Data Types

- __ Chase Car or Floating Car
- __ Freeway Surveillance System
- __ Arterial Surveillance System
- __ Photographic
- __ Simulation
- X Other

Factors Analyzed

- X Traffic Flow Characteristics
- __ Vehicle Emissions
- __ Fuel Consumption
- __ Maintenance
- __ Installation
- X Signal Timing
- __ Effects of Geometrics
- __ Other

Signal Types

- X Fixed Time
- __ Semi Actuated
- __ Fully Actuated
- __ Other

Summary/Abstract

Numerical comparisons of several expressions for the average delay to traffic passing a fixed time traffic signal have been made for a wide range of values of the arrival rate, saturation flow, cycle time, proportion of the cycle effectively green, and variance-to-mean ratio of the number of arrivals per cycle (I-Ratio). The values of average delay given by Miller's, Newell's, and Webster's simplified expressions, and by a new modification of the last incorporating the I-Ratio are compared with the value given by Webster's full expression. The differences are not usually more than 10 per cent when I=1, but the importance of the I-Ratio is shown by the differences reaching about 50 percent at high degrees of saturation when I=1.5. The differences between the values of the various expressions are also compared with the effects on the value of Webster's full expression of given errors in the parameters. These effects are found to be large enough to make it difficult to distinguish experimentally between the various expressions when the I-Ratio is near to 1 except by extensive measurements. Because of this the choice between expressions is often a matter of convenience of computation, and this choice is briefly discussed.

Reference 61

Irwin, Neal A. "The Toronto Computer-Controlled Traffic Signal System." Traffic Control Theory and Instrumentation, pp.209-218. Edited by Thomas R. Horton. New York: Plenum Press, 1965.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
x Installation
x Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

__ Fixed Time
__ Semi Actuated
__ Fully Actuated
__ Other

Summary/Abstract

This paper describes the Toronto application of digital computers for traffic control. It describes the equipment used and attendant costs.

Reference 62

ITE Southern Section Technical Committee 18. "Large-Area Detection At Intersection Approaches." Traffic Engineering & Control, June 1976, pp. 28-36.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
X Installation
__ Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

__ Fixed Time
__ Semi Actuated
X Fully Actuated
__ Other

Summary/Abstract

The purpose of this report is to pull together a number of references into a coherent re-statement of the relationship between controller operation and large-area detector design. Large-area detectors are designed to detect vehicles within a zone of substantial length upstream of the stop line, as contrasted with a point location. The advantages and disadvantages of this type detection is discussed in addition with discussions of detection of small vehicles, right turns, low-speed approaches, right-turn-on-red, and high speed approaches.

Reference 63

ITE Southern Section Technical Committee 18. "Small Area Detection At Intersection Approaches" Traffic Engineering & Control, February 1974, pp. 8-17.

This Literature Contains Information In the Following Categories:

Highway Types

- _ Rural
- _ Urban Arterial
- _ Urban Network
- _ Other

Data Types

- _ Chase Car or Floating Car
- _ Freeway Surveillance System
- _ Arterial Surveillance System
- _ Photographic
- _ Simulation
- _ Other

Factors Analyzed

- _ Traffic Flow Characteristics
- _ Vehicle Emissions
- _ Fuel Consumption
- _ Maintenance
- X Installation
- _ Signal Timing
- _ Effects of Geometrics
- _ Other

Signal Types

- _ Fixed Time
- _ Semi Actuated
- X Fully Actuated
- _ Other

Summary/Abstract

This report summarizes the most pertinent information, reviews standards, and restates the relationship between small area detector location and controller operation. Small area detectors, often referred to as point detectors, are those intended to detect vehicles at a stop location. The pressure-pad treadle detector and six-foot-long loop detector are prominent examples. Also included are ultrasonic and radar units.

Reference 64

ITE Technical Council Committee 4M-1. "Traffic Signal System Definitions." Traffic Engineering & Control, February 1976, pp. 42-51.

This Literature Contains Information In the Following Categories:

Highway Types

- _ Rural
- _ Urban Arterial
- _ Urban Network
- _ Other

Data Types

- _ Chase Car or Floating Car
- _ Freeway Surveillance System
- _ Arterial Surveillance System
- _ Photographic
- _ Simulation
- _ Other

Factors Analyzed

- _ Traffic Flow Characteristics
- _ Vehicle Emissions
- _ Fuel Consumption
- _ Maintenance
- X Installation
- _ Signal Timing
- _ Effects of Geometrics
- _ Other

Signal Types

- X Fixed Time
- X Semi Actuated
- X Fully Actuated
- X Other

Summary/Abstract

ITE Technical Council Committee 4M-1 has developed a set of standard definitions which can be universally applied in the area of traffic signal systems and associated hardware with particular emphasis on computerized systems and related technologies.

Reference 65

Jacks, Marshall Jr. "The Feasibility of Establishing Warrants for Signal Systems," Traffic Engineering Control, May 1969, pp. 46-47.

This Literature Contains Information in the Following Categories:

Highway Types

☐ Rural
☐ Urban Arterial
☐ Urban Network
☐ Other

Data Types

☐ Chase Car or Floating Car
☐ Freeway Surveillance System
☐ Arterial Surveillance System
☐ Photographic
☐ Simulation
☐ Other

Factors Analyzed

☒ Traffic Flow Characteristics
☐ Vehicle Emissions
☐ Fuel Consumption
☒ Maintenance
☒ Installation
☒ Signal Timing
☐ Effects of Geometrics
☐ Other

Signal Types

☐ Fixed Time
☐ Semi Actuated
☐ Fully Actuated
☐ Other

Summary/Abstract

The paper describes the three existing types of signal systems: flexible pretimed, traffic adjusted, and digital computer. It also discusses the control philosophies of different countries.

The author concludes that the establishment of warrants for utilization of specific types of signal systems is not presently feasible.

Reference 66

Jacobson, Kern Lee. "Quantitative Analysis Techniques For The Planning and Design of Signalized Intersections." University of Washington (1972).

This Literature Contains Information in the Following Categories:

Highway Types

☐ Rural
☐ Urban Arterial
☐ Urban Network
☐ Other

Data Types

☐ Chase Car or Floating Car
☐ Freeway Surveillance System
☐ Arterial Surveillance System
☐ Photographic
☒ Simulation
☐ Other

Factors Analyzed

☒ Traffic Flow Characteristics
☐ Vehicle Emissions
☐ Fuel Consumption
☐ Maintenance
☐ Installation
☒ Signal Timing
☐ Effects of Geometrics
☐ Other

Signal Types

☐ Fixed Time
☐ Semi Actuated
☒ Fully Actuated
☐ Other

Summary/Abstract

The author presents the commonly used techniques for analyzing the operating characteristics of signalized intersections.

He then discusses a new simulation model, SYMSYG, which simulates operation at a fully actuated signal, and compares it with the previous techniques.

Reference 67

Jacobson, Kern L. "SYMSYG: A Simulation Model of Traffic Flow At A Fully Actuated Signal." Washington State Department of Highways, February 1976.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☒ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

SYMSYG is a computer model which simulates the operation of one approach at a fully actuated traffic signal. The user is permitted to vary any of a large number of inputs to determine the effect of alternative designes and timing schemes on queue lengths, delay, cycle lengths, stops, and fuel consumption.

This paper comprises partial documentation of the FORTRAN version and includes the following sections:

1. Sample Output
2. Input Instructions
3. JCL and Data Card Listing
4. Program Listing
5. Variable Definitions
6. Sample Accounting Output

/Author/

Reference 68

Kay, Jack L. "Signal System Studies: A New Approach." Traffic Engineering, January 1970, pp. 24-31

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☒ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

This paper describes a technique for evaluating alternative signal systems to determine which system best meets the needs of a given area. This modified cost-utility technique was applied in a study conducted for the City of Baltimore. This technique develops a proxy value for those benefits which cannot explicitly be measured in dollars.

Reference 69

Kennedy, Norman; Kell, James H.; and Hamburger, Wolfgang S. "Traffic Signals Chapter XVI," Fundamentals of Traffic Engineering, 7th Edition. Berkeley: University of California, 1969.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☒ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☒ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

This chapter presents an overview of traffic signal technology and terminology. Included are discussions of both pretimed and traffic-actuated signals in both isolated and system configurations. Signal time and installation costs are also discussed.

Reference 70

Klatt, R. T. and Wilshire, R. L. "Buying A Signal System: A Two-Step Procedure." Traffic Engineering, April 1975, pp. 14-15.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☒ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

A description of methods used in the City of Omaha and results obtained in buying a complex signal system, and some thoughts for consideration.

Reference 71

Klijnhout, J. J. "A Digital Simulation Model For Single Intersections With Traffic Lights." Traffic Engineering & Control, Vol. 13, No. 4, pp. 147-150, 153

This Literature Contains Information In the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
X Simulation
__ Other

Factors Analyzed

X Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

__ Fixed Time
__ Semi Actuated
__ Fully Actuated
__ Other

Summary/Abstract

A model to simulate the performance of intersections with traffic lights is described. Tests have been made to discover the extent to which the model can be simplified in order to obtain a better ratio of simulation time to simulated time. /TEC/

Reference 72

Lee, C. E. and Vodrazka, W. C. "Evaluation of Traffic Control At Highway Intersections." Research Report 784, Texas University, Center for Highway Research.

This Literature Contains Information In the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
X Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

X Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

__ Fixed Time
__ Semi Actuated
__ Fully Actuated
__ Other

Summary/Abstract

The paper details the design and development of a digital delay data recorder and its use with computer programs for data reduction and analysis.

Currently used warrants for selecting traffic control devices and proposed warrants for actuated signals were evaluated.

Reference 73

Lepic, Donald E. "Advance Detection for Efficiency and Safety." OTE Field, April 1975, pp. 9-10

This Literature Contains Information In the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
X Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

__ Fixed Time
__ Semi Actuated
X Fully Actuated
__ Other

Summary/Abstract

The article was written to explain local (Oklahoma) applications of the article "Traffic Signal Operational Design" by R. Paul Grimm. Lepic points out that Grimm's recommended detector spacing is designed for a vehicle approaching within narrow limits of its design speed. Lepic also notes that this problem can be overcome by adding additional detectors for advance detection.

The article adds that Grimm's braking distances may be too short, particularly on wet pavements. Lepic stresses that safety should not be given up to reduce delay.

Reference 74

Little, James. "Queuing of Side Street Traffic At A Priority Type Vehicle Actuated Signal", Transportation Research, Vol. 5. (1971) pp. 295-300.

This Literature Contains Information In the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
X Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

__ Fixed Time
__ Semi Actuated
X Fully Actuated
__ Other

Summary/Abstract

The queuing of side- street traffic at a priority type, vehicle-actuated signal is studied. It is assumed that a minimum red period must elapse between side street greens. A discrete time model is formulated, and the steady-state distribution and mean value of the queue length at the end of the cycle and the steady-state distribution of the side-street red period length are found. Some numerical results are also presented. /Author/

Reference 75

Maintenance Management of Traffic Signal Equipment and Systems." National Academy of Sciences, NCHRP 22, 1974.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☒ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

This report describes the essentials of traffic signal maintenance procedures from a management point of view. Agency practices in executing the various management functions of staffing, equipping, establishing communications, budgeting, operating, and controlling to provide the services of routine maintenance, preventive maintenance, and emergency repair of traffic signal equipment and systems are reported and evaluated.

Reference 76

Marconi, W. "The Relative Efficiency of Various Types of Traffic Signal Controls." Traffic Engineering, April 1963, pp. 13-17.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☒ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☒ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☒ Semi Actuated
- ☒ Fully Actuated
- ☒ Other

Summary/Abstract

Four controllers were tested at several high volume intersections in San Francisco for their efficiency with respect to total vehicle delay. The four controllers were single-dial, fixed-time; semi-actuated; fully-actuated; and volume-density types. The volume-density controller was most effective for the intersection viewed as an isolated case; however, the fixed-time signal used as a part of a progressive system was more effective.

Reference 77

Matthews, R. and Schowengerdt, L. N. "High Speed Signal Design." Public Safety Systems (Nov. 1970) Vol. 35, No. 6, pp. 8-10.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☒ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☒ Other

Factors Analyzed

- ☒ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☒ Signal Timing
- ☐ Effects of Geometrics
- ☒ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

A difficulty that besets existing traffic-actuated control systems is that traffic dynamics make it impossible to extrapolate from time delays to spatial gaps, since acceleration and car following may occur in the interval between registration of an actuating time gap and the signal change from green to amber. A concept called "Area Detection" is proposed to overcome this shortcoming. A series of loop detectors with time delays is used to measure space gaps instead of time gaps. In "normal" traffic, any car within 300 feet of an intersection will go through on the green; it is assumed that an amber warning at a distance of 300 feet or more will induce the driver to prepare to stop. A 60-foot loop detector covers the first 60 feet from the stop bar, and a secondary zone of detectors covers distances out to 800 feet unless they are disconnected by a volumelevel indicator. The operation of the detector in light and heavy traffic is described, together with variable operating modes induced by traffic conditions. Two installations in San Diego have greatly reduced right-of-way accidents over the past two years. The drawbacks of the system are financial: additional detectors usually run $4-10,000 dollars more than conventional signals, maintenance labor is about doubled, and the overall cost increase is about 65 percent. However, an accident-cost analysis of the two San Diego intersections indicated that the new detectors have saved about $67,000.

Reference 78

Matthews, R. W. "Traffic Signal Experiments." Presented at 22nd California Street and Highway Conference, Monterey, California, January, 1970.

This Literature Contains Information in the Following Categories:

Highway Types

- ☒ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☒ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

The paper discusses several experiments in eliminating the "dilemma zone" problem.

An extinguishable message sign reading "PREPARE TO STOP" is illuminated when a gap is picked by the controller, so the next vehicle following the platoon can see it. Results were disappointing.

Extended-call ("stretch") detectors were also used, with some success.

This paper also discusses the use of a minicomputer for traffic signal operation.

Reference 79

Messiter, G. F. "A Traffic Signal System for High-Speed Roads." Traffic Accident Research Unit, Department of Motor Transport, New South Wales, June 1971.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☒ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☒ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

This report describes the development of a traffic signal system for use on high speed roads. The equipment developed consists of a series of conventional loop detectors installed on the high-speed approach to the intersection. These detectors are coupled to a standard controller through a timing and detector output control device which renders the detectors sensitive to vehicles in certain speed ranges.

Reference 80

Mitchell, M. E. "The Key to Preventive Maintenance on A Traffic Signal System." Traffic Engineering, November 1975, pp. 30-31.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☒ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

This article recommends a group lamp replacement program with complete simultaneous services and states that this is the key to the most economical maintenance of traffic signal heads and lamps. Detailed procedures for lamp maintenance are given.

Reference 81

Munjal, P. K.; Nemeczky, J. A.; Torres, J. F. "Diamond Interchange Traffic Control." Vol. 2 of Design Manual for Traffic Signal Control of Diamond Interchange Complexes, June 1972, Report FHWA-RD-73-35.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☒ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

Results of a research contract to improve the operational efficiency of high demand signalized diamond interchanges are presented in a six-volume report. In this volume, a manual has been developed to assist traffic engineers in selecting the most effective pretimed signal control parameter (cycle length, splits, phase sequence, offsets) for a given set of interchange geometrics and traffic demands. The procedures for determining the parameters are delineated and all necessary graphs and tables are presented. To illustrate the application of the design manual, a comprehensive example is used, paralleling the steps of the procedures.

Reference 82

National Advisory Committee on Uniform Traffic Control Devices. Traffic Control Devices Handbook—An Operating Guide. U.S. DOT, FHWA, 1975.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☒ Maintenance
- ☒ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☒ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

The Handbook is an operating guide intended to supplement the provisions of the MUTCD. Typical values and examples for implementing traffic control measures are given.

Reference 83

National Electrical Manufacturers Association. "Traffic Control Systems." NEMA Standards Publication No. TS1. 1976.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☒ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☒ Other

Summary/Abstract

The latest NEMA standards for traffic control equipment. This publication proposes the uniformity of definitions, environmental standards, test procedures, and hardware. Of major emphasis is the goal of interchangeability for solid state control equipment.

Reference 84

NCHRP Staff. "Traffic Signal Warrants—A Bibliography." Research Results Digest, Digest 78, August 1975.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☒ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

This annotated bibliography was compiled as part of the final report from NCHRP Project 3–20, Traffic Signal Warrants.

Reference 85

Newell, Gordon F. "Properties of Vehicle Actuated Signals: I. One Way Streets, and II. Two Way Streets." <u>Transportation Science</u>, February 1969, pp. 30-52, May 1969, pp. 99-125.

This Literature Contains Information In the Following Categories:

Highway Types

☐ Rural
☐ Urban Arterial
☐ Urban Network
☐ Other

Data Types

☐ Chase Car or Floating Car
☐ Freeway Surveillance System
☐ Arterial Surveillance System
☐ Photographic
☐ Simulation
☐ Other

Factors Analyzed

☒ Traffic Flow Characteristics
☐ Vehicle Emissions
☐ Fuel Consumption
☐ Maintenance
☐ Installation
☐ Signal Timing
☐ Effects of Geometrics
☐ Other

Signal Types

☐ Fixed Time
☐ Semi Actuated
☒ Fully Actuated
☐ Other

Summary/Abstract

These references derive mathematical models for vehicle delays at the intersection of two roadways. The main conclusions are:

- For one-way flow, the average delay per vehicle for an actuated signal is a factor of 3 less than for a fixed-time signal.
- For the intersection of two-way streets, the improvement in flow can be significantly reduced.
- For the case of opposing flows that are nearly equal at an intersection nearly saturated, it is very inefficient (worse than a fixed cycle) for the vehicle actuated signal to follow a policy of holding the green until the last of the two discharging has been discharged.

Reference 86

New York State Dept. of Transportation, Division of Traffic and Safety. <u>Safety With Traffic Technology Microcomputer Specifications</u>, January 1, 1976.

This Literature Contains Information In the Following Categories:

Highway Types

☐ Rural
☐ Urban Arterial
☐ Urban Network
☐ Other

Data Types

☐ Chase Car or Floating Car
☐ Freeway Surveillance System
☐ Arterial Surveillance System
☐ Photographic
☐ Simulation
☐ Other

Factors Analyzed

☐ Traffic Flow Characteristics
☐ Vehicle Emissions
☐ Fuel Consumption
☒ Maintenance
☐ Installation
☐ Signal Timing
☐ Effects of Geometrics
☒ Other

Signal Types

☐ Fixed Time
☐ Semi Actuated
☐ Fully Actuated
☐ Other

Summary/Abstract

New York State Dept of Transportation's detailed specifications for micro-computer signal controllers are given. Specifications for related equipment such as processor, signal monitor, loop detectors, solid state switches and flashers, and cabinets are also given.

Reference 87

Newell, G. F. "Statistical Analysis of the Flow of Highway Traffic Through a Signalized Intersection." Quarterly of Applied Mathematics, Vol. 13, No. 4, pp. 353-369.

This Literature Contains Information in the Following Categories:

Highway Types

- ☒ Rural
- ☒ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☒ Other

Factors Analyzed

- ☒ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

Some calculations are presented of the statistical distribution of delay times due to a fixed-time traffic signal on a single-lane highway. A model of a traffic light is proposed leading to a set of dynamic equations describing a relation between the times at which cars leave the light in terms of the times at which they arrive. Some equations are derived for the conditional probabilities that a car will leave at any specified time if it enters at some given time. For this, it is assumed that the time intervals between incoming cars form a set of indepenent ramdon variables and that one seeks only the equilibrium solutions for which the arrival time of any individual car has a constant probability density. A procedure for obtaining approximate solutions of these equations is derived which actually gives exact solutions for the special case in which the cars arrive at equally spaced time intervals. This procedure is applied to obtain first and second approximations in the special case in which cars arrive with the maximum disorder in spacing possible for this model. It is found that to a first approximation, it makes very little difference what statistical assumptions are made if one wishes to calculate the average delay. /Author/

Reference 88

OECD, Road Research Group. "Area Traffic Control Systems." Organization for Economic Cooperation and Development. February 1972.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☒ Urban Arterial
- ☒ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☒ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☒ Signal Timing
- ☐ Effects of Geometrics
- ☒ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

The report presents a critical review of the control of traffic at single intersections and in complete networks in a state-of-the-art manner. Subjects covered are:

- Performance evaluation
- Control strategies
- Technical specifications for representative installations
- Traffic simulation
- Control equipment
- Conclusions and proposals for future work

Reference 89

Office of Research, Federal Highway Administration. Selecting Digial Computer Signal Systems. Washington, D.C., December 1972.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☒ Urban Arterial
- ☒ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☒ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☒ Maintenance
- ☒ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

This paper points out the problem confronting traffic engineers and decisionmakers as they contemplate the selection of advanced traffic-control systems to alleviate traffic congestion in urban areas. The objective has been to provide guidelines by which alternatives may be evaluated and a traffic-signal system selected. Based on suggested evaluation criteria, each element of a complete signal system may be investigated. These elements include urban types, geographical control areas, control techniques, surveillance systems, intersection equipment communication systems, and data-processing equipment. No attempt has been made to recommend specific control systems, system components, or techniques, but preferred alternatives have been indicated as guides.

Benefits from existing computer installations indicate the general degree of improvements that can be expected in future installations. Total system costs are shown as a measure of expected future investments.

This paper concludes with a compilation of considerations and comparisons that can be used by the decisionmaker as guidelines for evaluating alternatives and selecting a comprehensive control system. The guidelines can also be used by the traffic engineer to formulate system plans and specifications for appropriate traffic control applications.

Reference 90

Ohno, K. and Mine, H. "Optimal Traffic Signal Settings—Part 1: Criterion for Undersaturation of a Signalized Intersection and Optimal Signal Setting; Part 2: A Refinement of Webster's Method." Transportation Research, Vol. 7, No. 3, (Sept. 1973).

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☒ Other

Data Types

- ☐ Chase Car or Floating Car
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- ☒ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
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- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

The first paper deals with an optimal signal setting of a fixed-cycle traffic signal based upon a new criterion of minimizing a degree of saturation of a signalized intersection. As preliminaries, a criterion for undersaturation of the signalized intersection is derived as the degree of saturation of the signalized intersection and mean effective green times of streams of lower priorities are determined as linear functions of the green times and cycle time. The optimal signal setting problem can be solved respectively by linear programming in case of nonoverlapping or overlapping phases and by mixed-integer programming in case of generalized overlapping phases. In the second paper, an optimal signal setting of a fixed-cycle traffic signal is based upon the criterion of minimum overall delay. Webster's method which is an approximation method for the optimal signal setting is theoretically elucidated. Furthermore, approximation algorithms which are a refinement of Webster's method and are applicable to all traffic signals are presented. The algorithms are a combination of linear programming or mixed-integer programming and one-dimensional minimization technique. /Author/

Reference 91

Olson, P. L. and Rothery, R. W. "Deceleration Levels and Clearance Times Associated With The Amber Phase of Traffic Signals." Traffic Engineering. Vol. 42, No. 7, pp. 16-19.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☒ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☒ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

A study of driver reaction to the yellow clearance is reported. Emphasis is placed on probability of stopping as a function of the time required to clear the intersection, and as a function of the deceleration rate required to stop.

Reference 92

Orcutt, F. L. "A Primer for Traffic Signal Selection," Public Works. March 1975, pp. 76-77.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☒ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

This discussion on traffic signals considers means of determining needs for a signal, what kinds are available, and what kinds to buy. Tips on writing the necessary specifications are included.

Reference 93

Parsonson, Peter S. "A System to Monitor Road-User Cost in Urban Traffic Congestion." HRR 383. ((1972) pp. 1-10.

This Literature Contains Information in the Following Categories:

Highway Types

☐ Rural
☒ Urban Arterial
☐ Urban Network
☐ Other

Data Types

☒ Chase Car or Floating Car
☐ Freeway Surveillance System
☐ Arterial Surveillance System
☐ Photographic
☐ Simulation
☐ Other

Factors Analyzed

☐ Traffic Flow Characteristics
☐ Vehicle Emissions
☐ Fuel Consumption
☐ Maintenance
☐ Installation
☐ Signal Timing
☐ Effects of Geometrics
☒ Other

Signal Types

☐ Fixed Time
☐ Semi Actuated
☐ Fully Actuated
☐ Other

Summary/Abstract

This project was directed toward developing techniques for measuring the total cost of time and vehicle operation in various traffic streams and for determining the component of that cost attributable to traffic congestion. Speed and delay runs were performed using a tachograph-equipped car on Atlanta arterials and freeways. The resulting graphs were converted to dollar costs of congestion using vehicle operating costs and costs of time.

Reference 94

Parsonson, Peter S. "Operation of Actuated Traffic Signals at Local Intersections." Parts 1 through 4. (Series of Films.) Produced 1974-1976. Available from Audio-Visual Department, Price Gilbert Memorial Library, Georgia Institute of Technology.

This Literature Contains Information in the Following Categories:

Highway Types

☐ Rural
☐ Urban Arterial
☐ Urban Network
☒ Other

Data Types

☐ Chase Car or Floating Car
☐ Freeway Surveillance System
☐ Arterial Surveillance System
☐ Photographic
☐ Simulation
☒ Other

Factors Analyzed

☒ Traffic Flow Characteristics
☐ Vehicle Emissions
☐ Fuel Consumption
☐ Maintenance
☐ Installation
☒ Signal Timing
☐ Effects of Geometrics
☐ Other

Signal Types

☐ Fixed Time
☒ Semi Actuated
☒ Fully Actuated
☒ Other

Summary/Abstract

A series of four films describes the timing operation and detectorization of various types of acutated traffic signals at isolated intersections. The series comprises the following parts:

Part I: Basic actuated controllers. 24 minutes. Conventional control using small-area detectors and controllers with locking detection memory circuits.

Part II: Adaunced acutated controllers. 16 minutes. "Density" features, including variable initial interval and reduction of allowable gap; the dilemma-zone problem at high-speed intersections.

Part III: Multiphase actuated controllers. 13 minutes. Summary of left-turn phasing, overlap movements, phase skipability, and diamond interchanges.

Part IV: Loop-occupancy control. 25 minutes. Applications of long-loop presence detectors with controllers having non-locking detection memory circuits.

Reference 95

Parsonson, Peter S., and Thomas, Joseph M. Jr. "A Case Study of the Effectiveness of a Traffic-Responsive Computerized Traffic Control System," Traffic-Signal Operations in Coordinated Systems. Vol. 1. Georgia Institute of Technology, 1976.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
[✓ Urban Network]
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

[✓ Traffic Flow Characteristics]
[✓ Vehicle Emissions]
[✓ Fuel Consumption]
__ Maintenance
__ Installation
[✓ Signal Timing]
__ Effects of Geometrics
__ Other

Signal Types

__ Fixed Time
__ Semi Actuated
[✓ Fully Actuated]
__ Other

Summary/Abstract

This paper deals with the control of traffic flow through improved traffic-signal timing, specifically through real-time traffic-responsive, traffic-signal systems utilizing digital computers and centralized monitoring stations. The principal features of such a system in Atlanta are described. Extensive evaluations of the effectiveness of the system have been performed. The impact of speed, stop probability, accidents, vehicle operating costs, fuel consumption, and air pollution were determined and summarized.

Reference 96

Patterson, Robert M. "Traffic Flow and Air Quality." Traffic Engineering, November 1975, pp. 14-17.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
[✓ Vehicle Emissions]
__ Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

__ Fixed Time
__ Semi Actuated
__ Fully Actuated
__ Other

Summary/Abstract

The author points out the potential conflict between traditional traffic engineering goals and environmental concerns. For example, cycle lengths that provide minimum delay do not provide the minimum emissions.

Other examples are given, and a recommendation that further studies be made to find out the environmental consequences of traffic engineering procedures.

Reference 97

Pignataro, L. J.; McShane, W. R.; et al. Traffic Control in Oversaturated Street Networks. NCHRP 3-18(2), Final Report. June 1975.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☒ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☒ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

This research investigated the scope and magnitude of the nationwide problem of traffic control and operations in oversaturated street networks. The possibilities were explored for combatting this problem with existing control techniques, and a set of guidelines was developed for treating the problem systematically.

Reference 98

Pinnell-Anderson-Wilshire & Associates, Inc. Traffic Control Systems Handbook. Federal Highway Administration, Offices of Research and Development, December 1975.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☒ Urban Arterial
- ☒ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☒ Other

Factors Analyzed

- ☒ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☒ Maintenance
- ☒ Installation
- ☒ Signal Timing
- ☒ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☒ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

This report presents the results of a thorough overview study of traffic control techniques in the form of a handbook of applicable technology, concepts, and practice. The handbook is intended to present basic principles for the planning, design, and implementation of traffic surveillance and control systems for the two basic application areas of urban streets and freeways. Major objectives of the handbook are (1) to provide a compendium of existing traffic control system technology, (2) to facilitate the understanding of the basic elements of traffic control systems, (3) to aid the understanding and application of new technology (such as computers and comunications) to the traffic control field, (4) to broaden the viewpoint of the field of traffic control, (5) to serve as a basic guideline to aid the practicing traffic engineer in implementing new and effective traffic control systems, and (6) to serve as a basic text for training programs in the area of traffic control systems.

Reference 99

Potts, R. B., and Gazis, D. C. "The Over-Saturated Intersection." Organization for Economic Cooperation and Development, Road Research Laboratory./UK/

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
x Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

x Fixed Time
__ Semi Actuated
__ Fully Actuated
__ Other

Summary/Abstract

The problem of minimizing delay at traffic signals which are overloaded during the peak period is studied. In the first instance, it is assumed that the cycle is fixed and that each green period is restricted in range between a minimum and a maximum value. It is shown that in the particular case in which the saturation flows in the two critical directions are equal the minimum delay is given by the fixed-time settings that cause both queues to disappear at the same time. This can be found by trial and error using curves of accumulated flow on each of the critical approaches. A method of solution is also given in the more general case where the saturation flows are different. This involves giving the maximum green period to the direction with the highest flow during the early part of the peak period and to the other direction in the later part of the peak period, as well as adjusting the settings to ensure that both queues are finally cleared at the same time.

Reference 100

Rach, L. Improved Operation of Urban Transportation Systems, Vol. 1: Traffic Control Strategies - A State Of The Art. March 1974.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
X Urban Arterial
X Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
X Installation
X Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

__ Fixed Time
__ Semi Actuated
__ Fully Actuated
__ Other

Summary/Abstract

This report presents a state-of-the-art review of current traffic signal control strategies. Existing off-line signal timing strategies for individual signals, arterials, and networks are reviewed and recent developments in the area of real-time traffic responsive control are described. The report ends with a comprehensive bibliography of 200 documents relating to the area of traffic control strategies.

Reference 101

Rach, L. Improved Operation of Urban Transportation Systems. Vol. 2: Evaluation of Off-Line Area Traffic Control Strategies. November 1975.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

_X_ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
_x_ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

__ Fixed Time
__ Semi Actuated
__ Fully Actuated
__ Other

Summary/Abstract

This report is aimed toward the evaluation of existing off-line area traffic control strategies. In particular, four off-line traffic signal optimization techniques (viz., SIGOP, TRANSYT, GLC-COMBINATION, and the existing Toronto Method) were utilized to obtain signal timing patterns for various periods of the day. The various timing patterns were implemented within Metropolitan Toronto and were evaluated through an analysis of detailed network survey statistics. The overall study results show that the signal timing plans developed by the four different methods provide similar levels of service.

Reference 102

Radelat, Guido. "Accident Experience as Related to Regular and Flashing Operation of Traffic Signals." D.C. Dept. of Highways and Traffic, Staff Report, June 1966.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
_X_ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
_X_ Other

Signal Types

__ Fixed Time
__ Semi Actuated
__ Fully Actuated
__ Other

Summary/Abstract

This staff report by the District of Columbia concludes that 24-hour "stop and go" operation of traffic signals is safer than flashing operation during night hours, based on accident records. Accidents decreased an average of 40 percent when 162 intersections were changed from night-time flash to 24-hour regular operation.

Reference 103

Reilly, William R., and Gardner, Craig C. "A Technique for Measurement of Delay at Intersections." Transportation Research Board, 56th Annual Meeting, January 1977.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☒ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☒ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

Presented in this report are findings related to the design of a technique for measurement of vehicular delay on the approach to a signalized intersection. Approach delay was selected as being the most representative of intersection efficiency. Four manual methods were tested in the lab using film taken at ten intersections. The values thus obtained were statistically compared with the true values from time lapse photography. /Author/

Reference 104

Retzko, I. H. "Traffic Signal Control Methods in West Germany." Traffic Engineering and Control, October 1970, pp. 318-320.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☒ Urban Arterial
- ☒ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☒ Installation
- ☒ Signal Timing
- ☐ Effects of Geometrics
- ☒ Other

Signal Types

- ☐ Fixed Time
- ☒ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

The status of traffic signal control methods in Germany is discussed in this paper. The evolution of signal types from few traffic-actuated signals to mostly coordinated traffic-actuated types is described. (One of the major differences between control principles in Great Britain and Germany is highlighted whereby in Great Britain delay is minimized for all approaches to an intersection, whereas in Germany priority is granted to selected streets in order to maximize speed (minimize delay) along those streets.) Other aspects of signal control are also discussed and areas for future research identified.

Reference 105

Richbell, L. E., and Van Averbeke, B. A. "Bus Priorities at Traffic Control Signals." Traffic Engineering and Control, June 1972, pp. 70-75.

This Literature Contains Information In the Following Categories:

Highway Types

- __ Rural
- X Urban Arterial
- __ Urban Network
- __ Other

Data Types

- __ Chase Car or Floating Car
- __ Freeway Surveillance System
- __ Arterial Surveillance System
- __ Photographic
- __ Simulation
- __ Other

Factors Analyzed

- X Traffic Flow Characteristics
- __ Vehicle Emissions
- __ Fuel Consumption
- __ Maintenance
- __ Installation
- X Signal Timing
- __ Effects of Geometrics
- __ Other

Signal Types

- __ Fixed Time
- __ Semi Actuated
- __ Fully Actuated
- __ Other

Summary/Abstract

An experiment was undertaken at Leicester, England, to examine how bus delays in mixed traffic flows could be reduced at traffic signal controlled intersections by introducing selective vehicle detection equipment to give buses priority. The experiment that this type of equipment, consisting of a transponder on the bus and receiver underground, could be used successfully to detect the presence of buses, reduce their delay time, and enable them to achieve a more consistent time through the junction.

Reference 106

Rioux, Thomas W., and Lee, Clyde E. "TEXAS - A Microscopic Traffic Simulation Package for Isolated Intersections." Transportation Research Board, 56th Annual Meeting, January 1977.

This Literature Contains Information In the Following Categories:

Highway Types

- __ Rural
- __ Urban Arterial
- __ Urban Network
- X Other

Data Types

- __ Chase Car or Floating Car
- __ Freeway Surveillance System
- __ Arterial Surveillance System
- __ Photographic
- __ Simulation
- X Other

Factors Analyzed

- __ Traffic Flow Characteristics
- __ Vehicle Emissions
- __ Fuel Consumption
- __ Maintenance
- __ Installation
- __ Signal Timing
- __ Effects of Geometrics
- __ Other

Signal Types

- __ Fixed Time
- __ Semi Actuated
- __ Fully Actuated
- __ Other

Summary/Abstract

This paper is a description of a new microscopic traffic simulation package, called the TEXAS model, which can be used to evaluate traffic performance at isolated intersections, operating under various types of control. Several new factors in the simulation include lane change decision, sight distance restrctions, and intersection conflict checking.

Reference 107

Robertson, D. I. "The Use of the TRRL Transyt Method." Traffic Engineering and Control, December 1975, pp. 562-564.

This Literature Contains Information in the Following Categories:

Highway Types

_ Rural
_ Urban Arterial
X Urban Network
_ Other

Data Types

_ Chase Car or Floating Car
_ Freeway Surveillance System
_ Arterial Surveillance System
_ Photographic
_ Simulation
_ Other

Factors Analyzed

_ Traffic Flow Characteristics
_ Vehicle Emissions
_ Fuel Consumption
_ Maintenance
_ Installation
X Signal Timing
_ Effects of Geometrics
X Other

Signal Types

X Fixed Time
_ Semi Actuated
_ Fully Actuated
_ Other

Summary/Abstract

This paper describes some of the trials, applications, and extensions which have been made since the original development of Transyt. This method was developed in 1967 by the Transportation and Road Research Laboratory (TRRL) for calculating by computer the best way of coordinating fixed-time traffic signals.

Reference 108

Robertson, D. I. "TRANSYT Method for Area Traffic Control." Traffic Engineering and Control, October 1969, pp. 276-281.

This Literature Contains Information in the Following Categories:

Highway Types

_ Rural
_ Urban Arterial
_ Urban Network
_ Other

Data Types

_ Chase Car or Floating Car
_ Freeway Surveillance System
_ Arterial Surveillance System
_ Photographic
X Simulation
_ Other

Factors Analyzed

_ Traffic Flow Characteristics
_ Vehicle Emissions
_ Fuel Consumption
_ Maintenance
_ Installation
X Signal Timing
_ Effects of Geometrics
_ Other

Signal Types

_ Fixed Time
_ Semi Actuated
_ Fully Actuated
X Other

Summary/Abstract

This paper is a discussion of the TRANSYT computer program, used to find the best timings for coordination of a traffic signal system.

The program uses a simulation model to predict the average number of stopped vehicles within a network and seeks to minimize that number.

Reference 109

Robertson, D. I. "Urban Traffic Control Systems - What Comes Next?" Traffic Engineering and Control, March 1976, p. 105.

This Literature Contains Information In the Following Categories:

Highway Types

- ☐ Rural
- ☒ Urban Arterial
- ☒ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☒ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

This article presents the results of an informal discussion on Urban Traffic Control (UTC) which was held at the Institute of Civil Engineers in England in February 1976. The future potential of UTC in a number of areas is discussed including responsive systems, bus priority, freeway control, parking control, microprocessors, traffic restraint, and vehicle detection.

Reference 110

Robinson, K. P. "Modern Developments in Traffic Control Equipment." Traffic Engineering and Control, July 1970, pp. 139-140.

This Literature Contains Information In the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☒ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

The author gives a status report of equipment then available, including inductive loop detectors, solid state vehicle controllers, and signal lamps, and refers briefly to the application of these component parts in traffic systems.

Reference 111

Rodgers, L. M. "Detector Placement - A Misunderstood Subject." Traffic Engineering, April 1973, pp. 42-44.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☒ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

The placement of loop detectors in service and fully-actuated intersections is discussed in this article, drawing upon both theoretical and practical knowledge.

Reference 112

Roehl, Joseph E. "Applying Microcomputer Technology to Problems in Traffic Signalization." Special Report No. 19, November 1973, New York Department of Transportation.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☒ Other

Summary/Abstract

The report first presents a basic background information on traffic control equipment, then discusses the application of the microcomputer to provide the same functions. Flow charts for programs and subroutines are included in the discussion..

Reference 113

Sackman, Harold; Monahan, Bruce; Parsonson, Peter S.; and Trevino, Alberto F. Vehicle Detector Placement for High-Speed, Isolated Traffic-Actuated Intersection Control. U.S. Department of Transportation, May 1977.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☒ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☒ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

This study was undertaken to improve understanding of how to place vehicle detectors at high-speed (at least 35 mph), isolated, trafifc-actuated intersections, and how to test and evaluate alternative detector/controller configurations for intersection traffic safety and efficiency.

Drivers are often indecisive in approaching such intersections. If a vehicle is being operated at high speed, and a green signal changes to yellow, driver indecision may lead to various types of accidents. Strategies that have been advanced for detector placement to minimize the untimely display of yellow are illustrated and reviewed in the volume. This is the first time that available knowledge on detector placement for such intersections has been systematically integrated within a single publication.

This volume is the second in a series of three:

Vol. No.	FHWA No.	Short Title
1	77-31	Executive Summary
2	77-32	Manual of Theory and Practice
3	77-33	Case Study: Local Field Test and Evaluation

Reference 114

Sarasota Engineering Company, Inc. "Improve Safety and Efficiency with Sarasota Green Extension Systems." Pamphlet GES, January 1973.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☒ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☒ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

This product bulletin describes a green extension system (GES). The equipment extends the green when a vehicle is at high speed and it is unsafe for the clearance interval to begin, and also extends the green when a platoon is approaching the intersection.

The GES uses either two or three loops in the traffic stream extending as far back as 650 feet from the stop bar. A succession of time-stretch intervals carries the vehicle from loop to loop and through the intersection.

Wiring block diagrams and spacing graphs are included.

Reference 115

Schempers, William, Jr. "Loop Detectors." Traffic Engineering, September 1966, pp. 34-36.

This Literature Contains Information In the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☒ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☒ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

This article reviews applications of presence detection and proposes functional requirements for loop detectors.

Reference 116

School of Civil Engineering, Georgia Institute of Technology. Traffic/Signal Operation in Coordinated Systems, Volumes 1 and 2, 1976.

This Literature Contains Information In the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☒ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☒ Other

Factors Analyzed

- ☒ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☒ Installation
- ☒ Signal Timing
- ☐ Effects of Geometrics
- ☒ Other

Signal Types

- ☒ Fixed Time
- ☒ Semi Actuated
- ☒ Fully Actuated
- ☒ Other

Summary/Abstract

These two volumes comprise the course material used for a week-long course presented by GIT concerning traffic-signal operations. Subjects covered include:

1. Traffic-signal systems: characteristics, warrants, and design data requirements
2. Time space diagrams
3. Coordination of pre-timed controllers
4. Coordination of semi-actuated controllers
5. Traffic adjusted systems using volumes-only parameters
6. Coordination of fully-actuated controllers
7. Computer aids to time-space calculations
8. Network coordination
9. Traffic parameters for advanced systems
10. Advanced traffic-adjusted analog systems
11. Before-and-after studies of stops and delays and their costs
12. Digital computers and their applications to traffic control
13. Case studies of centralized traffic control systems
14. Communication system technology
15. Analyses of alternative systems

Reference 117

Scott, J. B. "Traffic Control Equipment Study - Annual Expenditures and Current Inventories for the U.S." American City, 1974, pp. 56-57.

This Literature Contains Information in the Following Categories:

Highway Types

_ Rural
_ Urban Arterial
_ Urban Network
_ Other

Data Types

_ Chase Car or Floating Car
_ Freeway Surveillance System
_ Arterial Surveillance System
_ Photographic
_ Simulation
X Other

Factors Analyzed

_ Traffic Flow Characteristics
_ Vehicle Emissions
_ Fuel Consumption
_ Maintenance
_ Installation
_ Signal Timing
_ Effects of Geometrics
_ Other

Signal Types

X Fixed Time
X Semi Actuated
X Fully Actuated
X Other

Summary/Abstract

Statistical data on major types of traffic control equipment owned and operated by U.S. city, county, and state governments for 1972, 1973, and 1974. Items tabulated are:

- Vehicular signal heads
- Pedestrian signal heads
- Controllers
- Detectors
- Signal poles
- Conduit and span wire
- Computers

Reference 118

Selby, D. L.; Cobbe, B. M.; and Ridley, G. "Traffic Signs and Markings, Part 1. Traffic Signals, Part 2." Institute of Highway Engineers Journal 17 (May 1970): 67-79, 81-87.

This Literature Contains Information in the Following Categories:

Highway Types

X Rural
X Urban Arterial
X Urban Network
_ Other

Data Types

_ Chase Car or Floating Car
_ Freeway Surveillance System
_ Arterial Surveillance System
_ Photographic
_ Simulation
X Other

Factors Analyzed

_ Traffic Flow Characteristics
_ Vehicle Emissions
_ Fuel Consumption
X Maintenance
_ Installation
_ Signal Timing
_ Effects of Geometrics
_ Other

Signal Types

X Fixed Time
X Semi Actuated
X Fully Actuated
_ Other

Summary/Abstract

"Clear and efficient signing is an essential part of highway and traffic engineering, and a road with poor signing or with badly maintained signs is an unsatisfactory road." This quotation from the introduction to the traffic signs manual (U.K.) expresses the viewpoint of road users and highway engineers alike. Unfortunately, with the increase in the number of traffic signs and road markings, there is a danger that the proportion of unsatisfactory roads may increase. The Worboy's report estimated that the changeover of the 1,600,000 signs in the United Kingdom would cost about $60 million. There are now several million signs, with a very high total capital cost and the prospect of a major and rapidly increasing maintenance bill. Road markings, with an annual maintenance expenditure of $8 million form an essential part of the total aids to movement budget. Part I looks at the maintenance of traffic signals from a national (U.K.) point of view. Satisfactory maintenance of signals depends not only on the reliability of the equipment and speed of fault clearance but also on the early detection of faults. Factors affecting these requirements are discussed and suggestions made for the reorganization of the whole maintenance service both for existing equipment and for equipment likely to be available in the future. Part II looks at the maintenance of traffic signals from the local authority's viewpoint. Faults in signal installations are too frequent and the methods of dealing with them unsatisfactory. A proposed new form of maintenance contract is discussed including the possible inspection organization necessary to make it effective in a large urban authority.

Reference 119

Shannon, G. F.; Howard, N. R.; and Phillips, G.R. "A Traffic Light Control Scheme Giving Consideration to the Speed of Approaching Traffic." Traffic Engineering and Control, December 1973, pp. 387-389.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☒ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☒ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

This paper gives a control scheme for extending the green for vehicles in the detection zone unable to stop safely. A calculation of speed is made by two loops and compared to a simple inequality. If the vehicle can stop safely, the green ends; if not, the green is extended.

A detailed diagram of the circuitry is included.

Reference 120

Shindler, R. "A Comparative Study of Semi-Actuated and Volume Density Trafifc Signal Operation." Proceedings of the Northwest Traffic Engineering Conference, 1958, pp. 112-116.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☒ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☒ Other

Signal Types

- ☐ Fixed Time
- ☒ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

A report of a study of accidents as related to type of controller, this paper shows the advantage of volume-density equipment. A suburban intersection on a four-lane highway was studied for five-years with semi-actuated control and two years with fully-actuated volume-density control. Rear-end accidents were reduced by 62 percent after the change.

The study indicates that lower accident potential may result when vehicles on the major highway are detected, and unnecessary stops of high-speed traffic are eliminated.

Reference 121

Smith, S. A. and Carter, E. C. "Pretimed Signal-Control System for an Underwater Vehicular Tunnel." <u>TRR 533</u>, 1975.

This Literature Contains Information in the Following Categories:

Highway Types

- __ Rural
- __ Urban Arterial
- __ Urban Network
- __ Other

Data Types

- __ Chase Car or Floating Car
- __ Freeway Surveillance System
- X Arterial Surveillance System
- __ Photographic
- __ Simulation
- __ Other

Factors Analyzed

- __ Traffic Flow Characteristics
- __ Vehicle Emissions
- __ Fuel Consumption
- __ Maintenance
- __ Installation
- __ Signal Timing
- __ Effects of Geometrics
- __ Other

Signal Types

- __ Fixed Time
- __ Semi Actuated
- __ Fully Actuated
- __ Other

Summary/Abstract

A pretimed control system consisting of a standard traffic signal was used to meter traffic entering the Baltimore Harbor Tunnel. Four different cycle lengths and splits were tested, and the results were compared to those obtained from the uncontrolled situation. The increase in flow rates and speeds of three of the control strategies increased over those in normal operation. The operation of the tunnel was observed in its two basic states—congested and uncongested. The quality of flow in a tunnel is poorest on the downgrade, better on the level section, and best on the upgrade. /Author/

Reference 122

Sperry Systems Management Division. "Urban Traffic Control and Bus Priority System Operations and Maintenance." FHWA Report No. FHWA-RD-76-160, June 1976.

This Literature Contains Information in the Following Categories:

Highway Types

- __ Rural
- __ Urban Arterial
- X Urban Network
- __ Other

Data Types

- __ Chase Car or Floating Car
- __ Freeway Surveillance System
- __ Arterial Surveillance System
- __ Photographic
- __ Simulation
- X Other

Factors Analyzed

- __ Traffic Flow Characteristics
- __ Vehicle Emissions
- __ Fuel Consumption
- X Maintenance
- X Installation
- __ Signal Timing
- __ Effects of Geometrics
- __ Other

Signal Types

- X Fixed Time
- __ Semi Actuated
- __ Fully Actuated
- __ Other

Summary/Abstract

This report contains a comprehensive review of the UTCS/BPS operations and maintenance. The results and conclusions presented highlight system and equipment operating and maintenance experience and costs, management and staffing for these related tasks.

Reference 123

Staunton, M. Traffic Control Devices: Vehicle Actuated Signal Controls at Isolated Locations. The National Institute for Physical Planning and Construction Research: Dublin, January 1976.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
X Other

Signal Types

X Fixed Time
X Semi Actuated
X Fully Actuated
__ Other

Summary/Abstract

This report examines the performance and capability of controller strategies and develops guidelines for local engineers in Ireland faced with the selection and installation of these devices. Fully-actuated controllers are recommended for isolated locations in view of fixed-time or semi-actuated control. Subjects covered include:

- Detection
- Control strategies
- Appraisal and Usage of Controllers
- Signal-Controlled Pedestrian Crossings
- Construction of Control Equipment

Reference 124

Stemmler, R.; Sheck, D.; Kapka, S.; and Hon, L. T. Determination of Optimum Inventory Levels and Storage Centers for Traffic Signal Materials. Ohio Department of Transportation-13-74 Final Report, June 30, 1974.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
X Maintenance
X Installation
__ Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

__ Fixed Time
__ Semi Actuated
__ Fully Actuated
__ Other

Summary/Abstract

A detailed study of the inventory of traffic signal equipment. Recommendations include short- and long-term inventory control improvements and the decentralization of equipment storage.

Reference 125

Swale, D. L. and Guin, M. G. "The Marconi/RRL Vehicle Detector." <u>Traffic Engineering and Control,</u> October 1969, pp. 268-272.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
X_ Other

Signal Types

__ Fixed Time
__ Semi Actuated
X_ Fully Actuated
__ Other

Summary/Abstract

This article describes a vehicle detector which was developed by Marconi Company and the Road Research Laboratory. The work was initiated in 1966. The result was a "tribo-electric" detector consisting of (1) a sensor assembly, which is bonded into the road with its top flush with the road surface and (2) a signal processing unit. It is basically a passage-type detector designed to replace pneumatic tubes.

Reference 126

Texas State Department of HIghways and Public Transportation. <u>Manual of Uniform Traffic Control Devices</u>, Volume 2, 1973.

This Literature Contains Information in the Following Categories:

Highway Types

X Rural
__ Urban Arterial
__ Urban Network
X Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

X Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

X Fixed Time
__ Semi Actuated
X Fully Actuated
__ Other

Summary/Abstract

The 1973 edition of the Texas MUTCD incorporates the curves proposed by Bodrazka, Lee, and Haenel in 1971. The curves are volume warrants for determining whether a fully-actuated traffic signal should be installed at a particular inersection. The curves were derived when the national MUTCD had volume warrants only for pretimed signals. The Texas Department of Highways found thatthe warrants for actuated signals gave good results and, therefore, incorporated them into the 1973 edition of its MUTCD. The warrants have been approved by the FHWA.

Reference 127

Thomas, G. J. and Shuken, H. L., Los Angeles City Department of Traffic. "Improved Effectiveness of Traffic Signal Systems." NTIS (PB251821), June 1975.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
X Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

X Fixed Time
X Semi Actuated
__ Fully Actuated
__ Other

Summary/Abstract

This paper is the Final Summary report which summarizes the findings of six previous reports:

1. Semi-Actuated Signal Study Preliminary Report - January 1971
2. Improved Signal Systems Timing Strategies, Small Network - May 1972
3. Effects of Changes in Signal Operations on Traffic Flow - January 1973
4. Conventional Signal Network Timing Strategies - January 1973
5. The Use of TRANS Traffic Simulation, A Critique - February 1974
6. Semi-Actuated Signals on Arterial Streets, Final Report - June 1975

The broad objectives of the project were to investigate means of improving the traffic handling capability of an arterial street network by optimizing the operation of the network traffic signals.

Reference 128

Tidwell, J. E. and Humphreys, J. B. "Relation of Signalized Intersection Level of Service to Failure Rate and Average Individual Delay." Highway Research Record, No. 321, 1970, pp. 16–32.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

X Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
X Other

Signal Types

__ Fixed Time
__ Semi Actuated
__ Fully Actuated
__ Other

Summary/Abstract

The paper analyzes two methods of determining level of service and proposes a third, based on average individual delay. The paper is discussed by three other persons.

Reference 129

Tillotson, H. T. "Delays Caused by Traffic Signal Failures." Traffic Engineering and Control, October 1975, pp. 420-422.

This Literature Contains Information in the Following Categories:

Highway Types

☐ Rural
☐ Urban Arterial
☐ Urban Network
☐ Other

Data Types

☐ Chase Car or Floating Car
☐ Freeway Surveillance System
☐ Arterial Surveillance System
☐ Photographic
☒ Simulation
☐ Other

Factors Analyzed

☐ Traffic Flow Characteristics
☐ Vehicle Emissions
☐ Fuel Consumption
☐ Maintenance
☐ Installation
☐ Signal Timing
☐ Effects of Geometrics
☐ Other

Signal Types

☐ Fixed Time
☐ Semi Actuated
☐ Fully Actuated
☐ Other

Summary/Abstract

The purpose of this paper was to quantify the vehicle delay due to traffic signal failures which caused the signals to revert to long-fixed cycles. The calculations were made using Webster's formula and typical hourly flows. These calculations were supplemented with information obtained from two isolated signals in the Birmingham, England, area. The results showed large amounts of excess delay as a result of signal failures. The need for maintaining the signals to exacting standards is emphasized. The consideration of abandoning vehicle-actuated signals in favor of more reliable fixed-cycle systems is advanced.

Reference 130

Tindale, S. A. "Solid State Traffic System Battles Environment." Traffic Engineering, December 1975, pp. 21-23.

This Literature Contains Information in the Following Categories:

Highway Types

☐ Rural
☐ Urban Arterial
☐ Urban Network
☐ Other

Data Types

☐ Chase Car or Floating Car
☐ Freeway Surveillance System
☐ Arterial Surveillance System
☐ Photographic
☐ Simulation
☐ Other

Factors Analyzed

☐ Traffic Flow Characteristics
☐ Vehicle Emissions
☐ Fuel Consumption
☒ Maintenance
☐ Installation
☐ Signal Timing
☐ Effects of Geometrics
☐ Other

Signal Types

☐ Fixed Time
☐ Semi Actuated
☐ Fully Actuated
☐ Other

Summary/Abstract

Adverse weather poses special problems for computerized traffic control systems. This report deals with Tampa, Florida's efforts to keep traffic moving through rain, storm, thunder, and lightening.

Reference 131

Tindale, Stephen A. "Tampa's Lamp Maintenance Program." Traffic Engineering, November 1976, pp. 39-41.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☒ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

This paper describes the Tampa, Florida, traffic signal lamp maintenance program. The benefits and costs are calculated for periodic lamp replacement versus emergency lamp replacement. Guidelines are presented for lamp purchases and recommendations presented for lamp maintenance programs.

Reference 132

Torres, J. F. Test and Evaluation of Computerized Traffic Control System (Diamond Interchange Traffic Control, Vol. 9, Final Report. July 1973.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☒ Chase Car or Floating Car
- ☒ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☒ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☒ Other

Summary/Abstract

The paper reports an evaluation of the installation of a computerized controller at a diamond interchange. The degree of improvement over a three-dial pretimed system showed that the new installation was cost-effective.

Reference 133

Treiterer, J.; Nemeth, A.; and Vecellio, R. Effect of Signal Spacing on Platoon Dispersion. Ohio Department of Highways, Final Report, July 1973.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☒ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☒ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☒ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

The study was conducted to investigate platoon movements on urban arterials and to relate variation in platoon behavior to variation in signal control and to changes in traffic volumes. This objective was accomplished in the form of determining platoon characteristics for traffic traveling on signalized urban arterials and developing a mathematical model to simulate the behavior of a group of vehicles as it passes through a series of signalized intersections. The developed model can be used to establish signal settings allowing for the dispersion of traffic and to study the effect of a change in a signal system on expected queue lengths and mean delays per vehicle./Author/

Reference 134

U.S. Department of Transportation, Federal Highway Administration. Manual on Uniform Traffic Control Devices, Part IV: Signals. FHWA, 1971, pp. 215-257.

This Literature Contains Information in the Following Categories:

Highway Types

- ☒ Rural
- ☒ Urban Arterial
- ☒ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☒ Maintenance
- ☒ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☒ Semi Actuated
- ☒ Fully Actuated
- ☒ Other

Summary/Abstract

The chapter sets forth the basic principles that govern the design and usage of traffic signals. The standards apply to all streets and highways regardless of type, class, or governmental jurisdiction. The traffic signals discussed include: traffic control signals, beacons, lane-use control signals, drawbridge, emergency and train approach signals. The advantages and disadvantages of traffic control signals, the meaning of the signal indications, traffic signal warrants, location and maintenance of signals and related equipment, and information relating to other traffic signals are all discussed.

Reference 135

U.S. Department of Transportation, Federal Highway Administration. Manual on Uniform Traffic Control Devices for Streets and Highways, pp. 215-255.

This Literature Contains Information in the Following Categories:

Highway Types

- ☒ Rural
- ☒ Urban Arterial
- ☒ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☐ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

This manual is designed to provide the traffic engineering community with the basis for determining whether intersection conditions warrant the installation of a traffic signal. The following eight warrants are contained in the manual:

1. Minimum vehicular volume required for signalization
2. Interruption of continuous traffic to provide access from the side street
3. Minimum pedestrian volume
4. Presence of schoolcrossing
5. Providing a progressive movement to maintain proper grouping of vehicles and to regulate group speed
6. Accident experience
7. System warrant to encourage concentration of traffic flow thorugh certain intersections in a network
8. An installlation is justifiied if no single warrant is satisfied, but two or more of warrants 1, 2, and 3 are satisfied to the extent of 80 percent or more.

The MUTCD gives extremely general guidance for the selection of actuated- or fixed-time control or for the identification of a requirement for coordination.

Reference 136

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

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☒ Urban Arterial
- ☒ Urban Network
- ☒ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☒ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

The handbook presents the results of a thorough overview study of traffic control techniques. It presents basic principles for the planning, design, and implementation of traffic surveillance and control systems for urban streets and freeways.

Reference 137

Vodrazka, Walter C.; Lee, Clyde E.; Haenel, Herman E. "Traffic Delay and Warrants for Control Devices." Highway Research Record, No. 366 - Traffic Control and Driver Information, 1971, ppl 79-91.

This Literature Contains Information in the Following Categories:

Highway Types

☐ Rural
☐ Urban Arterial
☐ Urban Network
☐ Other

Data Types

☐ Chase Car or Floating Car
☒ Freeway Surveillance System
☐ Arterial Surveillance System
☐ Photographic
☐ Simulation
☐ Other

Factors Analyzed

☒ Traffic Flow Characteristics
☐ Vehicle Emissions
☐ Fuel Consumption
☐ Maintenance
☐ Installation
☐ Signal Timing
☐ Effects of Geometrics
☐ Other

Signal Types

☐ Fixed Time
☐ Semi Actuated
☐ Fully Actuated
☐ Other

Summary/Abstract

A digital delay data recorder was used to provide data to aid in the development of a new set of minimum volume warrants for the installation of four-way stop control and the validation of a proposed set of traffic volume warrants for the installation of actuated signal control.

Reference 138

Wagner, F. A.; Barnes, G.C.; and Gerlough, D. L. "Improved Criteria for Traffic Signal Systems in Urban Networks," NCHRP Report 124, 1971.

This Literature Contains Information in the Following Categories:

Highway Types

☐ Rural
☐ Urban Arterial
☐ Urban Network
☐ Other

Data Types

☒ Chase Car or Floating Car
☐ Freeway Surveillance System
☐ Arterial Surveillance System
☐ Photographic
☒ Simulation
☒ Other

Factors Analyzed

☐ Traffic Flow Characteristics
☐ Vehicle Emissions
☐ Fuel Consumption
☐ Maintenance
☐ Installation
☐ Signal Timing
☐ Effects of Geometrics
☐ Other

Signal Types

☐ Fixed Time
☐ Semi Actuated
☐ Fully Actuated
☐ Other

Summary/Abstract

This research involved the development, computer simulation testing and comparison, and field verification of advanced methods of traffic signal control in urban networks. The emphasis was on developing reliable and inexpensive methods of settings. A secondary objective was to verify, through field studies, the ability of computer simulation methods to predict accurately the effects of signal timing modifications.

A large number of traffic signal timing plans were developed for controlled testing by simulation. In addition, three different signal system timing alternatives were tested under actual operating conditions, and large quantities of operations were gathered to test the validity of the simulation predictions. /Author/

Reference 139

Wagner, F. A.; Gerlough, D.C.; and Barnes, G. C. "Improved Criteria for Traffic Signal Systems on Urban Arterials," NCHRP 73, 1969.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

X Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
X Photographic
__ Simulation
X Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

__ Fixed Time
__ Semi Actuated
__ Fully Actuated
__ Other

Summary/Abstract

This report documents methods, results, interpretations, and applications of research on the development and closely controlled scientific testing of the effectiveness of several advanced concepts for traffic signal system control on urban arterial streets.

The research agency's urban arterial and network simulation model, TRANS, was used to evaluate 11 alternative traffic signal operation test conditions employing various control concepts for a selected arterial street system in the city of Los Angeles. Subjected to tests were four strategic (fixed-time) control concepts applied in various combinations. A total of 100 hours of traffic operation was simulated to produce statistically reliable results in conjunction with the effectiveness tests of alternatives. /Author/

Reference 140

Waight, Vernon H. "Designing with Maintenance in Mind." Traffic Engineering, May 1976, pp. 26-28.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
__ Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

__ Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
X Maintenance
__ Installation
__ Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

__ Fixed Time
__ Semi Actuated
__ Fully Actuated
__ Other

Summary/Abstract

This paper is a discussion of signal design based on ease of maintenance. Topics mentioned include cabinet wiring, cabinet placement, conduit, and solid state equipment.

The ability of technicians to service complex equipment is also mentioned. The author concludes by saying the designer and technician should collaborate in the preparation of equipment specifications.

Reference 141

Webster, F. V. "Traffic Signal Settings." Road Research Laboratory, Road Research Technical Paper No. 39, HMSO, London, 1958.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☒ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☐ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☒ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

Results of research into traffic-signal settings and expected delay to vehicles. The investigation has been made simulating the behavior of traffic at signals. A delay formula was developed and a simple relationship between green time and total cycle time was determined. The results can also be used to assess the gains expected due to road improvements, banning right turns and parking lanes. /Author/

Reference 142

Webster, F. V. and Ellson, P. B. "Traffic Signals for High-Speed Roads." Road Research Laboratory (U.K.), Road Research Technical Paper No. 74, 1965.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☒ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☒ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☒ Fully Actuated
- ☐ Other

Summary/Abstract

The paper defines the problem of the clearance interval at high speed and reports the experimental limits of the "dilemma zone."

The Laboratory recommends a speed-sensitive detector approximately 500 feet from the stop line and a regular detector 130 feet from the stop line. The first detector would extend the green for a fast-moving vehicle, and not for a slower vehicle.

Reference 143

Wilshire, Roy L. "The Benefits of Computer Traffic Control." Traffic Engineering, April 1969, pp. 16-20.

This Literature Contains Information in the Following Categories:

Highway Types

- _ Rural
- _ Urban Arterial
- _X Urban Network
- _ Other

Data Types

- _ Chase Car or Floating Car
- _ Freeway Surveillance System
- _ Arterial Surveillance System
- _ Photographic
- _ Simulation
- _ Other

Factors Analyzed

- X Traffic Flow Characteristics
- _ Vehicle Emissions
- _ Fuel Consumption
- X Maintenance
- _ Installation
- X Signal Timing
- _ Effects of Geometrics
- _ Other

Signal Types

- _ Fixed Time
- _ Semi Actuated
- _X Fully Actuated
- _ Other

Summary/Abstract

This paper describes the digital computer traffic-signal control system operating in Wichita Falls, Texas. Included are components of the cost/benefit analysis justifying the system.

Reference 144

Wingerd, N. C. and Nevis, C. "Traffic Signal Control Strategy at Isolated Intersections." California Department of Transportation, December 1974.

This Literature Contains Information in the Following Categories:

Highway Types

- _ Rural
- _ Urban Arterial
- _ Urban Network
- _ Other

Data Types

- _ Chase Car or Floating Car
- _ Freeway Surveillance System
- _ Arterial Surveillance System
- _ Photographic
- _ Simulation
- _ Other

Factors Analyzed

- X_ Traffic Flow Characteristics
- _ Vehicle Emissions
- _ Fuel Consumption
- _ Maintenance
- _ Installation
- X_ Signal Timing
- _ Effects of Geometrics
- _ Other

Signal Types

- _ Fixed Time
- _ Semi Actuated
- X_ Fully Actuated
- _ Other

Summary/Abstract

The two major problems encountered at intersections are delay and accidents. Both may be reduced by application of a new strategy for determining when to change the signal indications. The objectives are: (1) develop a traffic signal control strategy based on the probability of finding a space-gap in a known traffic volume and (2) test control strategy for space-gap selection.

Reference 145

Wohl, Martin and Martin, Brian V. "Capacity Performance Relationships for Time-Sharing on Signalized Intersections - Chapter 14." Traffic Systems Analysis for Eningeers and Planners. New York: McGraw-Hill Book Company, 1967, pp. 426-494.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☒ Urban Arterial
- ☒ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☒ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

The purpose of this chapter is to determine the characteristics of intersections under different control strategies. The major emphasis is on the use of pretimed signals and the computation of delay, queue lengths, etc. with various timings. Timing of progressive signal control systems using space-time diagrams is also discussed.

Reference 146

Yagoda, H. N.; Morris, A. A.; and Pignataro, L. J. "The Design of Multiphase Intersection Signal Systems." Traffic Engineering, April 1970, pp. 20-27.

This Literature Contains Information in the Following Categories:

Highway Types

- ☐ Rural
- ☐ Urban Arterial
- ☐ Urban Network
- ☐ Other

Data Types

- ☐ Chase Car or Floating Car
- ☐ Freeway Surveillance System
- ☐ Arterial Surveillance System
- ☐ Photographic
- ☐ Simulation
- ☐ Other

Factors Analyzed

- ☐ Traffic Flow Characteristics
- ☐ Vehicle Emissions
- ☐ Fuel Consumption
- ☐ Maintenance
- ☐ Installation
- ☒ Signal Timing
- ☐ Effects of Geometrics
- ☐ Other

Signal Types

- ☐ Fixed Time
- ☐ Semi Actuated
- ☐ Fully Actuated
- ☐ Other

Summary/Abstract

Guidelines are proposed for determining the optimal phase sequence, cycle split, and cycle length for proposed demands at a multiphase intersection.

Reference 147

Yagoda, H. N.; Stevens, E.E.; Mogridge, P.R. "Computer Aided Signal Timing." *Traffic Engineering*, Vol. 42, No. 5, pp. 12-16.

This Literature Contains Information in the Following Categories:

Highway Types

__ Rural
__ Urban Arterial
X Urban Network
__ Other

Data Types

__ Chase Car or Floating Car
__ Freeway Surveillance System
__ Arterial Surveillance System
__ Photographic
__ Simulation
__ Other

Factors Analyzed

X Traffic Flow Characteristics
__ Vehicle Emissions
__ Fuel Consumption
__ Maintenance
__ Installation
X Signal Timing
__ Effects of Geometrics
__ Other

Signal Types

__ Fixed Time
__ Semi Actuated
__ Fully Actuated
__ Other

Summary/Abstract

The forecast program, developed in Albany, is capable of diagnosing a highway network with up to 2,000 traffic signals and providing revised timings for each signal. Optimization is based on number of platoon stops, number of vehicle stops, vehicle delay, saturated intersection location, and on specified demand and service levels. The program provides time-space diagrams comparable to those normally used by an engineer in developing signal timing manually, and also provides measures of effectiveness.

APPENDIX B

PLATOON MODEL DEVELOPMENT

The purpose of this appendix is to describe the mathematical basis for the development of a model of traffic platooning characteristics that can be used for the manual estimation of the benefits resulting from the implementation of a coordinated signal system. This model relies on the work of Robertson (*B-1*).

PLATOON DISPERSION

Robertson's model is based on the theory that the platoon of vehicles leaving an upstream intersection is formed by the queue of vehicles waiting at the start of green departing at the saturation flow rate (the maximum rate of flow in vehicles per hour) that is possible for the facility under the study and dispersing as the platoon travels along the roadway. This effect is shown in Figure B-1. Robertson developed the following recurrence relationship to describe this phenomenon:

$$q'_{(i+t)} = F \times q_{(i)} + (1 - F) \times q'_{(i+t-1)}$$

where:

$q_{(i)}$ = the flow in the i^{th} time interval of the initial platoon;

$q'_{(i)}$ = the flow in the i^{th} time interval of the predicted platoon; and

t = 0.8 times the average travel time over the distance for which the platoon dispersion is being calculated. (This term is measured in time intervals being used for $q_{(i)}$.)

The factor F, which controls the rate at which the platoon disperses, controls the best fit between the actual and calculated platoon shapes. This factor was expressed by Robertson as

$$F = \frac{1}{1 + Kt}$$

where K is a constant designated as the platoon dispersion rate that can assume values between 0 and 1.0. Robertson measured the dispersion of 700 platoons and selected a value of 0.5 for K in order to achieve the best agreement between actual and computed platoon dispersion. Lam (*B-2*) conducted a similar series of experiments on Leslie Street in Toronto in order to evaluate the adequacy of the K factor and to determine the errors associated with the calculation of delay when Robertson's model is used.

Applying Robertson's model and recommended values for K to six roadway segments on Leslie Street for three times of day, Lam found that the average error in the computation of delay was 13.8 percent. It is interesting to note that this error is less than the 15 percent accuracy established for the selection guidelines in the main body of this report.

Lam then used the data to determine the value of K that would provide the best estimate of platoon dispersion for the conditions actually existing on Leslie Street. This analysis indicated that K should be 0.24. Again comparing the estimated delay with the true delay that would result using the actual platoon produced a significant reduction in the error of the delay estimate to 8.2 percent.

It is concluded from a comparison of the K values and the accuracy of results that:

1. The K value is sensitive to the conditions on the street that affect platoon dispersion. Robertson's data are typical of conditions found in an urban central business district (CBD). Many of the sites used in his study contained conditions such as lane flow, heavy parking, and restricted overtaking. The Leslie Street site is a high type suburban arterial with no driveways, left-turn bays, and multiple lanes.
2. Applying Robertson's K factor of 0.5 produces results that are within the desired accuracy of the procedure. However, the accuracy of these results can be improved if this factor is adjusted to reflect actual street conditions.
3. Calibration of K values using actual roadway conditions can be an expensive process. Therefore, general guidelines for the selection of this factor based on the characteristics of the roadway are required.

Model Verification

To validate the accuracy of this model for conditions found within the United States, traffic flow data were collected on Route 7 east of its intersection with Towlston Road in Fairfax County, Virginia. During this activity, data were collected at 100, 400, and 800 ft (30.5, 121.9, and 243.8 m) from the intersection. Vehicle speeds were 55 mph (89 km/hr) corresponding to travel times of 3.4 and 8.7 sec between the first and second and the first and third data collection stations respectively.

The data were collected using observers with synchronized watches and metronomes at each of the three locations The metronomes were adjusted to provide a constant time interval of 4 sec. The observers recorded the total number of vehicles in all lanes passing their location during each 4-sec period. In addition, the observer at the 100-ft (30.5-m) location recorded the start of green for the signal phase controlling the platoons being measured. The platoons recorded at the start of each green phase were plotted and averaged to produce the data discussed in the following.

The traffic flow measured at each of these stations is

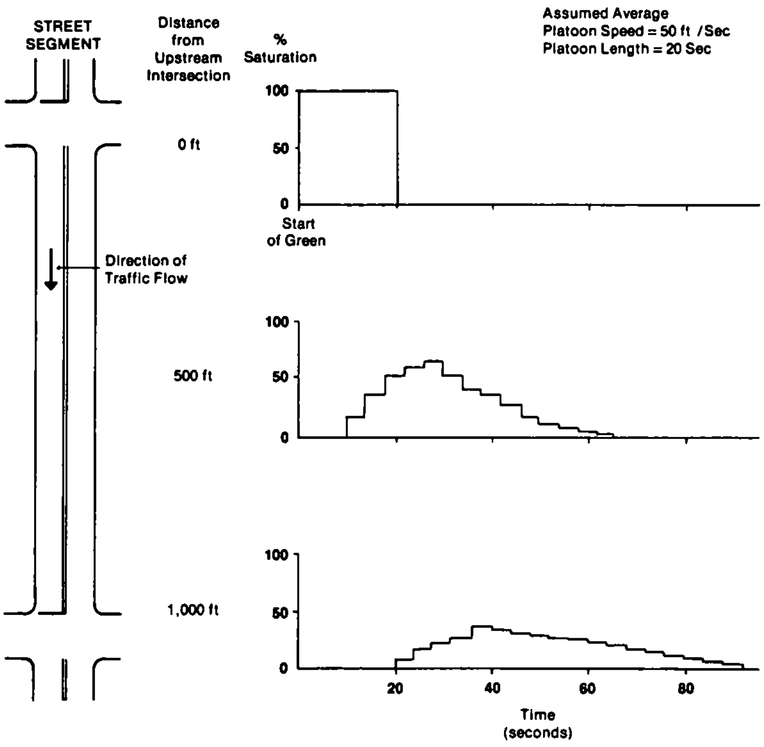


Figure B-1. Platoon dispersion patterns

shown in Figures B-2 and B-3 for p m. peak and off-peak traffic conditions These figures represent composite plots of the average of 11 flow profiles measured during the time periods indicated on the figures.

Robertson's recursion equation was then applied to the data collected at the 100-ft station to estimate the resulting flow patterns at the 400- and 800-ft stations for each time of day. A K factor of 0.24 was used in making these estimates because the data closely matched the free flow suburban arterial case evaluated by Lam. These estimates are shown in the figures by the dashed lines. In both cases, close agreement was obtained between the actual traffic flow and the estimated traffic flow Better agreement was obtained during peak conditions because the heavier traffic volumes that exist during this time of day reduced the variability of the data and hence the reliability with which an accurate prediction could be made.

On the basis of these results, the general acceptance of this model for evaluation of traffic signal timing, and the relative insensitivity of the results to the computation of the K factor, it is concluded that this model can be used to evaluate the relative benefits of signal coordination. Although additional research should be conducted to further refine the relationship between the K factor and roadway conditions, it is possible to develop some general recommendations regarding the relationship between K and these conditions. Recommended values are given in Table B-1.

Effects of Midblock Driveways

The effect on traffic flow of both midblock driveways that

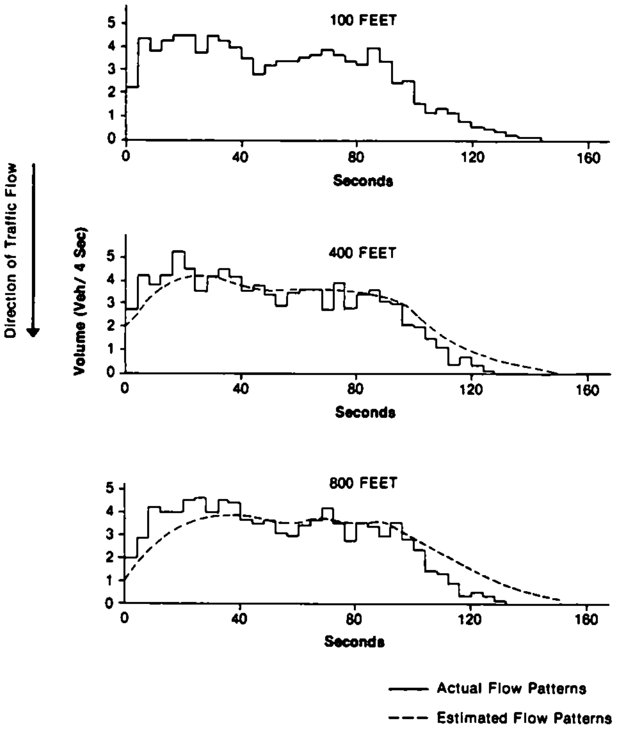


Figure B-2 Composite traffic flow for Rte. 7 at Towlston Rd. (55 mph) 5 00-5 30 p m , April 6, 1978.

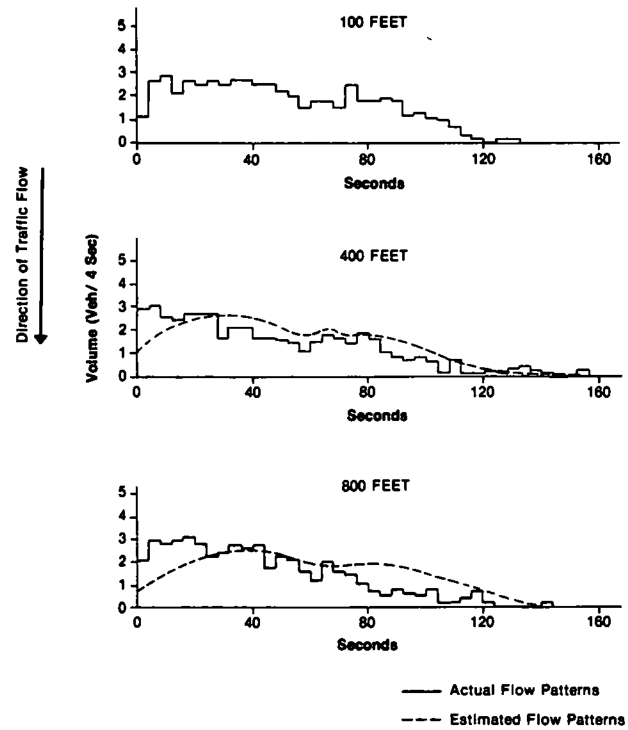


Figure B-3. Composite traffic flow for Rte. 7 at Towlston Rd. (55 mph) 3:30-4:00 p.m., April 6, 1978.

introduce a heavy volume of turning vehicles and a heavy volume of vehicles turning right-on-red from a sidestreet is equivalent. This effect is to add vehicles to the traffic flow patterns when suitable gaps are present in the traffic stream.

Incorporation of these effects into Robertson's model is based on the use of gap acceptance theory as described by Cleveland and Capelle (*B-3*), which indicates that a waiting vehicle will, on the average, accept a gap of between 3.3 and 5 9 sec. It is possible to relate this fact to the influence of driveways with measurable exit volumes using the procedure shown in Figure B-4. As shown in this figure, the traffic flow pattern is not affected for volume levels (percent saturation) which correspond to vehicle headways of less than the gap acceptance rate. However, when the volume level drops below a threshold that corresponds to vehicle headways in excess of the gap acceptance threshold, vehicles will begin exiting from the driveway at a constant average rate equal to the average driveway demand. Vehicles that were not able to leave the driveway when the main street volume did not provide adequate gaps must be added to the demand after the main street volume falls below the threshold.

Thus, in the figure the flow pattern downstream from the driveway is the sum of the main street flow pattern and the constant flow pattern from the driveway. When the threshold, *Vg*, is exceeded, the downstream flow pattern is equal to the main street flow pattern indicating that no vehicles are leaving the driveway. When the main street volume again falls below *Vg*, the driveway volumes are again added up to the *Vg* limit.

TABLE B-1

RECOMMENDED VALUES FOR *K*

K	Roadway Characteristics	Description of Conditions
.5	Heavy friction	Combination of parking, moderate to heavy turns, moderate to heavy pedestrian traffic, narrow lane width. Traffic flow typical of urban CBD.
.37	Moderate friction	Light turning traffic, light pedestrian traffic, 11- to 12-foot (3.4- to 3.6-meter) lanes, possibly divided. Typical of well-designed CBD arterial.
.24	Low friction	No parking, divided, turning provisions, 12-foot (3.6-meter) lane width. Suburban high-type arterial.

As noted in Figure B-4, the effect of vehicles turning into driveways should probably be treated as a constant average volume subtracted from the driveway exit demand.

The effects of right-turn-on-red can be incorporated into the model in the same manner as driveway exit volumes with the driveway located at the position of the upstream intersection.

An attempt to validate this model was made by collecting traffic flow patterns in Fairfax County, Virginia, for eastbound traffic on Route 29 east of Gallows Road. These data were collected for both off-peak conditions (3·03 to 3:33 p.m) and peak conditions (5:20 to 5:50 p.m.). In both cases, although relatively high driveway volumes in excess of 200 vph entering and 300 vph leaving were present, these volumes were not high enough to have a measurable influence on the shape of the platoon pattern.

This lack of sensitivity is a result of the fact that for the conditions measured, the net driveway volume was 108 vph

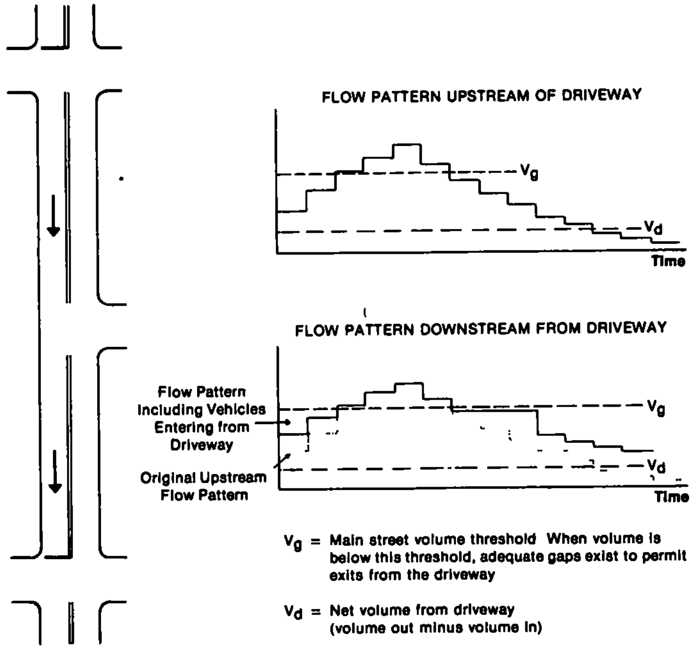


Figure B-4. Application of traffic flow pattern procedures to mid-block sources of vehicles.

which corresponds to a rate of 0.12 veh per 4 sec. This is significantly less than the 1 to 5 veh per 4 sec that are typical volumes for the development of the platoon pattern.

Thus, in order for this aspect of the model to have an influence on the development of a platoon flow pattern, net driveway exit volumes must at least exceed 0.5 veh per 4 sec, or 450 vph. However, under these conditions, it is likely that the minimum vehicular volumes for warrant 1 for traffic signalization would be exceeded (*B-4*). As a result, it would be likely that the driveway would be signalized with the result that the flow pattern could be computed directly. For this reason, the model refinement, to include driveway exit volumes, will not generally be required.

Computation of Flow Patterns

The traffic flow pattern arriving at an intersection approach is a result of the combined effects of platoon discharge through street traffic flow and turning movements during upstream red. Because it is the objective of this project to develop a manual procedure that will serve as the basis for the development of these profiles, it is desirable to be able to consider each of the effects of these three traffic flow categories independently. In order to determine whether they can in fact be treated in this manner, it is necessary to prove that the calculated traffic flow estimated at the downstream intersection approach is independent of whether Robertson's flow dispersion model is applied to the sum of the traffic flows, or the model is applied to each flow source independently and the resulting model outputs are summed. This can be stated mathematically in the following terms:

If

$$q'_{(i+t)} = F \times q_{(i)} + (1 - F) \times q'_{(i+t-1)} \qquad \text{(B-1)}$$

$$q_{(i)} = q_{1(i)} + q_{2(i)} + \ldots + q_{n(i)} \qquad \text{(B-2)}$$

and

$$\begin{aligned} q'_{1(1+t)} &= F \times q_{1(i)} + (1 - F) \times q'_{1(i+t-1)} \qquad \text{(B-3)} \\ q'_{2(i+t)} &= F \times q_{2(i)} + (1 - F) \times q'_{2(i+t-1)} \\ &\vdots \\ q'_{n(i+t)} &= F \times q_{n(i)} + (1 - F) \times q'_{n(i+t-1)} \end{aligned}$$

Then the problem is to prove that:

$$q'_{(i+t)} = q'_{1(i+t)} + q'_{2(i+t)}\, T \ldots q'_{n(i+t)} \qquad \text{(B-4)}$$

In the preceding statement of the problem, Eq. B-1 will be recognized as Robertson's platoon dispersion model. The notation used is consistent with the notation used in previous sections; $q_{1(i)}$, $q_{2(i)}$, and $q_{n(i)}$ are the component sources of traffic flow that make up $q_{(i)}$.

The desired proof is arrived at by substituting Eq. B-2 into Eq. B-1, which gives:

$$\begin{aligned} q'_{(i+t)} = F[q_{1(i)} + q_{2(i)} + \ldots + q_{n(i)}]\, t_1\, (1 - F) \\ \times q'_{(i+t-1)} \qquad \text{(B-5)} \end{aligned}$$

Then for $i = 0$,

$$q'(t) = F[q_1(0) + q_2(0) + \ldots + q_n(0)] \qquad \text{(B-6)}$$

For $i = 1$,

$$\begin{aligned} q'(1 + t) = F[q_1(1) + q_2(1) + \ldots + q_n(1)] \\ + (1 - F) \times q'(t) \qquad \text{(B-7)} \end{aligned}$$

Substituting Eq. B-6 into Eq. B-7 for $q'(t)$ gives:

$$\begin{aligned} q'(1 + t) = F[q_1(1 + q_2(1) + \ldots + q_n(1)] + (1 - F) \\ \times \{F[q_1(0) + q_2(0) + \ldots + q_n(0)]\} \end{aligned}$$

Collecting terms:

$$\begin{aligned} q'(1 + t) = {} & [Fq_1(1) + (1 - F) \times F_q1(0)] \\ & + [Fq_2(1) + (1 - F) \times Fq_2(0)] \\ & + \ldots + [Fq_m(1) + (1 - F) \times Fq_n(0)] \end{aligned}$$

But this expression could be rewritten as:

$$q'(1 + t) = q_1'(1 + t) + q_2'(1 + t) + \ldots + q_n'(1 + t)$$

In a similar manner, it can be shown that

$$q'(2 + t) = q_1'(2 + t) - q_2'(2 + t) + \ldots + q_n'(2 + t)$$

Or, in general:

$$q'_{(i+t)} = q'_{1(i+t)} + q'_{2(i+t)} + \ldots + q'_{n(i+t)}$$

Therefore, it is concluded that the individual flow patterns can be calculated separately and added to complete the aggregate pattern at the downstream intersection.

USE OF FLOW PATTERNS TO COMPUTE STOPS AND DELAY

The computation of stops and delays from the derived flow patterns is based on the delay relationships developed by Gartner (*B-5*) and validated on Bloor Street in Toronto. Using Gartner's nomenclature, a signal cycle C is made up of effective red time, r, and green time, g, such that:

$$C = r + g \qquad \text{(B-8)}$$

He also defines a reference for the beginning of green as the 0 time point so that the effective red period can be represented as the time period $-r < t \leq 0$, and the effective green period is represented as the time period $0 < t \leq g$. Then, using the following notation:

$q_a(t)$ = arrival rates as a function of time, veh/sec, corresponding to the arrival flow patterns;
$q_d(t)$ = departure rate as a function of time, veh/sec, corresponding to the departure flow pattern; and
S_o = saturation flow rate corresponding to the queue discharge rate, veh/sec.

It is then possible to calculate the cumulative arrival rate, $A(t)$, and the cumulative departure rate, $D(t)$, as:

$$A(t) = \int_{-r}^{t} q_a(t)\,dt \qquad \text{(B-9)}$$

$$D(t) = \int_{-r}^{t} q_d(t)\,dt \qquad \text{(B-10)}$$

Assuming that arrivals are periodic, i.e., $q_a(t) = q_a(t - nC)$, the signal is undersaturated, i.e., $A(g) < gS_o$, and the arrival flow rate does not exceed the saturation flow rate, i.e., $q_a(t) < S_o$, it is possible to conclude that once the queue has vanished during a given green period, it cannot begin to reform until the start of the next red period.

Using Eqs. B-8 through (B-10), and the foregoing assumptions, it is possible to compute the queue length at any point in time as the difference between the arrivals and departures. Or, in other words:

$$Q(t) = A(t) - D(t) = \begin{cases} A(t) & \text{for } -r < t \leq 0 \\ A(t) - tS_o & \text{for } 0 < t \leq t_o \\ 0 & \text{for } t_o < t \leq g \end{cases} \qquad \text{(B-11)}$$

where t_o denotes the point in time at which the queue disappears. According to the previously stated assumptions, this must occur prior to the end of green or $(0 \leq t_o < g)$. Obviously from Eq. B-11, $t - t_o$ when:

$$Q(t_o) = A(t_o) - t_oS_o = 0 \qquad \text{(B-12)}$$

Using these relationships, it is then possible to represent delay, d, as the area under the queue length curve:

$$d = \int_{-r}^{0} Q(t)\, d(t) + \int_{0}^{t_o} Q(t)\, dt \qquad \text{(B-13)}$$

Thus, delay is represented as the area under the curve of queue length as a function of time, and stops is represented as the total number of arrivals during the time period for which a queue exists.

Substituting Eq. B-11 into Eq. B-13 yields:

$$d = \int_{-r}^{0} A(t)\, dt + \int_{0}^{t_o} (A(t) - tS_o) dt \qquad \text{(B-14)}$$

Substituting Eq. B-9 into Eq. B-14 gives the expressions for delays in terms of the arriving flow pattern $q_a(t)$ as:

$$d = \int_{-r}^{t_o} \int_{-r}^{t_o} q_a(t) dt dt - \frac{1}{2} t_o^2 S_o \qquad \text{(B-15)}$$

As discussed in preceding sections, the arrival flow patterns are approximated by either measuring or computing their values for discrete time increments, T. It is recommended that a value of $T = 4$ sec be used. Thus, the integral of Eq. B-15 can be replaced with the following summation:

$$d = T^2 \sum_{n=-r}^{t_o} \sum_{n=-r}^{t_o} q_a(n) - \frac{1}{2} t_o^2 S_o \qquad \text{(B-16)}$$

The equation for stops, s, can be derived in a similar manner. Stops will be equal to the total number of vehicles arriving while the queue exists. Thus:

$$s = \int_{-r}^{t_o} q_a(t) dt \qquad \text{(B-17)}$$

When processing vehicle arrivals for a discrete arrival pattern, stops can be estimated as:

$$s = T \sum_{n=-r}^{t_o} q_a(n) \qquad \text{(B-18)}$$

Equations B-16 and B-18 then form the basis for the computation of the benefits of signal coordination described in the test and in the signal selection guidelines.

CONCLUSIONS

On the basis of the activities described in this appendix, it is concluded that flow patterns can be reliably estimated from a knowledge of the upstream intersection and that midblock driveways will have a negligible effect on the structure of the arriving platoons. It is further concluded that stops and delays can be estimated from these flow patterns using simple algebraic summations. The implementation of these calculations is discussed in the main body of this report. A step-by-step procedure for the calculations is given in the signal selection guidelines.

The promising results of the developments described in this appendix could provide the basis for additional research to further refine the platoon dispersion factors and quantify the effects of various types of traffic impedances.

REFERENCES

B-1. ROBERTSON, D. I., *TRANSYT: A Traffic Network Study Tool.* Road Research Laboratory, *Report LR 253,* Crowthorne, England (1969).

B-2. LAM, J. K., "Studies of a Platoon Dispersion Model and Its Practical Implications." *Proc.,* Seventh International Symposium on Transportation and Traffic Theory, Kyoto, Japan, published by the Institute of Systems Science Research, Kyoto.

B-3. CLEVELAND, D. E., and CAPELLE, D. G., "An Introduction to Traffic Flow Theory." *HRB Special Report 79* (1964) pp. 57-59.

B-4. U.S. Department of Transportation, Federal Highway Administration. *Manual on Uniform Traffic Control Devices for Streets and Highways* (Nov. 13, 1970) p. 236.

B-5. GARTNER, N., "Microscopic Analysis of Traffic Flow Patterns for Minimizing Delay on Signal-Controlled Links," *HRB Record 445* (1973) pp. 13-15.

APPENDIX C

VALIDATION OF SIMULATION MODEL

It was the original intent of this project to use field data for the baseline data which would form the starting point for simulation studies. The simulation results would then be used to interpolate and extrapolate the results of the field data collection.

This concept was followed to a certain extent. However, it was difficult to identify the precise set of circumstances in the field with the specific conditions required to form a good starting point for the simulation activities. Furthermore, the initial plans to collect data at 10 sites could not represent all of the cases to be studied. Thus, the data collected in the field were used more for the validation of the simulation rather than as the basis for the actual comparisons made during this project. The high quality of the validation results as well as the consistency of the simulation results with the data presented by other researchers led to the conclusion that the simulation data presented in this report are a reliable representation of controller performance under real-world conditions.

The field data collection procedures were developed after a review of the various ways in which delay data could be collected. This review relied on the information presented in Reilly and Gardner's, "Technique for Measurement of Delay at Intersections" (*C-1*). They recommend that the point sample stopped delay method be used for field measurement of delay.

This method, also known as the Berry-Vantil procedure, is outlined by Box and Oppenlander (*C-2*). It is based on a periodic sample of the number of stopped vehicles on the intersection approach—a series of instantaneous samples having an interval of time between each sample.

The number of vehicles actually stopped in the approach at the start of the sampling time was recorded. At each consecutive 15- or 13-sec interval the number of vehicles stopped in queue was recorded in the appropriate columns of the data sheet (see Figure C-1). At the same time a count was made of the total approach volume in two separately tabulated categories· the number of approach vehicles stopping and the number of approach vehicles not stopping. Thirteen-second intervals were used for fixed-time signals, while either 13- or 15-sec intervals were used for fully actuated signals.

It was found useful and timesaving to have a tape recorder that gave the data collector a cue at each 13-sec interval. Using the tape recorder eliminated the need for the collector to be constantly checking a stop watch and, thus, his full attention could be focused on counting vehicles. It was also possible to have two people share the recorder and each count an approach, provided there was good visual access to the respective approaches.

The sample size required for at least a 90 percent confidence level was 50 vehicles. The information calculated from the data included total delay (vehicles per second), average delay per stopped vehicle (seconds), average delay per approach vehicle (seconds), and percentage of vehicles stopped (percent).

The conditions existing at the five sites at which field data collection was performed are given in Table C-1. These sites represent a range of intersection phasing (2 to 6 phases) and controller types. These sites are all isolated intersections in the sense that the distance to the closest upstream intersection is greater than ½ mile

The simulation and field data results are compared in Table C-2. The simulation results were obtained by duplicating the controller settings, traffic, and roadway conditions. In all cases, the error in delay between simulation and field data was 15 percent or less. The error in stops was greater than 15 percent This increase in error is probably due to two factors:

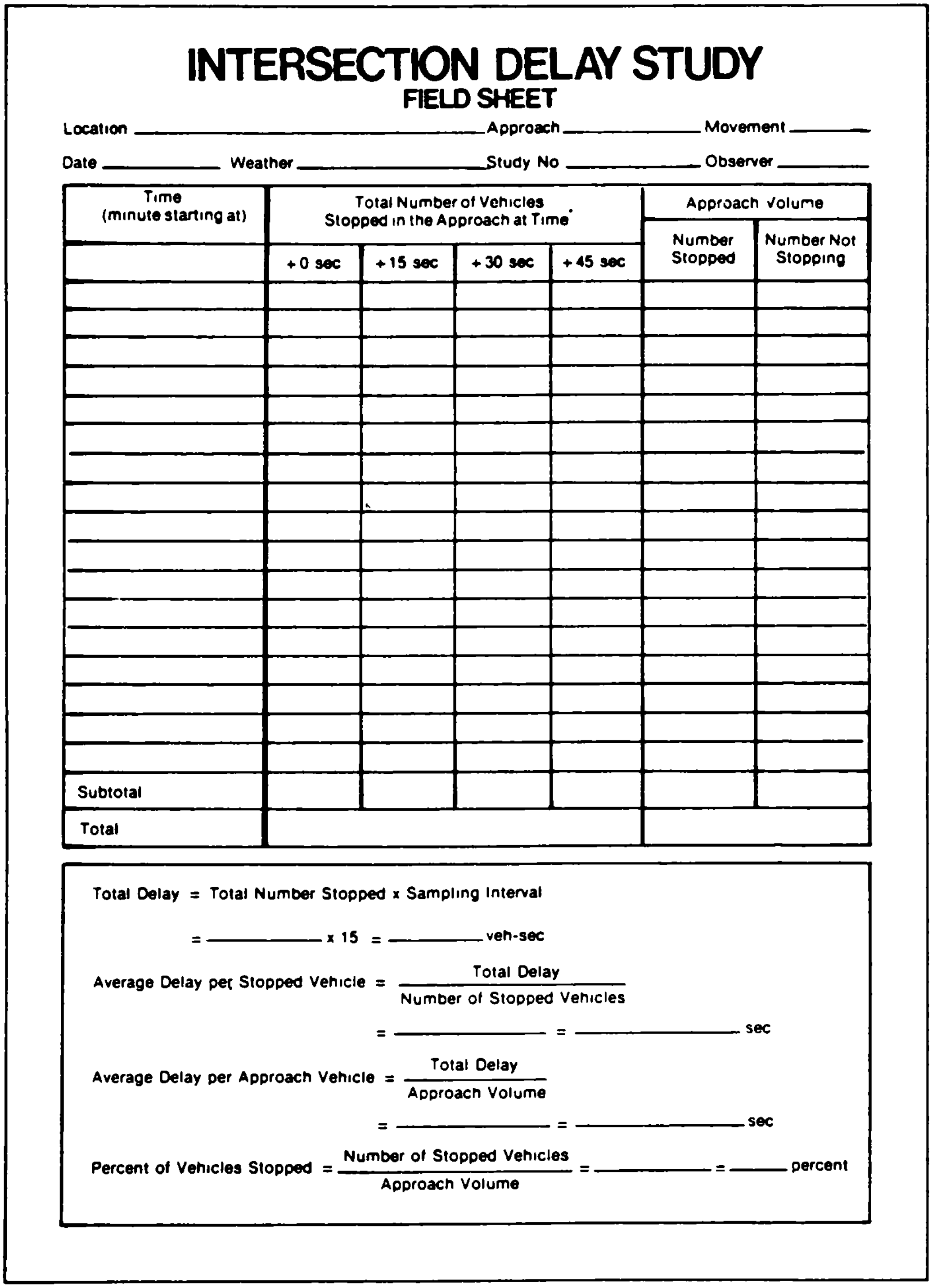
1. Measurement of stops in the field is extremely difficult because of the problem of defining a stopped vehicle. Many motorists will anticipate the need to stop and creep at a slow speed prior to the change in signal state. The field data collection team was instructed to interpret slow moving vehicles as stopped vehicles, which apparently led to the basis of consistently higher values for stopping in the field.
2. Simulation runs have consistently shown stops to have a high variance from cycle to cycle. Thus, the sample size required for field measurement of stops is greater than that required for delay. As a result, larger errors can be anticipated.

On the basis of these results, it was concluded that the NETSIM simulation would provide a reliable tool for the evaluation of signal control performance on this project. Emphasis was placed on the use of NETSIM for the data presented in this report.

REFERENCES

C-1. Reilly, W. R., and Gardner, C. C., "A Technique for Measurement of Delay at Intersections." Presented to Transportation Research Board Fifty-Sixth Annual Meeting (Jan. 25, 1977).

C-2. Box, P. C., and Oppenlander, J. C., *Manual of Traffic Engineering Studies*. Institute of Transportation Engineers, Arlington, Virginia, Fourth Edition (1976).



INTERSECTION DELAY STUDY

FIELD SHEET

Location ________________ Approach ________ Movement ______

Date ________ Weather ____________ Study No ________ Observer ______

Time (minute starting at)	Total Number of Vehicles Stopped in the Approach at Time*				Approach Volume	
	+0 sec	+15 sec	+30 sec	+45 sec	Number Stopped	Number Not Stopping
Subtotal						
Total						

Total Delay = Total Number Stopped x Sampling Interval

= ________ x 15 = ________ veh-sec

Average Delay per Stopped Vehicle = $\dfrac{\text{Total Delay}}{\text{Number of Stopped Vehicles}}$

= ________ = ________ sec

Average Delay per Approach Vehicle = $\dfrac{\text{Total Delay}}{\text{Approach Volume}}$

= ________ = ________ sec

Percent of Vehicles Stopped = $\dfrac{\text{Number of Stopped Vehicles}}{\text{Approach Volume}}$ = ________ = ________ percent

Figure C-1 Sample field sheet for intersection delay study as arranged for 15-sec time intervals

TABLE C-1

FIELD DATA COLLECTION SITES

Site Number	Location	Left Turns (%)	Total Volume (VPH)	Number of Turn Lanes	Number of Phases	Type Controller	Controller Model
1	River Rd. and Bradley Blvd., Md.	16	1,015	1	2	Semi Actuated	Econolite D-2000
2	Sully Rd. and Rt. 606, Va.	14	979	1	2	Full Actuated	Automatic Signal 807R
3	Rt. 50 and West Ox Rd., Va.	18	1,971	2 on Route 50 1 on West Ox	6*	Volume Density	Automatic Signal 90B
4	Braddock Rd. and Ravensworth Rd., Va.	24	1,968	2 on Braddock Rd. 1 on Ravensworth	3	Full Actuated	Automatic Signal 1826 NM2
5	Rt 236, Old Columbia Pike and Columbia Rd., Va.	7	1,165	2 on Rt. 236 1 on Columbia	3	Full Actuated	Automatic Signal 1826 NM2

* Dual ring controller

TABLE C-2

SIMULATION AND FIELD DATA RESULTS

Site Number	Delay (Sec/Veh) Field	Delay (Sec/Veh) Simulation	Delay (Sec/Veh) % Error	Stops (%) Field	Stops (%) Simulation	Stops (%) % Error
1	11.3	12.95	15	41	25	29
2	14.2	14.2	0	63	60	5
3	18.9	21.8	15	67	62	7
4	13.0	14.3	10	59	49	17
5	9.9	11.0	11	28	28	0

APPENDIX D

ESTIMATING THE EFFECTS OF EXTENSION ON LOST TIME

The lost time for an intersection approach is a function of the extension setting on the controller and the headways between the approaching vehicles. This lost time, L, will be the product of the expected value of the lost time, $E[L]$, and the number of vehicles, V, arriving during the phase. These values are given by Eqs. D-1 and D-2, respectively.

$$E[L] = \int_2^X (T-2)P(T)dT \qquad \text{(D-1)}$$

where T = headway between vehicles, and X = controller extension.

$$V = (\text{Phase length}) \times (\text{Vehicle arrival rate}) \qquad \text{(D-2)}$$

Assuming a Poisson distribution of vehicle arrivals, $P(T)$, in Eq. D-1,

$$P(T) = \lambda e^{-\lambda T} \qquad \text{(D-3)}$$

where

$$\lambda = \text{vehicle arrival rate} = \frac{\text{Vol (vph)}}{3600}$$

Substituting Eq. D-3 into Eq. D-1 gives:

$$E[L] = \int_2^X (T-2)\,\lambda e^{-\lambda T}\,dT \qquad \text{(D-4)}$$

Integrating this expression gives the result:

$$E[L] = e^{-\lambda X}\left(2 - X - \frac{1}{\lambda}\right) + \frac{1}{\lambda}\,e^{-2\lambda} \qquad \text{(D-5)}$$

Solving Eq. D-2 to obtain the number of vehicles arriving during a phase gives:

$$V = P \times \lambda \qquad \text{(D-6)}$$

where P = phase length.

In Eq. D-6, the phase length, P, is calculated as the product average number of vehicles that pass through the intersection before the headway between two successive vehicles exceeds the extension, causing the termination of the phase, and the average vehicle headway. Thus:

$$P = \frac{1}{P[T \geqq X]} \, \frac{1}{\lambda} \qquad \text{(D-7)}$$

where $P[T \geqq X]$ = the probability of a vehicle headway greater than the extension.

Using the assumption of Poisson arrivals:

$$P[T \geqq X] = e^{-\lambda X} \qquad \text{(D-8)}$$

Substituting Eqs. D-7 and D-8 into Eq. D-6 gives the result

$$V = \frac{1}{e^{-\lambda X}} \qquad \text{(D-9)}$$

The lost time, L, is then the product of Eqs. D-5 and D-9. In other words:

$$L = \left(2 - X - \frac{1}{\lambda}\right)\frac{1}{\lambda}\, e^{-\lambda(2-X)} \qquad \text{(D-10)}$$

The units of λ in this expression are vehicles per second. If approach volume in vehicles per hour is used, this equation becomes:

$$L = \left(2 - X - \frac{3600}{V}\right) + \frac{3600}{V}\, e^{-\frac{V(2-X)}{3600}} \qquad \text{(D-11)}$$

For the range of lane volumes between 600 and 1200 vph, average values of L as a function of vehicle extension were calculated and are as follows:

Extension	Lost Time
2.5	0.68
3.0	1.15
3.5	1.85
4.0	2.58
4.5	3.48
5.0	4.51

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