NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT **124**

IMPROVED CRITERIA FOR TRAFFIC SIGNAL SYSTEMS IN URBAN NETWORKS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
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IMPROVED CRITERIA FOR TRAFFIC SIGNAL SYSTEMS IN URBAN NETWORKS

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OF STATE HIGHWAY OFFICIALS IN COOPERATION
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AREAS OF INTEREST:
TRAFFIC CONTROL AND OPERATIONS
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HIGHWAY RESEARCH BOARD
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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

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

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

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

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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

The opinions and conclusions expressed or implied in these reports are those of the research agencies that performed the research. They are not necessarily those of the Highway Research Board, the National Academy of Sciences, the Federal Highway Administration, the American Association of State Highway Officials, nor of the individual states participating in the Program.

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FOREWORD

By Staff
Highway Research Board

This report will be of interest to all traffic engineers, traffic control manufacturers, and operations research scientists responsible for the efficient timing of urban network traffic signal systems. By use of computer simulation techniques and real-life field testing, several methods of operating a network of urban traffic signals were scientifically tested to determine the comparative effectiveness of alternate timing methods. This research indicates that significant improvements in traffic operations may be achieved through application of better timing methods. For the practicing traffic engineer, a special chapter on applications is included. A thorough search of the literature has been completed, and a listing of select references is presented.

This report stem from NCHRP Project 3-5, entitled "Improved Criteria for Designing and Timing Traffic Signal Systems." Previously completed NCHRP research involving improved signal timing methods for isolated intersections has been published as *NCHRP 3* and *32*. Improved methods for timing signals on arterial streets are presented in *NCHRP Report 73,* "Improved Criteria for Traffic Signal Systems on Urban Arterials." On completion of the urban arterial phase of research, the project was extended to include this study of signal timing methods for an urban street network.

This research by the Planning Research Corporation and Alan Voorhees and Associates 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 improving traffic operations through simple modifications of fixed-time signal 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. The following concepts were employed in various combinations as tools in developing alternative signal timing plans: (1) Webster's cycle and split optimization method; (2) the delay-difference method for optimizing signal offsets; (3) the volume-priority method of establishing a network offset plan; (4) the preferential street method of establishing a network offset plan; (5) the mixed-cycle method of signalized network operation; (6) Little's maximal bandwidth method for optimizing offsets; (7) the SIGOP traffic signal optimization method; (8) the British combination method for optimizing offsets; and (9) Allsop's graph theory method for optimizing offsets. One tactical control concept, the basic queue control technique, was also studied.

Two California grid networks were used as test sites—a 26-intersection network in Los Angeles, and a 22-intersection network in the San Jose CBD. Simulation tests were conducted in the Los Angeles network for 3:00 to 6:00 PM traffic conditions. The tests were divided into offpeak and peak subperiods of 90 minutes each. In San Jose, simulation tests were performed for the 4:00 to 6:00 PM traffic conditions. Comprehensive field studies were conducted in Los Angeles after the simulation tests. Two purposes were served: (1) three different signal system timing alternatives were tested under actual operating conditions; and (2) large quantities of operations data were gathered to test the validity of the simulation predictions.

This project was heavily applications oriented, and conscious efforts were made to emphasize investigation of improved traffic control techniques that could be used immediately and widely, without expending large sums of money. The research results are in easy-to-understand terms and are specific enough to permit the signal optimization procedures to be used immediately by state traffic engineering departments. Future research could be devoted to the development, simulation testing, and full-scale experimentation with innovative methods for coping with severe oversaturation in signalized street networks.

CONTENTS

ACKNOWLEDGMENTS

The research project reported herein was conducted by a team comprising traffic engineering specialists from Alan M. Voorhees & Associates and computer systems specialists from its parent firm, Planning Research Corporation (PRC). Frederick A. Wagner, Jr., and Frank C. Barnes served as co-principal investigators. Dr. Daniel L. Gerlough made important contributions on assignment as senior consultant to the research team. Key PRC personnel assigned to the project were Nancy A. Bryant and Victoria A. King, experienced computer systems specialists. Margaret A. Tutone supported the project staff as administrative assistant throughout the course of the project.

The Bureau of Research of the Los Angeles City Traffic Department, headed by Deane S. Terry, Jr., Senior Traffic Engineer, fulfilled an invaluable cooperative role in this project by providing engineering consultation, signal system modifications planning and implementation, and specialized traffic data collection and processing. The research team is indebted to Mr. Terry and his staff for their valuable contribution to the success of this project.

The Department of Public Works of the City of San Jose also provided valuable assistance and cooperation. E. E. Mahoney, Traffic Control Project Engineer, participated enthusiastically on many occasions in meetings to plan and discuss the research relating to San Jose, and was most helpful in assisting with the compilation of control system data needed for the study. His assistance is gratefully acknowledged.

Special thanks go to R. E. Allsop of University College, London, for supplying valuable information and computer programs developed by him. Thanks are due also to Dr. Tony M. Ridley and K. W. Huddart of the Greater London Council, for supplying the GLC signal timing program and notes concerning its operation. Appreciation is also extended to John A. Hillier of the British Road Research Laboratory, who kept the research team up to date on developments in the Glasgow traffic control project.

IMPROVED CRITERIA FOR TRAFFIC SIGNAL SYSTEMS IN URBAN NETWORKS

SUMMARY

This research project 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 but inexpensive methods of improving street system operation through simple modifications of fixed-time signal settings. The secondary objective was to verify the ability of computer simulation methods to predict accurately the effects of signal timing modifications. Thorough field studies, under different traffic control conditions, were conducted for this purpose.

A large number of traffic signal timing plans were developed for controlled testing by simulation. The following concepts were employed in various combinations as tools in developing alternative signal timing plans: (1) Webster's cycle and split optimization method; (2) the delay-difference method for optimizing signal offsets; (3) the volume-priority method of establishing a network offset plan; (4) the preferential street method of establishing a network offset plan; (5) the mixed-cycle method of signalized network operation; (6) Little's maximal bandwidth method for optimizing offsets; (7) the SIGOP traffic signal optimization method; (8) the British combination method for optimizing offsets; and (9) Allsop's graph theory method for optimizing offsets. One tactical control concept, the basic queue control technique, was also studied.

Two grid networks were used as test sites: a 26-intersection network in Los Angeles, and a 22-intersection network in the San Jose CBD. Simulation tests were conducted in the Los Angeles network for 3:00 to 6:00 PM traffic conditions. The tests were divided into offpeak and peak subperiods of 90 min each. In San Jose, simulation tests were performed for the 4:00 to 6:00 PM traffic conditions.

For the Los Angeles offpeak conditions, 11 separate signal system timing alternatives were simulated. All of the alternatives tested were substantially more effective than the existing timing plan. Average network speed was increased from approximately 17 mph to the range of 20 to 21 mph for the improved timing plans. In other words, network speed was increased by 18 to 22 percent.

For the Los Angeles peak conditions, 15 separate alternatives were simulated. All but one of the alternatives were significantly more effective than the existing timing plan. For 10 of the improved plans, average network speed was increased from the existing level of 15.4 mph to the range of 18 to 19 mph. In other words, average network speeds for the 10 best alternatives were 17 to 24 percent higher than the existing speed.

For the San Jose network, nine different signal control alternatives were simulated. The existing system is operated by an IBM 1800 traffic control computer using a library of strategic timing plans. The level of improvement produced by the

alternative control concepts was substantially lower than in the Los Angeles tests. Network speed for the best alternative was approximately 5 percent higher than the existing speed. However, substantial improvements in operation were produced only when the cycle length was reduced. These findings are not unreasonable, because existing signal operation is the product of continuing intensive operational analysis by the traffic control project staff.

Comprehensive field studies were conducted in Los Angeles after the simulation tests. Two purposes were served: (1) three different signal system timing alternatives were tested under actual operating conditions; and (2) large quantities of operational data were gathered to test the validity of the simulation predictions. The results of the field verification studies were excellent. The degree of improvement in network performance predicted by the simulation was closely approximated in the field studies.

The research team believes that many of the traffic signal system timing methods developed in this project can immediately be applied in practice. Traffic engineers are strongly urged to initiate systematic signal operations analysis and improvement programs in which selected techniques studied here can be implemented.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

This research project is the last major phase in a research series on "Improved Criteria for Designing and Timing Traffic Signal Systems" sponsored by the National Cooperative Highway Research Program (NCHRP). The first major phase of work, conducted from July 1963 to December 1965, involved the modeling of individual intersection operation and control, and development and controlled testing of alternative traffic signal control concepts. The second major phase, performed from July 1966 to July 1967, extended the research approach to the study of operation and control along urban arterial streets. The prior research was published in *NCHRP Reports 3, 32,* and *73* (*1, 2, 3*).

The earlier research efforts showed that computer simulation of traffic operation can perform an important role in the development of improved design and operation of traffic signal systems. Simulation serves essentially as a useful middle ground between theoretical or conceptual design and full-scale installation and evaluation of new or modified systems. More important, the earlier research demonstrated that significant improvements in traffic operation can be obtained through the application of relatively inexpensive traffic signal system improvements.

This research project used previously developed simulation techniques to pursue the study of improved operation of traffic signal systems in urban street networks.

PROJECT OBJECTIVES

The principal objective of this research was to formulate, test and evaluate (by simulation), and verify (by field testing) alternative methods of traffic signal system control for urban street networks. Emphasis was directed specifically to the evaluation of traffic signal system improvement techniques that could be applied by traffic engineering agencies over the short term without necessitating major investments of resources, including time, for complex systems development work. Special attention was devoted to field verification studies designed to reliably determine the validity of the simulation model's predictions of the effects of changes in the traffic signal system.

PROJECT TASKS

The project objectives were pursued through performance of the following project tasks:

1. Prepare and submit a detailed working plan, including a work-flow diagram by task and time, for review by the NCHRP Projects Engineer. As part of the detailed working plan, establish cooperative arrangements with one or more municipal traffic engineering agencies for assistance in the performance of full-scale field tests of improved traffic signal system control.

2. Review recently published literature, and investigate progress of closely related research activities dealing with improved operation of traffic signal systems in urban networks. Prepare preliminary descriptions and discussions of alternative traffic signal control techniques for urban networks.

3. With the assistance of cooperating, operating agencies, select street networks containing approximately 15 to 30 signalized intersections that will serve as pilot areas for testing and evaluating improved traffic signal operation methods.

4. Compile an inventory of physical characteristics, traffic regulation and control characteristics, and traffic flow characteristics in the selected test networks. Prepare plans for special empirical traffic operations data acquisition in the test networks required as input data for determining signal system improvements, for simulation, and for full-scale measurement and evaluation of network performance.

5. Formally define traffic signal system operation alternatives to be investigated, concentrating on readily implementable methods of strategic modification of the existing signal system and giving secondary attention to experimental traffic-responsive concepts of control.

6. With the assistance of cooperating, operating agencies, acquire special data required as input for traffic signal timing computation programs and the TRANS simulation model.

7. Perform detailed preparation of traffic signal system control improvements, including (1) operation of special computer programs to yield strategic modifications of fixed-time settings in the test networks, and (2) preparation of special subroutines for inclusion in the TRANS model to simulate selected experimental traffic-responsive concepts.

8. Using the TRANS simulation model, conduct, analyze, and interpret controlled tests of the effectiveness of the traffic signal system control alternatives selected for each of the test networks, under a pertinent range of traffic demand conditions encompassing peak-period and offpeak-period conditions.

9. With the assistance of the cooperating, operating agencies, implement one or more promising traffic signal operation alternatives in the field, and gather traffic operations data to evaluate the effect of traffic signal system modifications and to verify the results of simulation analyses.

CHAPTER TWO

FINDINGS

DEVELOPMENT OF ALTERNATIVE CONTROL CONCEPTS

Literature Review

The first step in the development of network control concepts was the review of recently published literature and activities dealing with improved operation of traffic signal systems. In accordance with the research plan, heavy emphasis was placed on the review of strategic techniques of signal system improvement that involve development of predetermined signal settings for networks. It was the research agency's judgment that the greatest payoff—in terms of rapid application of research results—could be obtained by emphasizing research on strategic methods. It was the specific intention of this project to produce results concerning the effectiveness of signal timing techniques that could be employed immediately by traffic engineering agencies without new investments in traffic control hardware.

As a result of the initial screening of literature, only cursory attention was given to research on tactical control techniques for urban networks. Because tactical control methods involve extensive traffic sensing, communications, and real-time execution of control decisions, the practical implementation of such methods in urban networks requires substantial investments of time and capital for system development. Interestingly, even in systems employing centralized digital computer control of traffic signals (such as in San Jose and Wichita Falls), the predominant underlying control concept is still strategic in nature. Several predetermined signal timing plans are stored in memory and called into operation as traffic conditions and decision rules dictate. Hence, a key problem even in the computerized systems is how to develop the most effective fixed-time plan for a given set of traffic flow conditions in the network. Research concerning tactical techniques must be considered of longer-range interest; thus, larger time periods must be allowed for payoff in the form of extensive practical implementation. The research agency believes that the San Jose control system is the only one in the United States at present (1969) with a sufficient concentration of traffic sensing to take immediate advantage of tactical network control concepts.

In keeping with the preceding reasoning, the bulk of the time devoted to literature review was spent in detailed study of candidate strategic control methods that had not previously been investigated in depth. Among the new concepts studied were the SIGOP traffic signal optimization program (*4, 5, 6*); the Road Research Laboratory (in England) combination method (*7, 8, 9, 10*); the Allsop graph theory method (*11, 12, 13*); and Robertson's Traffic Network Study Tool, TRANSYT (*14, 15*). All of these techniques, with the exception of TRANSYT, were used in developing signal timing plans for testing by simulation. Also, techniques that had been used extensively by the research agency in the prior research phase concerning traffic signal systems on urban arterials were used again in this project. Specifically, Webster's optimization of cycles and splits (*16*), Little's maximal bandwidth model (*17*), and the delay-offset difference method developed by the research agency (*3*) were used as tools in developing control alternatives.

With the exception of SIGOP and TRANSYT (the latter of which is not programmed for operation on any U.S. computer), it should be understood that the various concepts mentioned do not by themselves produce complete signal timing plans (cycles, splits, and offsets). The manner in which various techniques can be used in concert to produce complete plans will become evident in the subsequent descriptions of control alternatives.

SIGOP

The SIGOP Traffic Signal Optimization Program is the result of approximately three years of development, testing, and refinement by Peat, Marwick, Livingston and Co. under contract to the Federal Highway Administration. Given a set of data describing the geometrics of a signalized street network and traffic characteristics for a given period of interest, the function of SIGOP is to determine an optimum plan of cycle length, phase splits, and offsets for the traffic signals in the network. The SIGOP program consists of six program blocks, written in FORTRAN IV, which perform the following functions:

1. Read and check for logic and consistency the input data supplied by the user.
2. Compute and tabulate proper phase splits for each intersection.
3. Compute and tabulate ideal offset differences between each pair of intersections.
4. Determine the optimum offset plan that maximizes a weighted sum of stops and delays in the network.
5. Perform a coarse simulation of traffic operation under the optimum plan to estimate delays, stops, and cost in the network.
6. Tabulate recommended traffic timing plan, and print time-space diagrams for selected streets if desired.

Originally prepared for operation on the IBM 7094 computer, SIGOP was converted by Kelly Scientific Corporation for execution under the IBM System/360 Operating System (OS) (*18*). The program system has been successfully executed on the 360/50. All six program blocks can be executed singly or in an uninterrupted sequence.

SIGOP can be used for networks of any configuration up to a maximum size of 150 signalized intersections. The user can specify as many as 10 separate cycle lengths for which timing plans will be produced for a given optimization time period, and as many as 12 time periods can be processed in one computer run. The program will perform the evaluation process for an existing or otherwise predetermined timing plan if the cycle, splits, and offsets are specified as input. This is a useful feature of the program because it provides a method by which alternative plans can be compared. A warning is given to treat such comparisons with caution, however, because the simulation process used in SIGOP tends to be coarse for each independently evaluated link in the network.

The SIGOP *User's Manual* (*5*) provides complete instructions in the use of the program, including detailed explanations of input data and program output. One indication of the complexity of input data preparation is the fact that 18 separate input card types exist, each with its own data format. The program output is extensive, providing detailed information on a link and intersection basis. The number of pages of output generated is surprisingly large—even for the moderately sized networks studied in this project—and one is impressed that the volume of output would tend to become unwieldy for very large networks.

As discussed in the *User's Manual,* the input data required by the program include the following:

1. *Intersection data:*
   a. Identification and number.
   b. Number of signal phases.
   c. Phase sequence.
   d. Special vehicular or pedestrian interval times.
   e. Minimum green times.
   f. Minimum average platoon headways.
   g. Queue discharge headways.
   h. Passenger-car equivalence factors for trucks, buses, and turning vehicles.
2. *Link data:*
   a. Upstream and downstream intersection numbers.
   b. Total flow rate.
   c. Percentage of secondary flow.
   d. Turning movement percentage.
   e. Truck and bus percentage.
   f. Link length.
   g. Number of arrival and departure lanes.
   h. Average running speed.
   i. Platoon coherence coefficient.
   j. Relative link importance coefficient.
3. *Optimization parameters:*
   a. Relative importance of critical flow versus total flow.
   b. Relative importance of stops versus delay.

Study of the data requirements reveals that several of the input variables are at least partly judgmental. The program was purposely designed in this manner so that the traffic engineer can exercise his own judgment with respect to certain key factors. Although it may be argued that this characteristic of the SIGOP program is meritorious because individual engineering judgment must be deemed important, the fact that different traffic engineers using SIGOP could obtain substantially different signal timing plans of varying effectiveness is considered a disadvantage. Furthermore, the provision of user flexibility necessarily complicates the input data requirements. However, the research agency is inclined to agree with the developers of SIGOP that the advantages of flexibility outweigh the disadvantages.

British Combination Method

For the purposes of simplicity, the second new control concept investigated in detail has been termed the combination method. In actuality, it is a compendium of techniques developed and refined primarily by the Road Research Laboratory. As originally developed, the combination method consists of two basic ideas: (1) the obtaining of delay/difference-of-offset relationships for each network link; and (2) the combining of links in series and parallel arrangements in such a way that offsets, which minimize delay in the network, can be determined for each intersection. The principal simplifying assumption of the method is that, given the cycle length and splits at each signal, the delay to traffic in one direction along any link of a network depends solely on the offsets of the signal cycles at the two ends of the link.

The original combination method yields a complete solution only for networks that can reduced to a single link by successive combinations of links in series and parallel. This process of combining links has been termed "network condensation." Networks that can be reduced to single link by the combination process are called completely condensable networks. Appendix F presents a step-by-step example of the the combination method for a completely condensable network.

The difficulty that becomes immediately apparent when one deals with grid networks is that only the simplest network forms are completely condensable. For example, any grid network with at least three streets in both crossing directions cannot be condensed to a single link by the combination method. As shown in Appendix F, some networks can be conveniently split into parts for solution, but the complexities that arise as the network size grows severely restrict the use of the combination method as a practical tool.

The inability to deal with networks that are not completely condensable has been overcome by the graph theory method developed by Allsop. Once a network has been condensed as much as possible, the Allsop method proceeds to find optimum offsets by starting with one link and building the network by an iterative process, one or more links at a time. In addition to developing the technique for building the optimized network, Allsop prepared a set of computer programs (written in FORTRAN IV) that (1) condenses the network to the greatest possible extent by using the combination method; (2) determines the order in which an uncondensable network is to be built from subroutines; and (3) builds the network to find delay-minimizing offsets. These programs were obtained from Allsop and used to develop a control plan in one of the test networks.

The combination and Allsop optimization procedures must be preceded by two steps: (1) signal cycle length and phase splits must be determined by some other method (e.g., the Webster equations); and (2) delay-offset difference tables must be determined for each link in the network (e.g., by use of the research agency's delay-offset difference computer program).

The Greater London Council (*19*) has also prepared a computer program that executes the combination method. This program gives solutions only for networks that are condensable; it does not contain the Allsop optimization process. The principal advantage of the GLC program is the automatic computation of delay-offset tables for each link in the network. This information can be obtained for individual links, even though the network may not be condensable. Additional refinements include the use of a stop penalty and link weighting in the delay computation. Platoon dispersion can be included in the computation of the delay-offset difference tables.

The computer program is written in FORTRAN IV and is used regularly by GLC on its IBM 360/50 computer. The GLC program was obtained by the research agency and tested successfully on a simple trial network. The input data required include cycle lengths and phase splits, volumes of all movements at each intersection, saturation flow rate for each link, and undelayed travel times between signals. The input data formats tend to be complicated; full understanding requires a substantial period of study and trial applications.

The GLC program was not applied to develop control plans for test networks studied in this project because the networks were not the condensable type. In any event, the GLC program should be considered a refinement of the combination method and not a uniquely new control concept.

Volume Priority Method

The two control concepts discussed in previous sections (SIGOP and the combination method) are similar approaches to network signal timing in that they both involve formalized mathematical optimization procedures requiring computer processing for execution. The research agency saw the need to develop and test network signal timing methods based on less sophisticated grounds that would be simpler to understand and apply and that would rely less extensively on complicated computer methods. The volume priority method for obtaining signal offsets, described in this section, was one such technique.

In the volume priority method, the first step is to compile a ranking of all links in the network on the basis of traffic volume. For simplicity, when one is dealing with two-way streets, the two opposite direction links connecting two intersections are combined and considered as a single link. Hence, the ranking of links is based on bidirectional volume. (Alternatively, some other quantitative measure of link importance could be used to rank the links.) The next step is to assign offset differences between signals on a priority basis. The offsets at the two intersections connected by the highest volume link (or link pair) are assigned first to provide an optimum offset difference. Then, the second highest volume link is assigned its optimum offset difference, and so forth, until one encounters a link for which the offsets at both ends are already established. One continues down the priority list until the offsets at all intersections are established. In typical grid networks, approximately 60 percent of all link pairs in the system will be assigned optimum offset differences when this technique is employed.

As is the case with the combination method, the volume priority method must be preceded by two steps: (1) signal cycle length and phase splits must be determined by some objective method, and (2) the optimum or ideal offset difference must be determined. In developing control plans for this project, the research agency used the Webster method—consisting of simple equations—to determine cycle and splits. A refined version of the research agency's delay-offset difference program, which automatically combines opposite direction link pairs, was used to obtain optimum offsets.

The volume priority method, as described previously, relies on the computer as little as possible. Only one computer program (the delay-offset difference program) is used in conducting the procedure, and it is a program for which the input data are uncomplicated. Only one type of input card is used, and each link in the networks requires only one data card. Hence, it is believed this method is as simple and straightforward as any systematic procedure could be. One advantage of the method is that, once the ranking criterion has been agreed on by two or more persons, they all should obtain the same timing plan.

Preferential Street Method

Another relatively straightforward approach that does not incorporate a formal mathematical optimization process is the preferential street method. It is one of the approaches most widely used by traffic engineers for developing network timing plans. The engineer employs his judgment and the information at hand to decide which streets are to be favored in designing the offset plan for a network. The preferential streets must be selected in a manner that avoids closure of any portion of the network. In a grid network, this generally results in a pattern in which all but one of the preferential streets are parallel and only one preferential street crosses the others. The intersections along each street selected as a preferential one are then given offsets based on some systematic offset determination technique. In this project, two different offset determination techniques were used in conjunction with the preferential street method: (1) the delay-offset difference technique discussed previously, and (2) Little's maximal bandwidth technique (*17*).

As noted earlier, the delay-offset difference program is relatively uncomplicated to use. This is true as well for the maximal bandwidth program, which was tested with a high degree of success in the research agency's previous research concerning urban arterials (*3*). The bandwidth program can be considered an automated implementation of the traditional time-space diagram technique. Using the program not only saves time but, for a given street with given traffic characteristics, also always produces the same timing plan.

The principal disadvantage of the preferential street method is the likelihood that different engineers may select different streets as the preferential ones and thus produce different network timing plans, the effectiveness of which may vary significantly.

Mixed Cycle Length Method

The first four strategic control methods discussed in this report require the use of a constant system cycle length for all intersections during a given time period of the day. However, even in relatively small networks, major differences in the degree of saturation may exist at individual intersections, with corresponding major differences in the cycle length required to efficiently process traffic demands. The mixed cycle length method, as the name implies, permits different cycle lengths to be operating at the same time in the network. Parallel arteries (or even adjacent intersections) are operated on different cycle lengths, depending on the specific intersection volumes existing during a given period of the day. In essence, this approach involves dividing the network into subsystems composed of intersections with similar cycle length requirements. Then, the signals within each contiguous subsystem are optimized by one of the methods discussed earlier. Such an approach is generally considered anti-traditional, but promising results were obtained with the mixed cycle method in the research agency's previous research (*3*). In this project, the mixed cycle scheme was again tested successfully using the delay-difference, volume priority method for optimizing the network subsystems.

Basic Queue Control

As explained earlier, investigation of tactical control concepts was deemphasized in this project in favor of more detailed study of strategic methods that could be used widely without incurring major costs. Consequently, only one traffic-responsive concept was tested in this study—the basic queue control method that had been developed and tested for individual intersection control and for arterial control in previous research phases (*2, 3*).

The essence of the basic queue control concept is to determine the length of each green interval by a computational estimate of the time needed to discharge the longest single-lane queue existing at the beginning of the green interval. Green times are subject to minimum and maximum time constraints selected by the system operator. In the version of basic queue control that was tested, the green intervals are extended up to the maximum green time if no demand exists on the red phase.

Further experimentation with the basic queue control methods was of interest for several reasons:

1. One question to be answered was how a non-interconnected, traffic-responsive control method would work in comparison with interconnected strategic plans in grid networks with fairly close signal spacing.

2. The basic queue control technique has a relatively infrequent duty cycle, with control computations required only twice per signal cycle. Therefore, a central computer could handle a larger number of intersections than would be feasible with more complicated traffic-responsive techniques.

3. The surveillance elements of the San Jose control system can provide exactly the kind of measurements required (continuous histories of queue size) to operate

full-scale tests of basic queue control. Preparation of control software would be required, of course.

4. The basic queue control was found to be highly effective in earlier studies when tested by simulation and field studies (*2, 3*).

TEST NETWORKS

With the assistance of the Los Angeles Department of Traffic and the San Jose Department of Public Works, two street networks were selected as pilot areas for testing and evaluating improved traffic signal control methods. The criteria used in selecting the test networks included the following:

1. The networks should be representative of the types found in most urban areas with respect to general layout, geometric design standards, and operational characteristics.
2. The networks should be of closed form, with more than two streets in the crossing directions.
3. The traffic signal systems should be completely interconnected with cycles, splits, and offsets that are readily modifiable within practical limits.
4. There must be a willingness on the part of the operating agency to modify traffic signal operation in the network for experimental purposes.
5. Networks with existing automatic systems for surveillance of traffic operation are preferable because of the resulting economies in data acquisition.

With the exception of the final criterion, the selected Los Angeles test network satisfied these conditions. The primary reason for selecting the second test network in San Jose was the existence there of the digital computer control system and its associated automatic traffic surveillance elements.

Los Angeles Test Network

The street network selected for study in Los Angeles lies approximately two miles southwest of the heart of the central business district (CBD), and immediately north and east of Exposition Park and the University of Southern California. As shown in the street map (Fig. 1), the network (bounded by 23rd Street, Jefferson Boulevard, Figueroa Street, and Main Street) contains 26 signalized intersections. The network includes six major north-south arterials, two major east-west arterials, and two secondary east-west streets, all signalized, as shown by the network diagram (Fig. 2) prepared for the simulation study. The Harbor Freeway traverses the network, and two freeway exit ramp termini are included as signalized intersections in the network. The street map shows that, with a few minor exceptions, all the intersections along east-west streets are signalized. On the north-south streets, with longer signal spacing, there are intervening minor street intersections controlled by STOP signs between the signalized intersections. The unsignalized minor streets were not included in the network simulation study.

Land use in the Los Angeles test area is mixed, containing a variety of commercial and light industrial activities as well as scattered pockets of residential uses. The highest density of activity, with accompanying off-street parking and substantial pedestrian traffic, lies mainly along Figueroa Street and Adams Boulevard.

All the major arterials are six lanes wide, with the exception of Adams and Main, which have four lanes. The two secondary streets, 23rd and 30th, are also four lanes wide. Left-turn storage lanes are provided on Figueroa, Main, and portions of Adams. Average signal spacing approximates 1,200 ft along the north-south streets and 400 ft along the east-west streets. During the afternoon peak period, curb-parking prohibitions are in effect in both directions in nearly all blocks of the east-west streets, and in the peak direction (southbound) on Figueroa Street and Main Street. Moderate amounts of curb parking are found along the other streets; this curb parking does not generally interfere with smooth traffic operation.

The preexisting traffic control system in the Los Angeles test network was an interconnected three-dial control system. During the morning and afternoon peak periods, an 80-sec cycle length was used, with offsets established to provide progressive movement for the heavier traffic flow direction on the north-south streets. Peak-hour offsets along the east-west streets were approximately simultaneous. During the offpeak period, a 60-sec cycle length was used, with the offsets roughly approximating a half-cycle plan along the north-south streets.

San Jose Test Network

The second system selected as a test network was a portion of the computer-controlled network in San Jose. Without question, the San Jose system is presently (1969) the most comprehensively instrumented network in the U.S. (*20*). The downtown network portion of the system (which excludes a nine-intersection arterial strip west of the CBD) contains 46 signalized intersections (Fig. 3). Virtually every lane of every link in this system is covered by loop detectors that can be used to estimate traffic demands, delays, stops, and occupancy. Although delays and stops are obtained by a computational process in the IBM 1800 control computer, based on certain assumptions, this system is the only one now in existence that obtains a complete enough set of traffic performance characteristics by automatic means for use in experimental research on network traffic control.

Because of an unfortunate combination of events during 1968, including revision of the one-way street pattern and localized repaving, a substantial portion of the traffic sensing system was temporarily out of operation when this research project began. Although it was anticipated that the sensing system would be operational in time to permit full-scale experimentation during this project, insufficient time was available for this purpose because unavoidable delays were experienced by the city in returning the sensing system to full operation.

However, in the late stages of this project, practically all the sensor system in a 22-intersection subsystem was operational, and data from the system were used in conjunction with simulation testing of several control alternatives. Figure 4 shows a network diagram of the subsystem selected for simulation analyses.

As noted previously, the area studied is in the CBD, with

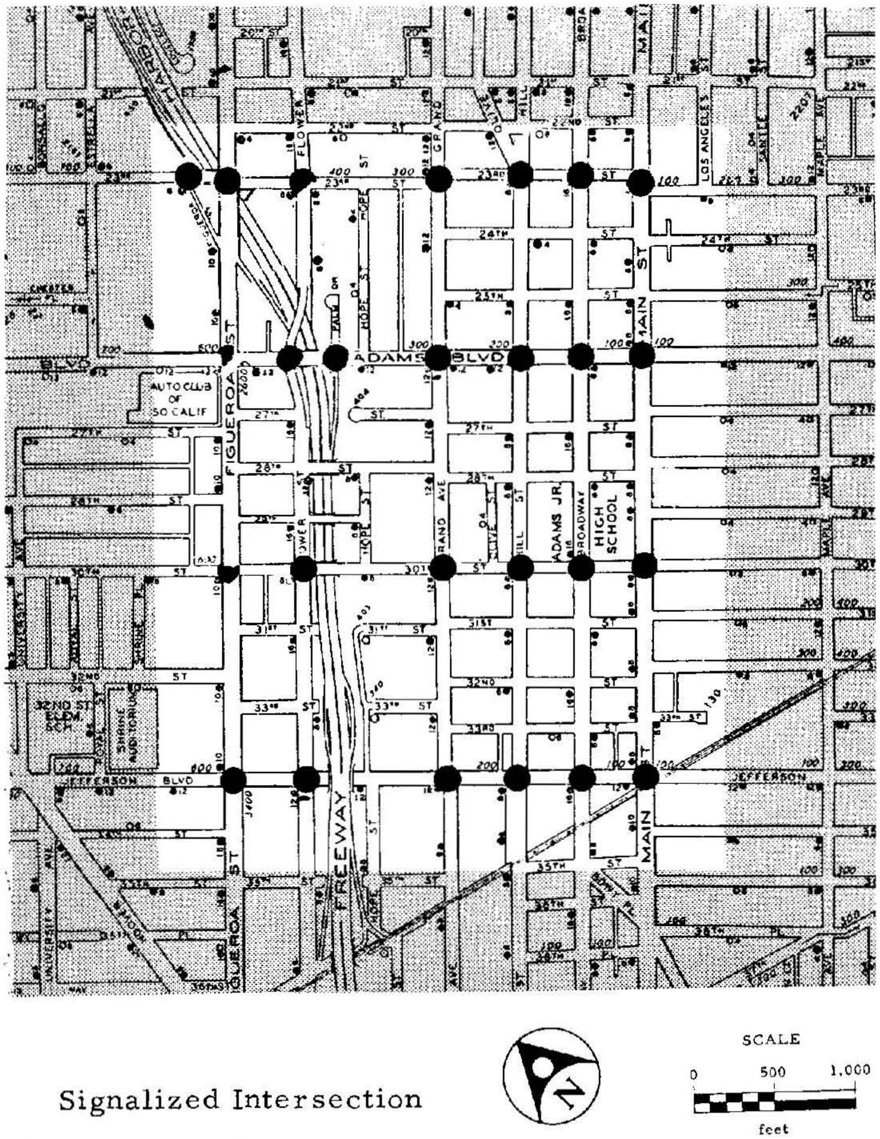

Figure 1. Street map of Los Angeles test network.

all streets and intersections signalized. Signal spacing is close—approximating 360 ft on the north-south streets. The street pattern, with a mixture of one-way and two-way streets, is considered typical of many CBD networks around the U.S. With the exception of San Carlos Street, curb parking is permitted on both sides of all streets in the network.

The traffic signals are controlled by the digital control computer at central headquarters. Pre-stored timing tables are used as a basis for controlling the downtown portion of the system. In the existing control system, a 50-sec cycle length is used during the afternoon peak period (4:00-6:00 PM). Existing phase splits are based on the city's extensive analysis of large quantities of traffic demand data produced daily by the surveillance system. Existing signal offsets in the existing system were developed, using traditional time-space diagram techniques.

INPUT DATA COLLECTION

Two basic categories of data were collected in the test networks: (1) inventory data on the physical characteristics and traffic regulation and control characteristics, and (2) special traffic operations data required as input data for alternative traffic signal optimization procedures and for the TRANS simulation model. In the Los Angeles network, a third category of data was collected—namely, the data collected for the purpose of field verification of control methods (see "Field Verification Studies," which follows).

The first phase of data collection, compilation of inventory data, was accomplished with the assistance of the cooperating city agencies. The following types of data were obtained from their files:

1. Base maps and plans of the test networks, depicting

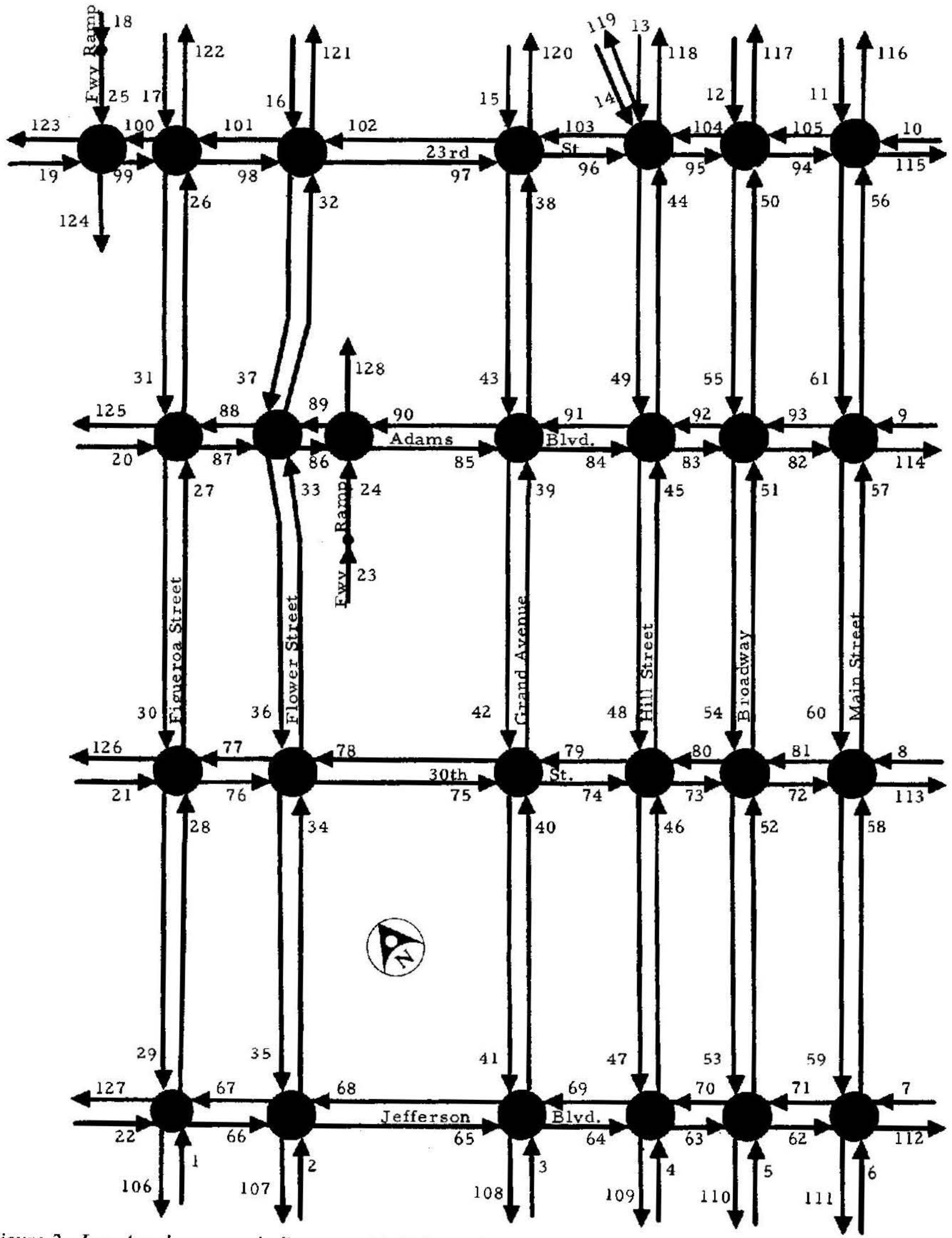

Figure 2. Los Angeles network diagram with link numbers.

the street system geometrics: distances between intersections; pavement and right-of-way widths; and intersection design details, including channelization.

2. Traffic regulation and control characteristics in the test networks: intersection signalization plans, including existing signal timing; traffic control signs; pavement markings; on-street parking regulations; and turning movement prohibitions.

3. All previously collected traffic flow characteristics data in the test networks.

For the second phase, special input data collection, it was determined that the input data required by the TRANS model also satisfied the data requirements of all the signal optimization techniques under investigation. The principal types of data were:

1. Total flow rates on all signalized intersection approaches.
2. Turning movement volumes on all approaches.
3. Lane distribution counts on all approaches.

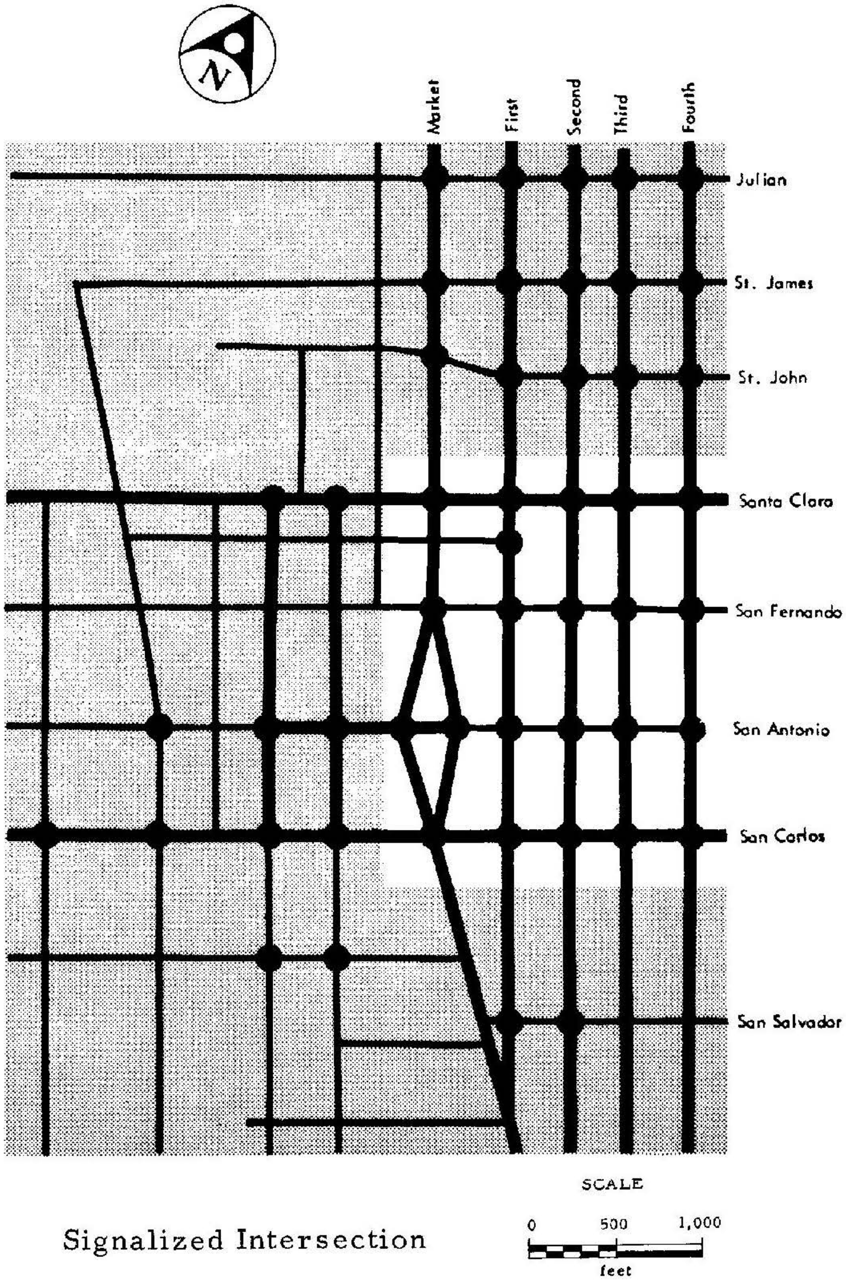

Figure 3. San Jose CBD street map, showing subsystem selected as test network.

4. Queue discharge characteristics (saturation flow rates and lost times) on selected intersection approaches.
5. Average running speeds between signalized intersections along all streets in the networks.

In Los Angeles, the time period 3:00 to 6:00 PM was chosen for detailed study. Analysis of total traffic volumes crossing the boundaries of the test network indicated that the 3-hr total period should be divided into two subperiods during which total traffic demands were relatively constant:

1. The peak subperiod from 4:00 to 5:30 PM.
2. The offpeak subperiod from 3:00 to 4:00 PM and 5:30 to 6:00 PM.

The Los Angeles Traffic Department provided complete intersection counts collected in the Winter 1969; automatic counts made at various locations in the network during 1968; and lane distribution count samples for all intersection approaches collected during March and April 1969. Traffic flow rates during the offpeak and peak periods in the Los Angeles network are shown in Figures 5 and 6, respectively. Additionally, data from the Summer 1968 speed and delay survey of the city's Coliseum area (which included all of the test network) were provided. In the Coliseum area study, each arterial route was studied for one full day, and a sample of approximately 16 test runs was acquired for the morning peak period, the afternoon peak period, and an offpeak period. These data were used for estimating free flow speeds on all streets in the network; they also served as preliminary data for checking the

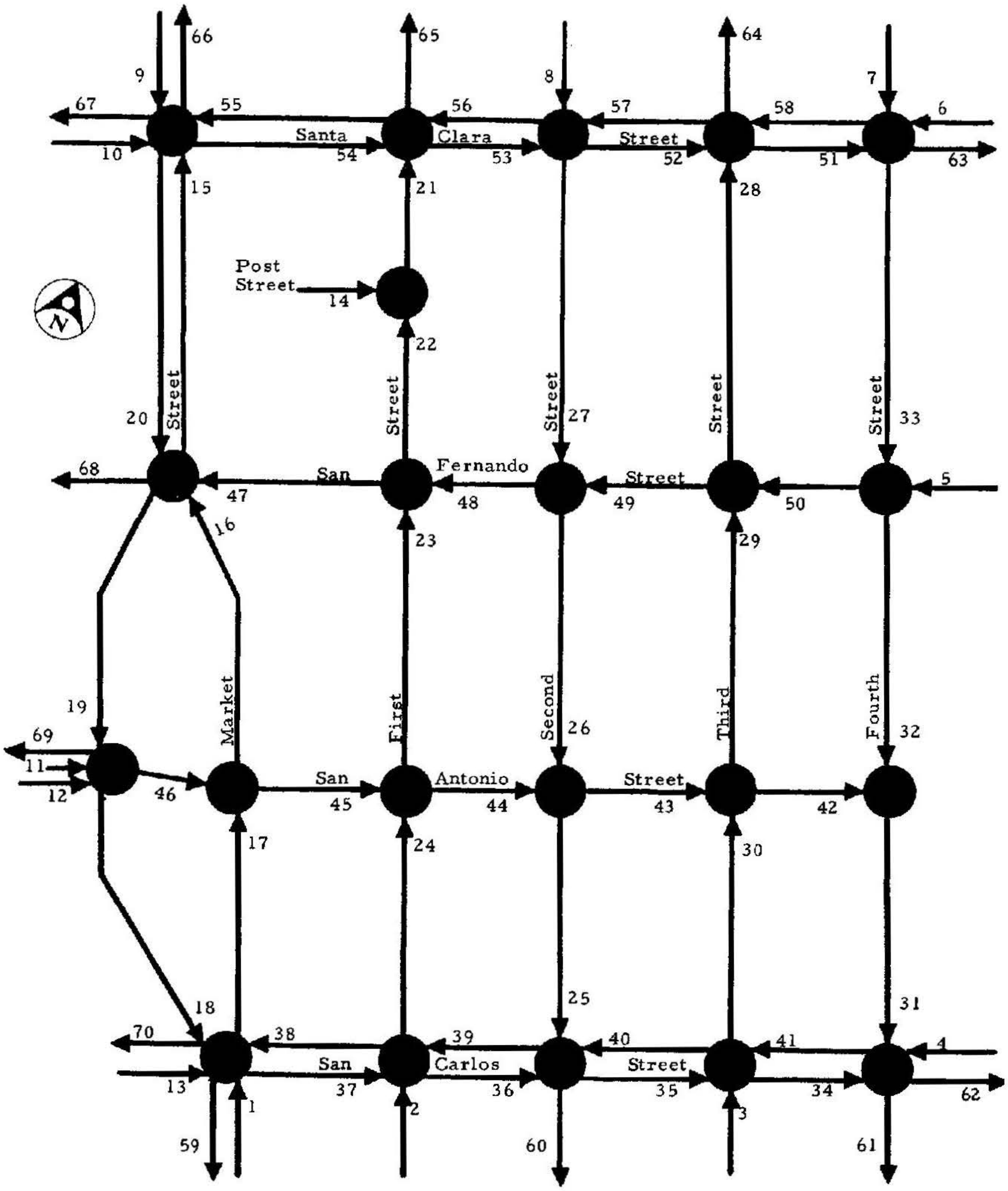

Figure. 4. San Jose network diagram with link numbers.

reasonableness of simulation results. The resulting estimates of free-flow speeds are given in Table 1.

The research agency gathered samples of queue discharge timing data at selected intersections along all streets in the network to obtain estimates of saturation flow rate and lost time. These data were analyzed and summarized by groups of streets as given in Table 2.

In the San Jose network, the time period 4:00 to 6:00 PM was chosen for detailed study. This is the time period during the afternoon when the system is generally under the control of the computer system and for which substantial data were available. Extensive cooperation was received from the representatives of the San Jose Department of Public Works, and especially from the staff of the traffic control project.

In addition to supplying physical and traffic control inventory data, the San Jose staff supplied the research agency with detailed tabulations of traffic demand and delay data produced by the computer system. These data were provided on a lane-by-lane sensor basis; thus, it was possible to derive reliable data for both total flow rates and lane distribution. Manual counts at several intersections were supplied by the city, and these were augmented by special turning counts collected by the research agency to determine turn probabilities on all intersection approaches. For the small number of links on which sensors were not

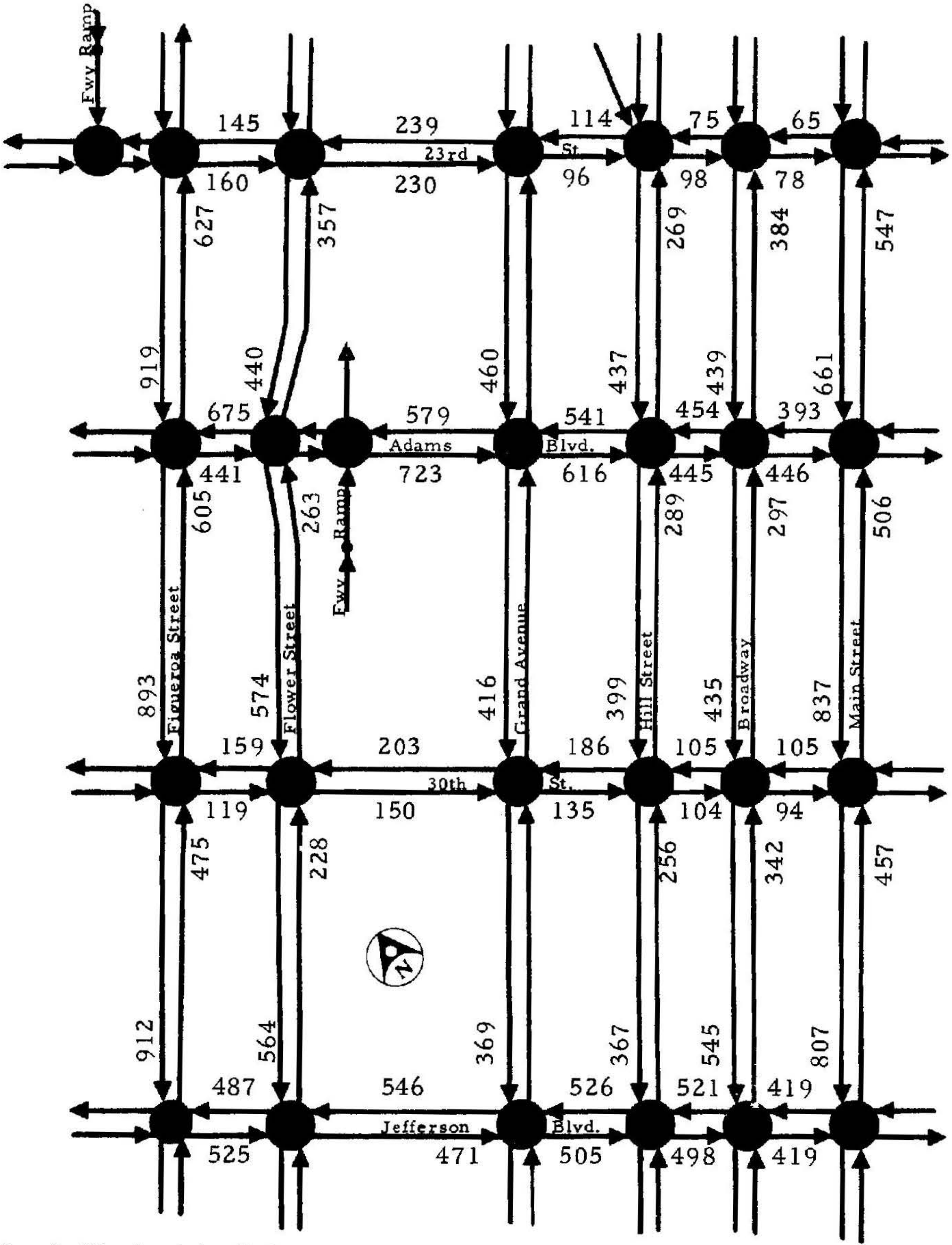

Figure 5. Offpeak period traffic flow rates in the Los Angeles network, 3:00–4:00 PM *and 5:30–6:00* PM.

operating, traffic flows were estimated by projecting data upstream or downstream from adjacent links. Total traffic flows in the San Jose network during the 4:00 to 6:00 PM study are summarized on the network diagram shown in Figure 7.

The research agency performed a floating-car speed and delay survey, testing all streets in the network to obtain reliable estimates of free-flow running speeds. As indicated by the summary given in Table 3, free-flow speeds typify CBD operation—approximating 20 mph. Queue discharge characteristics were timed at 11 intersections in the network, and differences in operation at the locations sample were negligible. Data were averaged for all locations to obtain values of saturation flow of 0.512 vehicle per second and 2.92 sec of lost time per green interval.

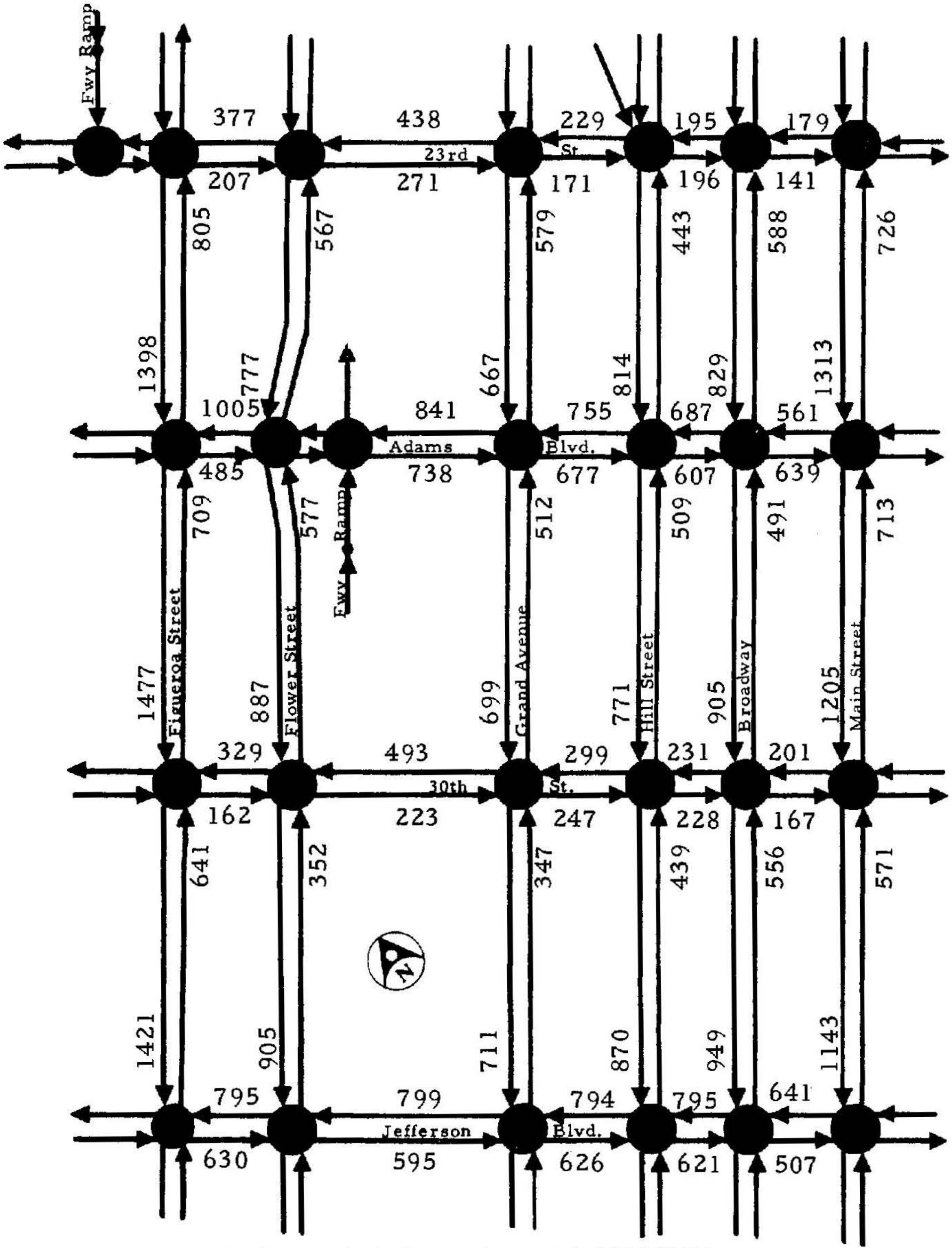

Figure 6. Peak period traffic flow rates in the Los Angeles network, 4:00–5:30 PM.

TRAFFIC CONTROL ALTERNATIVES TESTED

Using the control concepts introduced previously, a large number of alternative strategic signal timing plans were developed for the two test networks. In the Los Angeles network, 11 control alternatives were developed and tested for the offpeak period traffic conditions, and 15 alternatives were developed and tested for the peak period conditions. In the San Jose network, nine control alternatives were tested. Appendix A describes the control alternatives.

The following types of signal optimization procedures were employed in developing strategic timing plans:

1. Webster cycle and split optimization.

TABLE 1

FREE FLOW SPEEDS IN LOS ANGELES TEST NETWORK [a]

STREET	FREE FLOW SPEED (MPH)
Figueroa, NB and SB	27.9
Flower, NB and SB	27.0
Grand, NB and SB	26.3
Hill, NB and SB	27.1
Broadway, NB and SB	27.5
Main, NB and SB	27.7
Average of north-south streets	27.2
Jefferson, EB and WB	26.8
Adams, EB and WB	23.4
23rd, EB and WB	19.9
30th, EB and WB	22.9

[a] Based on data collected from 4:00 to 6:00 PM as part of Coliseum area speed and delay survey, Summer 1968. Data on 30th Street were collected in May 1969.

TABLE 2

QUEUE DISCHARGE PARAMETERS IN THE LOS ANGELES NETWORK

STREETS	SATURATION FLOW RATE (VEH/SEC) [a]	LOST TIME (SEC) [b]
NB Figueroa and Flower	0.495	4.89
SB Figueroa and Flower	0.529	5.32
EB Adams and Jefferson; EB and WB 23rd and 30th; and NB Grand, Hill, Broadway, and Main	0.420	3.02
WB Adams and Jefferson; and SB Grand, Hill, Broadway, and Main	0.472	4.19
Harbor Freeway exit ramp termini	0.472	2.81

[a] The average rate at which a single-lane queue of straight-through vehicles is serviced during the effective portion of the green interval.
[b] The portion of the green plus yellow interval for which flow rate is effectively zero. Lost time results from starting delay at the beginning of green and subsidence of flow during the yellow interval.

TABLE 3

FREE FLOW SPEEDS IN SAN JOSE TEST NETWORK [a]

STREET	FREE FLOW SPEED (MPH)
Market, NB and SB	21.8
First, NB	18.2
Second, SB	18.8
Third, NB	20.2
Fourth, SB	21.2
San Carlos, EB and WB	22.5
San Antonio, EB	21.6
San Fernando, WB	18.4
Santa Clara, EB and WB	18.7

[a] Based on floating-car data collected from 3:00 to 6:00 PM during April 1969. An average of 20 test runs were made on each street.

2. Computerized maximal bandwidth.
3. Delay-offset difference method.
    - Preferential street plans.
    - Volume priority plans.
    - Mixed-cycle plans.
4. SIGOP method.
5. Combination and graph theory method.

These techniques were applied with different cycle lengths to obtain the plans tested. In the Los Angeles network, for example, plans employing 80-, 60-, and 50-sec cycle lengths were tested. In San Jose, 60-, 50-, and 40-sec cycle length plans were tested.

Using peak-period flow rates in the Los Angeles network, and employing Webster's equation, optimum cycle length was calculated for each intersection. All intersections but two had optimum cycle lengths of less than 50 sec, which was considered to be the practical minimum cycle length to accommodate pedestrian crossings. (The two exceptions had calculated optimum cycles of 53.8 and 50.1 sec.) Generally, the intersection with the longest cycle length requirement dictates the network cycle length. In this case, with only two intersections slightly over the 50-sec optimum, it was decided that a 50-sec cycle should be tested. The longer cycle length plans of 60 sec and 80 sec were tested because of an interest in evaluating the influence of cycle length on network operating characteristics.

In the San Jose network, 40 sec was selected as the practical minimum cycle length. (Narrower streets result in shorter pedestrian crossing time requirements.) All the calculated Webster optimum cycle lengths were less than 40 sec.

Finally, the basic queue control technique—a traffic-responsive concept in which the intersections are controlled independently, without coordination—was tested by simulation in both the Los Angeles and San Jose networks.

SIMULATION TESTING OF CONTROL ALTERNATIVES

TRANS Simulation Model

Simulation testing of traffic control alternatives was performed using the TRANS network simulation model developed by the research agency. Appendix H describes the development and refinement of TRANS and reviews applications of the model on other projects. The most recently refined version of the simulation model, TRANS IV, was used in this project.

Simulation Exercises

Using TRANS IV, traffic operations were simulated in the Los Angeles network for the offpeak and peak portions of the 3:00 to 6:00 PM time period, and in the San Jose network for the 4:00 to 6:00 PM time period. Because a large number of alternative signal plans was of interest, and the computer time required for simulation of operation was fairly high, the simulation test runs were not replicated as had been done in the prior phase of research on urban arterials. Instead, each simulation period was stratified into subperiods, and intermediate output data were obtained for each subperiod. This technique permitted statistical com-

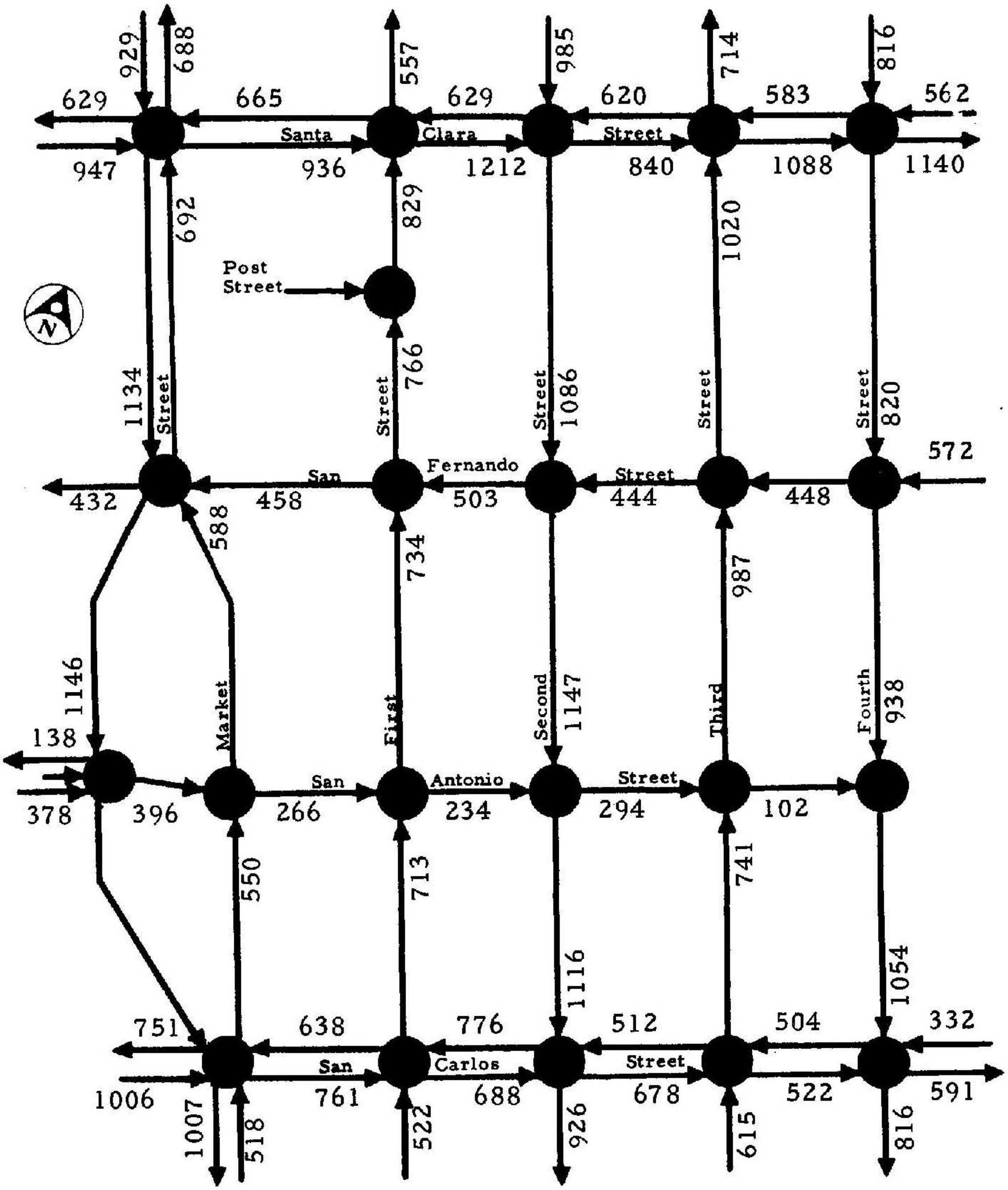

Figure 7. Traffic flow rates in the San Jose network, 4:00–6:00 PM.

parisons between control alternatives without wasting valuable computer time.

Detailed summaries of the results of the simulation exercises appear in Appendix B. In the Los Angeles network, considering all of the alternatives tested, 46.5 hr of traffic operation were simulated. In the San Jose network, 18 hr of operation were simulated in testing control alternatives.

Summary of Simulation Results

The results of simulation tests are given in Tables 4, 5, and 6.

Table 4 gives results for the offpeak study period in the Los Angeles network. Total vehicle-miles, total travel time, total delay, and average speed are given for each alternative. As indicated by the values of total vehicle-miles, which do not differ significantly, the traffic control alternatives were subjected to a controlled magnitude of traffic demand. Each of the alternatives tested resulted in substantial improvements in operational effectiveness. Total travel time and total delay in the network were significantly reduced and average network speed was increased compared with existing conditions for all of the strategic alternatives tested.

TABLE 4

SUMMARY OF SIMULATION RESULTS, LOS ANGELES NETWORK, OFFPEAK PERIOD, 3:00–4:00 PM AND 5:30–6:00 PM

ALTERNATIVE	CYCLE LENGTH (SEC)	SPLIT TECHNIQUE	OFFSET TECHNIQUE	TOTAL VEH-MILES	TOTAL TRAVEL TIME (VEH-HR)	TOTAL DELAY (VEH-HR)	AVERAGE SPEED (MPH)
1	Existing (80)	Existing	Existing (preferential directions)	7,966	467	163	17.0
2	Existing (60)	Existing	Existing	7,924	393	90	20.2
3	55	SIGOP	SIGOP	7,935	385	82	20.6
4	50	SIGOP	SIGOP	7,967	391	87	20.4
5	60	Webster	Delay-difference, preferential streets	7,937	389	86	20.4
6	50	Webster	Delay-difference, preferential streets	8,062	398	90	20.2
7	60	Webster	Delay-difference, volume priority	7,893	392	91	20.1
8	50	Webster	Delay-difference, volume priority	7,856	381	81	20.6
9	60	Webster	Maximal bandwidth, preferential streets	7,723	383	88	20.2
10	50	Webster	Maximal bandwidth, preferential streets	8,084	390	82	20.7
11	Basic queue control technique			7,925	399	97	19.8

The differences among the new alternatives are markedly smaller than the differences between any new alternative tested and the existing timing plan in effect during the offpeak period. It appears that improvement in offpeak operation can be attributed more to reduction in the signal cycle length than to the specific signal optimization procedures employed. The results of the simulation test with the basic queue control mode were nearly as good as the strategic alternatives, even though no coordination was maintained between intersections in the networks in the basic queue concept.

Results of simulation tests for the peak period in the Los Angeles network are given in Table 5. Once again, each signal system alternative was loaded with a controlled level of traffic demand as indicated by total vehicle-miles traveled in the network. The data indicate that the strategic alternatives tested, without exception, yielded improvements in operational effectiveness. In the peak period study, several strategic plans were tested that used the same cycle length as was used in the existing timing plan (80 sec). Although improvements over existing operation were smaller for 80-sec cycle alternatives than for shorter cycle alternatives, they were nevertheless significant. For example, in the 80-sec delay-difference, preferential street plan (Alternative 5), average network speed was increased to 16.8 mph compared with 15.4 mph with the existing time plan. It was still apparent, however, that larger improvements in operation accompanied reduction of the cycle length. The best results were obtained with signal timing plans employing a 50-sec cycle.

The results of peak-period tests of the basic queue control technique were similar to the offpeak period findings. This noncoordinated traffic responsive mode of control gave operation nearly as good as the best strategic plans tested. The good results obtained with the mixed-cycle plans were also of interest, because it was not previously known whether such an approach would work effectively in a compact grid network. The simulation test of the combination and Allsop method (Alternative 14) worked reasonably well, even though the massive computer time requirements permitted determination of optimum offsets to a resolution of only one-tenth of the cycle length (i.e., 5 sec).

Table 6 summarizes simulation results for the traffic control alternatives tested in the San Jose CBD network. The results of this study indicate that only modest improvements over existing system operation are possible, using the control concepts tested. This finding appears reasonable for several reasons: (1) the existing cycle length used in the San Jose CBD system is short (50 sec), (2) existing splits in the San Jose system are the results of continual studies of intersection traffic demands, using data from the sensor system, and (3) day-to-day attention is devoted to evaluating and improving the signal system operation.

Even with the foregoing starting conditions, it appears that modest improvements in operation are possible through application of some of the alternative techniques studied.

The San Jose network is considerably more compact than the Los Angeles test network. Therefore, the satisfactory operation of the noninterconnected basic queue control was surprising. Unmistakably, the cycle length—again in San Jose—appears to be the most influential signal system variable. Poorest operation was simulated for the alternative in which the cycle length was increased from 50 to 60 sec.

TABLE 5

SUMMARY OF SIMULATION RESULTS, LOS ANGELES NETWORK, PEAK PERIOD, 4:00–5:30 PM

ALTERNATIVE	CYCLE LENGTH (SEC)	SPLIT TECHNIQUE	OFFSET TECHNIQUE	TOTAL VEH-MILES	TOTAL TRAVEL TIME (VEH-HR)	TOTAL DELAY (VEH-HR)	AVERAGE SPEED (MPH)
1	Existing	Existing	Existing (preferential directions)	12,387	804	332	15.4
2	80	SIGOP	SIGOP	12,508	788	311	15.9
3	50	SIGOP	SIGOP	12,468	660	185	18.9
4	50	Modified SIGOP	SIGOP	12,399	647	174	19.2
5	80	Webster	Delay-difference, preferential streets	12,355	737	265	16.8
6	50	Webster	Delay-difference, preferential streets	12,422	662	188	18.8
7	80	Webster	Delay-difference, volume priority	12,461	771	296	16.1
8	60	Webster	Delay-difference, volume priority	12,433	686	212	18.1
9	50	Webster	Delay-difference, volume priority	12,420	662	188	18.8
10	80	Webster	Maximal bandwidth, preferential streets	12,365	796	324	15.5
11	50	Webster	Maximal bandwidth, preferential streets	12,454	687	212	18.2
12	50 and 60	Webster	Mixed cycle plan I	12,329	659	189	18.7
13	50 and 60	Webster	Mixed cycle plan II	12,418	685	211	18.1
14	50	Webster	Combination and Allsop method	12,347	679	208	18.2
15	Basic queue control technique			12,471	672	197	18.5

TABLE 6

SUMMARY OF SIMULATION RESULTS, SAN JOSE NETWORK, 4:00–6:00 PM

ALTERNATIVE	CYCLE LENGTH (SEC)	SPLIT TECHNIQUE	OFFSET TECHNIQUE	TOTAL VEH-MILES	TOTAL TRAVEL TIME (VEH-HR)	TOTAL DELAY (VEH-HR)	AVERAGE SPEED (MPH)
1	Existing (50)	Existing	Existing	6,321	411	99	15.4
2	60	SIGOP	SIGOP	6,225	421	114	14.8
3	50	SIGOP	SIGOP	6,189	398	92	15.6
4	40	SIGOP	SIGOP	6,218	383	76	16.2
5	50	Webster	Delay-difference, preferential streets	6,174	397	92	15.5
6	50	Webster	Delay-difference, volume priority	6,268	403	93	15.6
7	40	Webster	Delay-difference, volume priority	6,198	392	85	15.8
8	50	Webster	Maximal bandwidth, preferential streets	6,194	394	88	15.7
9	Basic queue control technique			6,223	408	100	15.3

The best operation was obtained for the two alternatives in which cycle length was reduced to 40 sec. However, use of a cycle as short as 40 sec begins to infringe on pedestrian crossing time requirements for some of the wider streets in the network. Consequently, the traffic engineer must judge whether the potential increases in effectiveness that are obtainable with very short cycles are practicable.

Ranking of Control Alternatives

Using average network speed as the criterion, the alternative traffic control concepts studied were ranked. Tables 7 and 8 give the results of the ranking process for the offpeak period and peak period, respectively, in the Los Angeles network. Results are given in Table 9 for the San Jose test

TABLE 7

RANKING OF CONTROL ALTERNATIVES, LOS ANGELES NETWORK, OFFPEAK PERIOD

ALTERNATIVE	CYCLE LENGTH (SEC)	CONTROL CONCEPT	AVERAGE SPEED (MPH)	IMPROVEMENT OVER EXISTING (%)	RANK
10	50	Maximal bandwidth preferential streets	20.7	21.8	1
3	55	SIGOP	20.6	21.2	
8	50	Delay-difference, volume priority	20.6	21.2	2
4	50	SIGOP	20.4	20.0	
5	60	Delay-difference, preferential streets	20.4	20.0	
2	60	Existing midday	20.2	18.8	
6	50	Delay-difference, preferential streets	20.2	18.8	
9	60	Maximal bandwidth, preferential streets	20.2	18.8	
7	60	Delay-difference, volume priority	20.1	18.2	3
11	Variable	Basic queue control	19.8	16.5	
1	80	Existing	17.0	—	4

TABLE 8

RANKING OF CONTROL ALTERNATIVES, LOS ANGELES NETWORK, PEAK PERIOD

ALTERNATIVE	CYCLE LENGTH (SEC)	CONTROL CONCEPT	AVERAGE SPEED (MPH)	IMPROVEMENT OVER EXISTING (%)	RANK
4	50	Modified SIGOP	19.2	24.7	1
3	50	SIGOP	18.9	22.7	
6	50	Delay-difference, preferential streets	18.8	22.1	
9	50	Delay-difference, volume priority	18.8	22.1	
12	50 and 60	Mixed cycle plan I	18.7	21.4	
15	Variable	Basic queue control	18.5	20.1	
14	50	Combination—Allsop	18.2	18.2	2
11	50	Maximal bandwidth, preferential streets	18.2	18.2	
13	50 and 60	Mixed cycle plan II	18.1	17.5	
8	60	Delay-difference, volume priority	18.1	17.5	
5	80	Delay-difference, preferential streets	16.8	9.1	3
7	80	Delay-difference, volume priority	16.1	4.5	4
2	80	SIGOP	15.9	3.2	
10	80	Maximal bandwidth, preferential streets	15.5	0.7	5
1	80	Existing (preferential directions)	15.4	—	

TABLE 9

RANKING OF CONTROL ALTERNATIVES, SAN JOSE NETWORK, PEAK PERIOD

ALTERNATIVE	CYCLE LENGTH (SEC)	CONTROL CONCEPT	AVERAGE SPEED (MPH)	IMPROVEMENT OVER EXISTING (%)	RANK
4	40	SIGOP	16.2	5.2	1
7	40	Delay-difference, volume priority	15.8	2.6	2
8	50	Maximal bandwidth, preferential streets	15.7	2.0	3
3	50	SIGOP	15.6	1.3	
6	50	Delay-difference, volume priority	15.6	1.3	
5	50	Delay-difference, preferential streets	15.5	0.7	
1	50	Existing	15.4	—	4
9	Variable	Basic queue control	15.3	−0.7	
2	60	SIGOP	14.8	−3.9	5

network. In each set of rankings, the alternatives are separated into groups and the entire group is assigned a rank. All the alternatives contained within such a group did not differ from one another when tested statistically using a paired *t* test. (Data were paired by 15-min intervals for test purposes.) In other words, because the simulation test data did not provide statistical evidence that the members of a given group differed, the members of the group could not logically be separately ranked.

The application of the ranking process to the Los Angeles offpeak data resulted in the division of alternatives into four ranks. The highest-ranking group contained the 50-sec maximal bandwidth plan, the 55-sec SIGOP plan, and the 50-sec delay-difference volume priority. These three alternatives produced essentially equally good network operation, with average network speed increased by more than 20 percent over existing speed. The second and third rank groups of offpeak alternatives were only slightly less effective than the highest ranking group, with average network speed increases ranging from 16 to 20 percent.

Statistical analyses of the Los Angeles peak period alternatives resulted in their separation into five ranks. The top-ranking group was crowded; it contained 6 of the 15 alternatives tested. Included in the top group were: two SIGOP plans; two delay-offset difference plans—one using the volume priority approach and the other the preferential streets approach; one mixed cycle plan; and the basic queue control concept. Simulated improvement over the existing signal timing plan ranged from 20 to 25 percent in the top group. With the exception of the mixed-cycle plan, all the other strategic plans in the top group had 50-sec cycle lengths.

The alternatives placed in lower ranking groups also produced significant increases in operational effectiveness compared with existing operation. Only one alternative, the 80-sec maximal bandwidth plan, failed to produce statistically significant improvements over existing operation.

As noted previously, operational improvements obtained from new alternatives were not as striking in the San Jose network because of the high quality of the existing signal system operation. The ranking procedure segregated the alternatives into five significantly different groups. Group 1 contained only the 40-sec SIGOP plan that yielded only 0.8 mph or 5 percent improvement over existing operation. The 40-sec delay-difference volume priority plan ran a close second. The four alternatives in the third ranking group were just barely better than existing operation. The previously noted influence of cycle lengths on operational effectiveness is clearly evident in the ranking of San Jose alternatives.

Network Effectiveness Related to Traffic Demand

Selected results of the simulation tests were plotted graphically to show the relationships between traffic demand, travel time, and average speed, and also to depict the degree of improvement over existing operation produced by various traffic control alternatives. Six graphs are shown in Figure 8, in which existing operation in Los Angeles is compared with operation using improved traffic control techniques. In each graph, network traffic demand rate, as measured by vehicle-miles per hour, is plotted against network travel time rate, as measured in vehicle-hours per hour. Sloped graph lines depict average network speed. Each point plotted on the graphs represents values of the network characteristics during a 15-min period. In most cases, the points clustered closely around straight lines that were fitted by judgment.

The degree of improvement possible through application of signal optimization techniques is clearly shown by the graphs. It is also clear that the approximate degree of

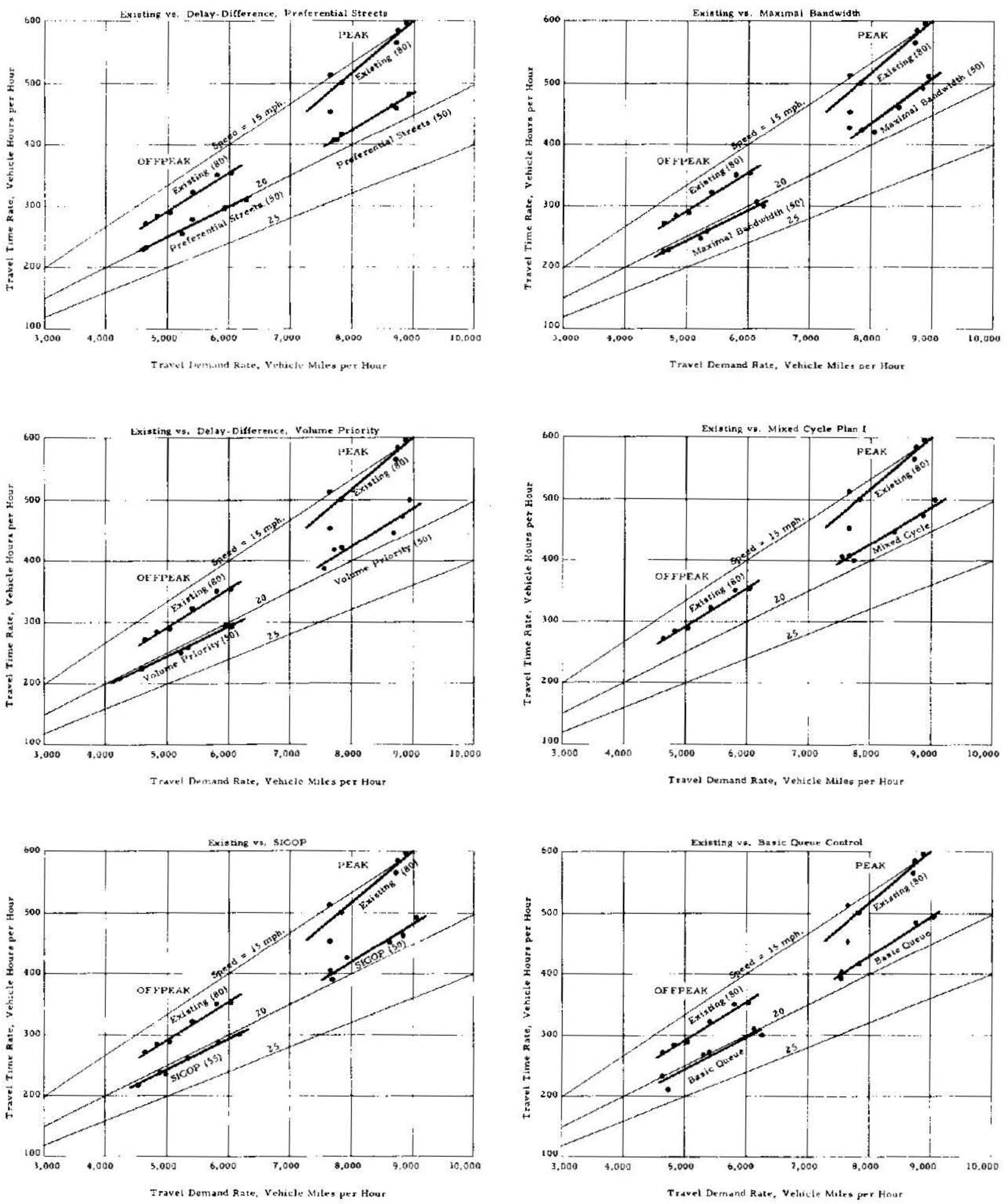

Figure 8. Interrelationships of demand, travel time, and speed, Los Angeles network.

improvement is similar for all of the alternatives shown in the figure. No single technique stands out as being vastly superior to the rest.

Distribution of Speeds in the Network

For selected alternatives in the Los Angeles network, simulation results were analyzed in detail to investigate the distribution of mean speeds on individual links throughout the network.

Figure 9 shows frequency distributions of speeds for the offpeak period, for the existing signal timing plus five control alternatives. Under existing signal timing there is a readily identifiable separation of mean speeds for the north-south streets (which cluster in the 20- to 25-mph range) and the east-west streets (which cluster around 10 mph). In the next four distributions shown, which represent improved strategic plans, mean speeds on individual links are increased, and the dispersion among link speeds is slightly reduced. North-south speeds cluster near 25 mph and east-west streets approximate 15 mph. Clearly, most of the improvement in operation with the alternative timing plans occurred along the east-west streets in the network. The final speed distribution obtained under the basic queue control mode of signal operation is most interesting of all because it differs radically from the others. The over-all range of link speeds was reduced with basic queue control, and there is a sharper peaked concentration of speeds between 20 and 25 mph for the north-south streets and near 15 mph for the east-west streets.

Similar results were obtained for the peak-period speed distributions in the Los Angeles network (Fig. 10). Under existing signal operation, mean speeds on individual links fell into lower speed and higher speed groups for the east-west and north-south streets, respectively. The strategic signal optimization plans tested had generally similar distributions but with concentrations of link speeds at slightly higher values. Once again, speeds resulting from basic queue control were less dispersed, with smaller differences between mean speeds in the north-south and east-west directions. In previous research on traffic control on urban arterials (*3*), findings concerning link speed distributions were similar in many respects to those presented here.

Effect of Cycle Length on Traffic Operation

In several previous locations in this report, the influence that cycle length has on operational effectiveness is noted. Previous projects in this series of research also have determined that cycle length is the single most important variable affecting operation, whether it be at a single intersection or along an arterial. As a general rule, longer cycles are associated with longer delays and lower average speeds, and shorter cycle operation produces reductions in delay and increases in average speed. The previous findings are strongly corroborated by this research in urban networks. Figure 11 shows the approximate relationships between average network speed and signal cycle length. The plotted points represent simulation results for the different control alternatives tested.

FIELD VERIFICATION STUDIES

Comprehensive field verification studies were conducted in the Los Angeles test network to evaluate the effects of actual changes in the traffic signal system, and thereby to verify the results of the simulation analyses. Three separate studies were made possible by the extensive assistance of the City of Los Angeles, Department of Traffic.

To prevent confusion regarding the exact correspondence between the lettered alternatives studied in the field and the numbered alternatives studied by simulation, correspondence information is given in Table 10.

Alternatives Studied

Alternative A

In the first study, termed Alternative A, the preexisting 80-sec signal timing plan was in effect during both the offpeak and peak portions of the 3:00 to 6:00 PM study period. The study was performed during the period June 19 to July 2, 1969. The basic measurements were made using a comprehensive speed and delay survey procedure. (Instructions to the survey teams appear in Appendix I. The analysis of variance of survey results is discussed in Appendix D.) In addition to the speed and delay data, automatic traffic counts and manual turning movement counts were gathered at selected locations to ensure that no major changes in network loading had occurred since the time counts had been made to compile data for simulation input.

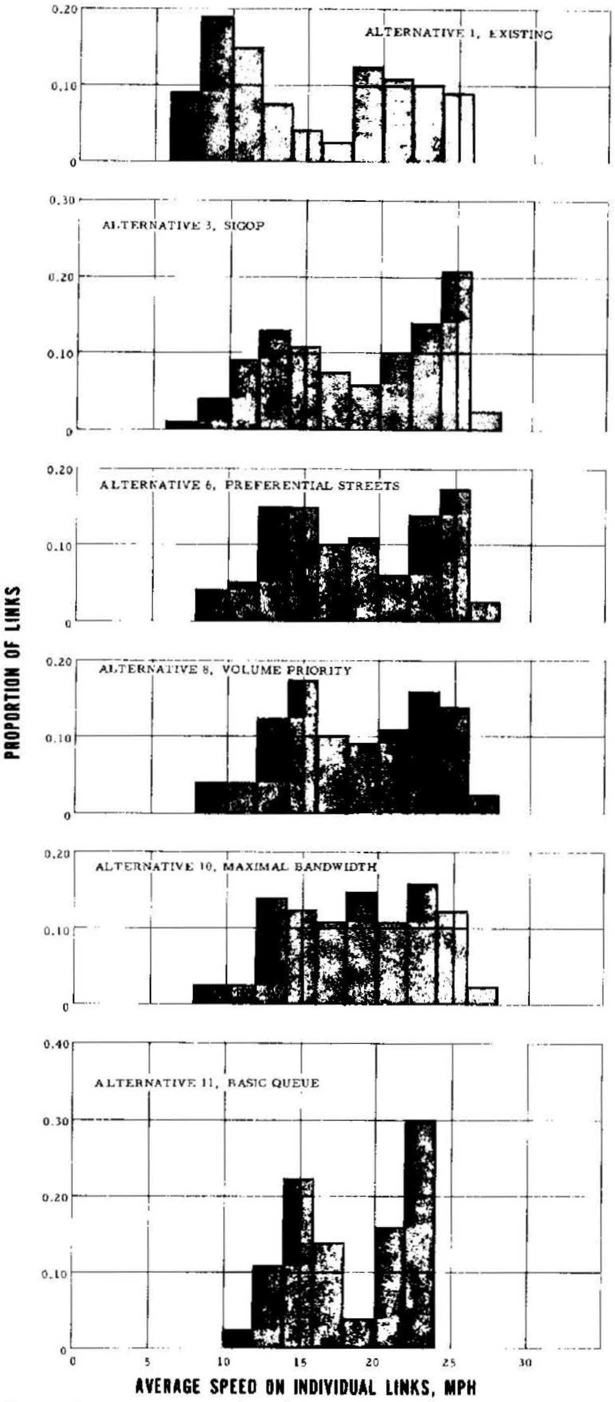

Figure 9. Frequency distributions of speeds in the Los Angeles network, offpeak period.

Alternative B

In the next study, termed Alternative B, different signal timing plans were used during the offpeak and peak portions of the study period. The 50-sec cycle length, refined SIGOP plan was in effect during the peak period (4:00 to 5:30 PM). During the offpeak period (3:00 to 4:00 PM and 5:30 to 6:00 PM), the preexisting 60-sec cycle length plan, that had formerly been used as the normal plan during nonpeak periods, was in effect. In other words, mid-

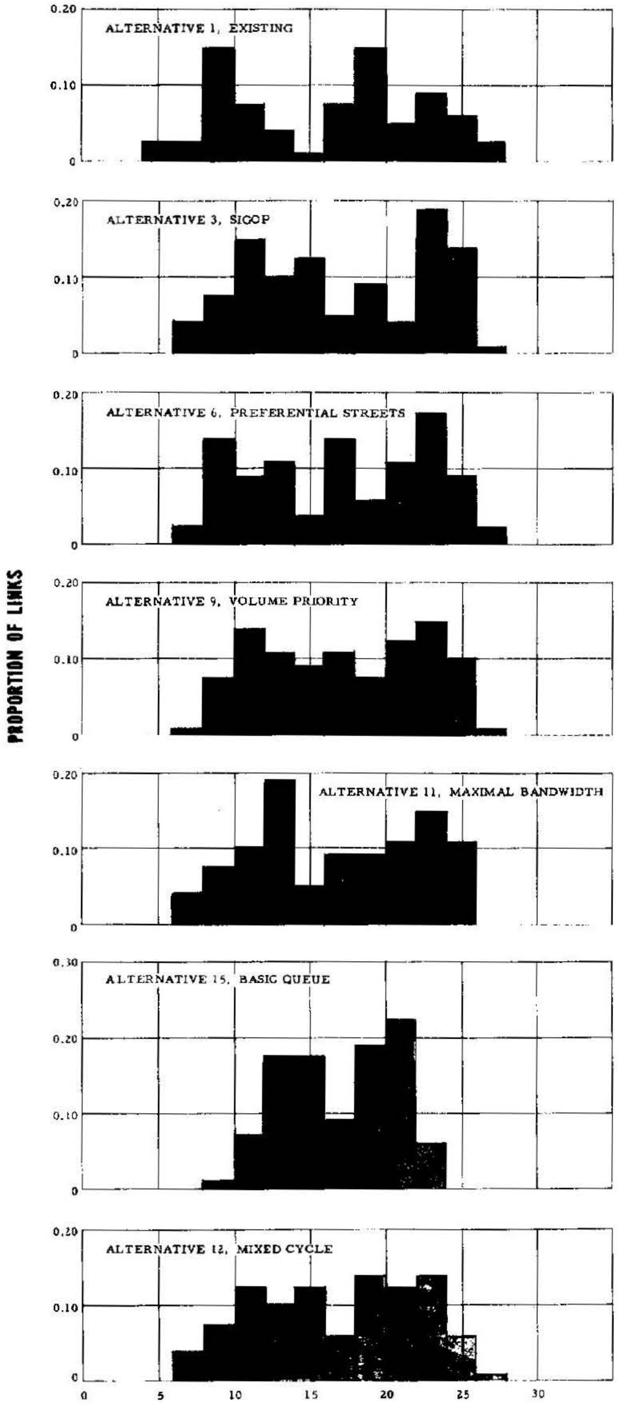

Figure 10. Frequency distribution of speeds in the Los Angeles network, peak period.

TABLE 10

CORRESPONDENCE BETWEEN FIELD VERIFICATION STUDIES AND SIMULATION TESTS

FIELD STUDY	CORRESPONDING SIMULATION TEST
Offpeak period:	
Alternative A	Alternative 1
Alternative B	Alternative 2
Alternative C	Alternative 2
Peak period:	
Alternative A	Alternative 1
Alternative B	Alternative 4
Alternative C	Alternative 12

day signal timing was held in effect longer and returned to operation more quickly after the late afternoon peak period. Because the existing control system in the Los Angeles network uses three-dial controllers, and only one dial is available for midday operation, it was considered reasonable not to attempt to put yet another special timing plan into effect to cater to the needs of only a small piece of over-all offpeak conditions. The study of Alternative B was performed during the period from August 25 to September 17, 1969, using the same measurement procedures employed for Alternative A.

Alternative C

In the final study, termed Alternative C, the mixed-cycle Plan I was in effect during the peak period. As with Alternative B, the final study employed the preexisting midday 60-sec cycle length plan during the offpeak portion of the late afternoon. This study was performed from October 14 to October 27, 1969.

Comparison of Simulated and Measured Results

Simulation validation is discussed in Appendix C, where descriptive validity comparisons based on the field verification studies are presented. As developed in the appendix, the descriptive validity of the model was considered to be satisfactory. Table 11 summarizes the precision with which the calibrated simulation data for each alternative conform to data estimated by field measurements. The poorest comparison in the table is for peak period, Alternative C, for which simulated network speed exceeded field estimated speed by approximately 10 percent, or 1.8 mph. Statistical tests were performed to determine the significance of differences in simulated and measured distributions of speed, and to test whether simulated and measured speeds differed significantly when compared on a pairwise basis for individual links.

In five cases out of six, there was no evidence to indicate that simulated and measured cumulative distributions of mean speeds on network links differed significantly. Similarly, in five cases out of six, there was no evidence to indicate that the mean differences between simulated and measured speed were greater than 1 mph.

Predictive validity of a simulation model is generally more important because the principal purpose of most models is their use as predictive tools. In this project a determination more exhaustive than ever before was made of the TRANS model's ability to accurately predict the effects of changes in signal operation. Tables 12 and 13 give summary comparisons of the alternatives tested in the field and by simulation.

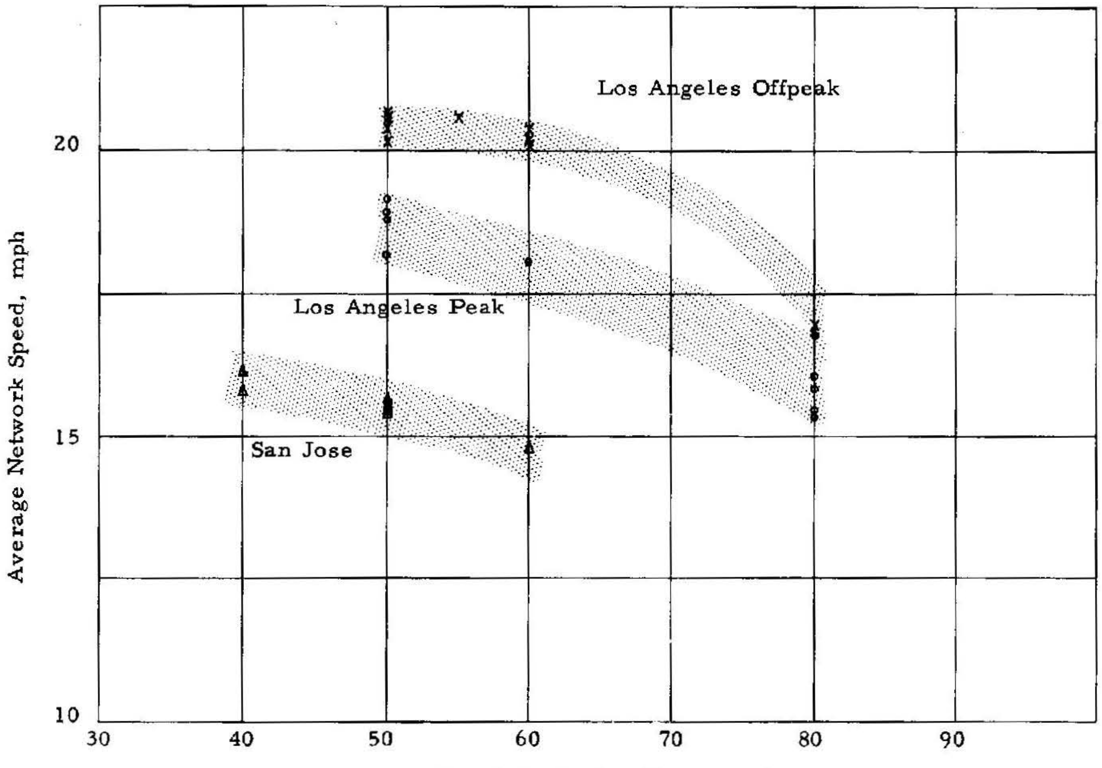

Figure 11. Approximate relationships between network speeds and cycle length.

Average network speeds are compared in Table 12. During the offpeak period, based on field measurements, Alternative A had the lowest speed, and Alternatives B and C (which were identical conditions) had higher and approximately equal speeds. The uncalibrated simulation accurately predicted these changes, and the calibrated simulation runs further substantiated the accuracy of the predicted effects. During the peak period, based on field measurements, Alternative A again had the lowest speed, Alternative B had the highest speed, and the speed of Alternative C was in the middle. The uncalibrated simulation accurately predicted these effects; and the calibrated simulation also yielded essentially the same predictions.

In Table 13, similar comparisons can be made to show that the simulation model performed well in predicting the effect of signal system changes on total travel time in the network.

Another method of presenting predictive validity comparisons, that is perhaps more enlightening, is used in Table 14. Both absolute and percentage changes in network characteristics are compared directly.

The results given in Table 14 provide the most impressive documentation of the ability of the TRANS model published to date. With one small exception, the uncalibrated simulation predictions were almost perfectly verified by the comprehensive field measurements. For example, in predicting the effect of changing from Alternative A to Alternative B, the model predicted increases in network speed of 18.8 percent and 24.7 percent, respectively, for the offpeak and peak periods. In the subsequent field study of the change from Alternative A to Alternative B, network speed rose by 17.5 percent and 26.9 percent, respectively, for offpeak and peak. The only comparison for which the simulation prediction was not equally as good as the previous example was Alternative A versus Alternative C for the peak period (see Table 14). In that case a speed increase of 3.3 mph was predicted by simulation, but an increase of only 1.9 mph occurred in the field. The fore-

TABLE 11

SUMMARY OF PERCENTAGE DIFFERENCES BETWEEN SIMULATED AND MEASURED TRAFFIC CHARACTERISTICS, LOS ANGELES NETWORK [a]

PERIOD	PERCENTAGE DIFFERENCE ALTERNATIVE A	 ALTERNATIVE B	 ALTERNATIVE C
	(*a*) Total vehicle-miles		
Offpeak	−0.4	−0.1	−2.2
Peak	+0.1	+1.5	−0.6
	(*b*) Average network speed		
Offpeak	−7.7	−7.9	+6.9
Peak	−0.2	+1.0	+10.3

[a] Percentage difference $= \frac{\text{simulated} - \text{measured}}{\text{measured}} \times 100$
Comparisons made for calibrated simulation runs.

TABLE 12

COMPARISON OF ALTERNATIVES BY FIELD MEASUREMENT AND SIMULATION, AVERAGE NETWORK SPEED, LOS ANGELES NETWORK

	AVERAGE NETWORK SPEED (MPH)		
ITEM	ALTERNATIVE A	ALTERNATIVE B	ALTERNATIVE C
Offpeak period:			
Field measurement	19.4	22.8	22.6
Uncalibrated simulation	17.0	20.2	20.2
Calibrated simulation	17.9	21.0	21.5
Peak period:			
Field measurement	15.6	19.8	17.5
Uncalibrated simulation	15.4	19.2	18.7
Calibrated simulation	15.3	20.0	19.3

TABLE 13

COMPARISON OF ALTERNATIVES BY FIELD MEASUREMENT AND SIMULATION, TOTAL TRAVEL TIME IN NETWORK, LOS ANGELES NETWORK

	TOTAL TRAVEL TIME (VEH-HR)		
ITEM	ALTERNATIVE A	ALTERNATIVE B	ALTERNATIVE C
Offpeak period:			
Field measurement	408	346	351
Uncalibrated simulation	467	393	393
Calibrated simulation	442	378	360
Peak period:			
Field measurement	799	628	712
Uncalibrated simulation	797	647	660
Calibrated simulation	814	635	640

going comparison was the worst example of the simulation's predictive ability. Without question, the TRANS model performed exceedingly well as a predictive tool in this series of studies in the Los Angeles network.

COMPARISON OF SIGOP AND TRANS ESTIMATES

The SIGOP traffic signal optimization program was used successfully in this project for developing effective fixed-time signal plans in the networks studied. Included in the SIGOP output are estimates of performance derived from a simulation process in the SIGOP program. Because several SIGOP timing plans were simulated by TRANS, it was possible to make limited comparisons of the SIGOP and TRANS predictions of the effects of different control alternatives.

Table 15 gives such a comparison for control alternatives studied in the Los Angeles network. Using total travel time as the criterion, the SIGOP and TRANS estimates of percentage improvements over existing operation pro-

TABLE 14

COMPARISON OF FIELD-MEASURED AND SIMULATED CHANGES IN OPERATION RESULTING FROM ALTERNATIVE CONTROL TECHNIQUES, LOS ANGELES NETWORK

	ALTERNATIVE A VS. ALTERNATIVE B		ALTERNATIVE A VS. ALTERNATIVE C	
ITEM	DIFFERENCE	DIFFERENCE (%)	DIFFERENCE	DIFFERENCE (%)
(a) Offpeak period				
Speed (mph)				
Field measurement	+3.4	+17.5	+3.2	+16.5
Uncalibrated simulation	+3.2	+18.8	+3.2	+18.8
Calibrated simulation	+3.1	+17.3	+3.6	+20.1
Total travel time (veh-hr):				
Field measurement	−62	−15.2	−57	−14.0
Uncalibrated simulation	−67	−14.6	−74	−15.8
Calibrated simulation	−64	−14.5	−82	−18.5
(b) Peak period				
Speed (mph):				
Field measurement	+4.2	+26.9	+1.9	+12.2
Uncalibrated simulation	+3.8	+24.7	+3.3	+21.4
Calibrated simulation	+4.7	+30.7	+4.0	+26.1
Total travel time (veh-hr):				
Field measurement	−171	−21.4	−87	−10.9
Uncalibrated simulation	−150	−18.8	−137	−17.1
Calibrated simulation	−179	−21.9	−174	−21.4

TABLE 15

COMPARISON OF SIGOP AND TRANS ESTIMATES OF EFFECTS OF CONTROL ALTERNATIVES, LOS ANGELES NETWORK [a]

SIGNAL TIMING ALTERNATIVE	TOTAL TRAVEL TIME IN NETWORK (VEH-HR) AS ESTIMATED BY: SIGOP	TRANS
(*a*) Offpeak period		
Existing timing plan, 80-sec cycle	416	467
55-sec SIGOP plan	351	385
(Percent improvement)	(16)	(18)
50-sec SIGOP plan	354	391
(Percent improvement)	(15)	(16)
(*b*) Peak period		
Existing timing plan, 80-sec cycle	671	804
80-sec SIGOP plan	650	788
(Percent improvement)	(3)	(2)
50-sec SIGOP plan	570	660
(Percent improvement)	(15)	(18)

[a] Undelayed travel time accumulated in network was added to SIGOP estimates of total delay to obtain SIGOP estimate of total travel time. Peak period undelayed travel time = 472 veh-hr; offpeak period undelayed travel time = 303 veh-hr.

duced by SIGOP timing plans were closely correlated. Absolute estimates of total travel time with SIGOP appear to be consistently lower than the TRANS estimates in the Los Angeles network.

Table 16 gives similar comparisons of SIGOP and TRANS for studies in the San Jose network. Both SIGOP and TRANS predicted that only modest percentage improvements over existing timing are produced in San Jose. For one of the alternatives (the 60-sec SIGOP plan) the SIGOP program estimated a 3 percent improvement over existing, whereas TRANS predicted a 2 percent degradation. Nevertheless, the similarities of the predictions obtained by the two methods are more impressive than the minor differences.

TABLE 16

COMPARISON OF SIGOP AND TRANS ESTIMATES OF EFFECTS OF CONTROL ALTERNATIVES, SAN JOSE NETWORK [a]

SIGNAL TIMING ALTERNATIVE	TOTAL TRAVEL TIME IN NETWORK (VEH-HR) AS ESTIMATED BY: SIGOP	TRANS
Existing timing plan, 50-sec cycle	399	411
60-sec SIGOP plan	388	421
(Percent improvement)	(3)	(−2)
50-sec SIGOP plan	387	398
(Percent improvement)	(3)	(3)
40-sec SIGOP plan	382	383
(Percent improvment)	(4)	(7)

[a] Undelayed travel time of 308 veh-hr accumulated in the San Jose network from 4:00-6:00 PM was added to SIGOP total delay estimates to obtain SIGOP estimates of total travel time.

It should be noted that TRANS can handle a wider range of conditions than SIGOP, which is basically applicable only for fixed-cycle signal operation. For example, SIGOP cannot test mixed-cycle plans, such as those studied in this project, unless the network is split into parts and the parts are studied separately. Then the links connecting intersections with different signal cycle lengths would be excluded from the SIGOP evaluation. Additionally, SIGOP cannot test traffic-responsive techniques. Finally, the SIGOP simulation process is a simplified one and is largely deterministic, whereas TRANS is a more detailed stochastic simulation. Therefore, SIGOP's operational estimates are not likely to be as reliable as TRANS for individual links and intersections. These comments should not be construed as criticisms of SIGOP, for its primary function is signal optimization. The simulation process in SIGOP is a supplemental function, but one that produces very useful data.

CHAPTER THREE

INTERPRETATIONS AND CONCLUSIONS

This project was designed as a direct extension of the research approach used successfully in the prior phase of research concerning improved signal operation on urban arterials. It was not surprising, therefore, that the findings in the study closely paralleled those in the previous research.

The simulation analyses indicated that all of the traffic signal system improvement methods investigated will result in substantive improvements in network traffic operation. Given a network of signalized intersections that has not recently been the subject of intensive traffic engineering attention devoted specifically to signal operation improvements, it is highly probable that initiation of systematic study, analysis, and implementation of signal timing changes will produce significant upgrading of performance. The findings of this study suggest that it is not so important *which* of the signal system improvement alternatives is selected for use. Rather, the important thing is to *select one of the approaches*, collect the necessary traffic data, and implement the signal timing improvements.

The following statement, which appears in *NCHRP Report 73* (*3*), is as good a general interpretation of this study as it was of the prior one:

> Thus, it appears that whatever efforts traffic engineers can devote to pursuing signal operation improvements by methods such as those tested, should result in measurable benefits.

The researchers believe that one important comparison made in this project was the effectiveness of relatively simple methods and complex methods for signal system optimization.

The relatively simple methods include Webster cycle and split optimization, Little's maximal bandwidth program, the delay-offset difference program, and several straightforward approaches for "building" the network timing plans (e.g., preferential streets, volume-priority, and mixed-cycle approaches). These so-called simple methods, when applied together, properly result in highly effective strategic plans for signal operation. Considering the entire process, the simple methods do not achieve a formalized mathematical optimization solution. Portions of the process involve deterministic or arbitrary rules. In applying the so-called simple methods, there is a minimum feasible degree of reliance on the computer. The computer programs that are used are relatively uncomplicated to understand and operate, and have brief and simple input-output formats. The two simple approaches involve the use of either of two computer programs: (1) the delay-offset difference program for link pairs developed by the researchers in the prior phase of research, and refined in the project (see Appendix E), or (2) the Little maximal bandwidth program.

The relatively complex methods investigated include SIGOP, the Road Research Laboratory's combination method, Allsop's graph theory augmentation of the combination method, and TRANSYT, the traffic network study tool. All these methods involve the use of complicated computer programs, the understanding of which requires the investment in a substantial intensive study and consultation period. All of the methods incorporate either a formalized mathematical optimization, or the attainment of a near optimum condition through a formal simulation and search procedure. Of the four complex methods, only SIGOP is considered feasible for use by operating agencies in grid networks. The combination method (see Appendix F) is useful only in networks that are completely condensable via the combination process. The computer program complexity and running time requirements in the augmentation of the combination method for noncondensable networks using the Allsop graph theory approach limit its current usefulness. The other British method, TRANSYT, is currently operational only on a British computer. All of these methods, particularly TRANSYT, are being used with success on an experimental basis, and further refinements are expected soon. Presently (1969), however, the complex British methods are not recommended for practical use by U.S. traffic engineering departments.

The research results indicate that improvements in operation produced by the relatively simple methods are equal or nearly equal to results produced by the substantially more complicated SIGOP process. It is true, of course, that once an engineer has learned how to use SIGOP (or any other complex approach), subsequent applications of the process take less time.

Another interesting area of interpretation concerns the prospects for more effective traffic responsive concepts of signal control in networks. The results of tests of noninterconnected basic queue control were surprisingly good, considering the short distances between signals in the networks tested. However, better operation was achieved with the good fixed-time plans. Research results from the Glasgow project also indicate that good strategic plans are difficult to improve on. They studied two control concepts that employed tactical elements integrated within strategic plans. Neither technique yielded improvements compared with the best strategic plan tested. Research on tactical control concepts is being pursued in the United States as well, the foremost of which is the developing advanced urban traffic control systems research sponsored by the Federal Highway Administration. At the current state of the art, however, it is difficult to demonstrate the cost-effectiveness of tactical control concepts in compact grid networks.

One of the most interesting findings of the research was the excellent results obtained in the comprehensive field studies. Not only were the signal modifications implemented in the Los Angeles network successful in the sense that significant operational improvements were achieved, but also the studies verified extremely well the results of the TRANS simulation predictions.

This finding was especially significant because earlier validation studies with TRANS had concentrated on the descriptive validity of the model. In this project, the ability of TRANS to reliably predict the consequences of alternative courses of traffic control action in a grid network was conclusively demonstrated.

CHAPTER FOUR

APPLICATIONS

The research agency considered this project to be heavily applications-oriented. Conscious efforts were made to emphasize investigation of improved traffic control techniques that could be used immediately and widely, without expending large sums of money. The researchers are convinced that many of the signal optimization procedures can immediately be put to work by a traffic engineering department, regardless of its size.

As noted previously, the most important recommendation to the traffic engineer set forth in this report is *to initiate a systematic program* of signal system operational analysis. Application of any one of the following methods will result in worthwhile operational improvements: (1) Webster optimization of cycles and splits; (2) delay-offset difference method using either the volume priority approach or the preferential street approach; (3) the maximal bandwidth method; (4) SIGOP; and (5) whenever appropriate the mixed-cycle approach. From among these alternatives, the traffic engineer should select the set of methods that he judges can be efficiently executed by his department. Under typical circumstances any systematic set of signal optimizing procedures should produce operational improvements on the order of 10 to 20 percent.

The Webster equations have been widely publicized, and in prior research (*3*) detailed instructions are given, including a worksheet and sample results. When the results of the Webster method are combined with any of the offset determination methods developed in this report to produce a complete signal timing plan, substantial improvements in operation can be anticipated. The Webster method requires only simple hand calculations, given data on intersection approach volumes, critical lane distribution proportions, and queue discharge parameters.

The delay-offset difference computer program has consistently given good results when used in developing timing plans. It was, for example, the most effective signal offset technique for arterials reported on by Wagner et al. (*3*). In this project, the delay-offset computer program was

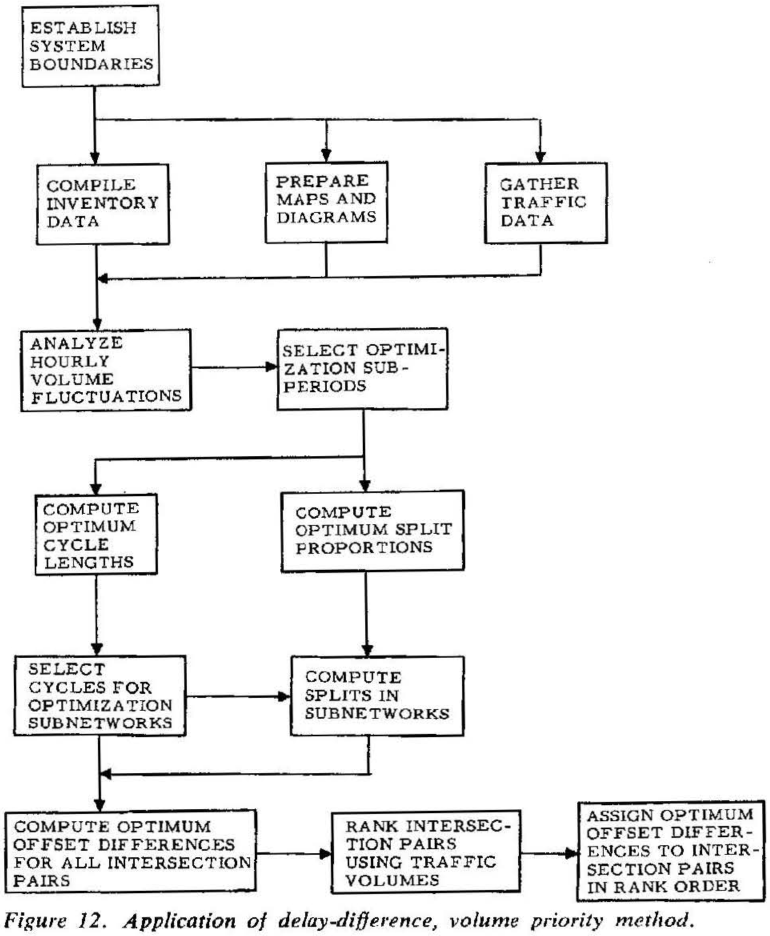

Figure 12. Application of delay-difference, volume priority method.

revised to make its use more efficient (see Appendix E). One of the advantages of the delay-offset difference program is the simplicity of its input format. Additional information concerning the application of this program can be requested from the research agency.

A new approach to the establishment of a network timing plan using delay-offset difference techniques—the volume priority method—was developed and tested in this project. The volume priority method appears to provide network timing plans that are near optimum, even though the method does not involve optimization in the formal sense. Figure 12 shows a work flow diagram that illustrates all of the tasks required in the application of the delay-difference, volume priority method. In actuality, only the three tasks in the bottom row of the chart are unique to the volume priority method. The other tasks in the chart pertain to establishing a plan of optimum cycles and splits, and are required regardless of the offset determination technique employed.

It should be pointed out that any technique used in applying the delay-offset difference program to a network situation (e.g., the volume-priority method) could also be used when any other function of offset differences is available. For example, it might be feasible to develop a program for estimating stops and delays as a function of offset difference. Then, if one considered some combination of stops and delays to be a better criterion than delay alone, he could substitute the most advanced program in place of the delay-offset difference program.

Another consistently effective offset determination technique tested during this project was Little's maximal bandwidth computer program. The maximal bandwidth method was also described in detail by Wagner et al. (*3*). Good results were obtained by using this method on selected preferential streets in the grid networks studied, thereby corroborating the success experienced with this method in the prior research on urban arterials. The maximal bandwidth is probably the least complicated of any of the computer programs used. Its input-output format is simple for the user to master. In a manner similar to the delay-difference method, the maximal bandwidth program is used in conjunction with the Webster cycle and split optimization to produce complete timing plans. Figure 13 is a work flow diagram showing the application of the preferential street, maximal bandwidth method. Requests for more detailed documentation should be directed to the Civil Engineering Systems Laboratory of the Massachusetts Institute of Technology (MIT).

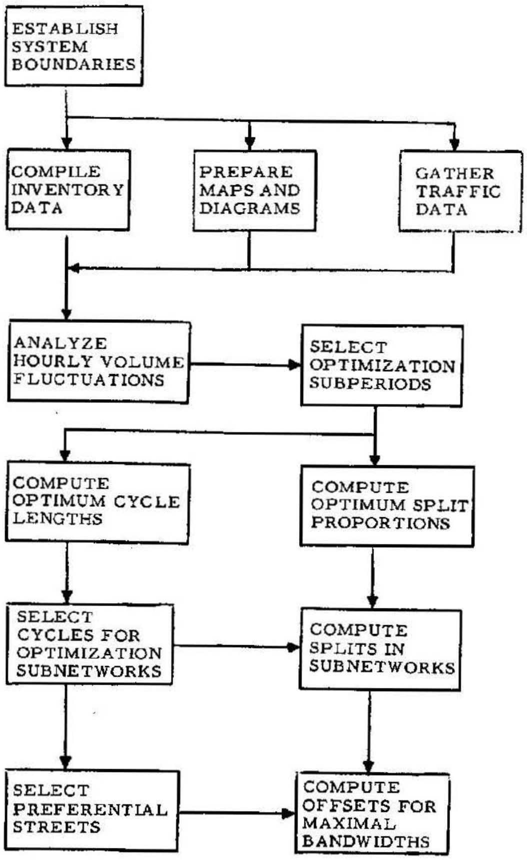

Figure 13. Application of preferential street, maximal bandwidth method.

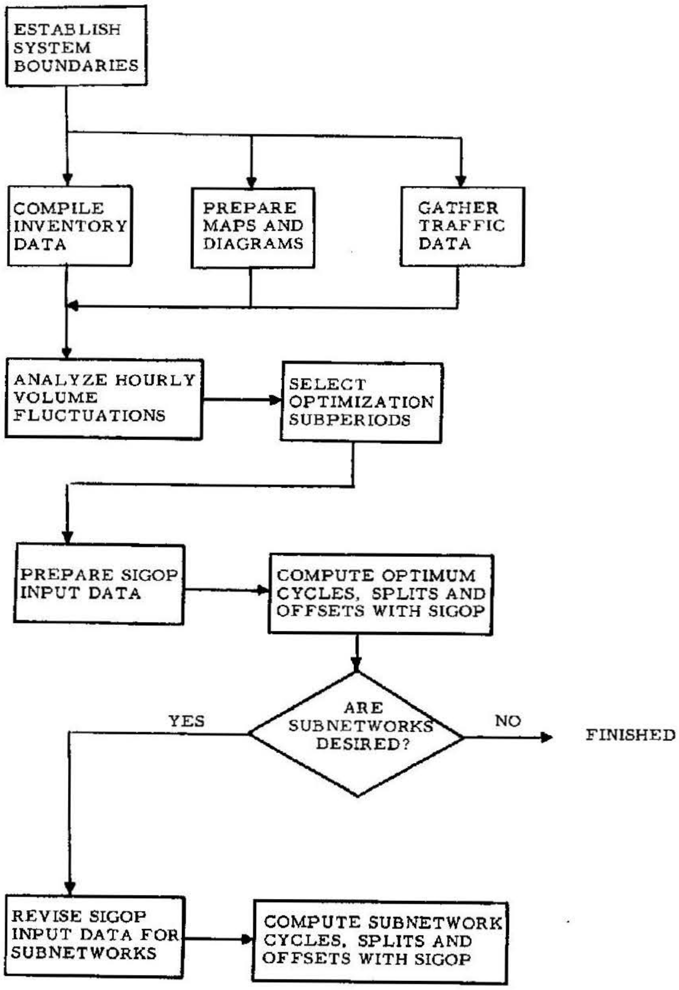

Figure 14. Application of SIGOP method.

The testing of the SIGOP traffic signal optimization program in the Los Angeles and San Jose study networks was very successful. SIGOP is the only computer program that by itself determines complete strategic signal timing plans for complex networks. A decision to use SIGOP, however, must be accompanied by a commitment to spend the necessary resources to learn in detail how to use the program system. SIGOP has by far the most complex input and output structure of any of the computer programs investigated in this project. Detailed documentation in the form of a user's manual is available. Requests for information may be directed to the Federal Highway Administration, Traffic Systems Division. Figure 14 shows a work flow diagram for application of SIGOP.

One refinement that may enhance the use of SIGOP is to investigate cycle length requirements to determine if the system under study can logically be divided into subnetworks having different cycle lengths. Thus, the mixed-cycle approach might be used in conjunction with the SIGOP method. Referring to Figures 12 and 13, it is noted that the mixed-cycle approach could also be used in conjunction with the delay-difference, volume priority method, or with the maximal bandwidth, preferential street method. The key question, which requires engineering study and judgment to answer, is: How can a network be appropriately divided into subnetworks with differing cycle lengths, based on the needs of traffic? It is hoped that the results of this study remove some of the bias against mixing lengths, even in fairly compact systems. Properly done, mixed-cycle plans can work very effectively.

The signal timing optimization techniques discussed in this section are at least partially dependent on computer programs. The three programs that produce effective network results when used in the manner described herein are the SIGOP program, the delay-offset difference program, and the maximal bandwidth program. Use of any one of the three programs results in very small computer-time costs relative to the total costs expended for data collection and coded input preparation. Of the three, SIGOP is most complex and has the longest running time, but even its associated computer cost is small. For example, in the 26-intersection Los Angeles network, SIGOP was run to obtain and evaluate optimum signal settings for eight possible cycle lengths and consumed only 0.08 hr of 360/50 computer time for each of the two periods of the day tested. The other two programs are less complex and consume even less computer time. Hence, the cost of computer use should not deter the use of the methods investigated.

CHAPTER FIVE

SUGGESTED RESEARCH

IMPLEMENTATION STUDIES OF SIGNAL OPTIMIZATION TECHNIQUES

Based on the results of this series of research and related activities on traffic signal system improvements, a number of cities should be selected as pilot cities for advanced signal system operational improvements. The principal objective of such a program of applied research would be to accelerate the transfer of research findings into practice.

Teams would be organized consisting of traffic research specialists and city traffic operations engineers. The teams would be responsible for organizing and executing several different signal system improvement techniques in different locations in a given city. More realistic information could be systematically obtained on relative cost and relative effectiveness of a wide variety of methods under conditions that more closely approximate actual traffic engineering department operations.

Studies with similar objectives are being pursued in several cities to test and evaluate the use of the SIGOP method. Perhaps these same cities would be logical candidates for testing of other alternative approaches to signal system improvement, including several of the promising but less complicated procedures.

AMERICANIZATION OF TRANSYT

The Road Research Laboratory signal system specialists are enthusiastic about the effectiveness of the TRANSYT study tool for obtaining strategic control plans. It is understood that the FORTRAN version of TRANSYT currently (1969) being developed should be available soon. At the earliest feasible time, this program should be obtained by U.S. traffic research specialists for study and experimentation. If possible, broad-scale testing should be undertaken to determine the relative merit of TRANSYT compared with SIGOP, the delay-difference methods, the maximal bandwidth method, mixed-cycle schemes, traffic responsive, and other control alternatives.

RESEARCH ON NETWORK SATURATION PROBLEMS

All of the research in this series has been devoted to investigation of traffic control techniques for subsaturation conditions. The strategic signal optimization concepts deteriorate on networks where severe oversaturation persists for any length of time. When severe queueing occurs in portions of a network, the underlying assumptions on which the strategic techniques are based become invalid. Accelerated efforts need to be devoted to the development, simulation testing, and full-scale experimentation with innovative methods for coping with severe oversaturation in signalized street networks.

EXTENSION OF RESEARCH ON TACTICAL CONCEPTS

At the current state of the art of traffic control in street networks, tactical control methods are unable to provide any clear-cut advantage over well-designed strategic methods. New ideas need to be explored under controlled research conditions to develop more effective ways of integrating tactical control into compact networks. For example, it is not known under what conditions it is most desirable to operate one or more intersections on a traffic responsive basis while a strategic plan is maintained for surrounding intersections.

Considerable research has been performed in Great Britain to evaluate control concepts in which cycle by cycle tactical modifications of splits are executed in a system with an essentially fixed cycle and offset strategic plan. Full-scale research of that type has been slow in developing in the United States, but the urban traffic control system research facilities under development by the Federal Highway Administration in Washington, D.C., should accelerate progress in tactical control research. Before that time, to the maximum extent feasible, many different traffic control specialists should be independently engaged in the conception, formalization, simulation, and analysis of potentially effective new techniques.

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APPENDIX A

DESCRIPTION OF TRAFFIC SIGNAL CONTROL ALTERNATIVES

This appendix describes the various traffic signal system alternatives developed for testing and evaluation. Information is presented for (1) the Los Angeles network offpeak alternatives; (2) the Los Angeles network peak alternatives; and (3) the San Jose test network.

LOS ANGELES NETWORK, OFFPEAK PERIOD ALTERNATIVES

The following 11 traffic control alternatives were developed for offpeak period (3:00 to 4:00 PM and 5:30 to 6:00 PM) conditions in the Los Angeles network. Summaries of splits and offsets for the strategic timing plans developed are given in Tables A-1 and A-2, respectively.

1. *Alternative 1.* Existing 80-sec cycle, existing splits, and existing offsets in use during the time period being tested.
2. *Alternative 2.* Existing cycle (60-sec), splits, and offsets used during the midday but applied to the late-afternoon offpeak period being studied.
3. *Alternative 3.* 55-sec cycle, splits, and offsets determined by the SIGOP technique.
4. *Alternative 4.* 50-sec cycle, SIGOP splits and offsets.
5. *Alternative 5.* 60-sec cycle, with splits determined by the Webster technique and offsets determined by the delay-offset difference technique for preferential streets. The selected preferential streets were all six north-south streets plus Adams Boulevard.
6. *Alternative 6.* 50-sec cycle, with Webster splits and preferential streets delay-difference offsets.
7. *Alternative 7.* 60-sec cycle, Webster splits, and offsets determined by the delay-difference technique using the volume priority approach. Figure A-1 shows the links in the network that were optimized as a result of the volume priority approach.
8. *Alternative 8.* 50-sec cycle, Webster splits, and volume priority delay-difference offsets.
9. *Alternative 9.* 60-sec cycle, Webster splits, and offsets determined by the Little maximal bandwidth technique for preferential streets. The preferential streets were the same as those in Alternatives 5 and 6.
10. *Alternative 10.* 50-sec cycle, Webster splits, and preferential streets maximal bandwidth offsets.
11. *Alternative 11.* Traffic-responsive basic queue control techniques. By means of this technique, each intersection in the network is controlled independently, with no regard for coordination between signals.

LOS ANGELES NETWORK, PEAK-PERIOD ALTERNATIVES

A total of 15 alternatives were developed, using the same concepts employed for the offpeak period. Additionally, alternatives were developed using the British combination and the mixed cycle approach. Splits and offsets for all the strategic alternatives are summarized in Tables A-3 and A-4, respectively.

1. *Alternative 1.* Existing 80-sec cycle, splits, and offsets in use during the time period being tested (4:00 to 5:30 PM).
2. *Alternative 2.* 80-sec cycle, splits, and offsets determined by the SIGOP technique.
3. *Alternative 3.* 50-sec cycle, SIGOP splits and offsets.
4. *Alternative 4.* 50-sec cycle, SIGOP splits and offsets,

TABLE A-1

SUMMARY OF SPLITS, BY CYCLE, LOS ANGELES NETWORK, OFFPEAK PERIOD[a]

STREET	NORTH-SOUTH GREEN PLUS YELLOW (SEC), BY CYCLE LENGTH (SEC) EXISTING (80)	EXISTING (60)	WEBSTER (60)	SIGOP (56)	WEBSTER (50)	SIGOP (50)
Figueroa at:						
23rd	52	36	38	34	30	30
Adams	48	30	32	32	26	28
30th	56	36	40	36	30	30
Jefferson	48	30	32	34	28	30
Flower at:						
23rd	56	36	28	22	26	20
Adams	40	30	22	20	20	20
30th	52	38	40	36	30	30
Jefferson	48	30	28	26	24	24
Grand at:						
23rd	56	36	32	24	26	22
Adams	40	26	22	22	20	20
30th	56	36	34	30	28	26
Jefferson	48	26	26	26	22	24
Hill at:						
23rd	30	24	28	22	18	18
Adams	48	26	24	24	20	22
30th	56	36	38	32	30	28
Jefferson	48	30	24	24	20	22
Broadway at:						
23rd	56	36	40	34	30	30
Adams	48	26	28	28	24	24
30th	56	36	40	34	30	30
Jefferson	48	34	30	28	24	24
Main at:						
23rd	56	34	32	24	28	22
Adams	48	30	30	32	26	28
30th	56	36	40	36	30	30
Jefferson	48	32	34	36	28	30
Freeway ramps at:						
23rd	52	36	32	30	26	28
Adams	28	26	24	32	20	28

[a] Splits rounded to even-number values for TRANS simulation input.

TABLE A-2

SUMMARY OF OFFSET DIFFERENCES, LOS ANGELES NETWORK, OFFPEAK PERIOD

STREET	OFFSET DIFFERENCES (SEC), BY TRAFFIC CONTROL ALTERNATIVE 1	2	3	4	5	6	7	8	9	10
Figueroa SB:										
23rd	26	32	26	26	32	30	32	30	26	26
Adams	28	28	32	28	24	28	24	28	34	26
30th	28	32	30	28	38	32	38	32	30	26
Jefferson										
Flower SB:										
23rd	26	32	20	24	32	32	32	32	28	26
Adams	30	26	28	28	14	22	14	22	32	24
30th	28	34	32	28	22	32	48	34	30	48
Jefferson										
Grand SB:										
23rd	26	34	30	26	38	30	38	30	28	26
Adams	28	22	32	28	20	24	20	24	32	24
30th	28	40	30	28	40	38	24	22	30	0
Jefferson										
Hill SB:										
23rd	26	22	26	22	32	22	32	22	26	24
Adams	28	22	30	30	18	22	18	22	34	26
30th	28	36	32	30	46	42	0	32	30	48
Jefferson										
Broadway SB:										
23rd	26	34	30	28	38	32	38	32	26	24
Adams	28	24	32	30	20	24	38	14	34	26
30th	30	30	30	28	38	38	38	38	30	48
Jefferson										
Main SB:										
23rd	26	30	30	26	30	26	30	26	28	26
Adams	28	28	28	28	22	26	22	26	32	24
30th	16	32	30	28	38	34	38	34	30	48
Jefferson										
23rd WB:										
Main	0	2	14	10	50	24	50	24	40	6
Broadway	52	22	52	46	44	38	44	38	54	16
Hill	28	8	0	26	44	28	44	28	30	6
Grand	2	28	30	24	12	10	12	10	0	26
Flower	76	0	6	6	20	16	20	16	32	22
Figueroa	10	8	2	2	2	38	2	8	58	48
Freeway ramp										
Adams WB:										
Main	0	0	0	0	48	26	48	26	28	0
Broadway	78	30	0	0	46	36	46	36	2	24
Hill	74	0	0	24	44	28	44	28	26	0
Grand	2	30	26	22	20	20	20	20	4	26
Fwy. ramp	0	0	0	2	50	42	50	42	0	0
Flower	8	0	6	6	20	16	20	16	30	24
Figueroa										
30th WB:										
Main	0	0	6	6	48	26	6	16	32	4
Broadway	78	18	0	0	46	38	28	48	4	28
Hill	2	0	2	22	44	28	44	28	22	46
Grand	0	32	30	28	10	12	10	12	10	28
Flower	2	0	54	48	20	16	20	16	22	20
Figueroa										
Jefferson WB:										
Main	14	0	0	0	44	26	2	16	28	0
Broadway	76	30	0	2	50	38	46	38	0	24
Hill	2	0	4	24	44	28	14	22	28	2
Grand	4	28	26	24	8	6	30	24	6	26
Flower	78	0	4	4	20	20	14	18	26	2
Figueroa										

but with splits checked for reasonableness and modified at two locations.*

5. *Alternative 5.* 80-sec cycle, Webster splits, offsets determined by delay-difference method for preferential streets.

6. *Alternative 6.* 50-sec cycle, Webster splits, and preferential streets delay-difference offsets.

7. *Alternative 7.* 80-sec cycle, Webster splits, and offsets determined by the delay-difference method using the volume priority approach. The volume priority approach is shown in Figure A-2.

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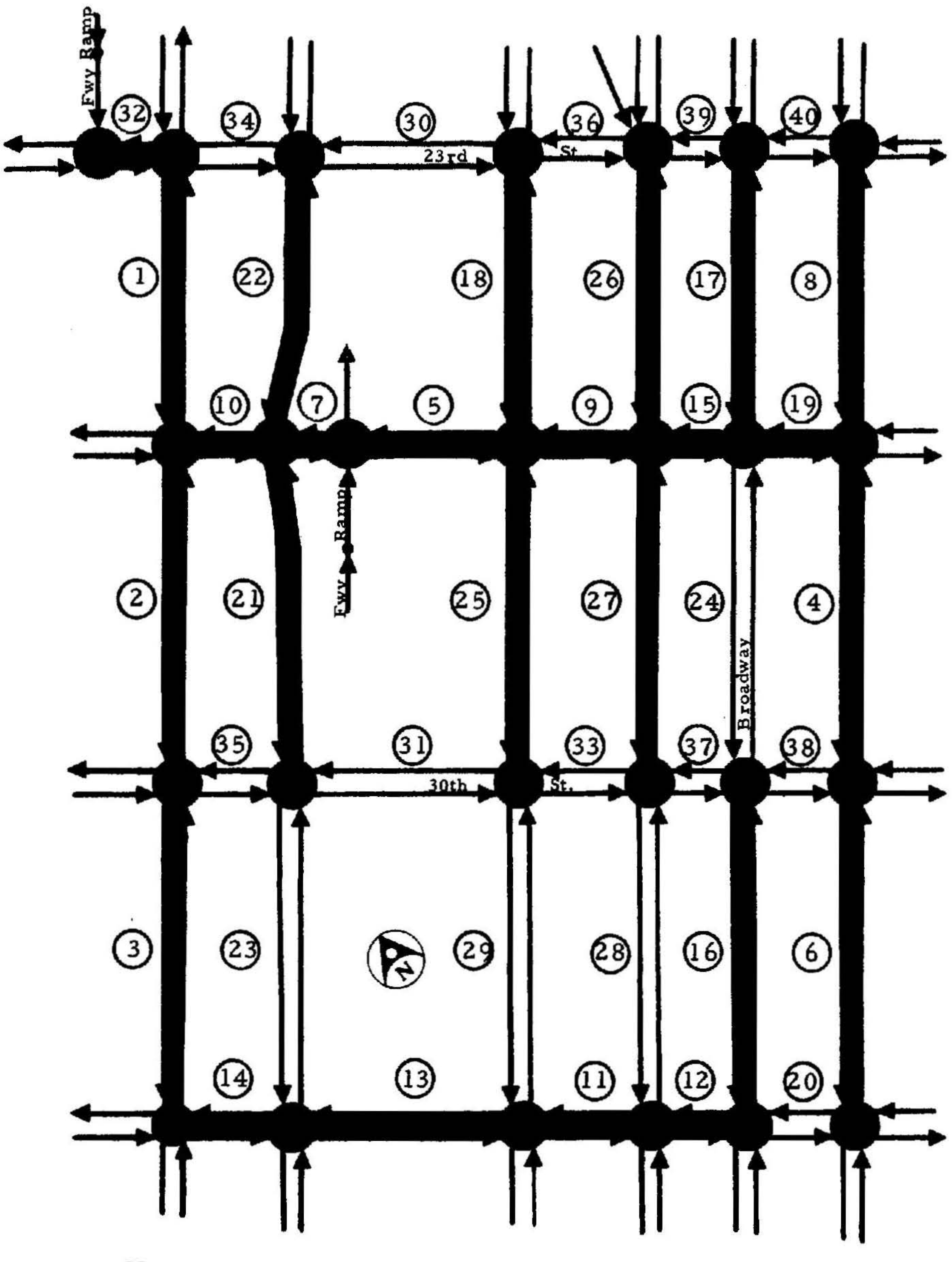
* Splits were compared with those computed by hand using the Webster method. At two of the intersections, the SIGOP program yielded splits that deviated significantly from Webster splits. This occurred because both intersections had one street with very high turning percentages. One intersection was a T intersection, and the other was an offset intersection. SIGOP applies a factor that transforms turning traffic into equivalent straight-through traffic, and such a technique works well most of the time. However, at intersections with abnormally high turning movements on one street, SIGOP allocates too much green time to that street. At the two intersections where this occurred, the Webster splits were substituted for the SIGOP splits.



Notes: Heavy lines denote links given optimum offsets.
Numbers denote volume priority ranking.

Figure A-1. Volume priority plan, Los Angeles network, offpeak period.

8. *Alternative 8.* 60-sec cycle, Webster splits, and volume priority delay-difference offsets.

9. *Alternative 9.* 50-sec cycle, Webster splits, and volume priority delay-difference offsets.

10. *Alternative 10.* 80-sec cycle, Webster splits, and offsets determined by the Little maximal bandwidth technique for preferential streets.

11. *Alternative 11.* 50-sec cycle, Webster splits, and preferential streets maximal bandwidth offsets.

12. *Alternative 12.* A mixture of 50- and 60-sec cycle

TABLE A-3

SUMMARY OF SPLITS, BY CYCLE, LOS ANGELES NETWORK, PEAK PERIOD [a]

	NORTH-SOUTH GREEN PLUS YELLOW (SEC), BY CYCLE LENGTH (SEC)					
STREET	EXISTING (80)	WEBSTER (80)	SIGOP (80)	WEBSTER (60)	WEBSTER (50)	SIGOP (50)
Figueroa at:						
23rd	52	52	52	38	30	30
Adams	48	44	44	32	26	28
30th	56	58	58	40	30	30
Jefferson	48	46	48	34	28	30
Flower at:						
23rd	56	36	36	28	24	24
Adams	40	34	34	28	28	22
30th	52	46	48	36	30	30
Jefferson	48	40	44	30	26	28
Grand at:						
23rd	56	48	40	36	30	26
Adams	40	40	36	30	26	24
30th	56	46	50	34	28	30
Jefferson	48	38	42	28	24	26
Hill at:						
23rd	30	34	34	26	18	20
Adams	48	42	44	32	26	26
30th	56	50	48	38	30	30
Jefferson	48	42	44	32	26	28
Broadway at:						
23rd	56	54	50	40	30	30
Adams	48	44	44	32	28	28
30th	56	54	48	40	30	30
Jefferson	48	46	46	34	26	28
Main at:						
23rd	56	46	38	34	28	24
Adams	48	48	52	36	30	30
30th	56	60	56	40	30	30
Jefferson	48	48	50	36	30	30
Freeway ramp at:						
23rd	52	36	28	26	22	20
Adams	28	26	40	20	20	24

[a] Splits rounded to even-number values for TRANS simulation input.

lengths used, Webster splits, and volume priority delay-difference offsets. This was the first "mixed cycle" plan tested. All intersections along Figueroa and Flower were operated on a 60-sec cycle, as was the Adams freeway ramp intersection. All other intersections were operated on a 50-sec cycle. Each subsystem's timing plan was developed using the volume priority approach. This control alternative is shown in Figure A-3.

13. *Alternative 13.* A mixture of 50- and 60-sec cycles, Webster splits, and volume priority delay-difference offsets. In this second mixed cycle plan (Fig. A-4), the intersections of Adams Boulevard with Figueroa, Flower, and the freeway ramp were operated on a 60-sec cycle. All other intersections in the system were operated on a 50-sec cycle.

14. *Alternative 14.* 50-sec cycle, Webster splits, and offsets determined by the British combination technique augmented by the Allsop graph theory optimization technique. Because of the difficulties involved in exercising these techniques, they were used only for the Los Angeles peak period conditions. Offsets were determined in units of tenths of the cycle length or 5 sec. Finer divisions of time would have required excessively long running times on the 360/50 computer to exercise the Allsop optimization program. The use of 10 divisions of the cycle length required more than one-half hour of computer time. Using Allsop's computer time estimation information, it was estimated that approximately 8 hr of computer time would have been needed to operate the program with the cycle divided into 16 increments.

15. *Alternative 15.* Traffic-responsive basic queue control technique.

SAN JOSE NETWORK ALTERNATIVES

The following nine control alternatives were developed and tested for the 4:00 to 6:00 PM period in the San Jose test network. Splits and offsets are summarized in Tables A-5 and A-6, respectively.

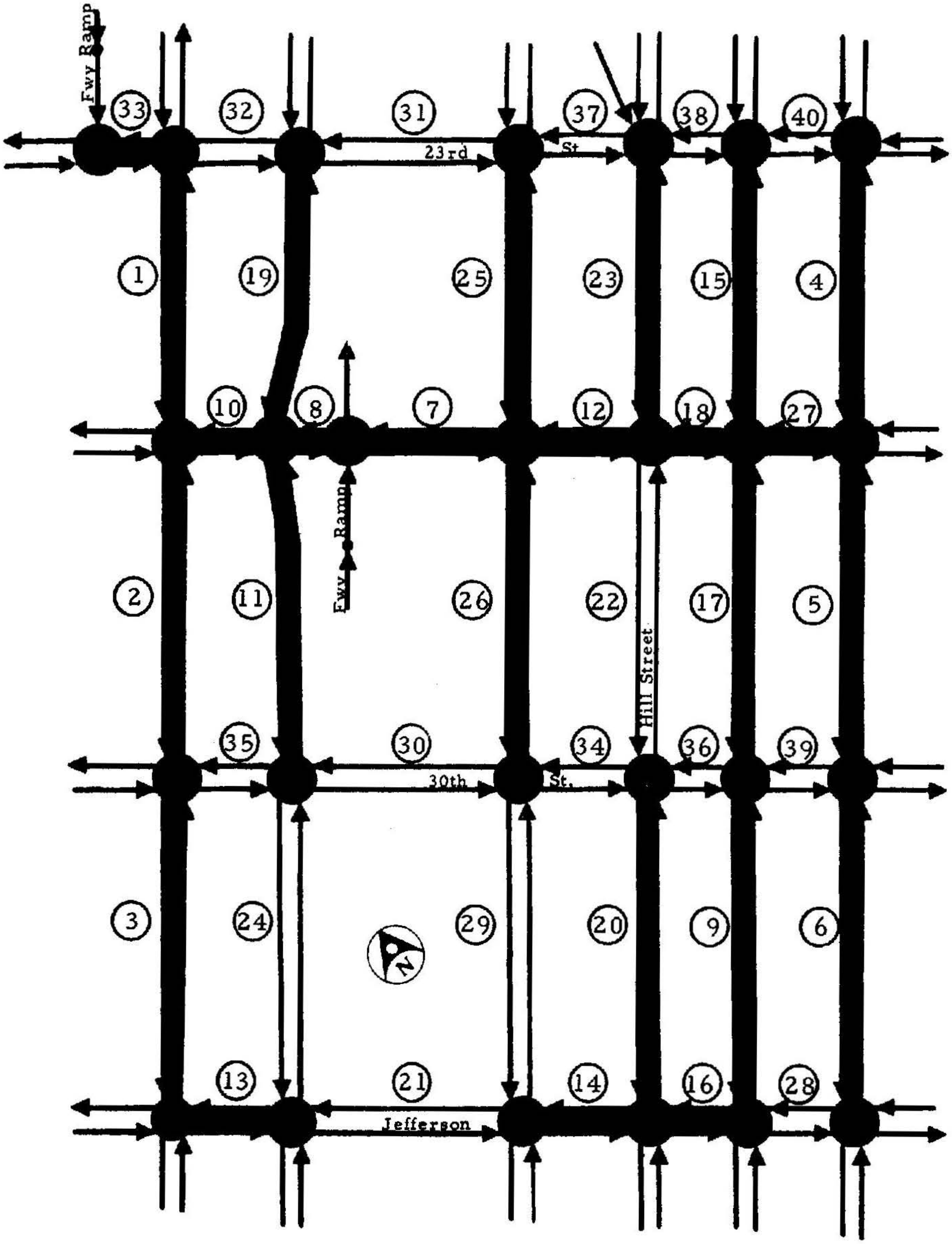
1. *Alternative 1.* Existing 50-sec cycle, splits, and offsets in use during the time period being tested.
2. *Alternative 2.* 60-sec cycle, splits, and offsets determined by the SIGOP technique.
3. *Alternative 3.* 50-sec cycle, SIGOP splits and offsets.
4. *Alternative 4.* 40-sec cycle, SIGOP splits and offsets.
5. *Alternative 5.* 50-sec cycle, Webster splits, and offsets determined by the delay-difference technique for preferential streets. The selected preferential streets were San Carlos, Market, and all the north-south one-way streets—First, Second, Third, and Fourth.
6. *Alternative 6.* 50-sec cycle, Webster splits, and offsets determined by the delay-difference technique using the volume priority approach as shown in Figure A-5.
7. *Alternative 7.* 40-sec cycle, Webster splits, and volume priority delay-difference offsets.
8. *Alternative 8.* 50-sec cycle, Webster splits, and offsets determined by the Little maximal bandwidth technique for preferential streets.
9. *Alternative 9.* Traffic-responsive basic queue control technique.

TABLE A-4

SUMMARY OF OFFSET DIFFERENCES, LOS ANGELES NETWORK PEAK PERIOD

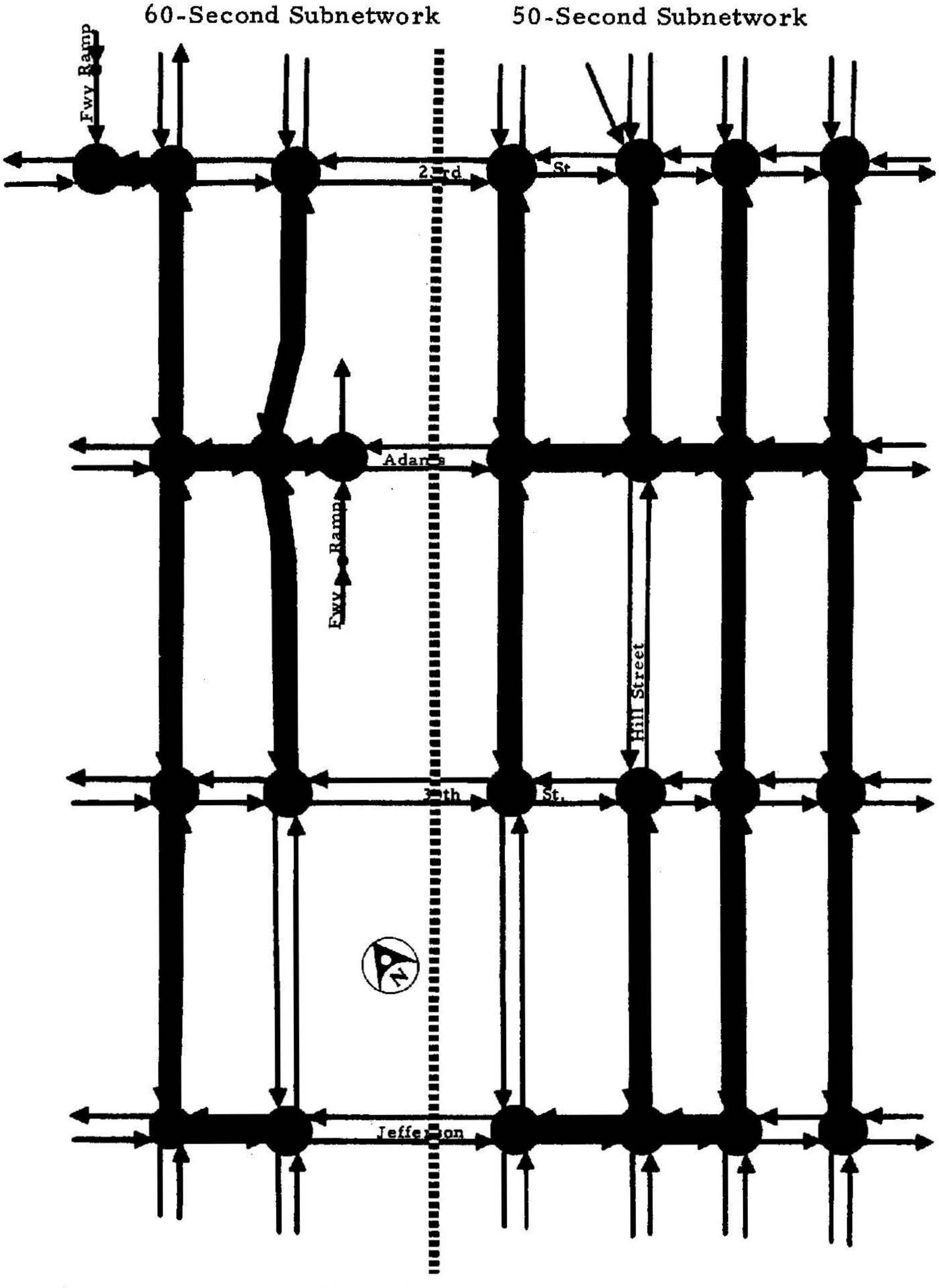
STREET	OFFSET DIFFERENCES (SEC), BY TRAFFIC CONTROL ALTERNATIVE													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Figueroa SB:														
23rd														
Adams	26	30	24	24	34	28	34	32	28	6	26	32	[a]	30
30th	28	34	28	28	28	30	28	24	30	40	28	24	[a]	16
Jefferson	28	34	30	30	42	32	42	36	32	40	26	36	32	36
Flower SB:														
23rd														
Adams	26	32	24	24	36	28	36	28	28	34	26	28	[a]	20
30th	30	32	28	28	30	24	30	22	24	38	24	22	[a]	34
Jefferson	28	32	28	28	38	34	40	38	34	8	48	38	34	8
Grand SB:														
23rd														
Adams	26	38	26	24	36	30	36	34	30	40	26	30	30	34
30th	28	34	28	30	34	28	34	26	28	40	48	28	28	24
Jefferson	28	34	28	28	40	36	56	42	36	38	26	48	48	24
Hill SB:														
23rd														
Adams	26	32	24	24	36	18	36	26	18	34	26	18	18	46
30th	28	36	30	30	34	28	52	42	28	6	24	48	48	26
Jefferson	28	34	28	28	40	36	40	38	36	40	48	36	36	34
Broadway SB:														
23rd														
Adams	26	34	28	28	38	28	38	36	28	40	26	28	28	32
30th	28	34	28	28	34	28	34	24	28	40	46	28	28	22
Jefferson	30	36	28	30	40	42	40	38	42	34	28	42	42	40
Main SB:														
23rd														
Adams	26	32	26	26	32	24	32	26	24	36	26	24	24	24
30th	28	34	30	30	30	30	30	28	30	38	24	30	30	30
Jefferson	16	36	28	28	44	32	44	36	32	6	46	32	32	30
23rd WB:														
Main														
Broadway	0	16	8	4	72	30	72	46	32	22	10	30	30	36
Hill	52	68	44	44	52	32	52	46	30	74	8	32	32	30
Grand	28	8	12	16	28	30	28	26	20	32	18	20	20	44
Flower	2	10	24	20	78	20	6	10	22	18	18	[a]	22	26
Figueroa	76	14	6	6	28	26	20	16	22	52	30	16	22	14
Fwy. ramp	10	0	2	2	72	0	72	56	0	72	46	56	0	0
Adams WB:														
Main														
Broadway	0	78	2	2	66	30	66	46	30	14	6	30	30	40
Hill	78	2	48	48	68	32	68	50	32	6	18	32	32	4
Grand	74	0	6	4	12	20	12	22	20	22	6	20	20	20
Fwy. ramp	2	6	20	22	4	16	4	8	16	18	26	[a]	[a]	16
Flower	0	0	2	2	0	10	0	0	10	0	0	0	0	4
Figueroa	8	6	6	6	20	18	20	16	18	18	22	10	16	16
30th WB:														
Main														
Broadway	0	78	2	2	68	30	68	46	36	14	30	30	30	34
Hill	78	4	2	2	66	34	4	6	34	50	48	4	4	10
Grand	2	8	6	6	10	18	72	4	18	54	28	48	48	16
Flower	0	4	24	24	6	22	6	10	28	22	2	[a]	38	30
Figueroa	2	8	0	0	20	26	20	16	14	22	28	16	12	0
Jefferson:														
Main														
Broadway	14	2	0	2	68	36	68	46	0	46	8	36	36	40
Hill	76	0	2	0	66	28	4	6	48	62	18	48	48	4
Grand	2	4	4	4	10	18	8	8	10	46	6	10	10	6
Flower	4	6	26	26	6	20	72	6	24	76	24	[a]	24	14
Figueroa	78	4	4	4	18	26	16	14	12	48	8	14	12	30

[a] No fixed relationship owing to different cycle lengths.



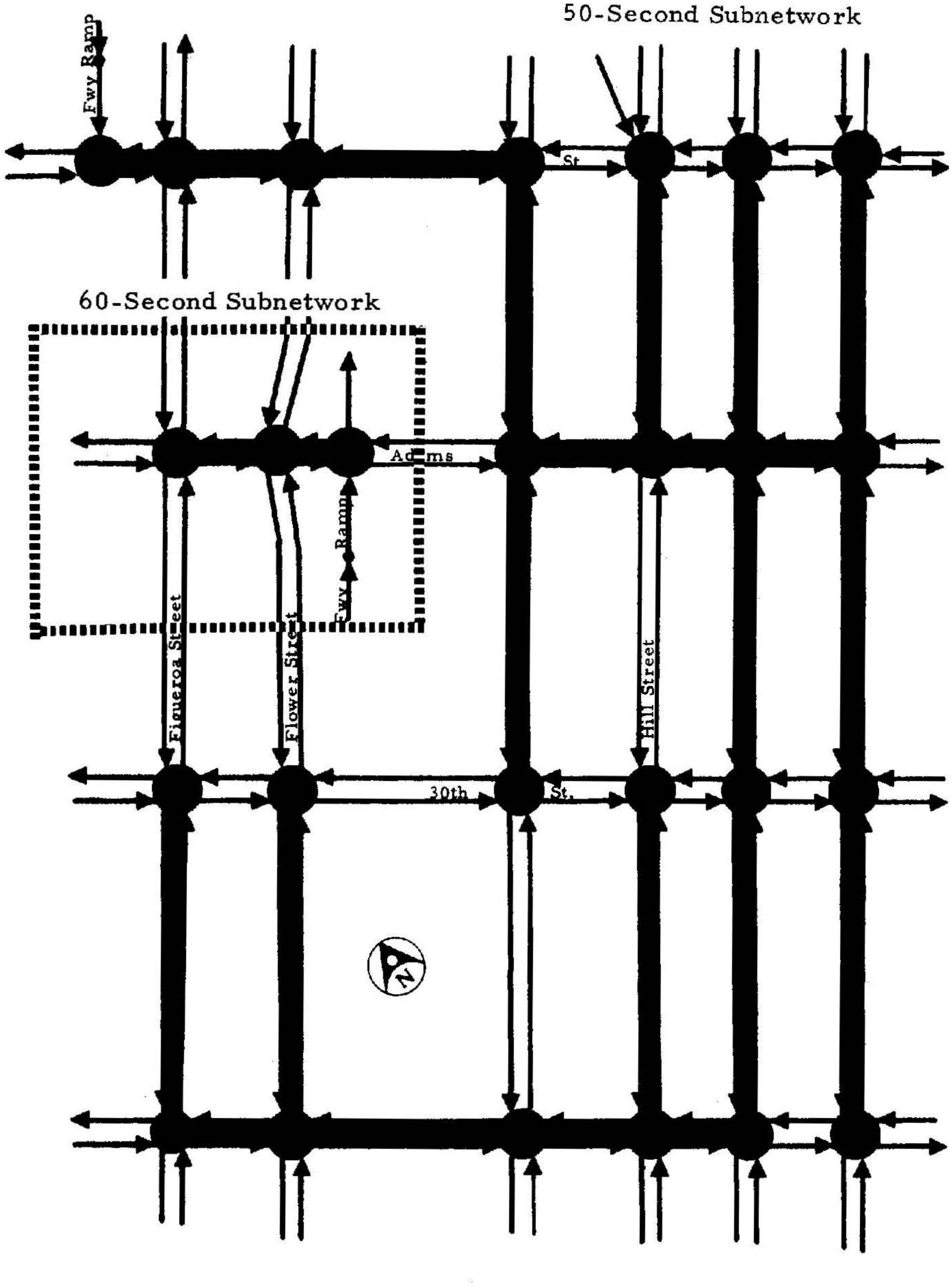
Notes: Heavy lines denote links given optimum offsets.
Numbers denote volume priority ranking.

Figure A-2. Volume priority plan, Los Angeles network, peak period.



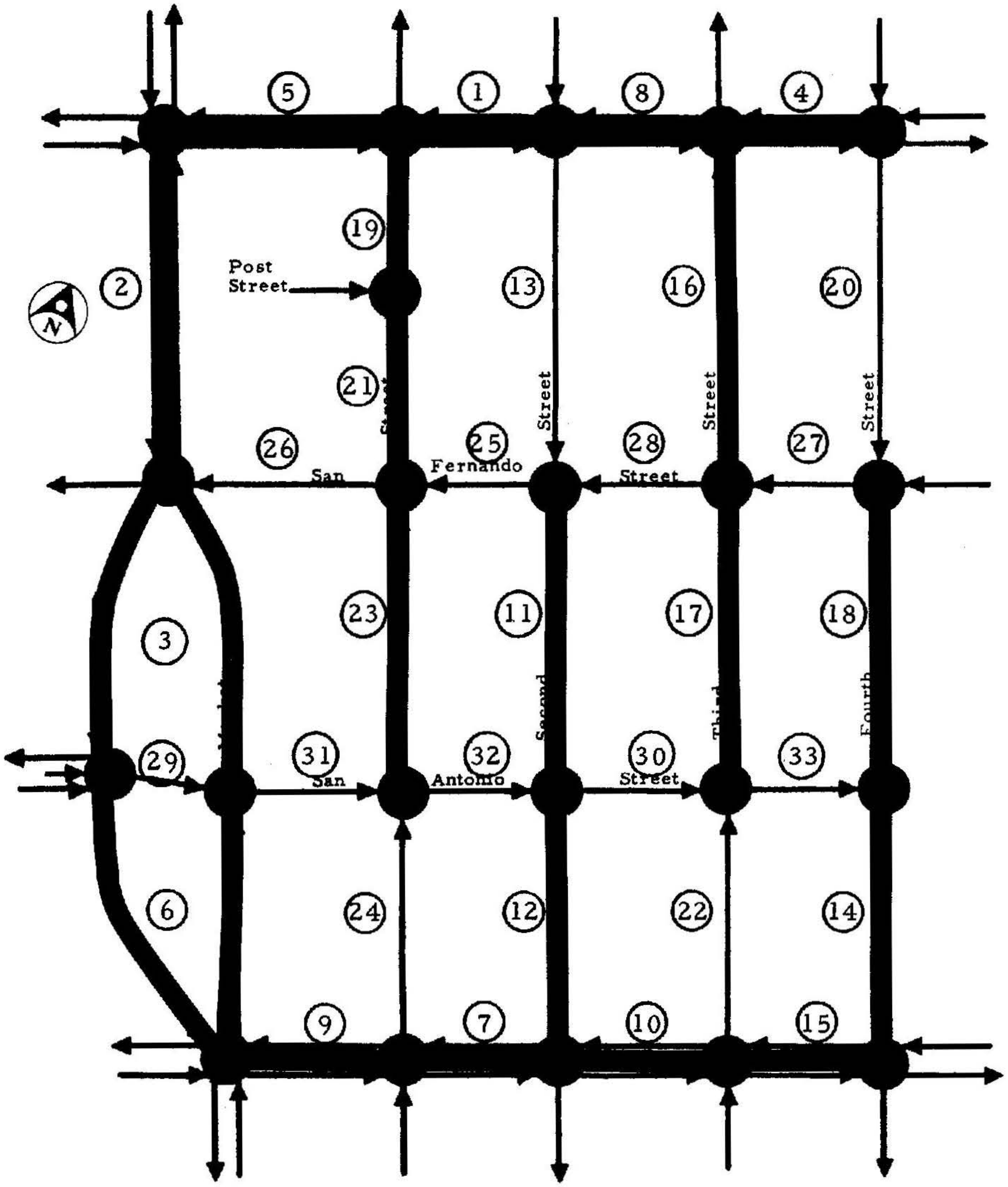
Note: Heavy lines denote links given optimum offsets.

Figure A-3. Mixed cycle plan I, Los Angeles network.



Note: Heavy lines denote links given optimum offsets.

Figure A-4. Mixed cycle plan II, Los Angeles network.



Note: Heavy lines denote links given optimum offsets.

Figure A-5. Volume priority plan, San Jose network.

TABLE A-5

SUMMARY OF SPLITS, BY CYCLE,
SAN JOSE NETWORK, 4:00–6:00 PM[a]

	NORTH-SOUTH GREEN PLUS YELLOW (SEC), BY CYCLE LENGTH (SEC)					
STREET	SIGOP (60)	EXISTING (50)	SIGOP (50)	WEBSTER (50)	SIGOP (40)	WEBSTER (40)
Market at:						
Santa Clara	34	24	28	24	22	22
San Fernando	42	26	32	32	22	22
Park	42	32	32	32	22	22
San Antonio	26	30	22	30	18	18
San Carlos	34	24	28	24	22	22
First at:						
Santa Clara	34	24	28	18	22	22
Post	42	22	32	32	2	22
San Fernando	28	26	24	26	18	18
San Antonio	34	26	28	32	22	22
San Carlos	24	28	20	20	18	18
Second at:						
Santa Clara	24	22	20	22	18	18
San Fernando	34	24	28	30	22	22
San Antonio	42	26	32	32	22	22
San Carlos	38	24	30	28	22	22
Third at:						
Santa Clara	30	22	26	22	20	20
San Fernando	32	24	26	28	22	22
San Antonio	30	24	26	28	20	20
San Carlos	30	26	24	24	20	20
Fourth at:						
Santa Clara	24	24	20	18	18	18
San Fernando	24	26	20	28	18	18
San Antonio	42	24	32	32	22	22
San Carlos	36	26	30	30	22	22

[a] Splits rounded to even-number values for TRANS simulation input.

TABLE A-6

SUMMARY OF OFFSET DIFFERENCES, SAN JOSE NETWORK, 4:00–6:00 PM

	OFFSET DIFFERENCES (SEC), BY TRAFFIC CONTROL ALTERNATIVE							
	1	2	3	4	5	6	7	8
Market NB:								
San Carlos	30	12	8	24	20	20	16	28
San Antonio	32	18	12	20	30	30	20	26
San Fernando	26	30	28	22	32	32	26	24
Santa Clara								
First NB:								
San Carlos	20	12	14	16	14	10	38	26
San Antonio	10	16	22	26	30	30	26	22
San Fernando	28	12	16	12	14	14	14	4
Post	4	10	12	12	28	28	18	12
Santa Clara								
Second SB:								
Santa Clara	40	18	30	28	20	6	6	24
San Fernando	12	16	16	22	20	20	22	26
San Antonio	20	18	20	22	26	26	22	24
San Carlos								
Third NB:								
San Carlos	20	8	26	16	16	46	18	24
San Antonio	12	16	20	16	22	22	22	22
San Fernando	32	26	24	26	32	32	30	24
Santa Clara								
Fourth SB:								
Santa Clara	30	22	22	22	16	10	36	24
San Fernando	14	18	24	18	16	16	20	48
San Antonio	18	18	22	18	22	22	20	48
San Carlos								
Santa Clara EB:								
Market	48	0	26	22	22	18	16	22
First	26	58	4	16	12	30	20	4
Second	0	56	2	16	46	12	12	20
Third	26	4	2	18	32	8	22	4
Fourth								
San Fernando WB:								
Fourth	12	10	2	16	16	46	34	44
Third	12	56	10	0	18	28	26	30
Second	12	6	36	4	26	22	14	46
First	8	6	32	24	38	42	34	30
Market								
San Antonio EB:								
Market West	4	12	14	0	48	48	36	48
Market East	10	18	22	18	20	16	8	32
First	12	28	12	0	20	24	30	48
Second	12	22	0	0	48	28	8	20
Third	12	44	4	24	26	46	14	30
Fourth								
San Carlos EB:								
Market	28	0	2	18	20	20	18	28
First	48	4	2	2	18	18	14	6
Second	26	0	4	2	6	6	8	22
Third	0	4	2	18	16	16	12	4
Fourth								

APPENDIX B

DETAILED PRESENTATION OF SIMULATION RESULTS

The research agency's traffic network simulation model, TRANS IV, was used to perform tests of the effectiveness of all the traffic control alternatives. (See Appendix H for details concerning the model.) In prior investigations of smaller street systems, several replications of the simulation tests were executed to obtain data for statistical analysis. In this study with larger networks and longer required computer time for simulation, different statistical methods were used to avoid the need for replications. Each hour-and-a-half simulation period in Los Angeles was stratified into 15-min intervals, and traffic operations data were obtained for each interval from intermediate simulation output list-

TABLE B-1

SIMULATION RESULTS FOR CONTROL ALTERNATIVES, LOS ANGELES NETWORK, OFFPEAK PERIOD, 3:00–4:00 PM AND 5:30–6:00 PM

ALTERNATIVE	TIME	VEH-MILES	TOTAL TRAVEL TIME (VEH-SEC)	AVERAGE SPEED (MPH)
1	3:00–3:15	1,172	245,800	17.2
	3:15–3:30	1,204	256,654	16.9
	3:30–3:45	1,358	290,488	16.8
	3:45–4:00	1,453	316,156	16.5
	5:30–5:45	1,513	320,370	17.0
	5:45–6:00	1,266	260,978	17.4
	Total	7,966	1,683,446	17.0
2	3:00–3:15	1,113	198,736	20.2
	3:15–3:30	1,159	207,136	20.1
	3:30–3:45	1,362	247,588	19.8
	3:45–4:00	1,449	255,486	20.4
	5:30–5:45	1,543	276,688	20.1
	5:45–6:00	1,298	228,558	20.5
	Total	7,924	1,414,192	20.2
3	3:00–3:15	1,132	196,116	20.8
	3:15–3:30	1,222	214,738	20.5
	3:30–3:45	1,336	236,170	20.4
	3:45–4:00	1,457	258,726	20.3
	5:30–5:45	1,546	268,922	20.7
	5:45–6:00	1,242	212,324	21.1
	Total	7,935	1,386,996	20.6
4	3:00–3:15	1,101	195,834	20.2
	3:15–3:30	1,198	212,002	20.3
	3:30–3:45	1,372	246,338	20.1
	3:45–4:00	1,489	266,916	20.1
	5:30–5:45	1,476	257,778	20.6
	5:45–6:00	1,331	229,956	20.8
	Total	7,967	1,408,824	20.4
5	3:00–3:15	1,106	196,716	20.2
	3:15–3:30	1,201	212,170	20.4
	3:30–3:45	1,309	232,280	20.2
	3:45–4:00	1,473	263,918	20.1
	5:30–5:45	1,508	265,572	20.4
	5:45–6:00	1,339	228,602	21.1
	Total	7,936	1,399,258	20.4
6	3:00–3:15	1,150	206,478	20.0
	3:15–3:30	1,167	208,360	20.2
	3:30–3:45	1,376	248,924	19.9
	3:45–4:00	1,480	264,206	20.2
	5:30–5:45	1,574	279,210	20.3
	5:45–6:00	1,315	226,398	20.9
	Total	8,062	1,433,566	20.2
7	3:00–3:15	1,118	201,004	20.0
	3:15–3:30	1,136	203,410	20.1
	3:30–3:45	1,311	234,066	20.1
	3:45–4:00	1,494	271,540	19.8
	5:30–5:45	1,560	279,558	20.1
	5:45–6:00	1,274	221,842	20.7
	Total	7,893	1,411,420	20.1
8	3:00–3:15	1,055	187,226	20.3
	3:15–3:30	1,150	201,880	20.6
	3:30–3:45	1,339	232,226	20.8
	3:45–4:00	1,491	263,714	20.4
	5:30–5:45	1,509	261,880	20.7
	5:45–6:00	1,311	225,332	21.0
	Total	7,855	1,372,258	20.6
9	3:00–3:15	1,120	203,520	19.8
	3:15–3:30	1,105	196,912	20.3
	3:30–3:45	1,290	231,312	20.1
	3:45–4:00	1,413	253,800	20.1
	5:30–5:45	1,508	269,272	20.2
	5:45–6:00	1,287	224,368	20.6
	Total	7,723	1,379,184	20.2
10	3:00–3:15	1,178	204,780	20.7
	3:15–3:30	1,162	203,792	20.5
	3:30–3:45	1,331	232,220	20.6
	3:45–4:00	1,533	270,508	20.4
	5:30–5:45	1,564	270,294	20.8
	5:45–6:00	1,306	223,160	21.1
	Total	8,084	1,404,754	20.7
11	3:00–3:15	1,079	190,960	20.3
	3:15–3:30	1,166	210,050	19.9
	3:30–3:45	1,337	242,382	19.8
	3:45–4:00	1,465	269,610	19.6
	5:30–5:45	1,528	281,144	19.6
	5:45–6:00	1,350	244,668	19.8
	Total	7,925	1,438,814	19.8

TABLE B-2

SIMULATION RESULTS FOR CONTROL ALTERNATIVES. LOS ANGELES NETWORK, PEAK PERIOD, 4:00–5:30 PM

ALTERNATIVE	TIME	VEH-MILES	TOTAL TRAVEL TIME (VEH-SEC)	AVERAGE SPEED (MPH)
1	4:00–4:15	1,916	409,146	16.9
	4:15–4:30	1,962	451,610	15.6
	4:30–4:45	2,225	537,006	14.9
	4:45–5:00	2,189	525,754	15.0
	5:00–5:15	2,179	509,154	15.4
	5:15–5:30	1,916	464,020	14.9
	Total	12,387	2,896,690	15.4
2	4:00–4:15	1,982	418,020	17.1
	4:15–4:30	1,941	418,658	16.7
	4:30–4:45	2,227	537,558	14.9
	4:45–5:00	2,171	494,908	15.8
	5:00–5:15	2,327	520,058	16.1
	5:15–5:30	1,960	447,922	15.8
	Total	12,508	2,837,120	15.9
3	4:00–4:15	1,925	352,446	19.7
	4:15–4:30	1,921	366,602	18.9
	4:30–4:45	2,267	445,382	18.3
	4:45–5:00	2,217	418,078	19.1
	5:00–5:15	2,155	408,716	19.0
	5:15–5:30	1,983	386,136	18.5
	Total	12,468	2,337,360	18.9
4	4:00–4:15	1,922	347,256	19.9
	4:15–4:30	1,886	350,026	19.4
	4:30–4:45	2,266	465,940	17.5
	4:45–5:00	2,219	414,130	19.3
	5:00–5:15	2,214	421,426	18.9
	5:15–5:30	1,892	349,844	19.5
	Total	12,399	2,330,622	19.2
5	4:00–4:15	1,924	395,280	17.5
	4:15–4:30	1,932	403,386	17.2
	4:30–4:45	2,242	500,246	16.2
	4:45–5:00	2,137	466,118	16.5
	5:00–5:15	2,231	486,676	16.5
	5:15–5:30	1,889	400,798	17.0
	Total	12,355	2,652,504	16.8
6	4:00–4:15	1,940	368,476	19.0
	4:15–4:30	1,931	369,208	18.8
	4:30–4:45	2,236	437,020	18.4
	4:45–5:00	2,183	414,988	19.0
	5:00–5:15	2,171	418,316	18.7
	5:15–5:30	1,961	376,358	18.8
	Total	12,422	2,384,366	18.8
7	4:00–4:15	1,987	408,104	17.5
	4:15–4:30	1,989	428,430	16.7
	4:30–4:45	2,226	518,610	15.5
	4:45–5:00	2,154	496,366	15.6
	5:00–5:15	2,127	475,912	16.1
	5:15–5:30	1,978	450,564	15.8
	Total	12,461	2,777,986	16.1
8	4:00–4:15	1,903	357,314	19.2
	4:15–4:30	1,964	390,526	18.1
	4:30–4:45	2,245	469,608	17.2
	4:45–5:00	2,186	438,044	18.0
	5:00–5:15	2,227	437,406	18.3
	5:15–5:30	1,908	378,024	18.2
	Total	12,433	2,470,922	18.1
9	4:00–4:15	1,896	348,032	19.6
	4:15–4:30	1,928	377,226	18.4
	4:30–4:45	2,242	450,168	17.9
	4:45–5:00	2,219	426,878	18.7
	5:00–5:15	2,175	401,940	19.5
	5:15–5:30	1,960	380,444	18.6
	Total	12,420	2,384,688	18.8
10	4:00–4:15	1,963	430,900	16.4
	4:15–4:30	1,917	422,822	16.3
	4:30–4:45	2,201	507,290	15.6
	4:45–5:00	2,173	517,134	15.1
	5:00–5:15	2,231	537,712	14.9
	5:15–5:30	1,880	451,030	15.0
	Total	12,365	2,866,890	15.5
11	4:00–4:15	2,017	380,520	19.1
	4:15–4:30	1,903	387,286	17.7
	4:30–4:45	2,237	462,918	17.4
	4:45–5:00	2,116	415,436	18.3
	5:00–5:15	2,218	443,994	18.0
	5:15–5:30	1,963	384,838	18.4
	Total	12,454	2,474,992	18.1
12	4:00–4:15	1,931	358,402	19.4
	4:15–4:30	1,918	366,868	18.8
	4:30–4:45	2,273	451,050	18.1
	4:45–5:00	2,100	403,362	18.7
	5:00–5:15	2,223	429,234	18.7
	5:15–5:30	1,884	365,774	18.6
	Total	12,329	2,374,690	18.7
13	4:00–4:15	1,952	371,276	18.9
	4:15–4:30	1,916	365,950	18.9
	4:30–4:45	2,237	457,294	17.6
	4:45–5:00	2,176	444,838	17.6
	5:00–5:15	2,229	452,434	17.7
	5:15–5:30	1,908	375,368	18.3
	Total	12,418	2,467,160	18.1
14	4:00–4:15	1,933	367,844	18.9
	4:15–4:30	1,891	392,596	17.1
	4:30–4:45	2,274	476,338	17.2
	4:45–5:00	2,174	425,924	18.3
	5:00–5:15	2,237	430,640	18.7
	5:15–5:30	1,838	350,092	18.8
	Total	12,347	2,445,434	18.2
15	4:00–4:15	1,888	353,688	19.2
	4:15–4:30	1,971	377,526	18.8
	4:30–4:45	2,269	444,710	18.4
	4:45–5:00	2,193	436,558	18.1
	5:00–5:15	2,261	445,918	18.3
	5:15–5:30	1,889	363,184	18.7
	Total	12,471	2,421,584	18.5

TABLE B-3

SIMULATION RESULTS FOR CONTROL ALTERNATIVES, SAN JOSE NETWORK, 4:00–6:00 PM

ALTERNATIVE	TIME	VEH-MILES	TOTAL TRAVEL TIME (VEH-SEC)	AVERAGE SPEED (MPH)
1	4:00–4:15	711	166,870	15.3
	4:15–4:30	747	171,918	15.7
	4:30–4:45	838	192,888	15.6
	4:45–5:00	847	197,974	15.4
	5:00–5:15	958	228,166	15.1
	5:15–5:30	866	202,920	15.3
	5:30–5:45	753	183,254	14.8
	5:45–6:00	601	135,790	15.9
	Total	6,321	1,479,780	15.4
2	4:00–4:15	730	176,330	14.9
	4:15–4:30	715	171,390	15.0
	4:30–4:45	840	203,852	14.8
	4:45–5:00	825	205,158	14.5
	5:00–5:15	941	232,570	14.6
	5:15–5:30	860	209,562	14.8
	5:30–5:45	731	176,522	14.9
	5:45–6:00	583	141,290	14.9
	Total	6,225	1,516,674	14.8
3	4:00–4:15	702	160,868	15.7
	4:15–4:30	732	168,508	15.7
	4:30–4:45	863	202,282	15.4
	4:45–5:00	841	195,282	15.5
	5:00–5:15	899	209,384	15.5
	5:15–5:30	824	190,624	15.5
	5:30–5:45	720	164,712	15.7
	5:45–6:00	608	140,308	15.6
	Total	6,189	1,431,968	15.6
4	4:00–4:15	664	144,986	16.5
	4:15–4:30	748	164,732	16.4
	4:30–4:45	836	187,118	16.1
	4:45–5:00	852	188,996	16.2
	5:00–5:15	964	216,826	16.0
	5:15–5:30	839	187,274	16.1
	5:30–5:45	734	162,216	16.3
	5:45–6:00	581	126,940	16.5
	Total	6,218	1,379,088	16.2
5	4:00–4:15	688	158,134	15.7
	4:15–4:30	735	166,772	15.9
	4:30–4:45	836	192,848	15.6
	4:45–5:00	795	183,460	15.6
	5:00–5:15	956	228,724	15.0
	5:15–5:30	857	202,106	15.3
	5:30–5:45	713	164,560	15.6
	5:45–6:00	594	134,610	15.9
	Total	6,174	1,431,214	15.5
6	4:00–4:15	721	165,812	15.7
	4:15–4:30	735	168,178	15.7
	4:30–4:45	867	203,288	15.4
	4:45–5:00	829	193,072	15.6
	5:00–5:15	949	226,538	15.1
	5:15–5:30	836	191,260	15.7
	5:30–5:45	730	167,752	15.8
	5:45–6:00	601	135,574	16.0
	Total	6,268	1,451,474	15.6
7	4:00–4:15	714	161,598	15.9
	4:15–4:30	749	169,212	15.9
	4:30–4:45	846	192,670	15.8
	4:45–5:00	818	188,286	15.6
	5:00–5:15	937	219,324	15.4
	5:15–5:30	815	184,108	15.9
	5:30–5:45	739	166,650	16.0
	5:45–6:00	580	129,448	16.1
	Total	6,198	1,411,296	15.8
8	4:00–4:15	687	155,280	15.9
	4:15–4:30	726	165,532	15.8
	4:30–4:45	835	190,824	15.8
	4:45–5:00	824	185,914	15.9
	5:00–5:15	938	221,000	15.3
	5:15–5:30	888	208,166	15.3
	5:30–5:45	706	159,734	15.9
	5:45–6:00	590	133,596	15.9
	Total	6,194	1,420,046	15.7
9	4:00–4:15	728	171,612	15.3
	4:15–4:30	773	180,664	15.4
	4:30–4:45	848	202,142	15.1
	4:45–5:00	825	193,812	15.3
	5:00–5:15	897	215,296	15.0
	5:15–5:30	826	194,822	15.3
	5:30–5:45	710	167,600	15.3
	5:45–6:00	616	142,488	15.6
	Total	6,223	1,468,436	15.3

ings. Similarly, the 2-hr simulation in San Jose was divided into 15-min subperiods for data analysis.

Detailed tabulation of the simulation results appears in this appendix. Tables B-1 and B-2 give data for the offpeak and peak periods, respectively, in the Los Angeles test network. Table B-3 gives detailed results for the San Jose test network. Data are included for all control alternatives tested by simulation.

It is important to note that all simulation runs in the Los Angeles network are based on input data gathered in early 1969, as described in Chapter Two in the section on "Input Data Collection." In other words, the simulation tests were made prior to the comprehensive field verification studies conducted later in the project. Consequently, the simulation was being used as a predictive tool in the truest sense of the word.

APPENDIX C

SIMULATION VALIDATION COMPARISONS

LOS ANGELES NETWORK

Three comprehensive field studies were performed under different traffic signal system conditions. These studies yielded reliable data for investigating the validity of the TRANS simulation model. Two types of validity were of interest:

1. Descriptive validity: how precisely simulated system characteristics conform to real system characteristics.
2. Predictive validity: how accurately the simulated effects of system changes predict real effects of system changes.

Predictive validity of a model is generally considered more important because the principal purpose of most simulation models is their use as predictive tools. The predictive validity of the TRANS simulation model in studies of the Los Angeles network is discussed elsewhere (see the section on "Field Verification Studies" in Chapter Two). This appendix pertains mainly to descriptive validity comparisons.

Descriptive validity of a simulation, although of somewhat lesser importance than its predictive ability, is a subject worthy of investigation as a general check of the reasonableness and realism of the simulated representation of the system. However, a high degree of descriptive validity is no guarantee that the model will be useful in predicting the effects of alternative courses of action. Conversely, the absence of precise descriptive validity does not necessarily render a model useless for predictive purposes. Descriptive validity is probably more strenuously studied by modelers, partly because data concerning the existing state of a given system are usually easier to acquire than data on the effects of system changes. Indeed, one reason the field of simulation has developed is the difficulty of full-scale system experimentation and measurement.

The data presented in this appendix compare simulated

TABLE C-1

COMPARISON OF SIMULATED AND MEASURED NETWORK TRAFFIC CHARACTERISTICS, LOS ANGELES NETWORK, EXISTING TIMING (ALTERNATIVE A)

ITEM	TOTAL VEH-MILES	TOTAL TRAVEL TIME (VEH-HR)	AVERAGE SPEED (MPH)
(a) Uncalibrated simulation			
Offpeak period:			
Simulated	7,846	460	17.0
Measured	7,932	408	19.4
Difference	−86	+52	−2.4
Percent difference	−1.1	+12.6	−12.4
Peak period:			
Simulated	12,267	797	15.4
Measured	12,469	799	15.6
Difference	−202	−2	−0.2
Percent difference	−1.6	−0.3	−0.1
(b) Calibrated simulation			
Offpeak period:			
Simulated	7,900	442	17.9
Measured	7,932	408	19.4
Difference	−32	+34	−1.5
Percent difference	−0.4	+8.3	−7.7
Peak period:			
Simulated	12,485	814	15.3
Measured	12,469	799	15.6
Difference	+16	+15	−0.3
Percent difference	+0.1	+1.9	−0.2

TABLE C-2

COMPARISON OF SIMULATED AND MEASURED NETWORK TRAFFIC CHARACTERISTICS, LOS ANGELES NETWORK, ALTERNATIVE B

ITEM	TOTAL VEH-MILES	TOTAL TRAVEL TIME (VEH-HR)	AVERAGE SPEED (MPH)
(a) Uncalibrated simulation			
Offpeak period (60-sec midday timing):			
Simulated	7,924	393	20.2
Measured	7,932	346	22.8
Difference	−8	+47	−2.6
Percent difference	−0.1	+13.6	−11.4
Peak period (50-sec refined SIGOP):			
Simulated	12,399	647	19.2
Measured	12,469	628	19.8
Difference	−70	+19	−0.6
Percent difference	−0.5	+3.0	−3.1
(b) Calibrated simulation			
Offpeak period:			
Simulated	7,923	378	21.0
Measured	7,932	346	22.8
Difference	−9	+30	−1.8
Percent difference	−0.1	+8.7	−7.9
Peak period:			
Simulated	12,660	635	20.0
Measured	12,469	628	19.8
Difference	+191	+7	+0.2
Percent difference	+1.5	+1.1	+1.0

traffic characteristics with estimates obtained by field measurement for the same traffic signal system conditions. In the Los Angeles network, three separate sets of comparisons are presented, based on results of the three comprehensive field studies.

Table C-1 compares simulated and field-measured estimates of total vehicle-miles for field Alternative A, existing signal timing conditions. Data are shown for total vehicle-miles, total travel time, and average speed in the network for both the offpeak and peak portions of the late afternoon study period. Results are tabulated for the "uncalibrated" and "calibrated" simulation tests. The uncalibrated simulation used unadjusted input data acquired, for the most part in early 1968, and free-flow speed input data collected in the 1968 Coliseum study. In the calibrated simulation, free-flow speeds on each route in the network were refined, based on data from the much more comprehensive speed and delay survey conducted for Alternative A.

Similar comparisons of simulated and measured traffic characteristics are made in Tables C-2 and C-3 for field Alternatives B and C, respectively. Note that the signal timing conditions for the offpeak portions of Alternatives B and C were actually the same alternative, whereas the signal timing for the peak portions of B and C were different alternatives.

As the data in Tables C-1, C-2, and C-3 indicate, the differences between simulated and measured characteristics in the network are relatively small. It was especially interesting that uncalibrated simulation data fit so closely. For example, in the poorest comparison of average speeds (Alternative B, Offpeak Period), uncalibrated simulation and field estimates differed by 2.6 mph, or 11.4 percent. The poorest fit comparing calibrated simulation with field estimates was for Alternative C, Peak Period, where the difference was only 1.8 mph, or 10.3 percent. Most of the comparisons indicate much closer fits between simulation and field data than for the worst cases cited previously.

TABLE C-3

COMPARISON OF SIMULATED AND MEASURED NETWORK TRAFFIC CHARACTERISTICS, LOS ANGELES NETWORK, ALTERNATIVE C

ITEM	TOTAL VEH-MILES	TOTAL TRAVEL TIME (VEH-HR)	AVERAGE SPEED (MPH)
(a) Uncalibrated simulation			
Offpeak period (60-sec midday timing):			
Simulated	7,924	393	20.2
Measured	7,932	351	22.6
Difference	−8	+42	−2.4
Percent difference	−0.1	+12.0	−10.6
Peak period (mixed cycle plan):			
Simulated	12,329	660	18.7
Measured	12,469	712	17.5
Difference	−140	−52	+1.2
Percent difference	−1.1	−7.3	+6.9
(b) Calibrated simulation			
Offpeak period:			
Simulated	7,754	360	21.5
Measured	7,932	351	22.6
Difference	−178	+9	−1.1
Percent difference	−2.2	+2.6	−4.9
Peak period:			
Simulated	12,394	640	19.3
Measured	12,469	712	17.5
Difference	−75	−72	+1.8
Percent difference	−0.6	−10.1	+10.3

Two types of statistical analyses were performed to determine if the differences between the calibrated simulation results and field-measured estimates were significant. The main emphasis was on the comparison of simulated and measured speeds.

First, the Kolmogorov-Smirnov (K-S) test was employed to test the differences between distributions composed of simulated and measured mean speeds for individual links. The K-S test is a two-sample test that is sensitive to any kind of difference in the distributions from which the samples are drawn. The test is based on simple measurement of the maximum vertical difference between two cumulative distributions. Tests were made at level of significance $\alpha = 0.05$.

Second, the simulated and measured results for individual links in the network were paired, and the Student's *t*-test for paired observations was performed. The hypothesis was tested that the mean difference between simulated and measured speeds for individual links is zero. Additionally, the hypothesis was tested that the mean difference between simulated and measured speeds on individual links is less than 1 mph.

Detailed results of the comparisons of simulation and measurement are shown in Figures C-1 through C-4. These figures contain comparisons of cumulative distributions of traffic characteristics composed of data for individual links, and frequency histograms of differences among characteristics for individual links.

Figure C-1 shows the results for simulated and measured traffic volume under Alternative A, Existing Timing. A high degree of precision is evident in the simulation of network loading. Both the K-S test and the paired *t*-test indicate that differences are not statistically significant.

Figures C-2, C-3, and C-4 show results for measured and simulated speeds under Alternatives A, B, and C, respectively. The results show that the model has an acceptable degree of descriptive validity for all three alternatives in the Los Angeles network. The general shape of the cumulative distribution of link speeds is approximated closely in all cases. In only one case (Alternative B, Offpeak Period) did the K-S test indicate a significant separation between the distributions.

The paired comparisons of speeds on individual links also yielded satisfactory results. As the frequency histograms show, the majority of individual links had differences between simulated and measured speeds that clustered between −4 and +4 mph. For all three alternatives tested, the simulated speeds on individual links were slightly lower than measured. These differences were generally statistically significant. However, the hypothesis was tested that the mean differences between simulated and measured

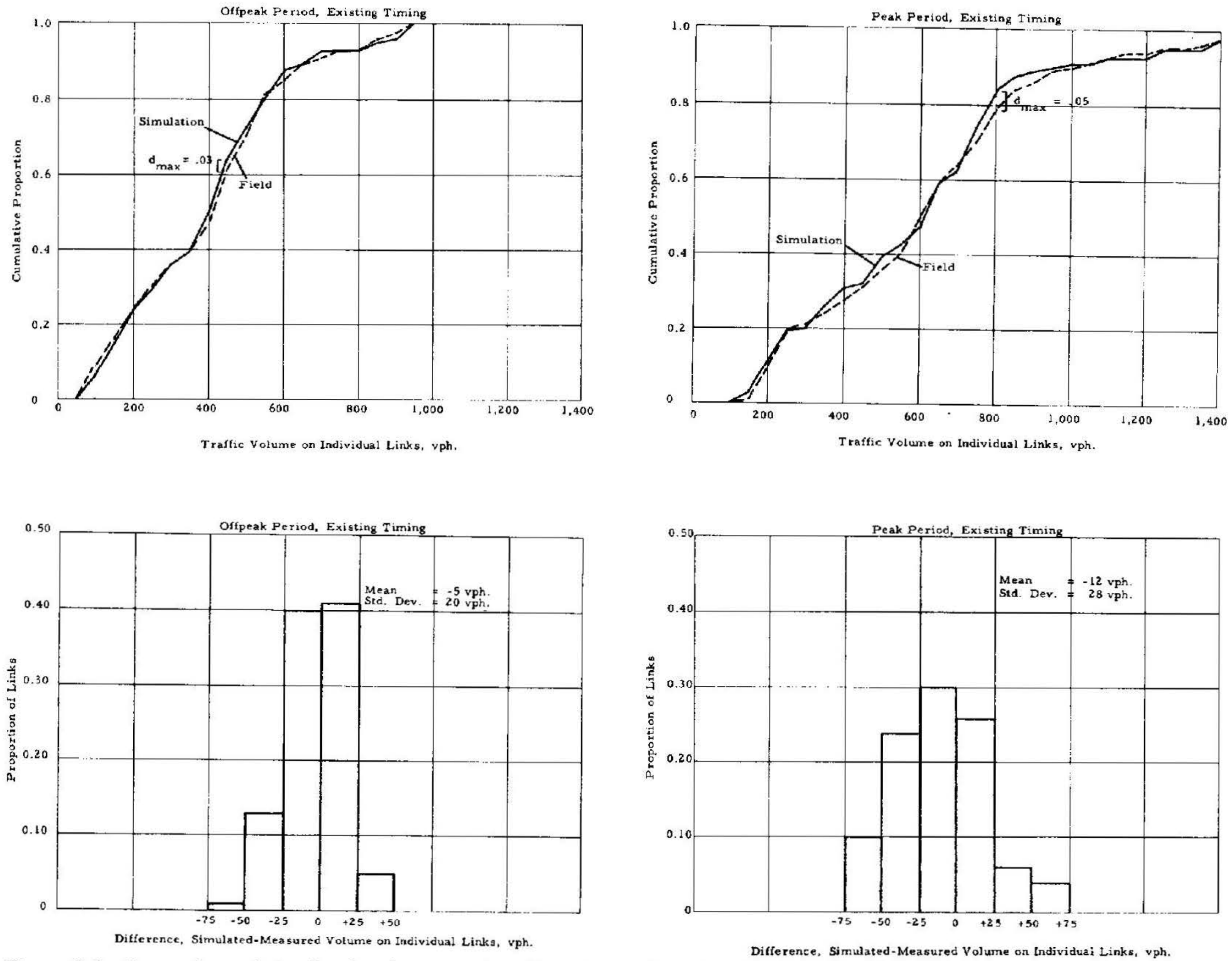


Figure C-1. Comparison of simulated and measured traffic volumes, Los Angeles network, Alternative A.

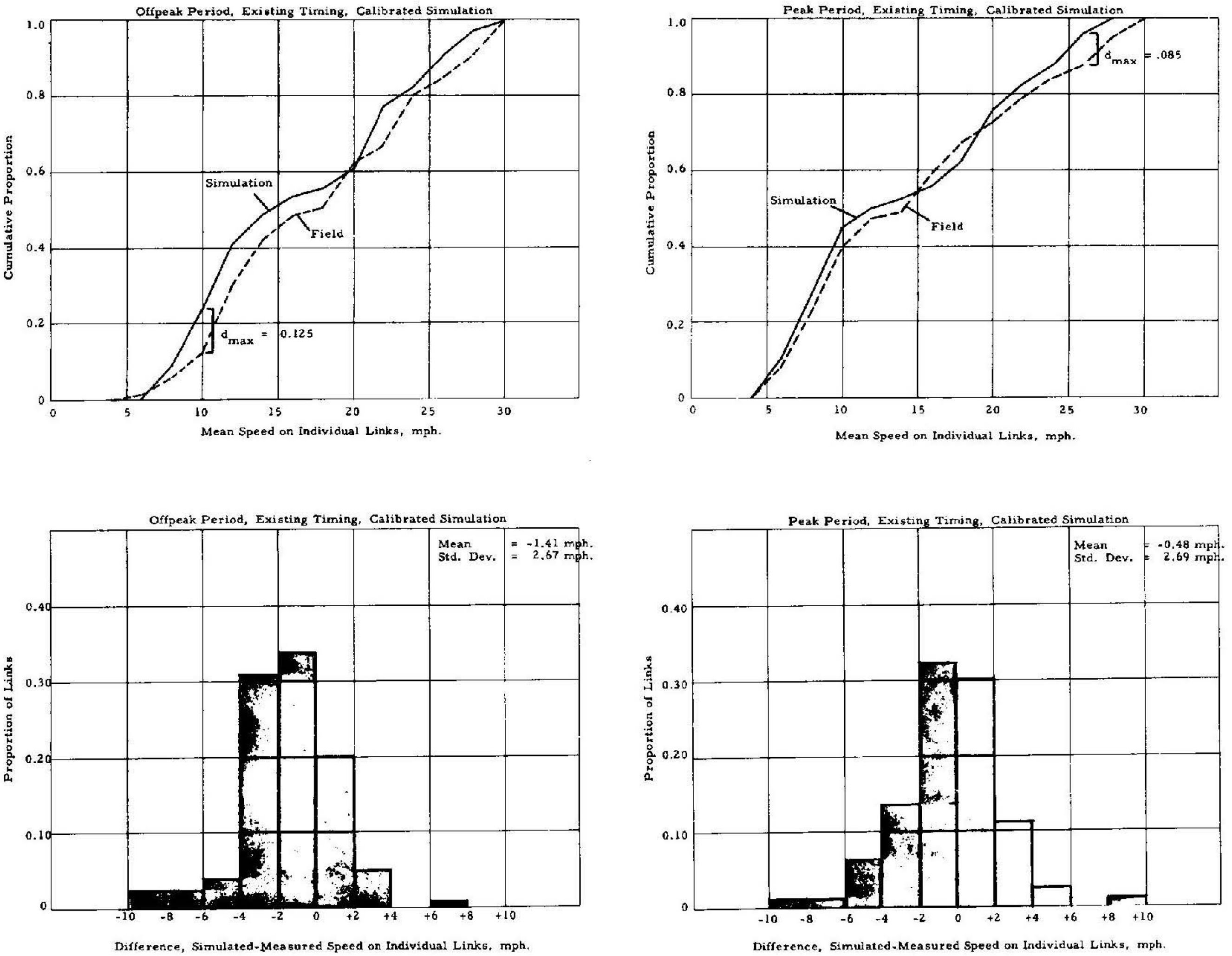


Figure C-2. Comparison of simulated and measured speeds, Los Angeles network, Alternative A.

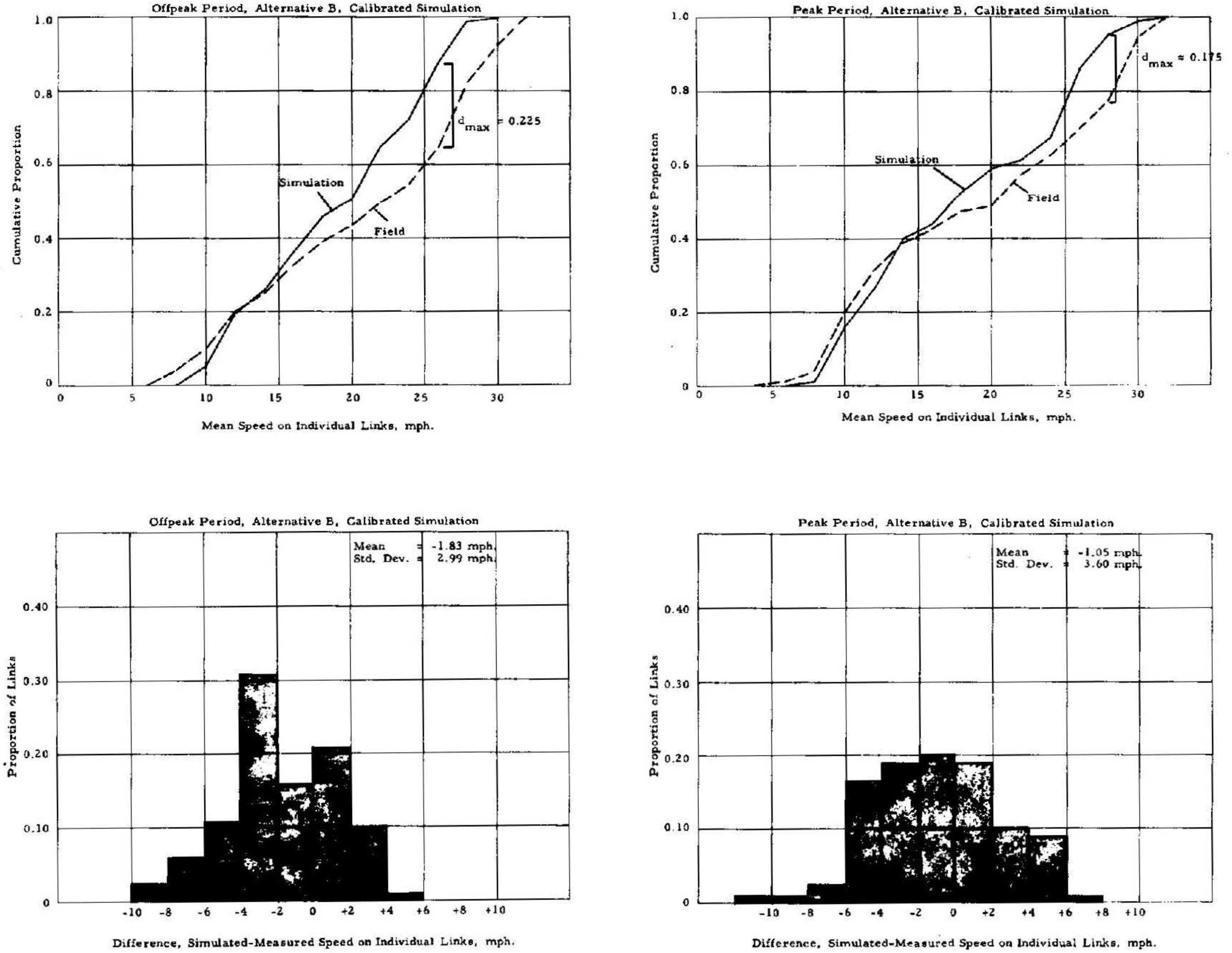


Figure C-3. Comparison of simulated and measured speeds, Los Angeles network, Alternative B.

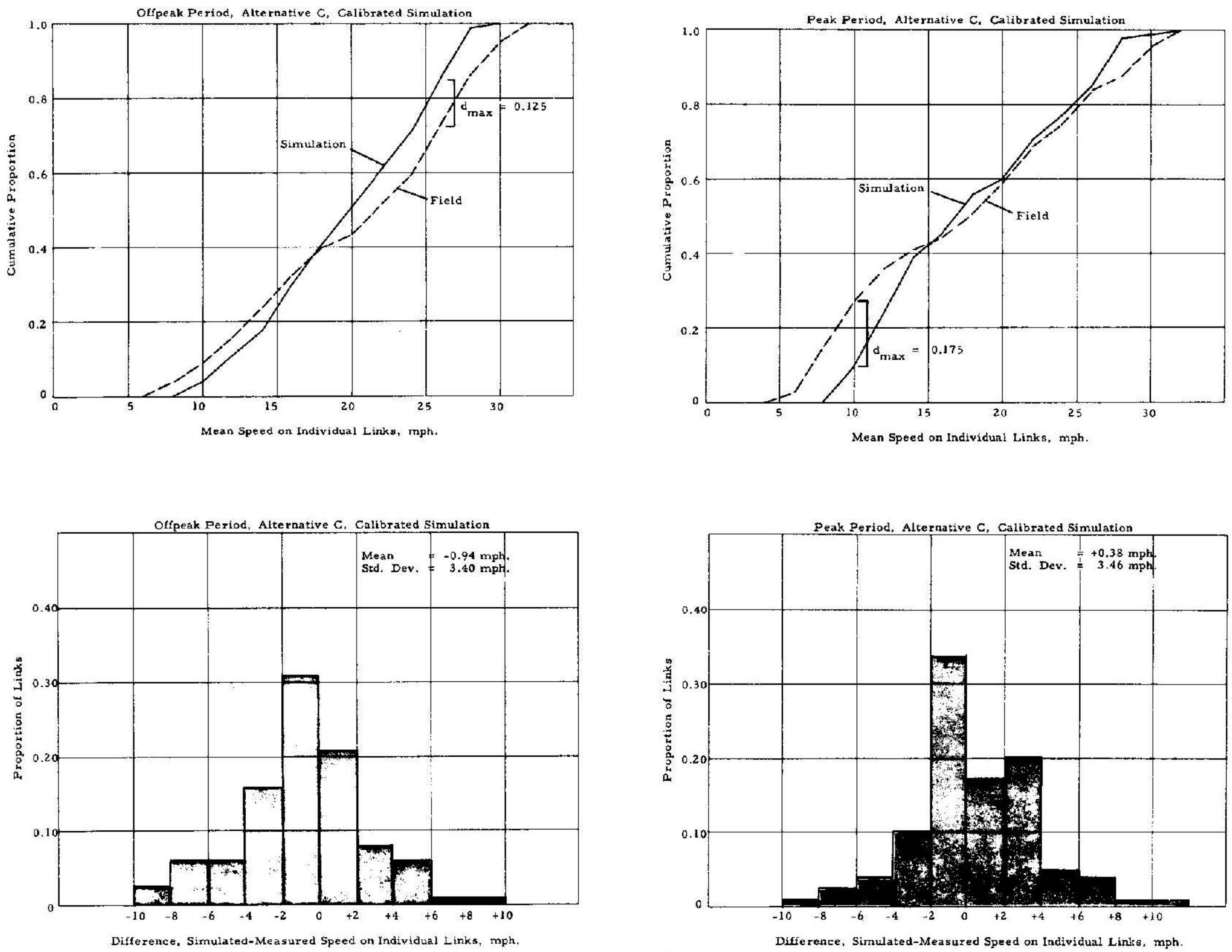


Figure C-4. Comparison of simulated and measured speeds, Los Angeles network, Alternative C.

speeds on individual links are less than 1 mph, and in only one case (Alternative B, Offpeak Period) was this hypothesis rejected.

On closer inspection of the field data, it was determined that the simulated speeds on the north-south links in the network were consistently lower by small amounts than measured speeds. This was not considered unrealistic because the speed and delay runs for all routes were on straight-through paths and did not include special measurement of delays to turning vehicles. In any event, in the worst case, the mean difference between simulated and measured speed on individual links was only 1.83 mph.

Table C-4 gives a summary of the statistical tests concerning simulated and measured speeds in the Los Angeles network.

SAN JOSE NETWORK

Comprehensive field verification studies of traffic control alternatives were not made in the San Jose network. However, preliminary comparisons were made of simulation results and estimates of performance compiled by the surveillance system. The results, summarized in Table C-5, indicate that a close fit was obtained between calibrated simulation and field measurements. Over-all average network speeds differed by less than 1 mph. It should be understood that the control computer in San Jose performs a simple real-time simulation of queuing in all lanes of all intersection approaches in order to estimate delays. Therefore, the performance statistics obtained by the San Jose surveillance system should be considered estimates derived computationally from sensed information, rather than direct measurements.

TABLE C-4

SUMMARY OF RESULTS OF STATISTICAL COMPARISONS OF SIMULATED AND MEASURED SPEEDS[a]

ITEM	DO DISTRIBUTIONS OF MEAN SPEEDS ON NETWORK LINKS DIFFER?	DO SPEEDS ON INDIVIDUAL LINKS DIFFER?	DO SPEEDS ON INDIVIDUAL LINKS DIFFER BY MORE THAN 1 MPH?
Offpeak period:			
Alternative A	No	Yes	No
Alternative B	Yes	Yes	Yes
Alternative C	No	Yes	No
Peak period:			
Alternative A	No	No	No
Alternative B	No	Yes	No
Alternative C	No	No	No

[a] Distributions compared using Kolmogorov-Smirnov test, $\alpha = 0.05$. Individual link differences compared using t-test for paired observations, $\alpha = 0.05$.

TABLE C-5

COMPARISON OF SIMULATED AND MEASURED NETWORK TRAFFIC CHARACTERISTICS, SAN JOSE NETWORK, EXISTING TIMING, 4:00–6:00 PM

ITEM	TOTAL VEH-MILES	TOTAL TRAVEL TIME (VEH-HR)	AVERAGE SPEED (MPH)
(*a*) Uncalibrated simulation			
Simulated	5,769	374	15.4
Measured	5,633	425	13.3
Difference	+136	−51	+2.1
Percent difference	+2.4	−12.0	+15.8
(*b*) Calibrated simulation			
Simulated	5,610	396	14.2
Measured	5,633	425	13.3
Difference	+23	−29	+0.9
Percent difference	+0.4	−6.7	+6.8

APPENDIX D

ANALYSIS OF VARIANCE OF COMPREHENSIVE SPEED AND DELAY STUDY

The comprehensive field verification studies in Los Angeles involved speed and delay measurements on each test route in the system, by each of five separate study teams, on each of five separate study days. Teams were rotated among the test routes so that each team collected data only once on each test route. The results of these field studies were organized in a series of latin square experimental designs to test the significance of the effects of days, test routes, and teams. The latin square analyses were performed only for field study Alternative A, existing timing conditions.

The first series of analyses investigated the effects of days, test routes, and teams on *mean time in motion*. A total of eight separate analyses were made, each involving five test routes. It was expected that mean time in motion (total travel time less stopped delay time) would be the variable most sensitive to differences in behavior of test-car drivers. Table D-1 summarizes the results of the latin square analyses on time in motion, and Figures D-1 through D-8 show the details of each analysis. The results indicate that the effects of teams and test routes on mean time in motion are consistently significant. Both of these sources of variation were statistically significant in six of the eight sets analyzed. The effect of study days, on the other hand, never had a significant effect on mean time in motion. In other words, the measurements did not vary significantly from day to day.

Latin square analyses were also performed to test the effects of the sources of variation on *mean travel time* for test routes. Table D-2 summarizes the results of these tests. The results indicate that test route differences are consistently significant, team differences are occasionally significant, and day effects are consistently nonsignificant. It was reasonable to find that teams had somewhat less significant effects on mean travel time (which includes delays at intersections) than they had on mean time in motion (which depends almost wholly on behavior between intersections).

It was interesting to find that significant differences were attributed to team effects. Knowing this, one must design speed and delay surveys that employ the floating-car method with care to ensure that results are not biased. It is clearly desirable to use several teams in testing alternative conditions in a street network. Furthermore, it is desirable to use the same set of teams when one is studying successive alternatives in order to minimize the effects of driver differences on comparative results.

TABLE D-1

SUMMARY OF RESULTS OF LATIN SQUARE ANALYSIS OF VARIANCE ON MEAN TIME IN MOTION FOR TEST ROUTES

	SOURCE OF VARIATION TESTED[a]		
ITEM	DAYS	TEST ROUTES	TEAMS
	(*a*) Routes 1–5		
Offpeak:			
NB	No	Yes	Yes
SB	No	No	Yes
Peak:			
NB	No	No	Yes
SB	No	Yes	Yes
	(*b*) Routes 6–10		
Offpeak:			
NB or EB	No	Yes	Yes
SB or WB	No	Yes	No
Peak:			
NB or EB	No	Yes	Yes
SB or WB	No	Yes	No

[a] "No" indicates that effect *was not* significant at $a = 0.05$. "Yes" indicates that effect *was* significant at $a = 0.05$.

TABLE D-2

SUMMARY OF RESULTS OF LATIN SQUARE ANALYSIS OF VARIANCE ON MEAN TRAVEL TIMES FOR TEST ROUTES

	SOURCE OF VARIATION TESTED[a]		
ITEM	DAYS	TEST ROUTES	TEAMS
	(*a*) Routes 1–5		
Offpeak:			
NB	No	Yes	No
SB	No	Yes	No
Peak:			
NB	No	Yes	Yes
SB	No	No	No
	(*b*) Routes 6–10		
Offpeak:			
NB or EB	No	Yes	No
SB or WB	Yes	Yes	Yes
Peak:			
NB or EB	No	Yes	Yes
SB or WB	No	Yes	No

[a] "No" indicates that effect *was not* significant at $a = 0.05$. "Yes" indicates that effect *was* significant at $a = 0.05$.

Mean Time in Motion, (Sec.) Offpeak Period, Routes 1-5 NB

DAYS

TEST ROUTES	1	2	3	4	5	Total
1	A 85	B 79	C 74	D 84	E 90	412
2	E 91	A 98	B 89	C 78	D 91	447
3	D 86	E 92	A 103	B 79	C 76	436
4	C 82	D 96	E 92	A 95	B 84	449
5	B 83	C 81	D 82	E 87	A 83	416
Total	427	446	440	423	424	2,160

TEAMS

	A	B	C	D	E	Total
Total	464	414	391	439	452	2,160

ANALYSIS OF VARIANCE

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Columns (Days)	86	4	21.50	1.5
Rows (Test Routes)	237	4	59.25	4.2*
Treatments (Teams)	696	4	174.00	12.3*
Residual	169	12	14.10	
Total	1,188	24		

*Effect is significant at $\alpha = .05$. Critical Region: $F > 3.26$.

Figure D-1. Analysis of variance results.

Mean Time in Motion, (Sec.) Offpeak Period, Routes 1-5 SB

DAYS

TEST ROUTES	1	2	3	4	5	Total
1	A 87	B 87	C 85	D 93	E 91	443
2	E 87	A 86	B 80	C 82	D 91	426
3	D 92	E 90	A 99	B 84	C 78	443
4	C 81	D 91	E 92	A 86	B 79	429
5	B 79	C 79	D 88	E 90	A 85	421
Total	426	433	444	435	424	2,162

TEAMS

	A	B	C	D	E	Total
Total	443	409	405	455	450	2,162

ANALYSIS OF VARIANCE

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Columns (Days)	50	4	12.50	1.3
Rows (Test Routes)	81	4	20.25	2.1
Treatments (Teams)	446	4	111.50	11.6*
Residual	115	12	9.58	
Total	692	24		

*Effect is significant at $\alpha = .05$. Critical Region: $F > 3.26$.

Figure D-2. Analysis of variance results.

Mean Time in Motion, (Sec.) Peak Period, Routes 1-5 NB

DAYS

TEST ROUTES

	1	2	3	4	5	Total
1	A 90	B 79	C 94	D 81	E 108	452
2	E 93	A 100	B 91	C 77	D 94	455
3	D 84	E 111	A 94	B 84	C 78	451
4	C 77	D 91	E 100	A 102	B 103	473
5	B 84	C 75	D 78	E 87	A 89	413
Total	428	456	457	431	472	2,244

TEAMS

	A	B	C	D	E	Total
Total	475	441	401	428	499	2,244

ANALYSIS OF VARIANCE

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Columns (Days)	282	4	70.50	1.3
Rows (Test Routes)	385	4	96.25	1.8
Treatments (Teams)	1,197	4	299.25	5.6*
Residual	643	12	53.58	
Total	2,507	24		

*Effect is significant at a = .05. Critical Region: F > 3.26.

Figure D-3. Analysis of variance results.

Mean Time in Motion, (Sec.) Peak Period, Routes 1-5 SB

DAYS

TEST ROUTES

	1	2	3	4	5	Total
1	A 91	B 85	C 92	D 89	E 92	449
2	E 94	A 93	B 88	C 80	D 93	448
3	D 87	E 105	A 101	B 92	C 84	469
4	C 85	D 93	E 96	A 94	B 84	452
5	B 84	C 75	D 78	E 87	A 89	413
Total	441	451	455	442	442	2,231

TEAMS

	A	B	C	D	E	Total
Total	468	433	416	440	474	2,231

ANALYSIS OF VARIANCE

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Columns (Days)	33	4	8.25	0.4
Rows (Test Routes)	334	4	83.50	4.0*
Treatments (Teams)	475	4	118.75	5.7*
Residual	249	12	20.75	
Total	1,091	24		

*Effect is significant at a = .05. Critical Region: F > 3.26.

Figure D-4. Analysis of variance results

Mean Time in Motion, (Sec.) Offpeak Period, Routes 6-10, NB or EB

DAYS

TEST ROUTES

	6	7	8	9	10	Total
6	A 92	B 87	C 79	D 90	E 97	445
7	E 68	A 67	B 64	C 59	D 66	324
8	D 70	E 68	A 78	B 67	C 63	346
9	C 60	D 71	E 77	A 75	B 67	350
10	B 90	C 81	D 86	E 95	A 79	431
Total	380	374	384	386	372	1,896

TEAMS

	A	B	C	D	E	Total
Total	391	375	342	383	405	1,896

ANALYSIS OF VARIANCE

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Columns (Days)	29	4	7.25	0.37
Rows (Test Routes)	2,403	4	600.75	31.00*
Treatments (Teams)	444	4	111.00	5.70*
Residual	233	12	19.4	
Total	3,109	24		

*Effect is significant at α = .05. Critical Region: F > 3.26.

Figure D-5. Analysis of variance results.

Mean Time in Motion, (Sec.) Offpeak Period, Routes 6-10, SB or WB

DAYS

TEST ROUTES

	6	7	8	9	10	Total
6	A 84	B 84	C 79	D 93	E 92	432
7	E 63	A 71	B 69	C 69	D 65	337
8	D 73	E 76	A 75	B 69	C 71	364
9	C 65	D 67	E 65	A 80	B 66	343
10	B 75	C 84	D 89	E 81	A 84	413
Total	360	382	377	392	378	1,889

TEAMS

	A	B	C	D	E	Total
Total	394	363	368	387	377	1,889

ANALYSIS OF VARIANCE

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Columns (Days)	107	4	26.75	1.3
Rows (Test Routes)	1,448	4	362.00	17.4*
Treatments (Teams)	132	4	33.00	1.6
Residual	249	12	20.75	
Total	1,936	24		

*Effect is significant at α = .05. Critical Region: F > 3.26.

Figure D-6. Analysis of variance results.

Mean Time in Motion, (Sec.) Peak Period, Routes 6-10, NB or EB

DAYS

TEST ROUTES	6	7	8	9	10	Total
6	A 92	B 92	C 84	D 96	E 100	464
7	E 76	A 77	B 66	C 66	D 61	346
8	D 67	E 72	A 71	B 70	C 65	345
9	C 68	D 73	E 96	A 82	B 72	391
10	B 96	C 79	D 88	E 94	A 82	439
Total	399	393	405	408	380	1,985

TEAMS

	A	B	C	D	E	Total
Total	404	396	362	385	438	1,985

ANALYSIS OF VARIANCE

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Columns (Days)	99	4	24.75	0.81
Rows (Test Routes)	2,319	4	579.75	18.90*
Treatments (Teams)	620	4	155.00	5.10*
Residual	368	12	30.67	
Total	3,406	24		

*Effect is significant at $\alpha = .05$. Critical Region: $F > 3.26$.

Figure D-7. Analysis of variance results.

Mean Time in Motion, (Sec.) Peak Period, Routes 6-10, SB or WB

DAYS

TEST ROUTES	6	7	8	9	10	Total
6	A 88	B 90	C 76	D 94	E 95	443
7	E 69	A 84	B 68	C 78	D 66	365
8	D 74	E 72	A 69	B 66	C 65	346
9	C 78	D 74	E 78	A 92	B 70	392
10	B 76	C 89	D 88	E 75	A 86	414
Total	385	409	379	405	382	1,960

TEAMS

	A	B	C	D	E	Total
Total	419	370	386	396	389	1,960

ANALYSIS OF VARIANCE

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Columns (Days)	155	4	38.75	0.81
Rows (Test Routes)	1,186	4	296.50	6.20*
Treatments (Teams)	255	4	63.75	1.33
Residual	574	12	47.83	
Total	2,170	24		

*Effect is significant at $\alpha = .05$. Critical Region: $F > 3.26$.

Figure D-8. Analysis of variance results.

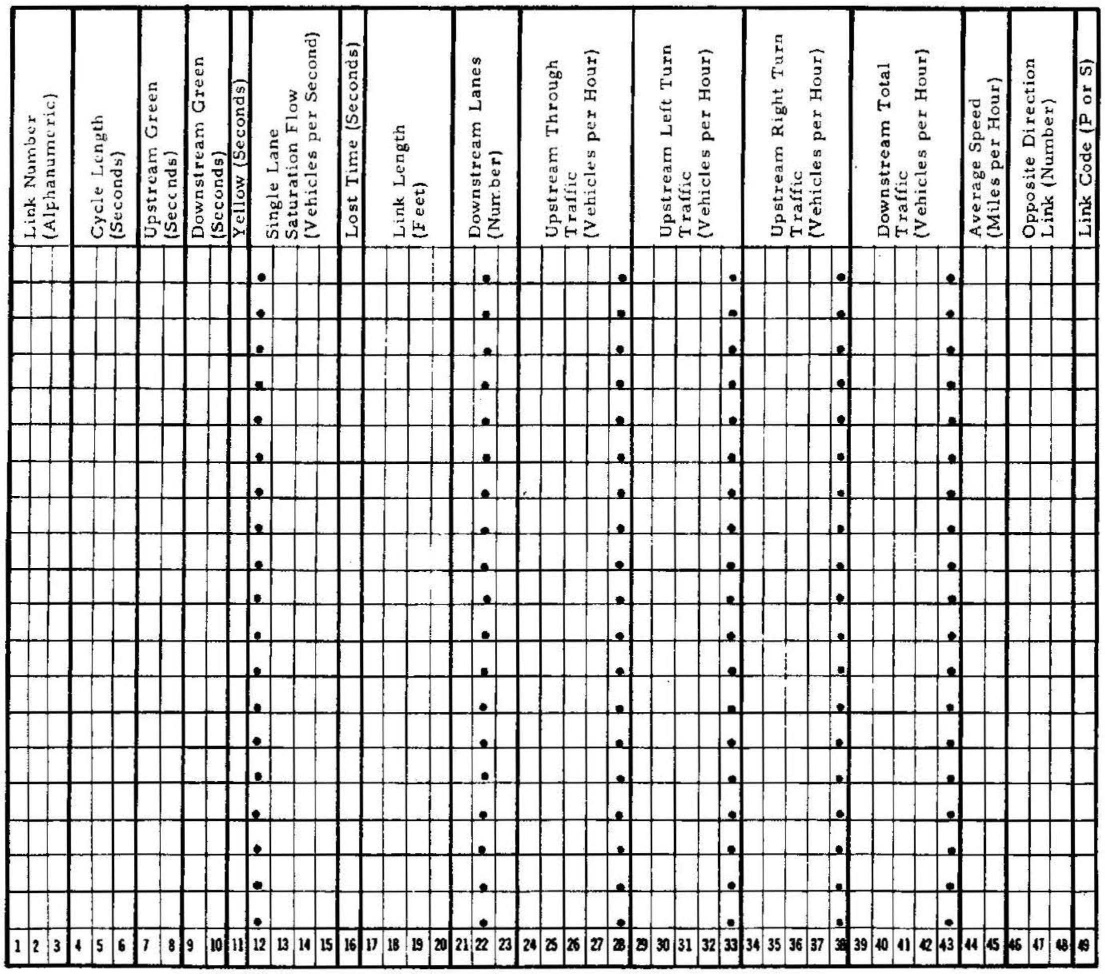
APPENDIX E

MODIFICATION OF COMPUTER PROGRAM FOR COMPUTING DELAY/DIFFERENCE-OF-OFFSET RELATIONSHIP

Appendix A of *NCHRP Report 73* (*3*) describes a method of computing the delay incurred by traffic due to queueing at the traffic signal on the downstream end of a link. This delay is estimated as a function of the difference of offset between the traffic signals at the upstream and downstream ends of the link, together with certain geometric, signal timing, and traffic demand characteristics of the link.

A computer program that performs the delay computations is also described in Appendix A of *NCHRP Report 73* (*3*). This program performs these computations for each link for which an input card is provided. When the original program for analyzing a two-way street was used, the output for the two opposite direction links between a pair of signalized intersections had to be combined manually. This was found to be a serious disadvantage in the practical use of the program; therefore, the program was revised to provide for the automatic combination of opposite direction links.

In addition to providing for the combination of delay for opposite direction links, two other minor modifications were included to make the program more flexible. The first of these was a revision to allow for a fractional number of effective lanes (e.g., 2.4 lanes). This allows a more realistic representation of curb lanes and of separate turn lanes that might not handle the volume of traffic that a normal through lane carries. The other modification was to input the average speed in miles per hour rather than feet per second.



Link Number (Alphanumeric)	Cycle Length (Seconds)	Upstream Green (Seconds)	Downstream Green (Seconds)	Yellow (Seconds)	Single Lane Saturation Flow (Vehicles per Second)	Lost Time (Seconds)	Link Length (Feet)	Downstream Lanes (Number)	Upstream Through Traffic (Vehicles per Hour)	Upstream Left Turn Traffic (Vehicles per Hour)	Upstream Right Turn Traffic (Vehicles per Hour)	Downstream Total Traffic (Vehicles per Hour)	Average Speed (Miles per Hour)	Opposite Direction Link (Number)	Link Code (P or S)
1 2 3	4 5 6	7 8	9 10	11	12 13 14 15	16	17 18 19 20	21 22 23	24 25 26 27 28	29 30 31 32 33	34 35 36 37 38	39 40 41 42 43	44 45	46 47 48	49

Figure E-1. Input coding form, revised delay/difference-of-offset program.

INPUT DATA

Figure E-1 shows the coding for the revised program input data. All input data for a given link are on a single punched card. When the results for two opposite links are to be combined, the cards must be ordered so that the secondary link card follows immediately after the card for the primary link opposite to it. (Either link may be defined as primary, but the delay function for the combination will be computed to correspond to the offsets in the direction of the primary link.) Any number of sets of link cards may be stacked for sequential processing, and these may be mixed with single cards for one-way links.

OUTPUT

The revised program provides for the output of the delay/difference-of-offset data for the primary and secondary links as well as for the combination. An example of the program output is shown in Figure E-2. Output is in two sections. First, the input data are listed, and then the results of the delay computations are tabulated. For every possible value of offset difference, in 1-sec increments, the following are tabulated:

1. PHI—the difference of offset of the signals at the link head and link tail, seconds. (Offset at head minus offset at tail.)
2. QSUM—the total delay-in-queue during one signal cycle, vehicle-seconds per signal cycle.
3. DPV—the average delay per vehicle, vehicle-seconds per vehicle.
4. QAVE—the average queue length, vehicles. This is also synonymous with the "total delay rate" (e.g., in vehicle-hours per hour, vehicle-minutes per minute, or vehicle-seconds per second).

COMPUTER PROGRAM

The revised program was written in FORTRAN IV. It has been run on the IBM 7094 under the IBSYS monitor system. The program can easily be compiled and run on other computers having FORTRAN IV compilers. A listing of the revised program is shown in Figure E-3.

```
INPUT

LINK C   G1 G2 A SAT  LOST  D    W     ST     LT     RT     VH    V  OPPLNK
 15  40 22 20 3 .512   3   775 2.0   523.     0.    78.   692.  22    20   P
 20  40 20 22 3 .512   3   775 2.0   704.   133.   170.  1134.  22    15   S

OUTPUT

PRIMARY LINK                              SECONDARY LINK                              COMBINATION

PHI    QSUM     DPV     QAVE              PHI    QSUM     DPV     QAVE                PHI    QSUM     DPV     QAVE
  0    64.4     8.4     1.61                0    93.8     7.4     2.35                  0   158.2     7.8     3.96
  1    68.8     8.9     1.72               39    94.5     7.5     2.36                  1   163.3     8.0     4.08
  2    68.4     8.9     1.71               38    91.2     7.2     2.28                  2   159.7     7.9     3.99
  3    67.9     8.8     1.70               37    88.0     7.0     2.20                  3   155.9     7.7     3.90
  4    67.4     8.8     1.68               36    84.7     6.7     2.12                  4   152.0     7.5     3.80
  5    66.7     8.7     1.67               35    81.4     6.5     2.03                  5   148.0     7.3     3.70
  6    65.8     8.6     1.64               34    78.1     6.2     1.95                  6   143.9     7.1     3.60
  7    64.7     8.4     1.62               33    74.9     5.9     1.87                  7   139.7     6.9     3.49
  8    63.5     8.3     1.59               32    72.0     5.7     1.80                  8   135.5     6.7     3.39
  9    62.2     8.1     1.55               31    69.3     5.5     1.73                  9   131.5     6.5     3.29
 10    60.8     7.9     1.52               30    66.7     5.3     1.67                 10   127.5     6.3     3.19
 11    59.2     7.7     1.48               29    64.3     5.1     1.61                 11   123.5     6.1     3.09
 12    57.5     7.5     1.44               28    62.0     4.9     1.55                 12   119.5     5.9     2.99
 13    55.5     7.2     1.39               27    60.0     4.8     1.50                 13   115.5     5.7     2.89
 14    53.5     7.0     1.34               26    58.1     4.6     1.45                 14   111.6     5.5     2.79
 15    51.4     6.7     1.28               25    56.4     4.5     1.41                 15   107.8     5.3     2.69
 16    49.1     6.4     1.23               24    54.8     4.4     1.37                 16   103.9     5.1     2.60
 17    46.6     6.1     1.17               23    53.5     4.2     1.34                 17   100.1     4.9     2.50
 18    44.0     5.7     1.10               22    52.3     4.2     1.31                 18    96.4     4.7     2.41
 19    41.4     5.4     1.04               21    54.8     4.3     1.37                 19    96.2     4.7     2.40
 20    38.8     5.0     0.97               20    57.2     4.5     1.43                 20    96.0     4.7     2.40
 21    36.2     4.7     0.90               19    59.6     4.7     1.49                 21    95.8     4.7     2.39
 22    33.5     4.4     0.84               18    62.1     4.9     1.55                 22    95.6     4.7     2.39
 23    30.9     4.0     0.77               17    64.5     5.1     1.61                 23    95.4     4.7     2.39
 24    28.3     3.7     0.71               16    66.9     5.3     1.67                 24    95.2     4.7     2.38
 25    25.7     3.3     0.64               15    69.3     5.5     1.73                 25    95.0     4.7     2.38
 26    23.1     3.0     0.58               14    71.8     5.7     1.79                 26    94.8     4.7     2.37
 27    24.6     3.2     0.62               13    74.1     5.9     1.85                 27    98.7     4.9     2.47
 28    26.4     3.4     0.66               12    76.3     6.1     1.91                 28   102.7     5.1     2.57
 29    28.3     3.7     0.71               11    78.4     6.2     1.96                 29   106.7     5.3     2.67
 30    30.6     4.0     0.76               10    80.4     6.4     2.01                 30   111.0     5.5     2.78
 31    33.0     4.3     0.83                9    82.3     6.5     2.06                 31   115.3     5.7     2.88
 32    35.6     4.6     0.89                8    84.0     6.7     2.10                 32   119.7     5.9     2.99
 33    38.4     5.0     0.96                7    85.6     6.8     2.14                 33   124.0     6.1     3.10
 34    41.5     5.4     1.04                6    87.2     6.9     2.18                 34   128.7     6.3     3.22
 35    44.8     5.8     1.12                5    88.6     7.0     2.22                 35   133.4     6.6     3.34
 36    48.3     6.3     1.21                4    89.9     7.1     2.25                 36   138.2     6.8     3.46
 37    52.0     6.8     1.30                3    91.0     7.2     2.28                 37   143.0     7.0     3.58
 38    55.9     7.3     1.40                2    92.0     7.3     2.30                 38   147.9     7.3     3.70
 39    60.0     7.8     1.50                1    93.0     7.4     2.32                 39   153.0     7.5     3.83
```

Figure E-2. Sample output data, revised delay/difference-of-offset program.

```
C     DELAY-DIFFERENCE OF OFFSET COMPUTATIONS, BIDIRECTIONAL LINKS,
C     TWO UNIFORM ARRIVAL RATES.
      DIMENSION ITAU(151,3),IPHI(151,3),QSUM(151,3),Q(301),DPV(151,3),
     1QAVE(151,3),AVH(3)
      REAL LINK
      DATA BLNK,S,P/1H ,1HS,1HP/
C     WRITE HEADING FOR INPUT DATA
 110  K = 1
      WRITE (6,102)
  102 FORMAT(1H1, 5HINPUT)
      WRITE (6,103)
  103 FORMAT(1H0, 68HLINK C  G1 G2 A SAT  LOST  D   W    ST    LT    RT
     1   VH   V  OPPLNK)
C     READ INPUT DATA
 100  READ(5,101)LINK,IC,IG1,IG2,IA,SAT,LOST,ID,W,AST,ALT,ART,AVH(K),IV,
     1OPPLNK,XLKCD
  101 FORMAT (A3,I3,I2,I2,I1,F4.3,I1,I4,F3.1,F5.0,F5.0,F5.0,F5.0,I2,A3,
     1A1)
C     WRITE INPUT DATA
      WRITE (6,104)LINK,IC,IG1,IG2,IA,SAT,LOST,ID,W,AST,ALT,ART,AVH(K),
     1IV,OPPLNK,XLKCD
  104 FORMAT (1H ,A3,1X,I3,1X,I2,1X,I2,1X,I1,1X,F4.3,2X,I1,2X,I4,1X,F3.1
     1,1X,F5.0,1X,F5.0,1X,F5.0,1XF5.0,1X,I2,3X,A6,A5)
C     PERFORM INITIAL COMPUTATIONS
  200 IR1=IC-IG1-IA
      IR2=IC-IG2-IA
      IT1=IG1+IA
      T1=IT1
      IT2=IR1
      T2=IT2
      IGE=IG2+IA-LOST
      IRE=IC-IGE
      GE=IGE
      AVT=AST+ALT+ART
      ANC=AVH(K) - AVT
      C=IC
      Q1= AST/((T1/C)*3600.)+ANC/3600.
      Q2= (ALT+ART)/((T2/C)*3600.)+ANC/3600.
      S=W*SAT
      V=IV
      V=(V*88./60.)+.5
      IV=V
C     CHECK SUBSATURATION
  300 IF(S*GE-(Q1*T1+Q2*T2))301,400,400
C     DUMBHEAD OUTPUT
  301 WRITE (6,302)
  302 FORMAT (1H0, 31HDUMBHEAD,THIS IS SUPERSATURATED)
      GO TO 900
C     SET INITIAL TAU
 400  IPHI(1,K) =0
C     SET UP OUTER LOOP TO COMPUTE QSUM FOR ALL TAUS
      DO 706 I=1,IC
C     COMPUTE TAU MODULO C
 401  ITAU(I,K) = IPHI(I,K)-ID/IV -IR2
 402  IF (ITAU(I,K)) 403,404,404
 403  ITAU(I,K) = IC +ITAU(I,K)
      GO TO 402
C     SET INITIAL J AND QSUM
 404  J = ITAU(I,K)
      QSUM(I,K) =0.
C     SET INNER LOOP TO COMPUTE QSUM FOR GIVEN TAU
      ISTA =ITAU(I,K) +1
      IFIN = ITAU (I,K) + IC
  406 DO 705 J=ISTA,IFIN
C     IS EFFECTIVE RED OR EFFECTIVE GREEN ON
      IF (J-(ITAU(I,K) +IRE)) 500,500,600
C     IS T1 OR T2 ON (EFFECTIVE RED)
  500 IF(J-IT1)510,510,501
  501 IF(J-IC) 520,520,502
  502 IF(J-(IC+IT1))510,510,520
  510 QCR=Q1
      GO TO 700
  520 QCR=Q2
      GO TO 700
```

(Continued)

```
C     IS T1 OR T2 ON (EFFECTIVE GREEN)
  600 IF(J-IT1)610,610,601
  601 IF(J-IC) 620,620,602
  602 IF(J-(IC+IT1))610,610,620
  610 QCR=Q1-S
      GO TO 700
  620 QCR=Q2-S
      GO TO 700
C     COMPUTE Q AND ACCUMULATE QSUM
 700  IF (J-(ITAU(I,K) +1)) 701,701,702
  701 Q(J)=QCR
      GO TO 703
  702 Q(J)=Q(J-1)+QCR
  703 IF(Q(J))704,705,705
  704 Q(J)=0.
 705  QSUM(I,K) =QSUM(I,K) + Q(J)
C     END OF INNER LOOP
      QAVE(I,K) =QSUM(I,K)/C
      DPV(I,K) =QAVE(I,K)*3600.
 706  IPHI(I+1,K) = IPHI(I,K) +1
C     END OF OUTER LOOP
      K = K+1
      IF (K.GT.2     .OR.OPPLNK.EQ.BLNK) GO TO 800
      GO TO 100
C     WRITE HEADING FOR OUTPUT DATA
  800 WRITE (6,105)
  105 FORMAT (1H0, 6HOUTPUT)
      WRITE(6,106)
      WRITE (6,107)
      IPAGE=1
C     WRITE OUTPUT DATA
      DO 802 I=1,IC
      IPAGE=IPAGE +1
      IF (IPAGE.LE.50) GO TO 422
      IPAGE =1
      WRITE (6,21)
  21  FORMAT (1H1)
      WRITE (6,106)
 106  FORMAT (1H0,12HPRIMARY LINK,29X,14HSECONDARY LINK,27X,11HCOMBINATI
     1ON)
      WRITE(6,107)
 107  FORMAT (1H0,3(28HPHI     QSUM      DPV      QAVE,13X))
 422  JJ =IC-I+2
      IF (JJ.GT.IC) JJ=JJ-IC
      IF (OPPLNK.NE.BLNK) GO TO 423
      QAVE(JJ,2) =0.
      QSUM(JJ,2) =0.
      DPV (JJ,2) =0.
 423  DPV(I,3) =(DPV(I,1) +DPV(JJ,2))/(AVH(1)+AVH(2))
      DPV(I,1) = DPV(I,1)/AVH(1)
      DPV(JJ,2) = DPV(JJ,2) /AVH(2)
      IPHI(I,3) = IPHI(I,1)
      QSUM(I,3) = QSUM(I,1) + QSUM(JJ,2)
      QAVE(I,3)=QAVE(I,1) +QAVE(JJ,2)
      WRITE (6,801) IPHI(I,1),QSUM(I,1),DPV(I,1),QAVE(I,1),IPHI(JJ,2),
     1QSUM(JJ,2),DPV(JJ,2),QAVE(JJ,2),IPHI(I,3),QSUM(I,3),DPV(I,3),
     2QAVE(I,3)
 801  FORMAT (1H ,3(I3,F9.1,F8.1,F8.2,13X))
  802 CONTINUE
C     IS THERE MORE DATA
  900 GO TO 110
      END
```

Figure E-3. FORTRAN listing, revised delay/difference-of-offset program.

APPENDIX F

THE COMBINATION METHOD OF DETERMINING TRAFFIC SIGNAL OFFSETS

The combination method, apparently conceived by P. D. Whiting and first presented by Hillier (*7, 8*), consists of two basic ideas: (1) the obtaining of delay/difference-of-offset relationships for each link, and (2) the combining of links in series and parallel arrangements in such a way that offsets at each intersection can be assigned values that will minimize delay in the network.

As the method was originally developed, there were limitations beyond which a network could not be condensed. This shortcoming has recently been removed by a technique of network building developed by Allsop (*11, 12*). Other improvements to facilitate computer use have been made by Robertson (*10*).

There have been several experimental studies to evaluate the combination method. Hillier and Lott (*9*) have conducted a before-and-after study to compare settings by the combination method with those obtained by manual (graphical) methods. In this study, vehicle time in the network was reduced from 169 veh-hr per hour to 155 veh-hr per hour—a reduction of 8 percent. Theory had predicted a reduction of 15 percent. Delays (assuming a speed of 26 mph) were reduced from 68 to 55 veh-hr per hour (20 percent), and stops were reduced by 10 percent.

The combination method has been used in the West London Experiment, which covers an area of 6.5 square miles containing 70 signalized intersections. Williams (*22*) reports that this method resulted in a travel time saving of 9.2 percent over the existing control scheme.

More recently, Holroyd and Hillier (*21*) have reported on the use of the combination method in the area traffic control experiment in Glasgow. It was concluded that the combination method produced an over-all reduction in travel time of 12 percent when compared with the existing standard control scheme.

COMBINING LINKS TO CONDENSE A NETWORK

In condensing a network, the objective is to arrive at one pair of nodes that can be used to represent the network. A delay/difference-of-offset relationship is assigned between this pair of nodes that results in a minimization of delay in the complete network.

The first step is to develop for each link a histogram, or table, giving the delay per vehicle (unit delay) for each value of offset. Because this technique is adequately covered in prior NCHRP work (*3*), it is not discussed here, except for the following note.

Before delay/difference-of-offset relationships are determined, it is necessary to define for each intersection the point in the signal cycle at that intersection that will be used as a reference point for offsets. Once a reference point is assigned for each intersection, no change may be permitted. A convenient method of assigning such reference points is to assign a uniform point at each intersection—e.g., the start of east/west green. To obtain delay/difference-of-offset relationships, the differences of these assigned reference points are used. The appropriate unit delays are then automatically weighted according to their respective flows by the procedure used to derive the delay/difference-of-offset relationships.

To present a complete example, the network of Figure F-1 is condensed to a single equivalent link, joining nodes D and A. The delay/difference-of-offset values are those given in Table F-1.

Determining Which Links to Combine

The next step is to determine which links can be combined in series and which can be combined in parallel. This can best be accomplished by a form of matrix. Consider the network of Figure F-1. Table F-2 is a connection matrix that indicates the number of links making the connection from the node given by the column to the node given by the row. Thus, for instance, the 2 in column D, row E, indicates there are two paths from node D to node E. The 1's indicate single connections. The two-way connection between nodes A and B is indicated by a 1 in column A, row B, and by a 1 in column B, row A.

Two rules are used in examining a connection matrix to determine possible reductions:

1. Rule 1. The existence of parallel links can be determined from the connection matrix by summing terms that are symmetric about the main diagonal—e.g., add the term in row A, column B, to the term in row B, column A. If the sum is 2 or more, then that number of parallel links exists between the node coordinates, and the parallel combination process can be used to derive the single equivalent link. The equivalent link will be represented in the connection matrix by a 1 at the appropriate node coordinates, depending on the link's assumed direction.
2. Rule 2. The existence of series links can be determined from the connection matrix by summing the terms in the row and column appropriate to each node—e.g., add the sum of the terms in row A to the sum of the terms in column A. If the total equals 2, a series combination process can be used to eliminate node A. The resulting equivalent link is then represented by a 1 entered into the connection matrix in the cell given by the node numbers associated with the eliminated node.

Parallel combinations are considered first. Applying Rule 1 to the matrix of Table F-2 yields:

$$X_{AB} + X_{BA} = 2$$

$$X_{DE} + X_{ED} = 2$$

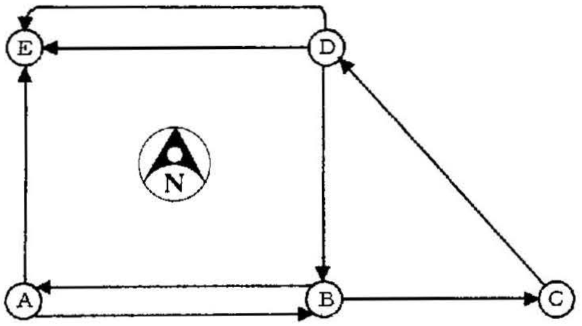


Figure F-1. Link diagram of simple traffic network.

in which X_{ij} = the matrix value for the link from i to j.

All other sums are 0 or 1. Thus, links AB and BA can be combined in parallel, as can the two links DE. The network is then simplified by combining these links, giving the result shown in Figure F-2 and given in Table F-3.

The network can be simplified further by series combinations. Applying Rule 2 to the matrix of Table F-3 yields:

$$\sum X_{\text{col A}} + \sum X_{\text{row A}} = 2 + 0 = 2$$
$$\sum X_{\text{col B}} + \sum X_{\text{row B}} = 1 + 2 = 3$$
$$\sum X_{\text{col C}} + \sum X_{\text{row C}} = 1 + 1 = 2$$
$$\sum X_{\text{col D}} + \sum X_{\text{row D}} = 2 + 1 = 3$$
$$\sum X_{\text{col E}} + \sum X_{\text{row E}} = 0 + 2 = 2$$

The interpretation is that nodes A, C, and E can be eliminated by series combinations. It is assumed, however, that A is one of the nodes to be retained for the final pair.

As a first step in series combinations of links, node C is eliminated by combining links BC and CD in series. The resulting link is considered as extending from node B to node D. Figure F-3 shows the resulting link diagram; the new link is at the far right. The corresponding connection matrix, with row C and column D dropped and a 1 entered in cell BD, is given in Table F-4.

Next, node E is eliminated by combining links DE and AE in series. The resulting link is considered as extending from node D to node A. Table F-5 gives the resulting matrix, with column E and row E eliminated and a 1

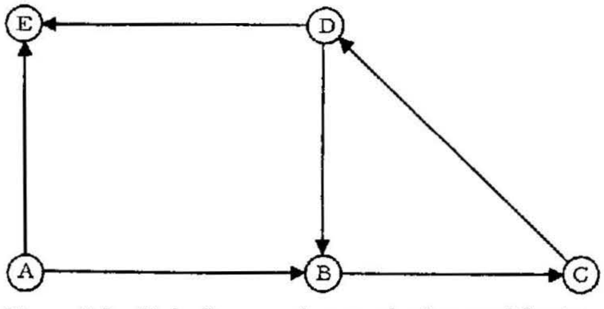


Figure F-2. Link diagram of network after modification by parallel combination.

TABLE F-1

DELAY FOR VARIOUS DIFFERENCES OF OFFSET FOR LINKS SHOWN IN FIGURE F-1[a]

	DELAY (VEH-SEC PER SIGNAL CYCLE), FOR DIFFERENCE OF OFFSET[b]				
LINK	0	1	2	3	4
AB	15	20	29	23	19
BA	10	20	17	15	13
BC	14	9	13	22	17
CD	13	19	27	20	11
DE_1	25	18	10	14	21
DE_2	30	27	20	16	25
DB	30	18	18	21	26
AE	12	40	33	26	20

[a] The cycle is divided into five parts, and offsets are given in units of 1/5 of cycle length.

[b] The difference of offset is based on the start of eastbound/westbound green at every intersection.

TABLE F-2

CONNECTION MATRIX OF NETWORK SHOWN IN FIGURE F-1

FROM NODE \ TO NODE	A	B	C	D	E
A	0	1	0	0	0
B	1	0	0	1	0
C	0	1	0	0	0
D	0	0	1	0	0
E	1	0	0	2	0

TABLE F-3

CONNECTION MATRIX OF MODIFIED NETWORK SHOWN IN FIGURE F-2

TO NODE \ FROM NODE	A	B	C	D	E
A	0	0	0	0	0
B	1	0	0	1	0
C	0	1	0	0	0
D	0	0	1	0	0
E	1	0	0	1	0

TABLE F-4

CONNECTION MATRIX OF NETWORK REPRESENTED BY FIGURE F-3, ELIMINATING NODE C

TO NODE \ FROM NODE	A	B	D	E
A	0	0	0	0
B	1	0	1	0
D	0	1	0	0
E	1	0	1	0

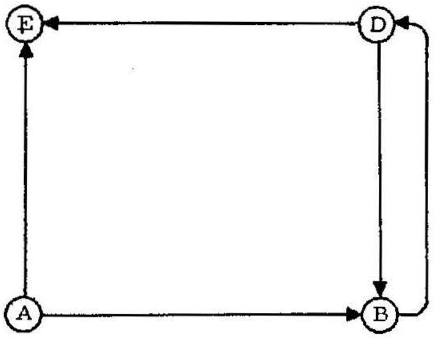


Figure F-3. Link diagram after first series combination, eliminating node C.

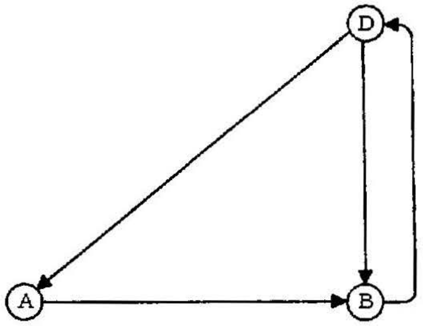


Figure F-4. Link diagram of network after combining links DE and AE in series.

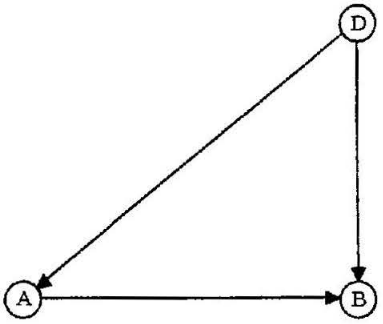


Figure F-5. Link diagram of network after parallel combination of two links between D and E.

TABLE F-5

CONNECTION MATRIX OF NETWORK SHOWN IN FIGURE F-4

TO NODE \ FROM NODE	A	B	D
A	0	0	1
B	1	0	1
D	0	1	0

TABLE F-6

CONNECTION MATRIX OF NETWORK SHOWN IN FIGURE F-5

TO NODE \ FROM NODE	A	B	D
A	0	0	1
B	1	0	1
D	0	0	0

TABLE F-7

CONNECTION MATRIX OF NETWORK SHOWN IN FIGURE F-6

TO NODE \ FROM NODE	A	D
A	0	2
D	0	0

TABLE F-8

FINAL CONNECTION MATRIX CORRESPONDING TO FIGURE F-7

TO NODE \ FROM NODE	A	D
A	0	1
D	0	0

entered in cell DA. Figure F-4 shows the resulting network.

Applying Rule 1 to Table F-5 demonstrates that two links between D and B can be combined in parallel. (Of course, this can be seen in Figure F-4, but the use of matrices and rules for their manipulation is important to the computer implementation of network condensation.) The result is shown in Figure F-5 and given in Table F-6.

The application of Rule 2 to Table F-6 indicates that node A, B, or D could be eliminated by series combination. Because it has been specified that A and D shall be the surviving nodes, node B is eliminated by series combination of links AB and DB; results are shown in Figure F-6 and given in Table F-7. Finally, the resulting two links between D and A are combined in parallel, with the result shown in Figure F-7 and given in Table F-8.

Combining Delay/Difference-of-Offset Relationships

Once the pattern of link combinations has been determined, it is possible to combine the delay/difference-of-offset data (Table F-1) on a link-by-link basis to determine that set of offsets that will result in minimum network delay. The delay data may be presented in the form of either histograms or tables. Histograms provide easier visualization, but manipulation is more convenient with tables.

When links are combined in parallel, their delay/difference-of-offset histograms are added. In performing

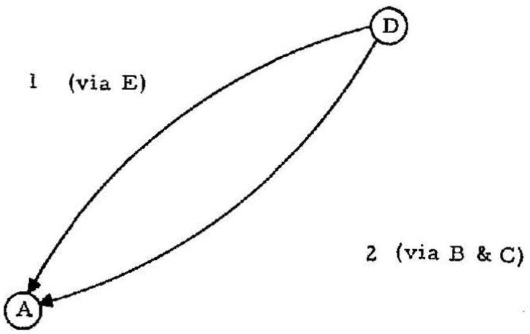


Figure F-6. Link diagram after elimination of node B.

addition of offsets, it must be remembered that the sum is modulo the cycle length. That is,

$$\theta_{ik} = \theta_{ij} + \theta_{jk} - n(C) \qquad \text{(F-1)}$$

in which

θ_{ik} = offset from i to k, etc.;
C = cycle length; and
n = the largest integer that still results in a non-negative value for θ_{ik}.

Note also that

$$\theta_{ij} = C - \theta_{ji} \qquad \text{(F-2)}$$

Table F-9 gives the addition of delay/difference-of-offset data for links AB and BA. The last column of this table duplicates the first column; it is provided for clarity, emphasizing that the cycle is divided into five segments and thus an offset of five is equivalent to an offset of zero.

Table F-10 accomplishes the addition of the two links DE in parallel.

When links are combined in series, a new delay/difference-of-offset relationship must be developed that considers the final difference of offset between the terminal nodes and the various selections for the offset of the common node. Table F-11 demonstrates this process for the series combination of links BC and CB to form a new BD.

Series and parallel additions, as appropriate, are continued through Tables F-12 to F-15. Table F-16 summarizes the final differences of offset for the original links.

Final Offsets

Table F-17 gives the absolute offsets (relative to a common timing reference) for each of the original nodes. Two different reference conditions are listed—node A as reference (i.e., zero offset), and node D as reference.

This completes the combination method for the network of Figure F-1.

BUILDING UNCONDENSABLE NETWORKS FROM SUBNETWORKS

When networks cannot be condensed, the solution of the optimization of offsets can be approached by building the network, starting with a single link and adding links until the appropriate network is obtained. The method may be described with the aid of Figure F-8 and Table F-18.

The process starts by laying out the nodes and links of the eventual network, and then selecting one link as a starting point. This step is shown in Figure F-8a. Subsequent steps require a classification of intersections according to a scheme given in Table F-18. The last three columns of this table contain information for theoretical developments and for computer programming (*11, 12, 13*)

Once the intersections are classified, it is possible to state a rule for adding to a subnetwork:

1. *Rule.* The subnetwork is extended by adding a sequence of links forming a path starting at an intersection of Type 2 or 3, passing only through intersections of Type 4 and ending at another intersection of Type 2 or 3 (*12*).

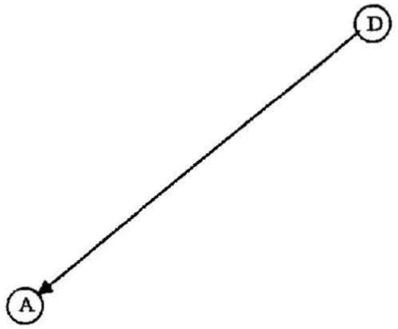


Figure F-7. Link diagram of completely condensed network.

Figures F-8b, c, and d show this process.

On approaching a new network, the procedure should be:

1. Condense the network to a single link if possible. Otherwise, condense the network as far as possible.
2. If the result of 1 is an uncondensable network, build this network from subnetworks.

COMPUTER PROGRAMS

Several computer programs have been written to implement the combination and graph theory methods. These programs, written in the FORTRAN IV language, were prepared by R. E. Allsop of the Research Group in Traffic

TABLE F-9

METHOD OF ADDING DELAYS FOR TWO-WAY LINK OR OTHER PARALLEL COMBINATION [a]

Offset from A to B	0	1	2	3	4	0
Offset from B to A	0	4	3	2	1	0
Delay A to B	15	20	29	23	19	15
Delay B to A	10	13	15	17	20	10
Total delay	25	33	44	40	39	25

[a] Cycle length = 5.

TABLE F-10

ADDITION OF DELAY/DIFFERENCE-OF-OFFSET DATA FOR PARALLEL COMBINATION OF TWO LINKS DE

	DELAY (VEH-SEC PER SIGNAL CYCLE), FOR DIFFERENCE OF OFFSET [a]					
LINK	0	1	2	3	4	0
DE_1	25	18	10	14	21	25
DE_2	30	27	20	16	25	30
Total	55	45	30	30	46	55

[a] Data from Table F-1.
Action: Parallel combination of DE_1 and DE_2.
Diagram of starting situation: Figure F-1.
Diagram of result: Figure F-2.

TABLE F-11

COMPUTATION OF DELAY/DIFFERENCE-OF-OFFSET RELATIONSHIP FOR NEW LINK BD BY COMBINING LINKS BC AND CD IN SERIES[a]

NEW OFFSET BD	OFFSET BC	OFFSET CD	DELAY (VEH-SEC PER SIGNAL CYCLE) BC[b] + CD[b] = BD	MINIMUM[c]
0	0	0	14 + 13 = 27	
	1	4	9 + 11 = 20	20 (1)
	2	3	13 + 20 = 33	
	3	2	22 + 27 = 49	
	4	1	17 + 19 = 36	
1	0	1	14 + 19 = 33	
	1	0	9 + 13 = 22	22 (1)
	2	4	13 + 11 = 24	
	3	3	22 + 20 = 42	
	4	2	17 + 27 = 44	
2	0	2	14 + 27 = 41	
	1	1	9 + 19 = 28	
	2	0	13 + 13 = 26	26 (2)
	3	4	22 + 11 = 33	
	4	3	17 + 20 = 37	
3	0	3	14 + 20 = 34	
	1	2	9 + 27 = 36	
	2	1	13 + 19 = 32	
	3	0	22 + 13 = 35	
	4	4	17 + 11 = 28	28 (4)
4	0	4	14 + 11 = 25	25 (0)
	1	3	9 + 20 = 29	
	2	2	13 + 27 = 40	
	3	1	22 + 19 = 41	
	4	0	17 + 13 = 30	

[a] $\theta_{BD} = \theta_{BC} + \theta_{CD} - n(c)$.

[b] Data from Table F-1.

[c] Figures are used as the desired relationship. Figures in parentheses contain the associated BC offsets for future reference.

Action:	Series combination of BC and CD.
Diagram of starting situation:	Figure F-2.
Diagram of result:	Figure F-3.

TABLE F-13

ADDITION OF DELAY/DIFFERENCE-OF-OFFSET DATA FOR LINKS DB (DIRECT) AND DB (INVERSE OF NEW BD FORMED BY DROPPING NODE C)

LINK	DELAY (VEH-SEC PER SIGNAL CYCLE), FOR DIFFERENCE OF OFFSET 0	1	2	3	4	5
DB (direct)[a]	30	18	18	21	26	30
DB (via C)[b]	20	25	28	26	22	20
Total	50 (1)	43 (0)	46 (4)	47 (2)	48 (1)	50 (1)

[a] Data from Table F-1.

[b] Data from Table F-11 (inverse of BD).

Note: Figures in parentheses are offsets for

Action:	Parallel combination of BD (via C) and DB (direct).
Diagram of starting situation:	Figure F-4.
Diagram of result:	Figure F-5.

TABLE F-12

SERIES COMBINATION OF DELAY/DIFFERENCE-OF-OFFSET DATA FOR LINKS DE AND EA

OFFSET DA	DE	EA	DELAY (VEH-SEC PER SIGNAL CYCLE) DE[a] + EA[b] = DA	MINIMUM[c]
0	0	0	55 + 12 = 67	
	1	4	45 + 40 = 85	
	2	3	30 + 33 = 63	
	3	2	30 + 26 = 56	56 (3)
	4	1	46 + 20 = 66	
1	0	1	55 + 20 = 75	
	1	0	45 + 12 = 57	57 (1)
	2	4	30 + 40 = 70	
	3	3	30 + 33 = 63	
	4	2	46 + 26 = 72	
2	0	2	55 + 26 = 81	
	1	1	45 + 20 = 65	
	2	0	30 + 12 = 42	42 (2)
	3	4	30 + 40 = 70	
	4	3	46 + 33 = 79	
3	0	3	55 + 33 = 88	
	1	2	45 + 26 = 71	
	2	1	30 + 20 = 50	
	3	0	30 + 12 = 42	42 (3)
	4	4	46 + 40 = 86	
4	0	4	55 + 40 = 95	
	1	3	45 + 33 = 78	
	2	2	30 + 26 = 56	
	3	1	30 + 20 = 50	50 (3)
	4	0	46 + 12 = 58	

[a] Data from Table F-10.

[b] Data from Table F-1 (inverse of AE).

[c] Figures in parentheses are associated DE offsets.

Action:	Series combination of DE and EA.
Diagram of starting situation:	Figure F-3.
Diagram of result:	Figure F-4.

Studies, University College, London. The following sections describe these programs, which are documented by Allsop (*13*). The programs are discussed in the order of their use.

Program Name: Allsop Program 4

Purpose

The purpose is to condense the network, producing an optimal delay/difference-of-offset relationship between two nodes (numbered 1 and 2).

Special Notes

Specified surviving nodes must be numbered 1 and 2. Other nodes may be numbered at will.

Inputs

1. NRUN—the number of complete sets of data that follow (integer).
2. NVERT—the number of intersections in the network (integer).
3. LIST—an array, NVERT × 10 (integers) giving the

TABLE F-14

SERIES COMBINATION OF DELAY/DIFFERENCE-OF-OFFSET DATA FOR DB (COMPOSITE) AND BA

OFFSET			DELAY (VEH-SEC PER SIGNAL CYCLE)			MINI-MUM[c]
DA	DE	EA	DE[a]	EA[b]	DA	
0	0	0	50 +	25 =	75	75 (0)
	1	4	43 +	33 =	76	
	2	3	46 +	44 =	90	
	3	2	47 +	40 =	87	
	4	1	48 +	39 =	87	
1	0	1	50 +	39 =	89	
	1	0	43 +	25 =	68	68 (0)
	2	4	46 +	33 =	79	
	3	3	47 +	44 =	91	
	4	2	48 +	40 =	88	
2	0	2	50 +	40 =	90	
	1	1	43 +	39 =	82	
	2	0	46 +	25 =	71	71 (0)
	3	4	47 +	33 =	80	
	4	3	48 +	44 =	92	
3	0	3	50 +	44 =	94	
	1	2	43 +	40 =	83	
	2	1	46 +	39 =	85	
	3	0	47 +	25 =	72	72 (0)
	4	4	48 +	33 =	81	
4	0	4	50 +	33 =	83	
	1	3	43 +	44 =	87	
	2	2	46 +	40 =	86	
	3	1	47 +	39 =	86	
	4	0	48 +	25 =	73	73 (0)

[a] Data from Table F-13.
[b] Data from Table F-9.
[c] Figures in parenthesis are offsets for BA.

Action: Series combination of DB and BA.
Diagram of starting situation: Figure F-5.
Diagram of result: Figure F-6.

connections of links between nodes. (See the following for details of connections.)

4. NINT—an integer giving the number of intervals into which each signal cycle is divided.

5. DELAY (I, J)—an array, NEDGE × NINT (integers) (where NEDGE = number of links in network). Lists delay per cycle on link I when:

$$(\text{Offset at intersection I, 1}) - (\text{Offset at intersection I, 2}) = \text{J} - 1 \pmod{\text{M}}$$

Note: M = NINT.

Output

The output is an over-all delay-offset relation between the specified nodes and optimum offsets at other nodes for each combination of offsets at the specified nodes.

There are two error messages. The first should never appear unless there is an undetected error in the logic. The second will appear at some stage if the network specified by LIST cannot be reduced to a single link between intersections 1 and 2 by series and parallel combination.

TABLE F-15

FINAL DELAY/DIFFERENCE-OF-OFFSET RELATIONSHIP BETWEEN D AND A (FROM PARALLEL COMBINATION OF TWO LINKS)

LINK	DELAY (VEH-SEC PER SIGNAL CYCLE), FOR DIFFERENCE OF OFFSET 0	1	2	3	4	0
DA_1[a]	56	57	42	42	50	56
DA_2[b]	75	68	71	72	73	75
Total	131	125	113	114	123	131
Offsets DE	(3)	(1)	(2)	(3)	(3)	(3)
Offsets BA	(0)	(0)	(0)	(0)	(0)	(0)

[a] Data from Table F-12.
[b] Data from Table F-14.

Action: Parallel combination of DA_1 and DA_2.
Diagram of starting situation: Figure F-6.
Diagram of result: Figure F-7.

TABLE F-16

FINAL OFFSET DIFFERENCES WITH ASSOCIATED DELAY COMPONENTS

LINK	DIFFERENCE OF OFFSET	DELAY COMPO-NENT	SOURCE OF DATA (TABLE NO.)
AB	0	15	F–9, F–11
BA	0	10	F–9, F–11
DE_1	2	10	F–10, F–12
DE_2	2	20	F–10, F–12, F–14
EA	0	12	F–12
DB (direct)	2	18	F–13
BC	4	17	F–11, F–13
CD	4	11	F–11
DA	2 (effective)	113 (total)	F–15 (check)

TABLE F-17

ABSOLUTE OFFSETS

NODE	WITH NODE A AS ZERO	WITH NODE D AS ZERO
A	0	2
B	0	2
C	4	1
D	4	0
E	0	2

Details of Connections

The array LIST contains one row for each node in the network. The row numbers correspond to the node numbers, and thus the node numbers for the origins of links

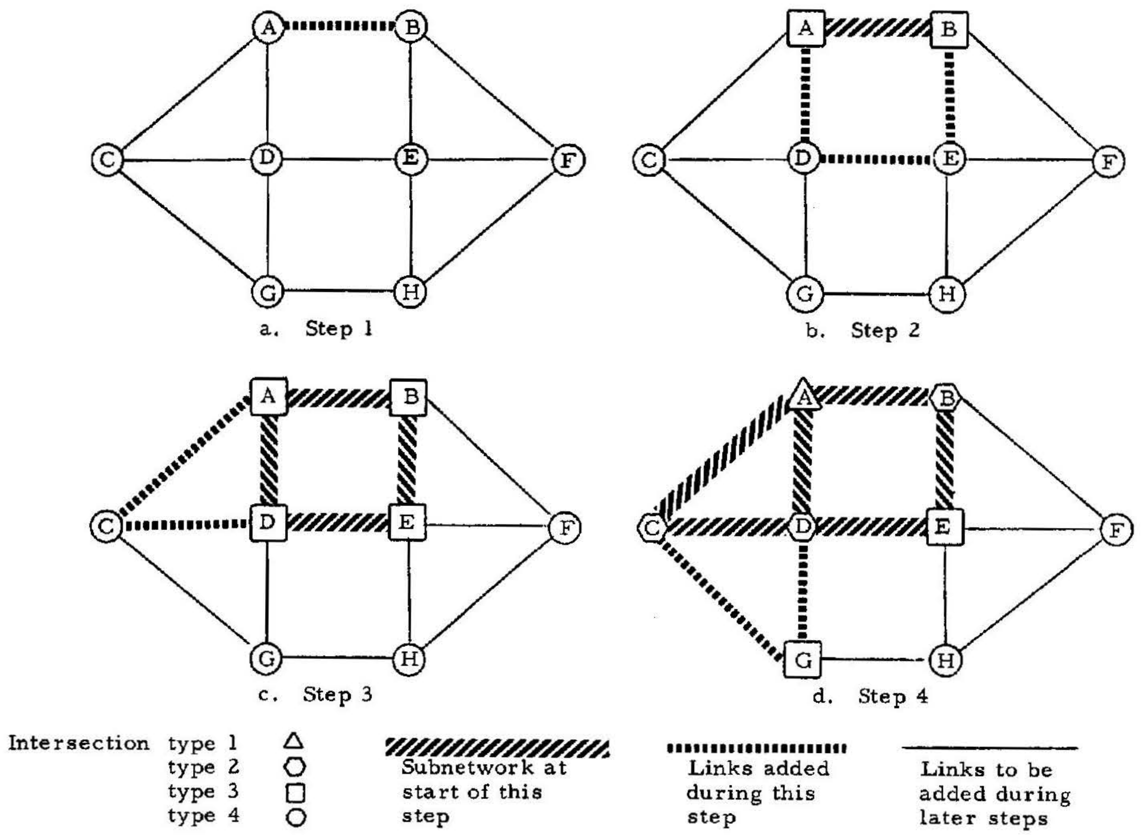


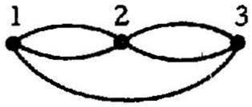
Figure F-8. Building condensed network from subnetworks.

need not be stated. In the row corresponding to each node of origin are listed the destinations of links from that origin. That is, the Ith row contains the destinations of links originating from node I. Where there are k parallel links between I and destination J, J must be repeated k times. Thus, in the network

TABLE F-18

TYPES OF LINKS USED IN BUILDING CONDENSED NETWORK FROM SUBNETWORKS

INTERSECTION TYPE	DESCRIPTION	GRAPH THEORY TERMINOLOGY	QUANTITY OF LINKS	NUMBERING OF LINKS
1	Endpoint only of links in subnetwork	Interior vertices of subnetwork	p	1 to p
2	Connected by single link to type 1 but not itself type 1	Inner vertices of attachment of subnetwork	q	$(p+1)$ to $(p+q)$
3	Not type 2. Junction of links that are included and links that are not included in subnetwork.	Outer vertices of attachment of subnetwork	r	$(p+q+1)$ to $(p+q+r)$
4	Endpoint of links not included in subnetwork	Exterior vertices of subnetwork	$(n-p-q-r)$, i. e., $n-(p+q+r)$	$(p+q+r+1)$ to n



From node 1 there are 2 links to node 2, 1 link to node 3. So row 1 in the LIST array will be (2, 2, 3, 0, 0, 0, 0, 0, 0, 0). (The zeros are required to fill out unused positions to a length of 10.) From node 2 there are 2 links to node 3, so row 2 in the LIST array will be (3, 3, 0, 0, 0, 0, 0, 0, 0, 0). There are no links originating at node 3, so row 3 will be all zeros. Thus, the resulting array

LIST = (2 2 3 0 0 0 0 0 0 0)
(3 3 0 0 0 0 0 0 0 0)
(0 0 0 0 0 0 0 0 0 0)

Program Name: Allsop Program 1

Purpose

The purpose is to determine the order in which an uncondensable network is to be built from subnetworks.

Special Notes

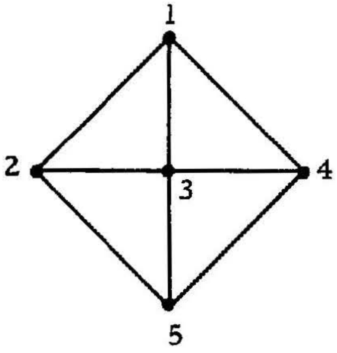
The program goes through many iterations. Informational outputs are provided by printer. Final output via punch is used as input for subsequent program. One output, PI, is a 1 × N array, listing in order of use the identification numbers of the various nodes (see last column of Table F-18). In current form, this program will handle up to 100 nodes.

Inputs

N: the number of nodes in network (integer).

LIST (I, J): An array $N \times 10$, integers, giving the connections of the various links. See the following for details.

Details of Connections: The array LIST contains one row for each node of the network. The Ith row contains the number of the nodes serving as destinations for links originating at node I. Each row must contain 10 integers, and thus unused positions are filled with zeros. For example, in the network,



the following links exist:

ORIGIN	DESTINATIONS	NOTATION IN ARRAY
1	2, 3, 4	2, 3, 4, 0, 0, 0, 0, 0, 0, 0
2	3, 5	3, 5, 0, 0, 0, 0, 0, 0, 0, 0,
3	4, 5	4, 5, 0, 0, 0, 0, 0, 0, 0, 0
4	5	5, 0, 0, 0, 0, 0, 0, 0, 0, 0,
5	None	0, 0, 0, 0, 0, 0, 0, 0, 0, 0

Thus, for this network,

$N = 5$ and LIST = (2 3 4 0 0 0 0 0 0 0)
(3 5 0 0 0 0 0 0 0 0)
(4 5 0 0 0 0 0 0 0 0)
(5 0 0 0 0 0 0 0 0 0)
(0 0 0 0 0 0 0 0 0 0)

Outputs

From Printer.—The network is built up by starting with a single link and adding, at each iteration, a path through the part not so far included. For each iteration is printed the following:

1. Values of P, Q, and R and the 1 × N array PI at the beginning of the iteration. (These are the p, q, and r, defined in Table F-18.)
2. The numbers of nodes on the path added during the iteration. (Note: The starting link is the link joining the two ends of the path found in the first iteration.)

The message "NETWORK COMPLETE" is printed after the last iteration.

Two error messages are provided for, but should not appear unless there are undetected errors in the logic.

From Card Punch (for Input to Allsop Program 3).—Integer PATHNO (the number of paths used to build up the network, counting the starting link as a path)

1 × PATHNO arrays INT, IVA, and OVA

$(N + 2)$ × PATHNO array PERM punched by columns

INT(I), IVA(I), and OVA(I) are the values of P, Q, and R before the Ith iteration if I ≠ PATHNO, and after the last iteration if I = PATHNO. and after the last iteration if I = PATHNO. PERM (I, J) $I = 1, 2, \ldots, N$ are the elements of array PI after the Jth iteration, if J ≠ PATHNO. PERM (I, PATHNO) = PERM (I, PATHNO − 1) for all I, and PERM $(N + 2, \text{J}) = N + 2$, PERM $(N + 1, \text{J}) = N + 1$ for all J.

Program Name: Allsop Program 3

Purpose

The purpose is to find optimal offsets, given the network condensation information from Allsop Program 1.

Inputs

Integer N and array LIST as for Allsop Program 1.

Integer M (number of steps into which signal cycle is divided).

NEDGE × M integer array DELAY punched by rows. (NEDGE is the number of links in the network; DELAY is defined in the following.)

Integer PATHNO and arrays INT, IVA, CVA, and PERM as output from Allsop Program 1.

Output

1 × N integer array of optimum offsets, in numerical order of the intersections to which they refer, followed by the value of the minimum total delay.

Notes:

DELAY (I, J) is integer array NEDGE × NINT

in which

NEDGE = number of links in network; and
NINT = M = number of intervals into which signal cycle is divided.

This array lists delay per cycle on link I when
(Offset at intersection I, 1) — (Offset at intersection I, 2) = J — 1 (mod M)

Program Name: Allsop Program 2

Superseded by Allsop Program 3.

APPENDIX G

OTHER BRITISH TRAFFIC SIGNAL TIMING OPTIMIZATION TECHNIQUES

In addition to the combination and graph theory methods described in Appendix F, the research agency investigated two other signal timing methods developed in England:

1. The GLC signal timing program.
2. The TRANSYT method.

These methods are discussed in the following paragraphs.

THE GREATER LONDON COUNCIL SIGNAL TIMING PROGRAM

The Greater London Council (GLC) (*19*), Department of Highways and Transportation, has prepared a computer program that executes the combination method with some added refinements. This program gives solutions only for networks that are condensable; it does not contain the Allsop graph theory optimization process. The principal advantage of the GLC program is the automatic computation of delay-offset tables for each link in the network. This information can be obtained for individual links, even if the network is not condensable. Additional refinements include the use of a stop penalty and link weighting factor in the delay computation. Platoon dispersion can be included in the computation of the delay-offset difference tables.

The computer program is written in FORTRAN IV and is used regularly by GLC on its IBM 360/50 computer. The GLC program was obtained by the research agency and tested successfully on a simple trial network. In the following description, British notation has been changed to that used in the United States.

Input Requirements

The inputs to this program are based on a network made up of one-way links between signalized intersections. The data required include signal cycle length(s) and splits, travel times along links, volumes of all traffic movements at each intersection, queue discharge rates, and coding for the special features of platoon dispersion, stop penalties, and delay (flow) weighting; also included are data on the connections of links in the network. In compiling data for input to the program it is recommended that charts of the phase splits at each intersection be drawn out so that the timing of each interval affecting a particular flow can be correctly selected.

If a network link carries some minor flows that can be distinguished from the main flow by origin-destination, signal interval, etc., it may be helpful to separate such minor flows by placing them on a separate link in parallel with the link carrying the main flow. Such minor flows often occur at offset (jog) intersections.

It is recommended that the signal timing intervals be expressed in percentage rather than seconds as the computer program does all computations on the basis of even increments (steps) that are more accurately expressed as percentage values. As many as six different cycle lengths may be treated in one computer run, provided that all have the same splits, when expressed in percentage.

Functions of Program

The computer program (written in FORTRAN IV) first computes the delay/difference-of-offset table for each link. This is done by a simple form of simulation. Then a search is made for ways in which the links can be combined in series and/or parallel. The appropriate delay/offset histograms are combined to give final histograms for each link.

Output

Several levels of output are available, and may be selected by appropriate coding of the input. Available outputs range from simple listing of the final optimum offsets with their delays to a complete listing of all input data, all intermediate delay/offset tables (minimum, maximum, and optimum), and final delay/offset table for the combined network.

Special Features

The program contains the possibility of selecting several special features designated as STOP PENALTY, DELAY WEIGHING FACTOR, and PLATOON DISPERSION. These features are discussed in the following paragraphs.

The STOP PENALTY is used to discourage queuing when storage is limited, such as where grades are important or where block lengths are short, etc. If stopping is to be encouraged, a negative constant should be used. This penalty is assigned for each cycle length.

The DELAY WEIGHTING FACTOR (known as Flow Weighting Factor by GLC) is assigned to each link. If it is omitted, the value is taken as 1.0. Factors both greater than and less than unity are permitted, providing for weights either greater than or less than the normal values.

PLATOON DISPERSION is performed using a relationship developed by the Road Research Laboratory (*23*) for this purpose. When the input card for platoon dispersion is coded 1 the dispersion factor is 1.0/(1.0 + 0.4 × travel time). When the card is coded 0, the dispersion factor is 1.0 (i.e., no dispersion). Thus, with the normal coding of 1, platoons experience a smoothing that is a function of the travel time along the link.

THE TRAFFIC NETWORK STUDY TOOL

The Traffic Network Study Tool (TRANSYT) developed by D. I. Robertson of Plessey Automation, in a joint project with the Road Research Laboratory, is a method for determining the offsets and splits that will result in minimum total delay and stops in a network (*14, 15*). The program consists of two parts: a simple simulation of traffic flow, and a hill-climbing optimization. A recent experiment in Glasgow (*21*) compared TRANSYT settings with those determined by the combination method. It was found that an average reduction of 4 percent in travel time resulted when TRANSYT settings compared were used.

Simulation

The simulation is based on the assumptions that (1) flows on all links are below saturation, and (2), as a result, there is a point in the signal cycle for each link during which the flow on that link is zero (in the steady state).

Each link contains provision for input, platoon dispersion, and discharge across the stop line (i.e., the output patterns are at the stop line). For closed loops it is necessary to provide dummy links to inject inputs into appropriate intersections. One dummy link can usually serve two adjacent loops. The flow on dummy links is uniform throughout the cycle.

The input to a link is first modified by platoon dispersion relationships developed by the Road Research Laboratory (*23*) that were derived by applying a curve to field data on platoon dispersion. The relationship used by TRANSYT is:

$$q'_{(i+\hat{t})} = Fq_i + (1-F)q'_{(i+\hat{t}-1)} \qquad \text{(G-1)}$$

$$\text{for } Fq'_{(i+\hat{t}-1)} \geqq 1 \qquad \text{(G-2)}$$

in which

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 (i.e., dispersed) platoon;

$\hat{t} = 0.8\bar{t}$ where the average journey time, $\bar{t}$, is measured in the time intervals used for q_i; and

$$F = \frac{1}{1 + 0.4\bar{t}}$$

The traffic pattern resulting from the platoon dispersion is then applied to the stop line where a queue forms during the red and dissipates at normal saturation flow rates during the green. Each link is treated for two cycles (before going to the next link). The first cycle is used to achieve flow patterns without measurement of delay. The second cycle is used to measure delay. It is not considered necessary to make any further correction for the effect of uniform flow on dummy links.

The delay due to random effects is handled by adding to the stop line delay a component, D_R, computed as follows:

$$D_R = \tfrac{1}{2}\,\frac{x^2}{(1-x)} \qquad \text{(G-3)}$$

in which

x = the degree of saturation.

Because the British traffic signals operate on a cycle of 50 increments, delay is obtained in increments of 1/50 of a cycle.

The effect of stops can be handled along with delay by adding WS to the delay, in which S = number of stops; and W = a weighting factor that is an integer. Values of W from 4 to 8 have been found suitable (at least in England). In one experiment the number of stops was reduced 10.6 percent at an increase of delay of 2.3 percent by using a W of 8 (*14*).

Optimization

The optimization makes use of a special search technique developed by Robertson to accomplish a hill-climbing procedure. In a sense the simulation exists only to evaluate each step in the optimization procedure so that arrival at the optimum can be determined.

The procedure described in the following assumes fixed cycle lengths and that some logical sequence has been established for treating the intersections. The step sizes are based on the fact that British traffic signal equipment provides 50 steps in every cycle.

1. Start with the first intersection in the sequence.
2. Alter offset by ±7 units, and recalculate (resimulate) delay in entire network. Continue to "local" minimum for first intersection.
3. Repeat 2 for each intersection in sequence.
4. Repeat 2 and 3 with steps of ±20 units.

5. Alter *split* at first intersection by ±1 unit in start of A phase. Continue to local minimum. Then treat B phase until local minimum. Then treat C phase, if any.
6. Repeat 5 for other intersections in sequence.
7. Repeat 2 and 3. (Offsets @ ±7 units.)
8. Repeat 4. (Offsets @ ±20 units.)
9. Operate on offsets @ ±1 unit.
10. Repeat 5. (Splits @ ±1 unit.)
11. Repeat 9. (Offsets @ ±1 unit.)
12. Repeat 10. (Splits @ ±1 unit.)

Note: Although the simulation and hill-climbing procedure are primarily for optimization of offset and split, they can be used also to test cycle length.

State of Development

The results of experiments to date in Glasgow and London indicate that TRANSYT has great potential as a signal optimization tool. However, at present (1969) the program is operational only on the Marconi Myraid computer. However, it is understood that the Road Research Laboratory is reprogramming TRANSYT in FORTRAN. When this has been accomplished, application of TRANSYT in the United States should be practicable. It is recommended that experimentation with TRANSYT be vigorously pursued.

APPENDIX H

TRANS SIMULATION MODEL

HISTORICAL DEVELOPMENT OF TRANS

TRANS is a general-purpose digital computer simulation model of traffic operation and control in signalized street systems. It was conceived in original form in 1962 in a study conducted for the District of Columbia Department of Highways and Traffic. It can be used in its present form to represent a variety of system configurations, ranging from a single intersection to a complex network having as many as 100 links. Among the engineering alternatives that can be systematically tested using TRANS are the following:

1. Geometric design changes, such as street and intersection widening, channelization, new street construction or closure, and intersection grade separations.
2. Traffic control changes, such as turning movement prohibitions, parking regulations, one-way street patterns, and reversible lane operations.
3. Traffic signal system changes, such as coordinated traffic signal settings; modifications of cycles, splits, and offsets; traffic-responsive control methods; and special signal phasing for turning traffic.
4. Changes in magnitudes and patterns of traffic demand, including future traffic flow levels.

To make feasible the simulation of relatively large networks, the TRANS model has a "macroscopic" character. Individual vehicles in the traffic system are not unique or identifiable (i.e., traceable through the system); all vehicles have identical physical and performance parameters. Except when they are being processed individually through signalized intersections, vehicles are handled in groups, and positions are registered in relatively coarse elements of the roadway (zones) that can contain more than one vehicle. Zones are one lane wide and are equal in length to the distance a free-moving vehicle can traverse in one simulation scan interval.

TRANS is a periodic scan type of model carried out in discrete time intervals of t seconds. Theoretically, any t between 2 and 5 sec may be specified; however, most realistic results that have been obtained used $t = 2$ sec.

The TRANS model was originally written in FAP (FORTRAN Assembly Program) language for the IBM 7090/94. The latest version of the program, which incorporates all the refinements in simulation logic, includes several subroutines written in FORTRAN IV in addition to the basic FAP coded routines. The program is compiled and executed under the IBSYS monitor system and has been operationally tested on the IBM 7094, the IBM 360/65/40 system's emulation of the 7094, and the Standard Computer IC-6000 system's emulation of the 7094.

Using the total 32K memory of the IBM 7094, the latest version of the TRANS model can simulate a network of 50 input links, 100 network links, and 50 output links. Table H-1 gives a listing of networks that have been simulated by various versions of the TRANS model, the network sizes, and computer time requirements.

1966 BPR Project

In a one-year project conducted by Wagner et al. (*24*) at the research agency for the Bureau of Public Roads (BPR), the original TRANS model was refined substantially to improve its realism and general applicability. Important changes in the model implemented during this project include:

TABLE H-1

SUMMARY OF IBM-7094 COMPUTER TIME REQUIREMENTS FOR NETWORKS SIMULATED BY TRANS

NETWORK NAME	NETWORK SIZE: INTER-SECTIONS	NETWORK SIZE: NETWORK LINKS	RATIO: SIMULATED TIME / COMPUTER TIME	VERSION OF TRANS
Original test network	81	217	4:1	I
Turns-phase study network (synthetic)	9	36	11:1	II
Flower-Figueroa	9	36	11:1	III
Pico-Venice	9	30	12:1	III
Barnes' thesis network (synthetic)	9	24	9:1	III
Pico arterial	6	24	14:1	IV
Detroit case study network	24	88	11:1	IV
Charlotte TOPICS network	10	34	11:1	IV
Boise CBD	35	61	6:1	IV
TRW surveillance methodology test	5	4	Unknown	IV
Figueroa-Adams	26	82	3.5:1	IV
San Jose CBD	22	44	7.5:1	IV

1. Generalization of the simulation scan cycle to reduce the original coarseness of the model.
2. Major refinements in left-turn interference logic.
3. Intra-link volume change scheme to accurately represent traffic gains or losses between signalized intersections.
4. Variable queue discharge rates on individual links in the network.
5. Pedestrian-turning vehicle conflict logic.
6. Right-turn-on-red maneuver logic.
7. Simplification of input format.

The final version of the simulation model containing the foregoing refinements was named TRANS III.

During 1966, field studies and simulation exercises of two test networks were conducted with TRANS III to investigate the model's ability to represent existing conditions and to predict the effect of changes in the control system. The results of these studies generally indicated that TRANS III was a significantly upgraded version of the original model that exhibited a fairly good degree of operational realism, adaptability to changing system conditions, and potential for a degree of validity that warranted further pursuit of its development and refinement into a polished traffic research tool. Although they showed great promise, the tests of the simulation model's validity were not exhaustive enough to determine conclusively its possible precision in reproducing existing systems or its predictive validity. It was determined that more rigorous statistical testing and functional refinement and extension of the model were required. A series of sensitivity experiments conducted in 1966 served to substantially support the researchers' confidence in the quality and reasonableness of the model. The model was especially sensitive to left-turn gap acceptance parameters, traffic volumes, and queue discharge parameters.

1967 BPR Report

In a one-year follow-up project in 1967 by Wagner et al. (*25*) at the research agency, additional studies of the calibration properties, validity, and sensitivity of the simulation model were conducted through (1) more rigorous statistical analyses of pertinent data; (2) collection of additional, more comprehensive empirical data on traffic operations; and (3) refinement and more extensive exercising of the simulation model. The realism of the model's representation of three test street networks in Los Angeles was thoroughly investigated.

The TRANS IV version of the model was prepared by incorporating the following important improvements and refinements:

1. Improved pedestrian-vehicle interference logic.
2. Platoon dispersion logic involving variable vehicle speeds and passing behavior.
3. Important refinements of queue discharge logic.
4. Incorporation of experimental traffic-responsive signal control techniques.
5. Major reorganization and improvement of input/output.

TRANS IV was found to operate with a relatively good degree of realism. In four of the eight data sets tested in 1967, no statistically significant differences were found between means of important traffic operations variables. The numerical differences between simulated and measured characteristics for the remaining four data sets were relatively small, with the worst-case difference approximating 16 percent. The relatively close fit was achieved without arbitrary adjustment of simulation input variables. The inherent realism of the model was further substantiated by statistical analyses of distributions of important variables for individual links in the test network, limited predictive validity tests, and a series of sensitivity experiments.

Detroit Case Study

In 1968, BPR funded a case study by Wagner and Barnes (*26*) to determine the ability of TRANS IV to represent traffic operations in a complex 24-intersection network in Detroit, Mich. Field data for model input and statistical comparisons were collected by the City of Detroit, Department of Streets and Traffic.

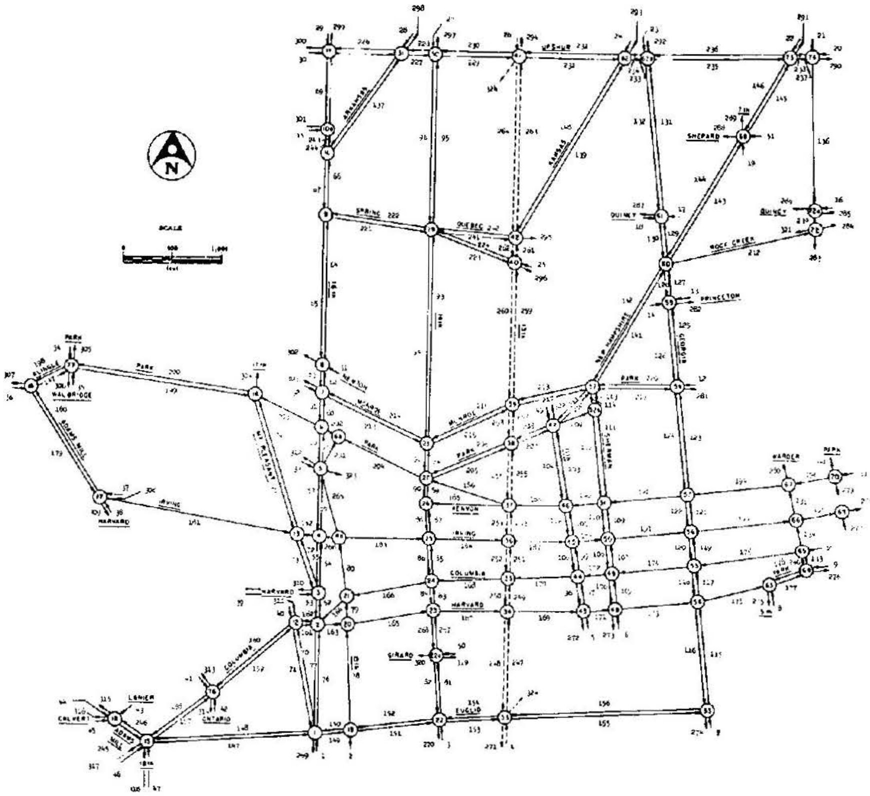
Field studies and simulation exercises were performed for the 3:30 to 6:30 PM time period, divided into three 1-hr analysis periods. The results of the analyses indicated that the simulation model represented the over-all network operational characteristics quite closely, as compared with field observations, for two out of three 1-hr study periods. For the other hour (4:30 to 5:30 PM), with the heaviest traffic flows of the three hours studied, the differences between simulation and field study estimates of the network operational characteristics were definitely significant.

A series of formal statistical analyses was performed, using four different nonparametric methods, to formally test a series of hypotheses concerning comparisons of distributions formed by simulated and field-measured traffic variables for the individual links in the street network. Distributions of four important traffic variables were investigated —traffic volume, average link content, average speed, and average travel time—and separate analyses were performed for each of the three 1-hr study periods. The results of this series of nonparametric tests clearly corroborated the findings described in the preceding paragraph. For two of the three study periods, 3:30 to 4:30 PM and 5:30 to 6:30 PM, the preponderance of tests (29 cases out of 32) yielded no evidence that the simulation and field results were significantly different. However, for the peak hour, 4:30 to 5:30 PM, the majority of statistical tests (11 cases out of 16) indicated significant differences between simulation and field results.

REVIEW OF APPLICATIONS OF THE TRANS MODEL

Since its initial development in 1962, the TRANS model has been used to simulate a number of traffic networks and a variety of traffic control alternatives. Brief descriptions of TRANS applications (Figs. H-1 through H-12) are presented. A network diagram is included with each description; approximately equal scales are used for comparison purposes.

Although TRANS was originally intended for the study of traffic signal timing schemes, it should be noted that additional applications have been found. Traffic engineering actions (such as turn prohibitions, street widening, and installation of channelization) have also been studied through the use of the TRANS model. Recently, TRANS was coordinated for the first time with results of a traffic assignment program to determine effects on traffic operation that would result from construction of a proposed mall in the central business district of Boise, Idaho.



<u>Network Location</u>: North Central Washington <u>Year of Study</u>: 1963

<u>Type of Development</u>: Mixed-Residential-Commercial

<u>Number of Intersections</u>: 81 <u>Number of Network Links</u>: 217

<u>Approximate Size of Network</u>: 9000 feet x 7500 feet

<u>Version of Simulation Program</u>: TRANS I, original

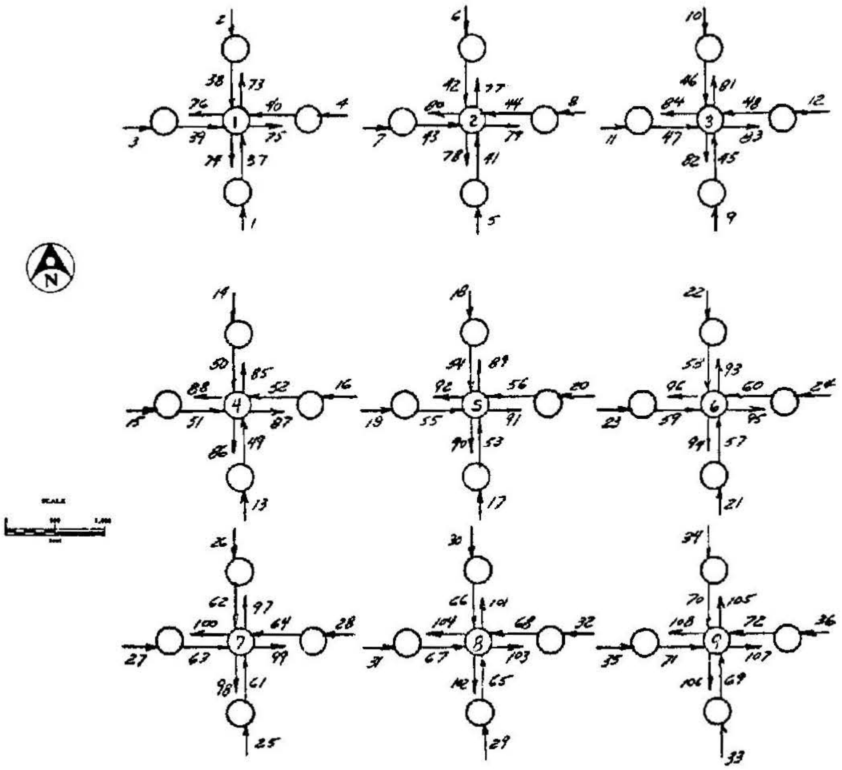
<u>Real Time--Computer Time Ratio (IBM 7094-I)</u>: 4:1

<u>Periods Simulated</u>: 7:00-9:00 am, 10:00-12:00 am, 4:00-6:00pm

<u>Summary</u>: This was the project in which TRANS was initially developed. It was intended to be used for studying the effects of different traffic signal timing techniques. This initial version of the model used a relatively coarse scan cycle of 5 seconds. A field study was carried out to determine the validity of the model.

References: Gerlough, D. L., Wagner, F. A., Rudden, J. B., and Katz, J. H., "A Traffic Simulation Program for a Portion of the Traffic Signal System in the District of Columbia, prepared for District of Columbia, Department of Highways and Traffic in cooperation with U. S. Department of Commerce, Bureau of Public Roads, April 1963.

Figure H-1. Original test network.



Network Location: Synthetic Year of Study: 1965

Type of Development: None

Number of Intersections: 9 Number of Network Links: 36

Approximate Size of Network: Not Applicable

Version of Simulation Program: TRANS II

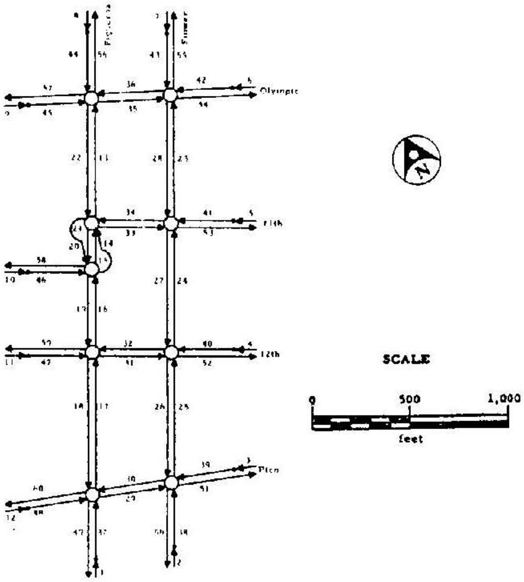
Real Time--Computer Time Ratio (IBM 7094-I): 11:1

Periods Simulated: 36 half-hour runs

Summary of Results: This project involved the use of TRANS to simulate nine separate (unconnected) intersections to determine the effects of various left-turn phasing schemes. The intersections were simulated simultaneously in order to conserve computer time. A total of 162 intersection-hours of traffic operation were simulated.

References: Gerlough, D. L., and Wagner, F. A. "Improved Criteria for Traffic Signals at Individual Intersections," National Cooperative Highway Research Program Report 32, Highway Research Board, Washington, 1967

Figure H-2. Left turn-phasing study network.



<u>Network Location</u>: Central Los Angeles <u>Year of Study</u>: 1966

<u>Type of Development</u>: Light Commercial

<u>Number of Intersections</u>: 9 <u>Number of Network Links</u>: 36

<u>Approximate Size of Network</u>: 2700 feet x 1000 feet

<u>Version of Simulation Program</u>: TRANS III

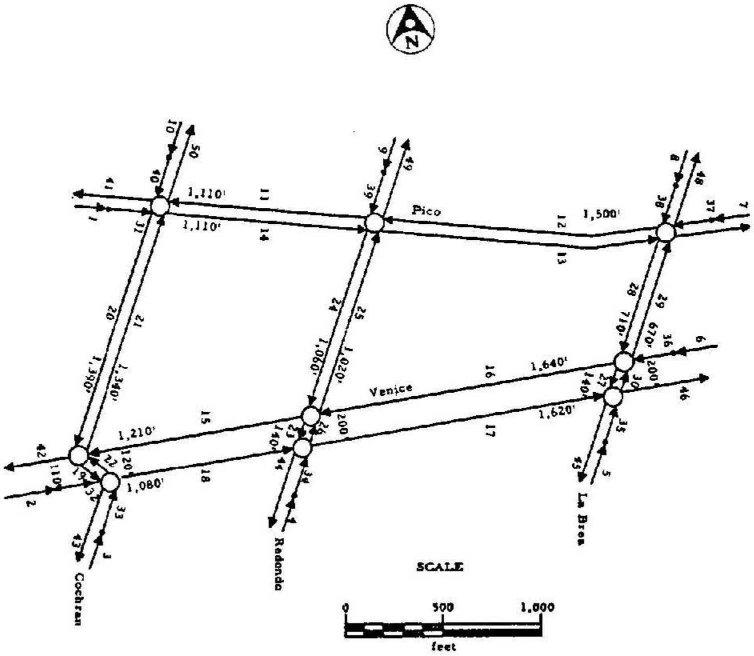
<u>Real Time--Computer Time Ratio (IBM 7094-I)</u>: 11:1

<u>Periods Simulated</u>: 7:00-8:00 am; 8:30-9:30 am,
3:00-4:00 pm, 4:30-5:30 pm

<u>Summary</u>: This project was performed to test the TRANS model. Calibration and validation studies were carried out as a part of this contract from the U. S. Bureau of Public Roads. The existing signal timing scheme was simulated along with two revised schemes.

<u>References</u>: Wagner, F. A., Barnes, F. C., Stirling, D. P., and Gerlough, D. L. "Urban Arterial and Network Simulation," <u>Planning Research Corporation Report PRC R-926</u>, Los Angeles, December 1966, PB 174629

Figure H-3. Flower-Figueroa network.



Network Location: West Central Los Angeles   Year of Study: 1966

Type of Development: Light Commercial-Residential

Number of Intersections: 9   Number of Network Links: 30

Approximate Size of Network: 3700 feet x 2000 feet

Version of Simulation Program: TRANS III

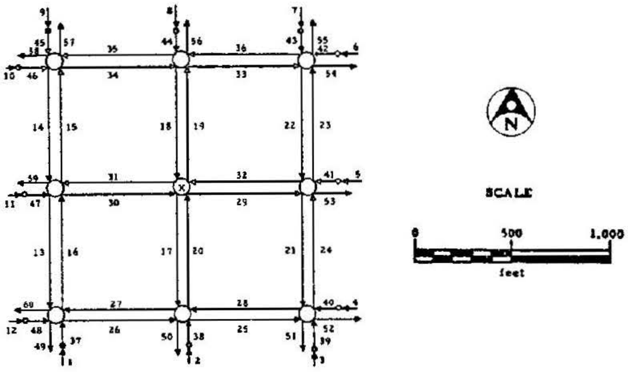
Real Time--Computer Time Ratio (IBM 7094-I): 12:1

Periods Simulated: 3:00-4:00 pm, 4:30-5:30 pm

Summary: This network was studied as a part of the TRANS development contract with the US Bureau Public Roads. Calibration and validation studies were carried out using the existing traffic signal timing plan.

Reference: Wagner, F. A., Barnes, F. C., Stirling, D. P., and Gerlough, D. L., "Urban Arterial and Network Simulation," Planning Research Corporation Report PRC R-926, Los Angeles, December 1966 PB 174 629

Figure H-4. Pico-Venice network.



Network Location: Synthetic Year of Study: 1967

Type of Development: None

Number of Intersections: 9 Number of Network Links: 24

Approximate Size of Network: 1320 feet x 1320 feet

Version of Simulation Program: TRANS III

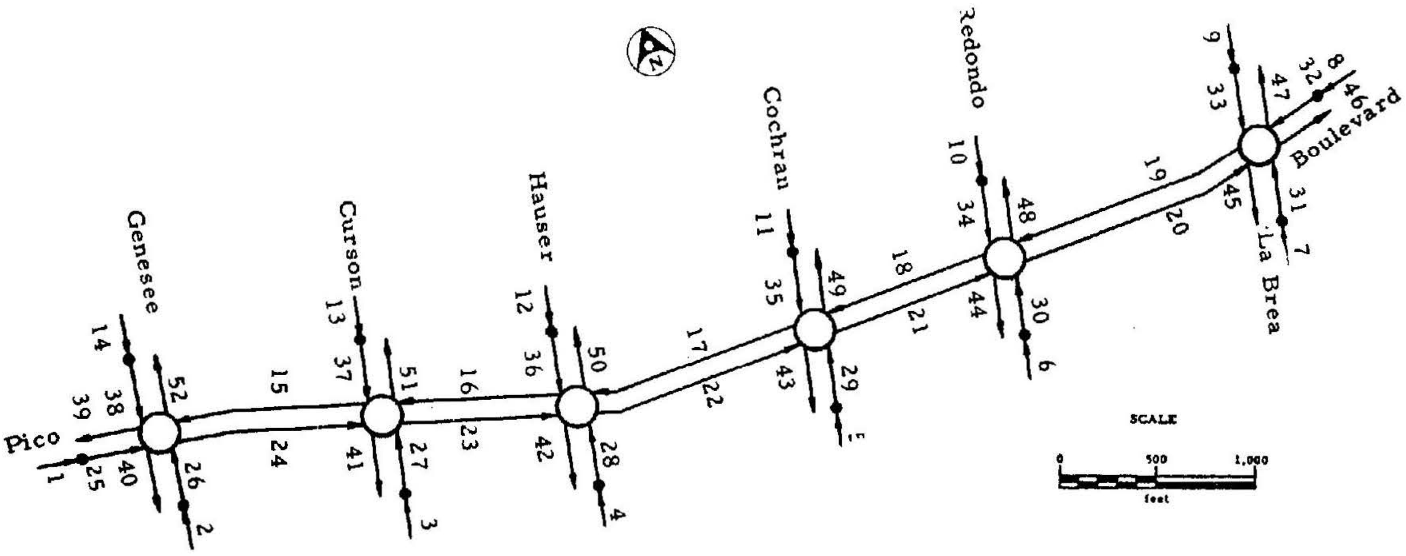
Real Time--Computer Time Ratio (IBM 7094-I): 9:1

Periods Simulated: 120 one-hour periods

Summary: The simulation was used to provide data for a thesis project. A nine-intersection network consisting of two intersecting major streets, each with parallel minor streets on either side, was synthesized. Four different control schemes were simulated, each at six different levels of traffic demand. Five replications were made of each possible combination of control scheme and traffic demand. The control schemes included (1) existing conditions, (2) prohibition of left turns on the major streets, (3) widening of major streets to provide left turn lanes, and (4) construction of a grade separation at the major intersection. It was found that, from an economic standpoint, such improvements should be made incrementally, as traffic demand increases.

References: Barnes, F. C., and Wagner, F. A., Case Study in the Application of a Traffic Network Simulation Mode (presented to the 34th National Meeting, Operations Research Society of America, Philadelphia, November 1968). Barnes, F. C. "An Investigation to Determine Possible Warrants for the Construction of Grade Separations in Lieu of Traffic Signals at Major Urban Street Intersections" unpublished M. Sc. Thesis, University of California, Los Angeles, Feb. 1968.

Figure H-5. Barnes' thesis network.



Network Location: West Central Los Angeles Year of Study: 1967

Type of Development: Light Commercial

Number of Intersections: 6 Number of Network Links: 24

Approximate Size of Network: 7000 feet x 800 feet

Version of Simulation Program: TRANS IV

Real Time--Computer Time Ratio (IBM 7094-I): 14:1

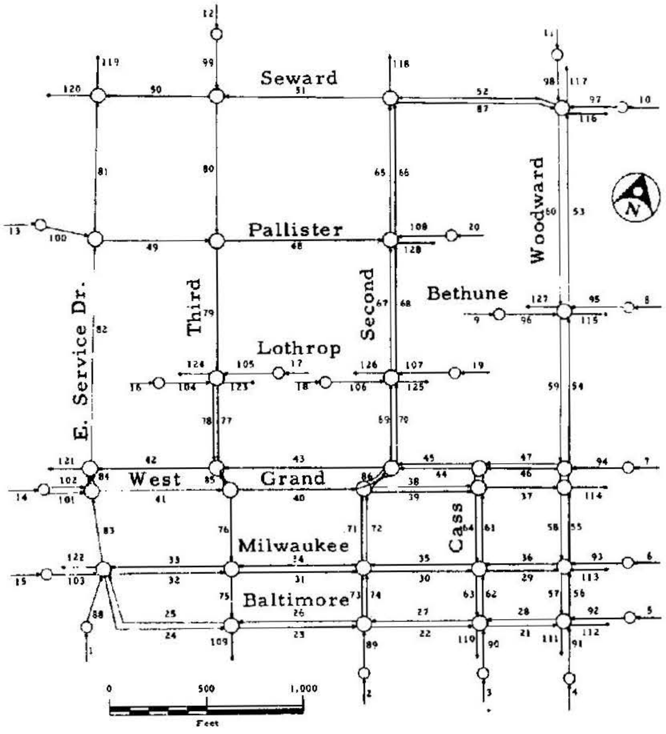
Periods Simulated: 3:00-4:00 pm; 4:30-5:30 pm.

Summary: This network was utilized in two studies. The study for NCHRP involved the development of improved techniques for timing of traffic signals on urban arterial streets. A total of eight different signal timing plans were simulated for the peak traffic hour. The same eight techniques were used to develop signal timing plans for the off-peak period. These, too, were simulated.

The second project using this network was a project to conduct additional tests and make refinements in the TRANS model under contract to the U.S. Bureau of Public Roads. This was the first network to be simulated using version TRANS IV. The refined version of TRANS was subjected to a series of sensitivity tests, in addition to the validation studies.

References: Wagner, F. A., Gerlough, D. L., and Barnes, F. C., "Improved Criteria for Designing and Timing Traffic Signal Systems: Urban Arterials," National Cooperative Highway Research Program Report 73, Highway Research Board, Washington, December 1969. Wagner, F. A., Barnes, F. C., and Gerlough, D. L., "Refinement and Testing of Urban Arterial and Network Simulation," Planning Research Corporation Report PRC-R-1064, Los Angeles, November 1967. PB 1776005

Figure H-6. Pico arterial network.



Network Location: New Center Area Year of Study: 1967

Type of Development: Commercial-Residential-Office

Number of Intersections: 24 Number of Network Links: 88

Approximate Size of Network: 3500 feet x 3500 feet

Version of Simulation Program: TRANS IV-B

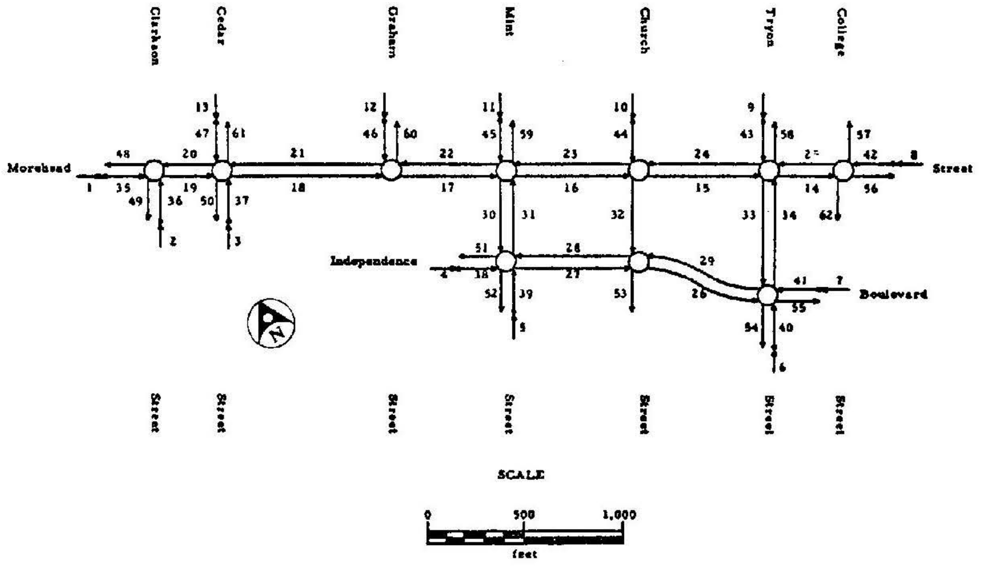
Real Time--Computer Time Ratio (IBM 7094-I): 4:1

Periods Simulated: 3:30-4:30 pm, 4:30-5:30 pm, 5:30-6:30 pm

Summary: This project was undertaken as a case study to determine if the TRANS model could accurately represent traffic operations in the selected network. For two of the study hours, the model represented traffic operations quite accurately. For the hour of heaviest traffic movement, TRANS was found to process traffic more efficiently than the real world.

References: Wagner, F. A. and Barnes, F. C., Traffic Simulation Case Study: City of Detroit, New Center Area Network," Planning Research Corporation Report PRC R1064B Los Angeles, July 1968 PB 179 861

Figure H-7. Detroit case study network.



Network Location: CBD Fringe, Charlotte Year of Study: 1969

Type of Development: Commercial

Number of Intersections: 10 Number of Network Links: 34

Approximate Size of Network: 4000 feet x 1200 feet

Version of Simulation Program: TRANS IV-B

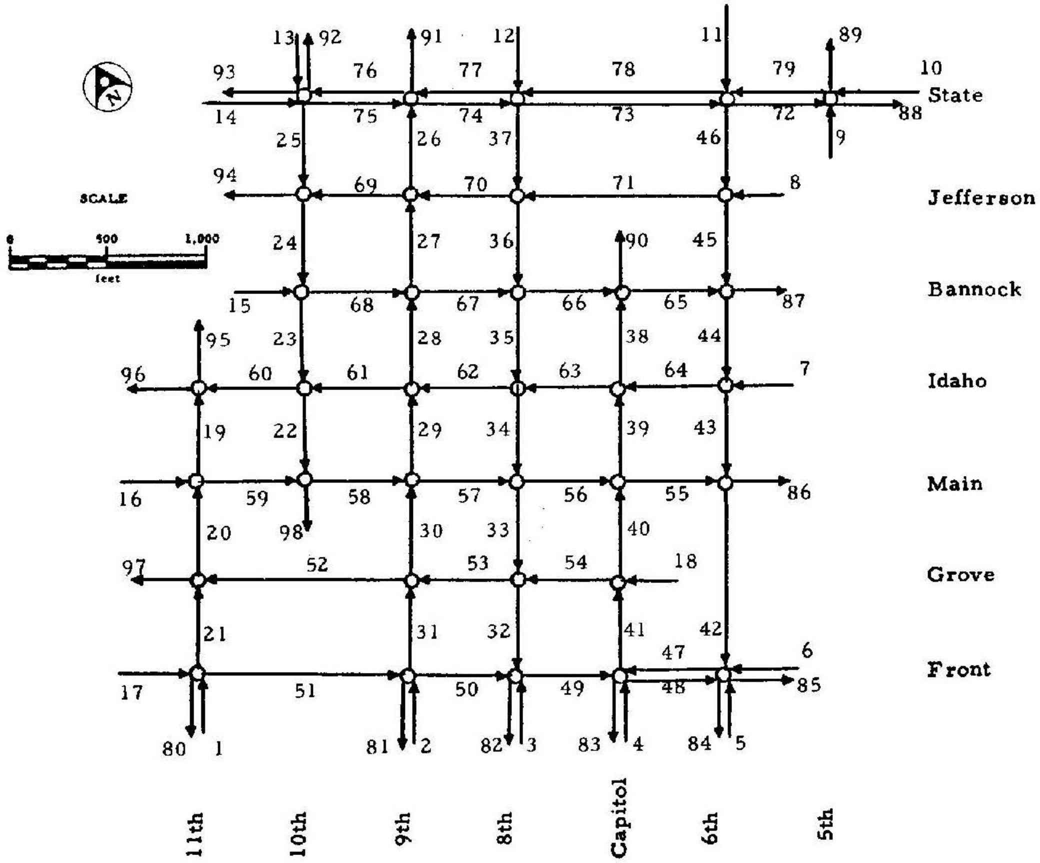
Real Time--Computer Time Ratio (IBM 7094-I): 11:1

Periods Simulated: 5:00-6:00 p. m.

Summary: Six alternative traffic control schemes were tested by simulation. The first alternative tested was the timing that was in use at the beginning of the study. The second alternative tested was a revised timing scheme implemented by the city early in the study period. The third alternative involved the use of improved splits and offsets. Alternative five included widening a major street to provide separate left turn lanes, thereby eliminating left turn prohibitions. The signal timing of alternative four was retained. Alternative six also involved widening of the street to provide separate left turn lanes. Signal timing was determined by the improved methods used in alternate three.

References: Topics Planning Study, Charlotte, North Carolina, Interim Report II, Improvement Proposals, Alan M. Voorhees & Associates, Inc. McLean, March 1969.

Figure H-8. Charlotte TOPICS network.



Network Location: Boise CBD Year of Study: 1969

Type of Development: Commercial

Number of Intersections: 35 Number of Network Links: 61

Approximate Size of Network: 4000 feet x 3500 feet

Version of Simulation Program: TRANS IV-B

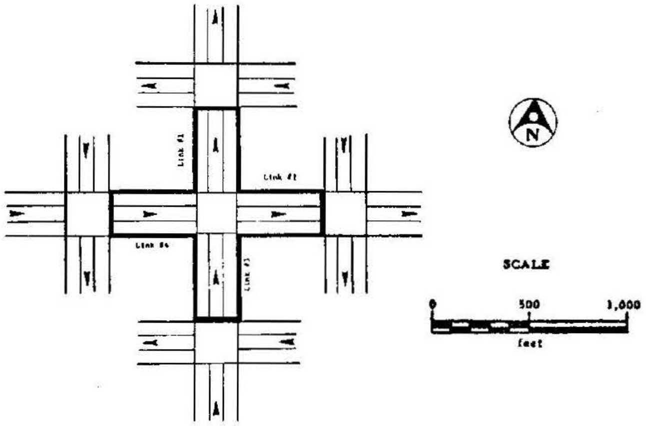
Real Time--Computer Time Ratio (IBM 7094-I): 6:1

Periods Simulated: 4:30-5:30 pm

Summary of Results: The simulation was used to evaluate the effect on traffic operations of a proposed nine-block mall to be constructed in the CBD. Traffic diverted by the street closures was assigned to other routes using standard assignment techniques. Conditions with current traffic columes and with projected 1990 volumes were simulated, both with and without the mall.

References: None

Figure H-9. Boise CBD network.



Network Location: Synthetic Year of Study: 1969

Type of Development: None

Number of Intersections: 5 Number of Network Links: 4

Approximate Size of Network: 1320 feet x 1320 feet

Version of Simulation Program: TRANS IV-B

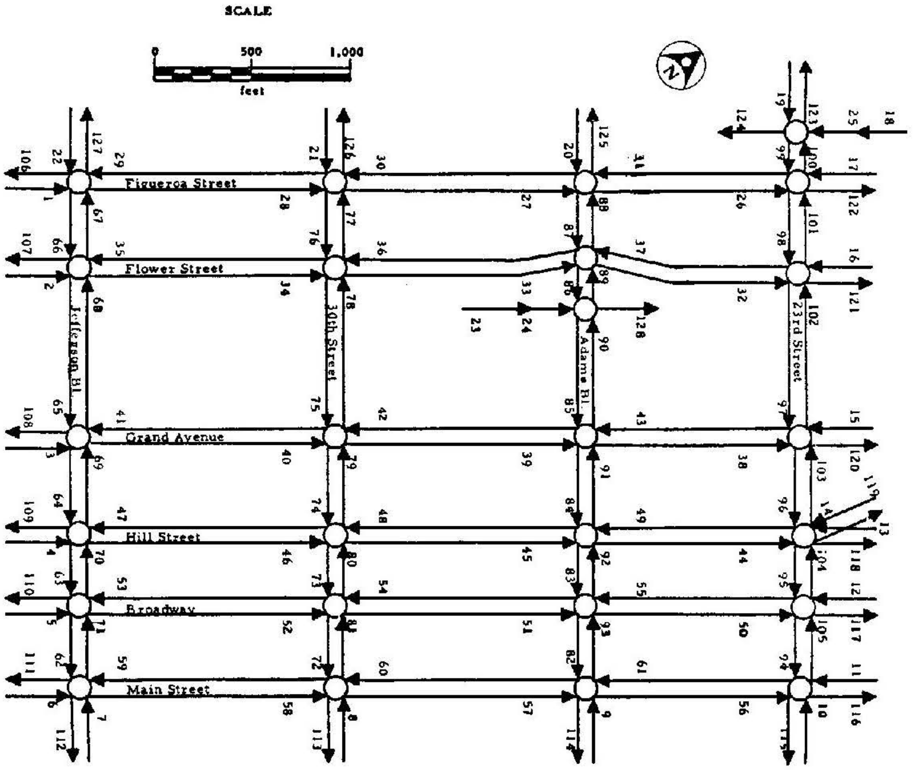
Real Time--Computer Time Ratio (IBM 7094-I): Unknown

Periods Simulated: Fifteen-minute periods

Summary: TRANS was used with a 1-second scan cycle to provide data for validation of a surveillance methodology subroutine being developed for the Urban Traffic Control Systems project. The project requirements that a zone contain no more than one car resulted in a nominal headway of 1 second. This is not a realistic use of the model, as such headways are extremely rare occurrences in the real world.

Reference: Cooper, D. L., Knox, R. M., and Walinchus, R. J., "Final Report: System Analysis Methodology in Urban Traffic Control Systems," TRW Systems Group Report 11644-H 014-R0-00, Houston, June 1969

Figure H-10. TRW surveillance methodology test network.



Network Location: Central Los Angeles Year of Study: 1969

Type of Development: Light Commercial-Residential-Light Manufacturing

Number of Intersections: 26 Number of Network Links: 82

Approximate Size of Network: 4000 feet x 3500 feet

Version of Simulation Program: TRANS IV-B

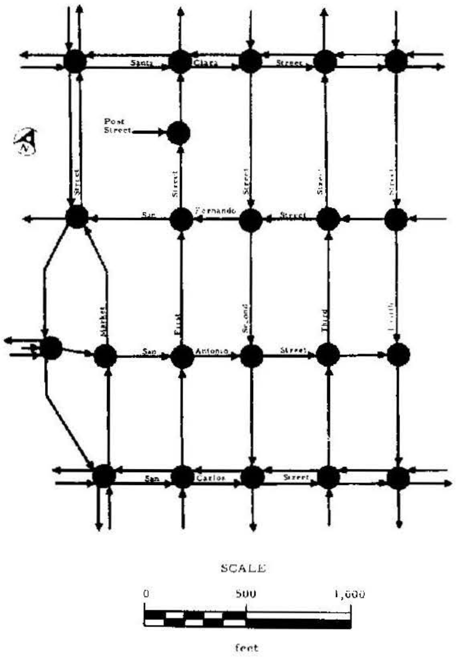
Real Time--Computer Time Ratio (IBM 7094-I): 4:1

Periods Simulated: 3:00-4:00 and 5:30-6:00 pm, 4:00-5:30 pm

Summary: This study was conducted as part of NCHRP Project 3-5/2 to develop improved techniques for controlling signal systems in urban networks. The simulation program was used to simulate 15 separate control alternatives during the peak period and 11 separate alternatives during the offpeak period. Comprehensive field verification surveys were conducted under existing control and with two promising alternatives. These studies closely corroborated the simulation model's predictions of the operational improvements obtained with control alternatives tested.

References: Wagner, F. A., Barnes, F. C., and Gerlough, D. L., Quarterly Report for Quarter Ending September 30, 1968, NCHRP Project 3-5/2, "Improved Criteria for Designing and Timing Traffic Signal Systems, Urban Networks," Planning Research Corporation Report D-1686, Los Angeles, October 1968.

Figure H-11. Figueroa-Adams network.



Network Location: San Jose CBD **Year of Study:** 1969

Type of Development: Commercial

Number of Intersections: 22 **Number of Network Links:** 44

Approximate Size of Network: 2000 feet x 2500 feet

Real Time--Computer Time Ratio (IBM 7094-I): 7.5:1

Periods Simulated: 4:00-6:00 pm

Summary: This study was conducted as part of NCHRP Project 3-5/2 to develop improved techniques for controlling signal systems in urban networks. The simulation program was used to test nine separate control alternatives developed by various signal optimization procedures.

Reference: Wagner, F. A., Barnes, F. C., and Gerlough, D. L., "Improved Criteria for Traffic Signal Systems in Urban Networks," Final Report--NCHRP Project 3-5/2, Alan M. Voorhees & Associates, Los Angeles, December 1969.

Figure H-12. San Jose CBD network.

APPENDIX I

INSTRUCTIONS FOR SPEED AND DELAY STUDY

A speed and delay study is being conducted in conjunction with NCHRP Project 3-5/2. A series of studies will be made during the summer (1969) to collect important data on traffic performance in the test network. Results will be used to compare different methods for controlling traffic signals in the network and to check computer simulation studies. Consistent efforts are essential to maintain a high degree of timing and recording of field data.

GENERAL PROCEDURE

Five study teams will be working on the project, each team consisting of a driver and an observer. The initial study will be conducted on 10 consecutive weekdays during the period from 3:00 to 6:00 PM. Each team will study a different test route on each day of the study. Assignments of test routes will be rotated so that each team will collect data for one day on each test route. Teammates will remain together for the entire 10 study days. The man on each team acting as driver will serve as driver for the duration of the study. (See Tables I-1 and I-2.)

Data booklets have been prepared for all five teams for each of the 10 study days. Each booklet contains a map of the test route as well as standard speed and delay data forms. The test routes consist of two separate test sections (for example, a southbound test section and a northbound test section). As organized in the data booklet, separate forms are used for recording data on the two test sections.

DATA COLLECTION INSTRUCTIONS

Drivers. Begin the study at 3:00 PM. Drive the test car on successive round trips over the assigned test route. Follow the route shown on the map in the data booklet. Consciously attempt to behave as an average car in the traffic stream. Try to get with a platoon of cars and stay with it. For each test route, the key points are at the center lines of signalized intersections:

1. The BEGIN RUN point is the center line of the first signalized intersection.
2. CHECKPOINTS are at the center lines of all intervening signalized intersections.
3. The END RUN point is the center line of the last signalized intersection.

For the benefit of the observer, call out BEGIN RUN, CHECKPOINT, or END RUN (as appropriate) when the test car crosses the center lines of the signalized intersections on the test route.

Observers. You will be equipped with two stopwatches—one for timing cumulative travel time along each test section, and the other for timing delay in queue at each signalized intersection.

Use Watch 1 for timing accumulative travel time:

1. Start timing at the BEGIN RUN point.
2. At the instant the test car passes each CHECKPOINT, read the watch and record the time on the data form.
3. Stop timing at the END RUN point. Read the watch and record the time on the data form.

TABLE I-1

SPEED AND DELAY STUDY PLAN: FIRST FIVE DAYS

TEST ROUTE	DAY 1 TUES., OCT. 14	DAY 2 WED., OCT. 15	DAY 3 THURS., OCT. 16	DAY 4 FRI., OCT. 17	DAY 5 MON., OCT. 20
1	Team A	Team B	Team C	Team D	Team E
2	Team E	Team A	Team B	Team C	Team D
3	Team D	Team E	Team A	Team B	Team C
4	Team C	Team D	Team E	Team A	Team B
5	Team B	Team C	Team D	Team E	Team A

Test Route 1. SB Figueroa from 23rd to Jefferson and NB Flower from Jefferson to 23rd.
Test Route 2. SB Flower from 23rd to Jefferson and NB Figueroa from Jefferson to 23rd.
Test Route 3. SB Grand from 23rd to Jefferson and NB Hill from Jefferson to 23rd.
Test Route 4. SB Hill from 23rd to Jefferson and NB Grand from Jefferson to 23rd.
Test Route 5. SB Broadway from 23rd to Jefferson and NB Main from Jefferson to 23rd.

TABLE I-2

SPEED AND DELAY STUDY PLAN: SECOND FIVE DAYS

TEST ROUTE	DAY 1 TUES., OCT. 21	DAY 2 WED., OCT. 22	DAY 3 THURS., OCT. 23	DAY 4 FRI., OCT. 24	DAY 5 MON., OCT. 27
6	Team A	Team B	Team C	Team D	Team E
7	Team E	Team A	Team B	Team C	Team D
8	Team D	Team E	Team A	Team B	Team C
9	Team C	Team D	Team E	Team A	Team B
10	Team B	Team C	Team D	Team E	Team A

Test Route 6. SB Main from 23rd to Jefferson and NB Broadway from Main to Figueroa.
Test Route 7. EB Jefferson from Figueroa to Main and WB 30th from Main to Figueroa.
Test Route 8. EB 30th from Figueroa to Main and WB Jefferson from Main to Figueroa.
Test Route 9. EB Adams from Figueroa to Main and WB 23rd from Main to Figueroa.
Test Route 10. EB 23rd from Figueroa to Main and WB Adams from Jefferson to 23rd.

Use Watch 2 for timing delay in queue on the approach to each signalized intersection CHECKPOINT and the last signalized intersection. Do not time delay in queue at the first signalized intersection because the test run does not begin until the test car crosses the center line of the first intersection. Use the following procedure:

1. Start Watch 2 at the instant the test car stops on a signalized intersection approach (either at the back of a line-up of cars on the approach or first in line at the red signal).

2. Stop Watch 2 at the instant the test car crosses the signalized intersection center line.

3. Immediately read Watch 2 and record the delay in queue at that intersection on the data form. The starting and stopping involved in advancing toward the intersection after once becoming part of the waiting queue is considered part of the total duration of delay at that signalized intersection. Let Watch 2 continue to run during such maneuvering.

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