TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-84/23+260-1F		

4. Title and Subtitle	5. Report Date
ADDING SIGNALS TO COORDINATED TRAFFIC SIGNAL SYSTEMS	August 1983
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Randy B. Machemehl and Clyde E. Lee	Research Report 260-1F
9. Performing Organization Name and Address	10. Work Unit No.
Center for Transportation Research The University of Texas at Austin Austin, Texas 78712-1075	11. Contract or Grant No. Research Study 3-18-80-260
	13. Type of Report and Period Covered Final
12. Sponsoring Agency Name and Address	
Texas State Department of Highways and Public Transportation; Transportation Planning Division P. O. Box 5051 Austin, Texas 78763	14. Sponsoring Agency Code

15. Supplementary Notes

Study conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration
Research Study Title: "Warrants for Traffic Signals Within A Coordinated System"

16. Abstract

The purpose of this research was to investigate the effect of adding or removing traffic signals within a coordinated, signal-controlled street network. The report includes a discussion of coordinated signal systems; arterial street network configurations; optimization of signal settings for progressive movements; simulation of traffic on street networks with specified off-peak vehicular volumes and different intersection control strategies; and analyses of statistical data resulting from the simulation of traffic on several representative street networks.

A signal timing optimization program, PASSER II, was used to determine the signal timing patterns for each of twelve representative street networks that were operated under different control strategies. The computer program called NETSIM was then used to simulate traffic on the networks and produce statistics concerning the relative effectiveness of the various control schemes. A total of 98 different network cases were simulated by NETSIM.

The best practicable estimate of the effects of altering the number of signalized intersections in a network can be made by applying computer optimization and simulation techniques directly to the specific before and after situations under consideration. This requires the use of computers and experienced personnel. Approximate methods for estimating these effects without using a computer are described in this report.

17. Key Words	18. Distribution Statement
coordinated signal system, NETSIM, arterial street, simulation models, adding signals to coordinated systems	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	90	

Form DOT F 1700.7 (8-69)

ADDING SIGNALS TO COORDINATED TRAFFIC SIGNAL SYSTEMS

by

Randy B. Machemehl
Clyde E. Lee

Research Report Number 260-1F

Warrants for Traffic Signals Within A Coordinated System

Research Project 3-18-80-260

conducted for

Texas
State Department of Highways and Public Transportation

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

Center for Transportation Research
Bureau of Engineering Research
The University of Texas at Austin

August 1983

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

SUMMARY

The purpose of this research was to investigate the effect of adding or removing traffic signals within a coordinated, signal-controlled street network. The report includes a discussion of coordinated signal systems; arterial street network configurations; optimization of signal settings for progressive movements; simulation of traffic on street networks with specified off-peak vehicular volumes and different intersection control strategies; and analyses of statistical data resulting from the simulation of traffic on several representative street networks.

A signal timing optimization program, PASSER II, was used to determine the signal timing patterns for each of twelve representative street networks that were operated under different control strategies. The computer program called NETSIM was then used to simulate traffic on the networks and produce statistics concerning the relative effectiveness of the various control schemes. A total of 98 different network cases were simulated by NETSIM.

The best practicable estimate of the effects of altering the number of signalized intersections in a network can be made by applying computer optimization and simulation techniques directly to the specific before and after situations under consideration. This requires the use of computers and experienced personnel. Approximate methods for estimating these effects without using a computer are described in this report.

The quantitative estimates of the effects of changing the signal control scheme on a network can serve as a basis for deciding whether a particular intersection in a network should be signalized or operated under sign control on the cross street approaches. The overall performance of the network can

be evaluated, and consideration can be given to individual intersections in the network.

KEY WORDS: Coordinated Signal System, NETSIM, Arterial Street, Simulation Models, Adding Signals to Coordinated Systems

IMPLEMENTATION STATEMENT

Coordination of traffic signals to provide platoon progression along arterial streets is a common technique of providing efficient traffic flow. Changes to the signal spacing within a coordinated system, through the addition or removal of signals may have significant effects upon traffic flow.

This study was an effort to examine possible effects of signal addition or removal upon traffic flow within a coordinated signal system. It also encompassed efforts to develop techniques for predicting the effects of signal addition or removal.

A sequential process for assessing the effects of signal addition or removal is described. The roles for computer based simulation and optimization are discussed along with graphical techniques.

TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION

Increasing traffic volumes continue to place heavy demands on many already overburdened city streets; therefore, effective means for handling this problem are needed. Coordinated signals along an arterial street system often provide a good solution. Stops and delays can frequently be minimized if the signals are coordinated in such a way that vehicles traveling through a series of intersections at a uniform speed receive a green indication when they arrive at each succeeding signalized intersection. The offset of the beginning of the green signal indication at successive signalized intersections is critical to providing continuous progression. Consideration must also be given to maximizing bandwidth, which is the duration of the green time that will be available at each intersection to accommodate the platoons of progressing vehicles. A coordinated signal system with offsets and bandwidths that are suitably designed to accommodate the traffic demand in each direction of travel can minimize stops and delays and move the maximum amount of traffic within the system.

In a typical coordinated signal system, not all the intersections will be signalized; some may be uncontrolled and some may operate under sign control, i.e. two-way stop control, with stop signs on cross street approaches. The sign-controlled intersections cause no extra delays or stops to major street flow, but vehicles on the cross streets (minor streets) may suffer large delays because of the stop sign control. If traffic volume on the major street is high, delay on the cross streets can reach intolerable levels because gaps of a size adequate to allow crossing are rare. The number of accidents might also, be large due to drivers attempting to use inadequate gaps to cross the major street. In this situation, drivers who frequently use the minor street may request replacement of the stop sign with a signal. In this case, considering only the local intersection traffic condition is not enough. The whole coordinated signal system must be evaluated as new signals can possibly affect progression and bandwidth on the major street as well as delay on the cross streets.

Since there are no generally recognized warrants and few specific guidelines for deciding whether signals should be added to or removed from a coordinated signal system, the investigation described in this report was undertaken. A number of intersection spacing arrangements have been studied, and quantitative evaluations have been made of the effects of replacing one or more stop-sign controlled intersections in a coordinated system with signals. The effects of removing one or more signals have also been implied from the results of these studies. A study technique which utilizes network simulation is suggested as a means of evaluating proposed modifications to traffic control schemes on specific arterial street systems.

STUDY TECHNIQUE

Traffic engineers have long sought tools which would enable them to predict the consequences of a new traffic control strategy without actually installing and operating the hardware in the field. Simulating the real condition with well-developed computer simulation models is one such tool. Before the existence of computer simulation programs, field observation was the only way to test the consequence of new control strategies. Field observation involves several problems:

(1) Each proposed control plan must be individually implemented. If a plan fails to achieve the desired results, it must be revised and reapplied.

(2) Evaluation of a new traffic control plan by comparing data collected before and after the implementation of the plan might be invalid because factors other than the applied test control measures might affect the observed results. It is thus necessary to collect and analyze a great amount of data in order to evaluate the time effectiveness of different plans.

(3) Experimenting with traffic control plans may have economic and safety repercussions, especially if congestion and accidents result.

(4) Conditions affecting traffic flow may vary significantly between the time data are collected and the time that the proposed control plan is implemented. Current data are required for each alternative plan.

(5) If there are several alternatives, it is virtually impossible to test a large number of alternatives one after another.

(6) Some kinds of data, such as individual vehicular delay and speed, are difficult to measure precisely by field observation.

The difficulties described above can be overcome to some degree by using simulation models, but there are also some questions and constraints in using simulation models. For example:

(1) Is the output of the simulation model reliable? Simulation models are calibrated and tested against data collected at specific times and places. Driving habits of drivers may, for example, vary from place to place and change as time changes. To account for this, calibration of the simulation model for specific conditions is needed if it is to produce reliable results.

(2) Some simulation models lack detail in describing real conditions. Factors which affect driver behavior such as visibility, road surface condition (e.g. a dip in the street) and the detailed geometry of streets are frequently not considered.

(3) Coding of input data is a tedious job. It is easy to make mistakes even for an experienced user. Illogical mistakes can be found by diagnostic subprograms in the simulation model, but more subtle errors can not be found automatically.

(4) Judgement is required in using simulation models. Also, experience in evaluating the results of simulation is needed.

(5) Adequate computer facilities, including hardware and software, are not always available to the user.

(6) The output of a simulation model might not include all information needed by the user even though it is included in the model. Program modifications to obtain the needed information are frequently impractical.

Since the purpose of this study is to find general guidelines for adding or removing signals within a coordinated signal system, a large number of practical situations (i.e. different vehicular volumes, different intersection geometries, different intersection spacings, and different types of control) must be considered. Cost, time, and the inherent problems associated with field observations as discussed above make it virtually impossible to make and interpret an adequate number of field observations; therefore, simulation was chosen as the more practical technique to apply in the study.

DEVELOPMENT OF GUIDELINES

The objective of this study is to develop guidelines for adding or not adding, removing or leaving, a signal in a coordinated arterial street system. The basic approach to developing these guidelines involved assessing the consequences of adding or removing a signal within coordinated signal systems on a series of arterial streets with different representative intersection spacings. Various traffic conditions were imposed on each street network, and two simulation runs (one with a new signal added and one without)were made for each configuration of intersections and traffic volume. The effect of adding or removing signals in a coordinated system was determined by comparing the output of the simulation runs, and guidelines were derived based on these comparisons. Details of these procedures are introduced in the following chapters.

CHAPTER 2. THEORY OF A PROGRESSIVE SIGNAL SYSTEM AND EXPERIMENTAL DESIGN

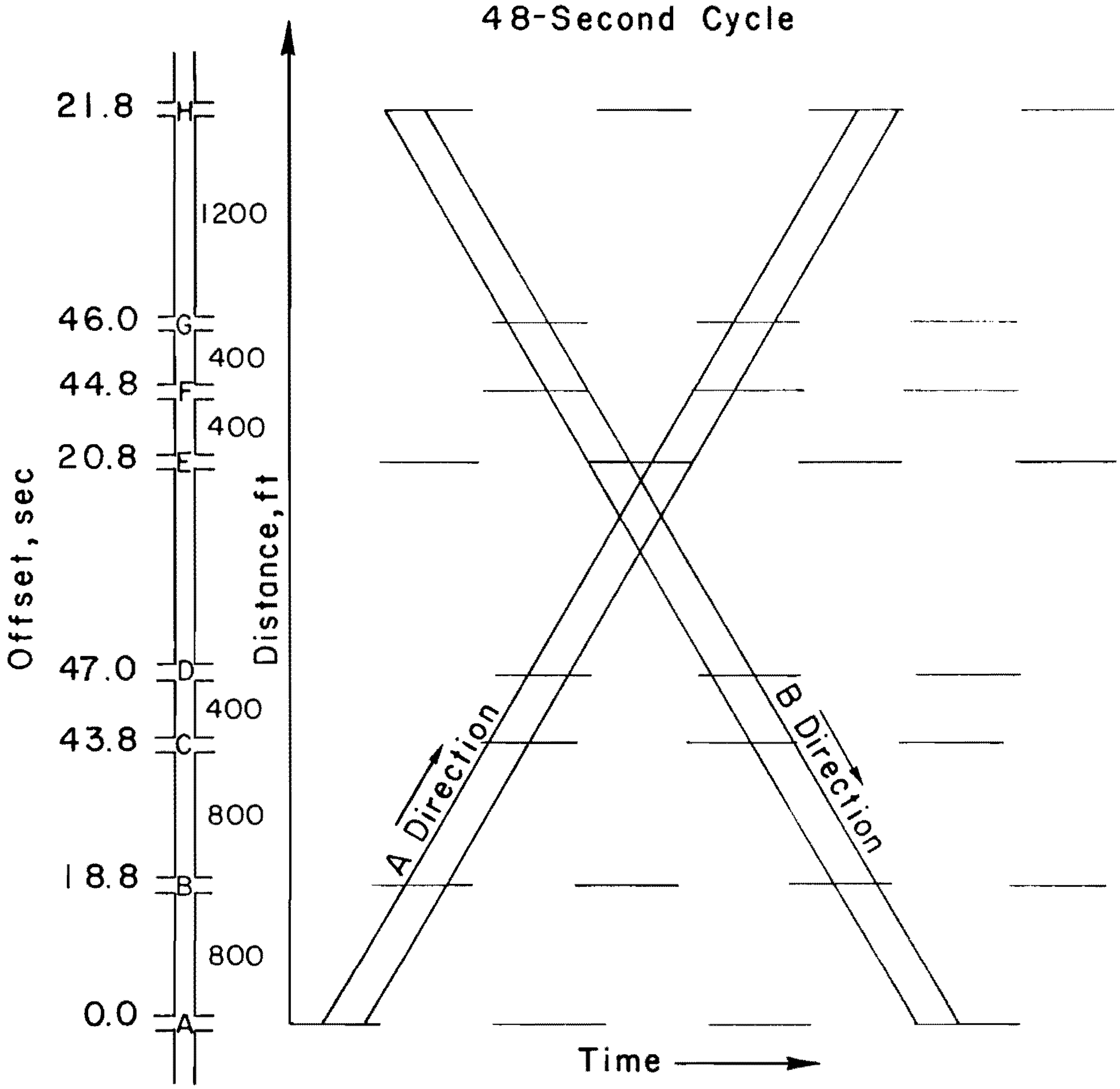
A brief description of the concept of the coordinated signal system was presented in the previous chapter; further details will be given in this chapter. The potential effects of adding new signals to an existing coordinated signal system will be discussed, and some factors related to evaluating the performance of the modified system will be introduced. The basic techniques which have been used for defining suitable street networks for study by simulation are presented in the second half of this chapter.

THE EFFECT OF ADDING OR REMOVING SIGNALS IN A COORDINATED SIGNAL SYSTEM

Installation of a new signal at a previously sign-controlled intersection does not always reduce delays to minor street traffic, but it nearly always increases delays to major street flows. In a coordinated signal system, major street flow potentially experiences two kinds of delay as a result of adding new signals. First, extra delay can be caused by vehicles queuing and waiting during the red signal indication and by other vehicles ahead blocking immediate access to the intersection at the onset of the green indication. Second, delay to traffic on the major street can result from the interruption of progressive flow by new signals and from a reduction in the amount of time available for platoons of traffic to move progressively (reduced bandwidth) through the series of intersections. The latter kind of delay does not always result when a signal is added; it depends on where the new signal is located within the system and on the timing of the signal system.

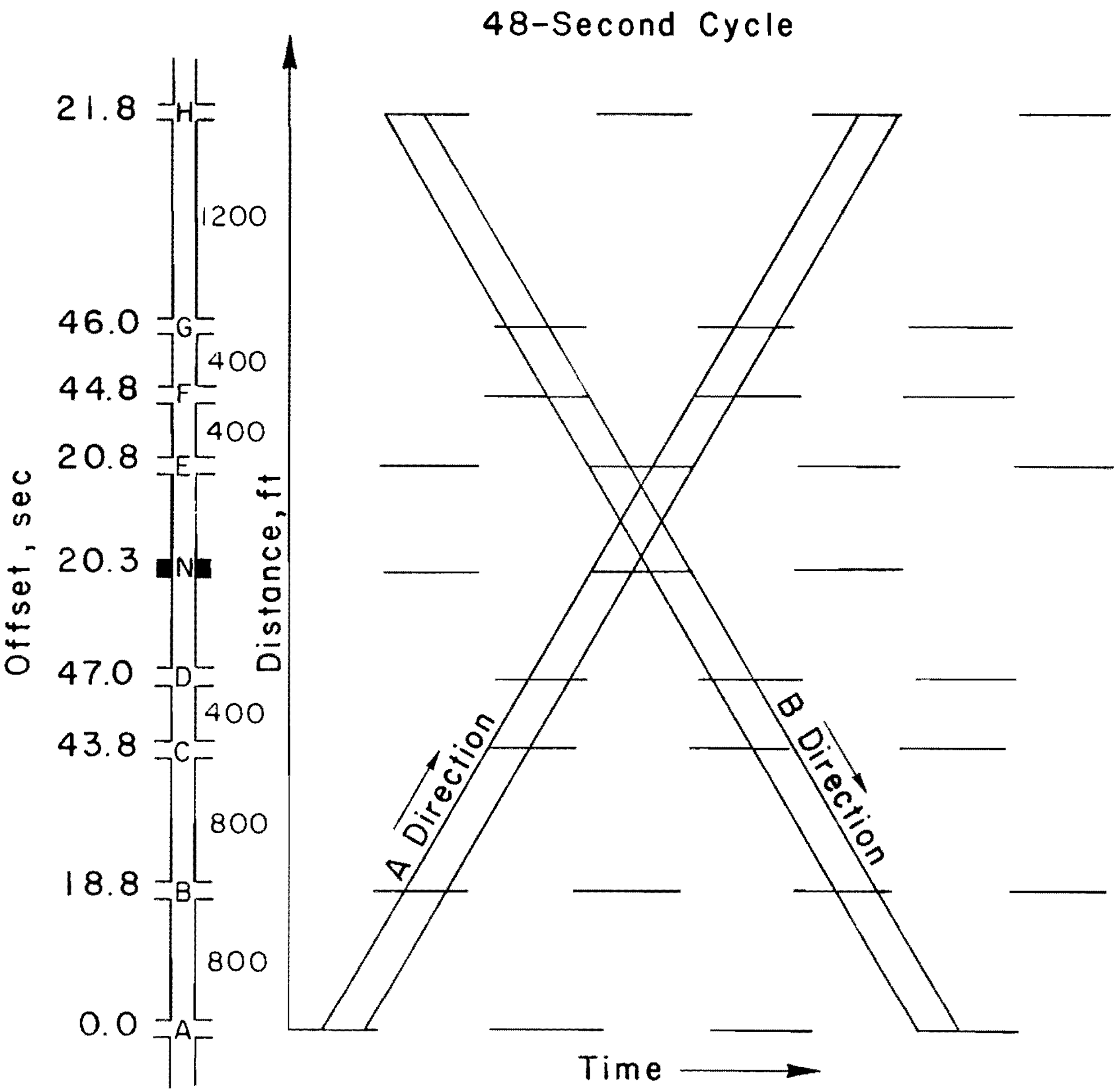
Examples of the effect of new signal locations in a coordinated system are given in Figs 2-1, 2-2, and 2-3. These figures are time-space diagrams for a coordinated system. Figure 2-1 shows a coordinated signal system with eight signalized intersections (from A to H). The spacing in feet between adjacent intersections is given by numbers between the letters. A forty-eight second cycle is the optimal cycle length for this system. The offset of each signal, the bandwidth, and the progression speed are also shown. In Fig 2-2, a new signal has been added at intersection N (between D and E). By appropriately adjusting the cycle split and offset of this added signal, the bandwidth and progression speed can be maintained; therefore, the major street traffic experiences no additional delay. In Fig 2-3, signal N is also located between D and E, but the exact location differs from that in Fig 2-2. For this location, optimal off-peak signal timing is attained with a cycle length of 53 seconds, and bandwidth is reduced by one second.

Obviously, a new signal can cause more delays to major street traffic, but how much more delay will be caused and what is the simultaneous effect to the minor street traffic are questions which must be answered. Whether or not a new signal should be installed depends to a large extent on whether the new signal can reduce the total delay to traffic in the whole system. This delay effect cannot be evaluated quantitatively by comparing time-space diagrams; therefore, a simulation method will be applied to obtain the needed quantitative data.



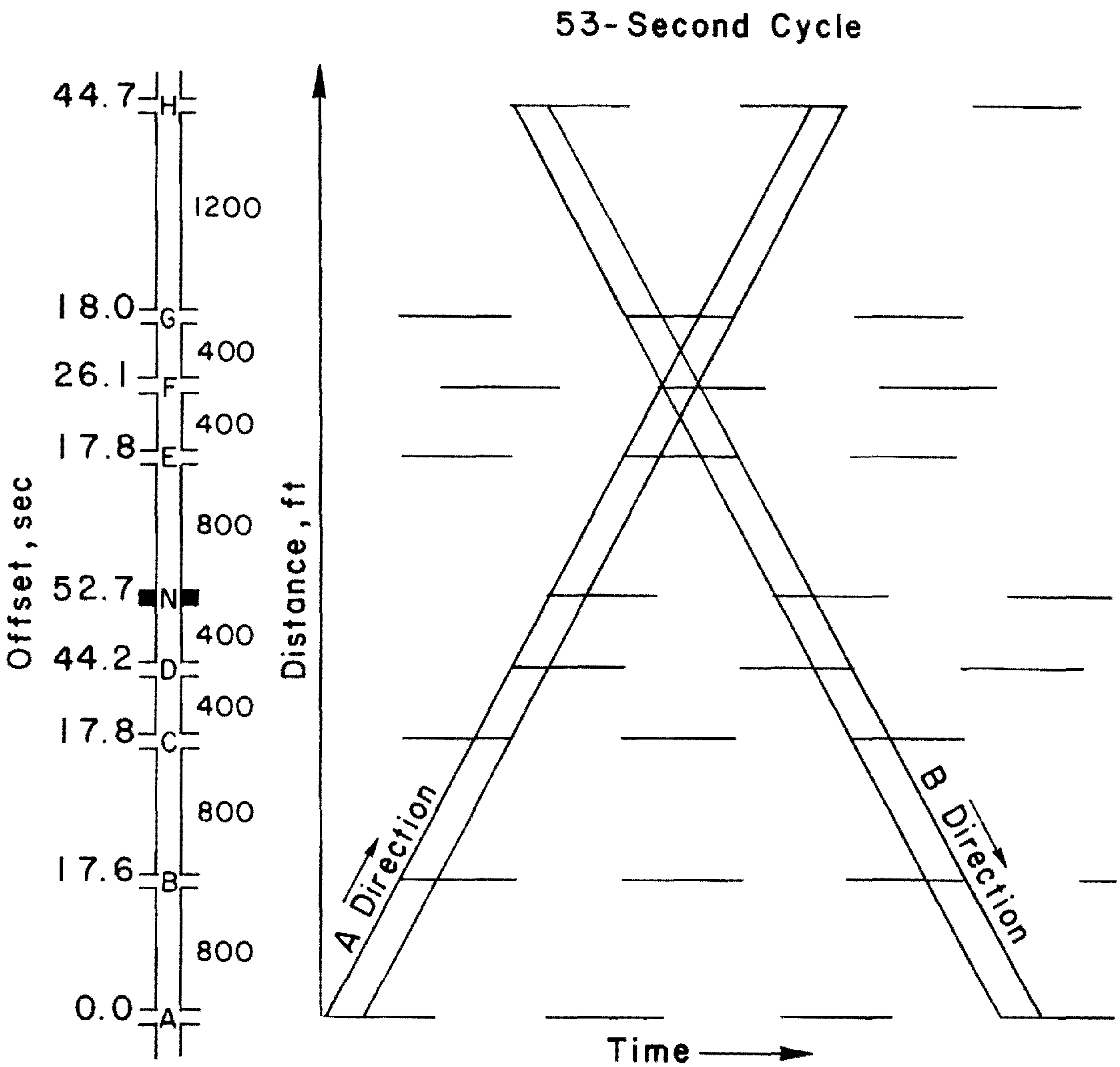
Direction	Average Speed	Band Width
A	29 mph	9 seconds
B	29 mph	9 seconds

Fig 2-1. Complete time-space diagram showing the optimal progression timing of an arterial street with eight signalized intersections.



Direction	Average Speed	Band Width
A	29 mph	9 seconds
B	29 mph	9 seconds

Fig 2-2. Complete time-space diagram for the same arterial street shown in Fig 2-1. One new signal was installed at our originally unsignalized intersection, but the optimal progression timing is still the same.



Direction	Average Speed	Band Width
A	31 mph	8 seconds
B	31 mph	8 seconds

Fig 2-3. Complete time-space diagram for the same arterial street shown in Fig 2-1. One new signal was installed at an originally unsignalized intersection. In this case, the optimal cycle length for the whole street network increased and bandwidth decreased.

FACTORS IMPORTANT TO A COORDINATED SIGNAL SYSTEM

Signal Spacing

Examples of time-space diagrams showing new signals in a coordinated system are presented in the previous paragraphs. From comparison among Fig 2-1 through 2-3, it can easily be understood that signal spacing is very important to the performances of coordinated signal systems. There are many possible combinations of signal spacing in real-world situations, but for analysis they can be grouped into two general categories: 1) uniform signal spacing, and 2) nonuniform signal spacing.

Uniform Signal Spacing. Usually, when approximately uniform signal spacing exists, an alternate system can be used to create equal speed of progression and bandwidth in both directions. In an alternate system, both green phases in the cycle are of equal duration and the offsets are either zero or one-half the cycle length. Generally, an alternate system could be a single, double, or triple alternate system. Selection of the type of alternate arrangement depends on system cycle length and a practical progression speed. Because signal systems on streets with uniformly spaced intersections can be analyzed easily and directly, uniform signal spacing is not included in later discussions.

Nonuniform Signal Spacings. For off-peak traffic conditions, short distances between signals tend to reduce bandwidth and short and long distances together may make development of equal bandwidth and progression speeds difficult. For a coordinated signal system, the character of the arrangement of signal spacing can be represented by the mean and the standard deviation of the signal spacings. Generally speaking, smaller means and/or larger standard deviations generate shorter bandwidths. However, two coordinated signal systems with the same mean and standard deviation of signal spacing, same cycle length, but different arrangement of signal spacings may still generate different bandwidths. It is apparent that the arrangement of signal spacing is important to the performance of coordinated signal systems, but this can not be easily generalized.

Vehicular Volume and Turning Movements

Vehicular volume and turning movements also affect the performance of a progressive signal system. High volume means more potential for queuing at the intersections and makes it more difficult for vehicles moving in the system to reach the desired progressive speed. On the major street, left-turning vehicles can block through movements when waiting for acceptable gaps in the opposing flow, and right-turning vehicles cause delay to other movements because they must decelerate when making turns. As to the cross street flow, vehicles entering the major street (either right turn or left turn from the minor street) usually can not catch the progression band, and queues will be developed on the major street at the next intersection by these entering vehicles. Obviously, these queues can adversely affect the progressive flow on the major street as they must accelerate from a stopped condition after the green signal indication is displayed.

Street Geometry and Signal Phases

On a one-lane approach to an intersection, considerable delay can be caused by left-turning vehicles, especially when traffic flow in the opposing direction is heavy. On approaches with two inbound lanes the pressure from left-turning vehicles is significantly reduced because there is more lane space for through vehicles. Delay caused by turning movements decreases as the number of lanes in one direction increases. Separate left-turning lanes and continuous two-way left-turning lanes are also helpful in reducing this kind of delay.

Multiple signal phases may not always reduce delay, but rather their effectiveness depends on the relative volume of turning movements. In a coordinated signal system, optimal signal timing is more difficult to derive when multiple signal phases are applied.

Coordinating signal timing for two-way traffic flow and for one-way flow is totally different. For a one-way system, the distance between a specified signalized intersection and the reference intersection (zero offset) divided by the desired progressive speed gives the required offset for the specified signal. Because of this special characteristic, all the green plus amber period can be used as a progressive band for major street traffic. Bandwidth will be determined by the shortest green plus amber time on the major street. Gaps in the major street traffic that are created automatically by the major street timing are available for cross street traffic. One-way systems are not included in this study because adding or removing signals generally has little or no effect on system performance.

In two-way coordinated signal systems, consideration must be given to progression in both directions during off-peak traffic periods. There are several techniques which can be used to find optimal solutions to two-way progression problems, but full usage of green plus amber time can not often be realized when dealing with two-way coordinated signal systems with nonuniform signal spacing. In this study, emphasis is put on evaluating the effect of adding or removing signals within a two-way coordinated signal system with nonuniform signal spacing for off-peak traffic conditions. Carefully calculated offsets combined with suitable cycle length can usually create adequate bandwidth and progression speed for two-way coordinated signal systems in most real-world situations.

DEFINING STREET NETWORKS FOR THE STUDY

In order to evaluate the effects of adding or removing signals in coordinated signal networks, it was necessary to define the range of representative conditions under which such a modification might be considered practicable. It was recognized that different combinations of signal spacings have different effects on system performance. The distance between signals had to be reasonable; it could be neither too short nor too long. Street geometrics and vehicular volumes needed to be representative, also. The rationale used in selecting and quantifying the factors used in the simulation studies are discussed below.

Signal Spacing

Limits had to be set on the range for spacing between adjacent signalized intersections. Three-hundred feet was chosen as the shortest spacing to be considered in the study. This is not the shortest spacing in the real world, but it is a reasonable lower limit for general analysis. There is no actual upper limit for distance between two signals, but in a coordinated system, the distance can not be too large, otherwise the advantages of platooning and of the progressive band will be lost. Figure 2-4 is a time-space diagram for traffic passing through a single intersection. This figure shows how a platoon of vehicles is formed in front of an intersection on the red indication and then moves through the intersection on the green indication. In a coordinated signal system, the platoons which are formed at the first signal can move within the progression band through the network without further stops so long as the platoon does not disperse or dissipate. As the distance beyond the intersections increases, the platoon normally starts to dissipate. Figure 2-5 shows the extent of dissipation with respect to distance. At a point 1/8 mile beyond

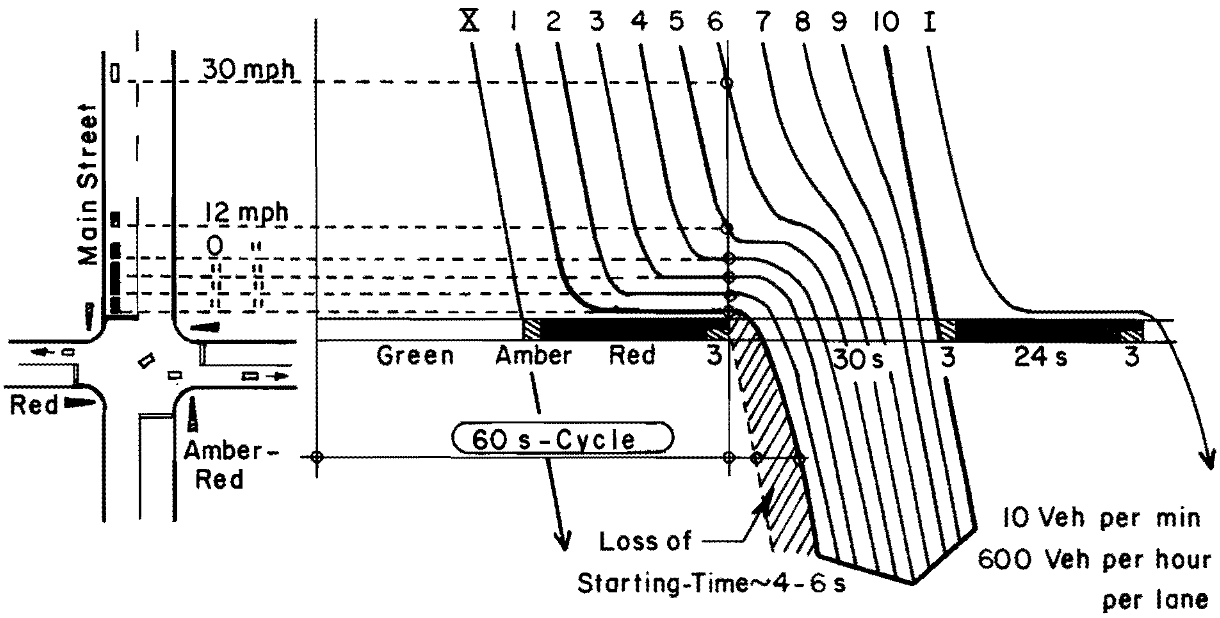


Fig 2-4. Time-space diagram of a normal crossing with start on the stop-line (after Ref 7 Fig I(a)).

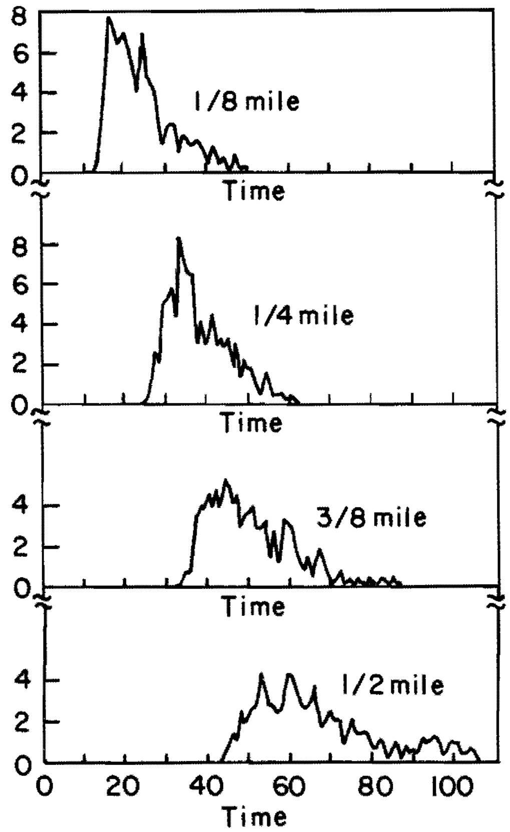


Fig 2-5. Dissipation of traffic platoon (after Ref 7, Fig 14).

the intersection, the platoon still appears to be consolidated. When distance increases to 1/2 mile, the effect of distance on the dissipation of the platoon is apparent. Distances of 1/8 mile and 1/4 mile have almost the same effect on platoons, but beyond about 3/8 mile, dispersion is considerable. For this reason, 1600 feet (approximately 1/3 mile) was selected as the maximum spacing between adjacent signals to be studied. As it was impractical to simulate all the possible spacing values from 300 feet to 1600 feet, 400, 800, 1200, and 1600 feet were selected as the spacings for developing the representative networks.

The total length of each network chosen for study was taken as approximately 1 mile. The combinations of signal spacing for each network were classified into three categories:

(1) combinations of 400 ft and 800 ft signal spacing,

(2) combinations of 400 ft, 800 ft, and 1200 ft signal spacing, and

(3) combinations of 400 ft, 800 ft, 1200 ft, and 1600 ft signal spacing.

The signal spacings for each category were chosen at random to create street networks. Four different networks were developed for each category.

Street Geometry

In a two-way two-lane street system (one-lane for each direction per leg), the effects of coordination are not always realized because flow at the intersections is interrupted by left-turning vehicles waiting for acceptable gaps. Two-way, four-lane streets (two lanes for each direction per leg), which are frequently encountered in the real world, can provide much better progressive flow because through traffic does not suffer as much disturbance from the left-turning vehicles. In this study, all intersections in the street network are represented as four-leg intersections with two inbound and two outbound lanes on each leg.

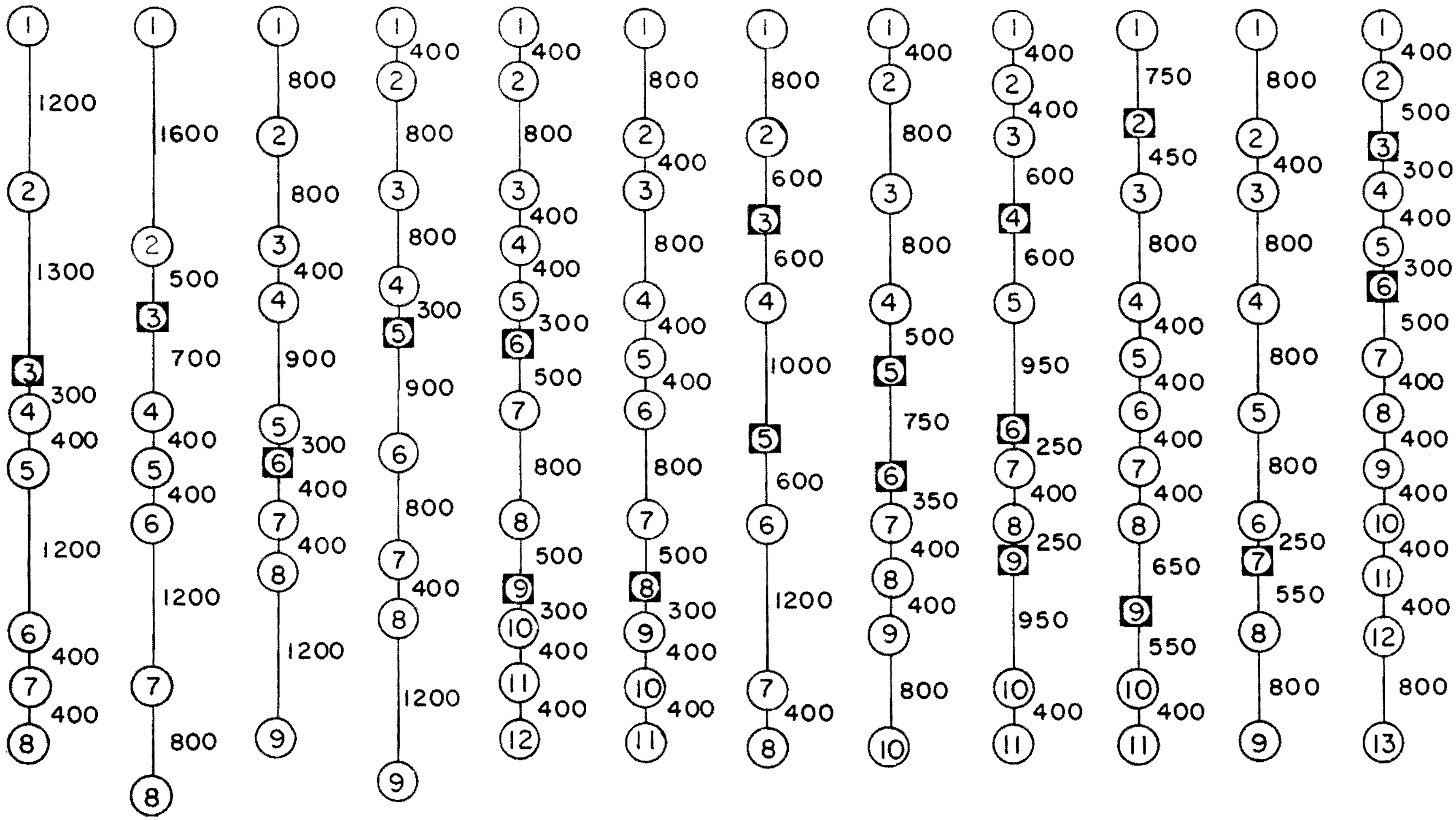
Level of Service and Signal Timing

For this study, the Highway Capacity Manual [Ref 8] method of calculating capacity and levels of service was used to select traffic volumes at each intersection which would result in a Level of Service C on both the major street and the cross street when a G/C ratio of 0.5 was assumed. Webster's [Ref 26 Section 14.4] method for determining cycle length was then used to define the cycle length needed for handling the respective volumes in a two-phase cycle. The computer program called Passer II [Ref 15 and 23] was run next to define the signal timing plan needed for coordinating the signals in each network. The same timing plans were maintained throughout the study while volumes of traffic on the major and minor streets were varied in order to represent real-world variability at typical fixed-time traffic control systems.

Before Case and After Case

The removal of signals has exactly the contrary effect on performance as the installation of signals has in a coordinated signal system; therefore, only the installation case was considered in the study.

The "before case" networks which are the original streets network before the installation of new signals, were created as the basis for developing the "after case" networks. Based on each before case network, one "after case" network was developed by adding one or more signals. Twelve different "pairs" of networks with each pair including one before and one after case were developed for this study. Figure 2-6 shows the twelve "after case" networks. Circled numbers stand for signalized intersections in both before



○ Intersection operating under signal control in both the "Before Case" and the "After Case"

■ Intersection under sign control in the "Before Case" and under signal control in the "After Case"

Fig 2-6. Illustration of all street networks developed for this study.

and after cases. Numbers in the square represent the location of intersections which were simulated under sign control in the before case and changed to signal control in the after case.

SUMMARY

Twelve pairs of street networks were configured in accordance with the feature selection criteria discussed earlier in this chapter. Streets in these networks were all two-way, four-lane streets with two lanes in each direction. If not specially specified, intersections within the street network were simulated as being operated under signal control. The added intersections were simulated under sign control in the before case and under signal control in the after case. Two-phase traffic signals were used at all signalized intersections.

For each of these 24 street networks, the program PASSER II [Ref 15 and 23] was run to obtain the optimal signal timing plan for volumes corresponding to Level of Service C on all approaches and G/C ratio of 0.5. The network performance was then simulated with these signal settings and various traffic volumes using the NETSIM [Ref 16 and 24] model. Data generated by these simulation runs provided the basis for the later comparison and regression studies.

CHAPTER 3. SIMULATION

The reason for choosing simulation as a means of evaluating the effects of adding or removing signals in a coordinated network was described in Chapter I, and representative networks were defined in Chapter II. The signal settings selected for each street network were derived in Chapter II by applying the computer program PASSER II. These efforts were made to prepare the necessary input data for traffic simulation programs. In this chapter, two network simulation models are described and the specific application of NETSIM, the simulation program selected for use in the study, is discussed.

TRAFFIC SIMULATION MODELS

A number of different traffic simulation models have been developed and used during the past few years as knowledge of traffic flow principles has increased and as computer facilities have improved. These models can be divided into two levels according to the amount of detail with which they attempt to represent real traffic flows.

Macroscopic simulation models treat the traffic stream as a continuum and generally conceptualize traffic movement as a flowing fluid. Individual vehicles are not identified in this kind of model. Macroscopic models are comparatively economical of computer storage and fast in execution; however, they do not represent traffic behavior in the detail that many traffic engineers would like. Microscopic simulation models attempt to describe the detailed behavior of individual driver-vehicle units moving in the traffic Each vehicle is characterized by unique attributes.

TEXAS Model

The TEXAS (Traffic Experimental and Analytical Simulation) Model for Intersection Traffic was developed at the Center for Highway Research at The University of Texas at Austin, under the Cooperative Research Program with the State Department of Highways and Public Transportation and the Federal Highway Administration [Ref 10]. This computer package, which utilizes a microscopic demand-response simulation technique, was developed specially for analyzing traffic performance at single, multi-leg, mixed-traffic intersections operating either with or without control devices. The model is an example of a microscopic simulation model, but it is not suitable for simulating traffic conditions on a street network. Within this study it was applied as a tool for further investigation of identified problem intersections.

TRANSYT Model

The TRANSYT Model [Refs 1 and 19], was developed basically to serve as a street network signal optimization program. However, it contains a simulation program that can be used without the optimization feature. Like other network simulation programs, the network being studied is represented by "nodes" inter-connected by "links". Each major intersection, either controlled by signals or by a priority rule (such as yield signs), is represented by a node, and each significant one-way traffic movement leading to a node is represented by a link. As to the logic of simulation, this model is totally macroscopic and completely deterministic; no random numbers are used.

NETSIM Model

Introduction. The NETwork SIMulation (NETSIM) Model is a microscopic simulation program developed for the Federal Highway Administration to evaluate various traffic control strategies and operational conditions on a street network [Refs 16 and 24]. It was designed primarily to serve as a vehicle for testing relatively complex network control strategies under conditions of heavy traffic flow. Problems such as parking and turn controls, channelization, bus priority systems, and a full range of standard fixed-time and vehicle-actuated signal control strategies can all be analyzed by applying this model. Summary statistics about traffic behavior can be produced as output from the model at specified intervals of time.

Major Features and Limitations of the NETSIM Model. The microscopic structure of the model permits detailed treatment of several aspects of traffic flow which are critical to a meaningful evaluation of network performance and which may otherwise be treated only roughly. These are: detailed treatment of intersection discharge and queuing behavior, treatment of the response of traffic to temporary blockages within the network, evaluation of vehicle-pedestrian conflicts, analysis of the impact of bus traffic on network performance, and simulation of real time signal control systems driven by on-line detection of traffic movements along individual network links.

Each individual vehicle in the network is treated as a separate entity. Its motion is governed by a series of microscopic car-following, queuing- discharge, and lane-switching algorithms. Vehicles are entered into the network via "entry" links surrounding the study area or from "source" nodes located within the network. After passing through the network, vehicles are discharged via "exit" links around the network or via "sink" nodes located on each internal link. At the time each vehicle enters the network, a set of performance characteristics are assigned to it stochastically. These characteristics include classification of the vehicle type, together with specification of its average discharge headway, average acceptable gap, etc. All vehicles are processed once every second.

The model is operated over a succession of short time periods or "sub- intervals" for which input conditions (flow rate, percentage of turning movements, etc.) are assumed to remain constant. The duration of a sub-interval may vary from as low as one minute to 30 minutes or more.

APPLICATION OF NETSIM

Because NETSIM offers the widest range of capabilities of all available network simulation programs, it was selected for application in this study. This program is well documented and has been in use for several years. The amount of detailed information produced by the model concerning traffic flow on a coordinated signal network and at each individual intersection allows direct comparison of before and after cases. For the example problem, there are sixteen internal links. Links (10,3) and (11,3) are cross street links and the rest are major street links. The two kinds of links must be treated separately. Each set of links are further divided into two directions. On the cross street, "A" direction is from Node 10 to Node 3 and "B" direction is from Node 11 to Node 3. On the major street, "A" direction is from Node 1 to Node 8 and the opposite direction is "B" direction.

Vehicle Trips (VEH TRP), Total Delay Time (DELAY TIME), Average Delay Time per Vehicle (D-TIME/VEH), and Number of Stops per Vehicle (STOPS/VEH) are the four measures selected from the available NETSIM link statistics to serve as the basis for evaluating the performance of the network. Vehicle Trips is a count of the total number of vehicles discharged from each link during the simulation interval (15 minutes). Total Delay Time is computed for the simulation interval as the difference between total travel time and ideal travel time based on the target speed of vehicles and expressed in vehicle minutes. The value of Average Delay Time per Vehicle is the average delay time for each individual vehicle to travel along the whole major street or the specified cross street and equals the Total Delay Time during the simulation interval divided by the number of vehicle trips during the simulation interval. Both Total Delay Time and Average Delay Time per Vehicle thus include delay attributable to decelerating, standing, and accelerating. Number of Stops per Vehicle is the average number of stops for each individual vehicle as it travels along the whole length of the major street or the specified cross street and equals the cumulative number of stops during the simulation interval divided by the number of vehicle trips during the interval.

If the network geometry and signal timing are fixed, vehicle stops and delays depend on the number of vehicle trips. In practice, it is difficult and expensive to collect accurate data on total delay, average delay per vehicle, and number of stops per vehicle. By contrast, vehicle trips can be counted easily and reliably. With appropriate regression analysis, the value of delays and stops from NETSIM can be related to vehicle trips. Regression analysis was performed for both the before cases (original network) and the after cases (with signal(s) added) using Vehicle Trips as one of the predictor variables in all situations.

All the internal links were separated into four groups for analysis. For "A" direction on the major street, all values of each measure for links from Node 1 to Node 8 were summed to give the total measure for this direction. Major street "B" direction was treated in the same way except that the links were those from Node 8 to Node 1. Since there is only one link for each direction on the cross street, the values for each cross street measure were used directly.

A vehicular volume of 825 vehicles per hour per direction for both the major street and the cross streets was used as input to PASSER II to determine the optimal signal settings for the coordinated signal system. In the NETSIM runs, the resulting optimal signal settings were applied, but the input vehicular volume was changed to 925 VPH per direction on the major street and 500 VPH per direction on the cross streets.

Table 3-1 shows the summary of the before case data, and Table 3-2 is for the after case of the example network. The effect of adding a new signal to the street network system can be seen by comparing the values in the two tables. Table 3-3 illustrates a summary comparison of effects. This table provides the type of quantitative information which can be considered in deciding whether a new signal should be added to an existing coordinated signal system or not.

Discussion of Vehicular Volumes Used for Simulation Study

The vehicular volumes used in the study included five percent trucks, ten percent left-turns, and ten percent right-turns in both PASSER II runs and NETSIM runs. In the real world, traffic conditions may change from time to time during the day, but a fixed-time signal system can not be timed differently in accordance with every possible traffic condition. Frequently, only one off-peak timing plan is used to accommodate all traffic conditions. Because of this, and limitations on the number of computer runs which could be made, only one signal timing plan was used for each specific street network of the study in simulating the network performance under different

TABLE 3-1. SUMMARY FOR THE "BEFORE CASE"

	DIRECTION	TOTAL DELAY (VEH M)	AVERAGE DELAY (SEC)	NO. OF STOPS
MAJOR STREET	A	222.2	76.3	3.18
	B	252.3	83.7	3.43
MINOR STREET	A	242.6	132.3	1.16
	B	89.3	45.0	1.05

TABLE 3-2. SUMMARY FOR THE "AFTER CASE"

	DIRECTION	TOTAL DELAY (VEH M)	AVERAGE DELAY (SEC)	NO. OF STOPS
MAJOR STREET	A	307.1	101.5	3.81
	B	274.1	92.0	3.28
MINOR STREET	A	25.4	12.2	0.48
	B	24.2	11.5	0.51

TABLE 3-3. COMPARISON BETWEEN THE "BEFORE CASE" AND "AFTER CASE"

		DIRECTION A	DIRECTION B	TOTAL
MAJOR STREET	INCREASED TOTAL DELAY	84.9	21.8	106.7
	INCREASED AVERAGE DELAY	25.2	8.3	33.5
	INCREASED NO. OF STOPS	0.63	-0.15	0.48
MINOR STREET	DECREASED TOTAL DELAY	217.2	65.1	282.3
	DECREASED AVERAGE DELAY	120.1	33.5	153.6
	DECREASED NO. OF STOPS	0.68	0.54	1.22
WHOLE NETWORK		AMOUNT OF INCREASE (+) OR DECREASE (-)		
	DIFFERENCE IN TOTAL DELAY	-175.6		(VHE-M)
	DIFFERENCE IN AVERAGE DELAY	-120.1		(SEC)
	DIFFERENCE IN NO. OF STOPS	-0.74		

traffic conditions. The optimal signal timing indicated by running PASSER II was based on volumes of 825 vehicles per hour per direction on both major and cross streets. The optimal signal timing from PASSER II for each before and after case of each network was subsequently coded into NETSIM, but different vehicular volume combinations were applied in the simulation runs to the various street network. Four levels of volume were used on the major street and two levels of volume were applied on the cross street; they are summarized in Table 3-4. The exact number of vehicles included in each of the levels for the major street and the high-volume level (Level 1) for cross streets were arbitrarily chosen. The same traffic volumes, once selected were used in both the before case and the after case for each of the twelve networks. As to the low-volume level on cross streets, the volume conditions were not selected arbitrarily. They were designed by successive approximation, and combined with the appropriate major street vehicular volume, to generate the special traffic condition under which the change of total delay for the whole network caused by the installation or removal of one or more traffic signals would be almost zero; that is, the increased total delay on the major street would approximately equal the decreased total delay on the cross street. A total of ninety-eight cases with various volumes of traffic were developed and simulated. For each case at least two replicates of at least 30 minutes of simulated observation time were utilized. Data generated by the simulation program runs of these ninety-eight cases were the basis for the regression analyses described in the next chapter.

TABLE 3-4. ILLUSTRATION OF LEVELS OF VOLUME CONDITIONS

Major Street		Minor Street	
Level	Range of Volume (VPH) Per Direction	Level	Range of Volume (VPH)
1	above 1001	1	above 701
2	1001 - 901	2	below 700
3	900 - 801		
4	below 800		

SUMMARY

Procedures concerning how to estimate the effect of adding signals to a coordinated signal system were described in Chapter III and Chapter IV in the form of an example problem. These procedures are summarized as follows:

(1) Prepare all the necessary information, such as network geometry and vehicular volume, and draw a street network map based on this information.

(2) Run an optimization model, such as PASSER II, to find the optimal signal timing plan. Two runs are required; one for the before case, and one for the after case.

(3) Make at least two replicate simulation runs with NETSIM based on the same street geometrics, same input vehicular volumes, but different traffic control plans.

(4) Summarize the output of each NETSIM run into tables such as Tables 3-1 and 3-2 and then construct a comparison table such as Table 3-3 to see what effects a newly installed signal will probably have on the network system.

These procedures can be used when access to computer simulation facilities are available. In the next chapter, efforts will be devoted to developing guidelines to help traffic engineers make decisions as to whether a signal should be added or removed in a coordinated system when simulation programs are not available.

CHAPTER 4. RESULTS

The simulation studies described in the previous chapter encompass a wide range of possible situations. These are, however, only a small sample of all possible cases. Based upon analysis of these example cases and additional experimentation, several generalizations can be developed. A sequential procedure for determining whether or not to add a signal to an existing coordinated system in lieu of stop signs is presented below.

QUALITY OF SERVICE ON CROSS STREET

Before examining the potential effects of signalization upon arterial street traffic, conditions on the cross street should be carefully evaluated. When cross street traffic demand approaches or exceeds the maximum possible flow rates attainable under stop sign control, signalization will normally increase the potential flow rates and reduce total traffic delay. The magnitude of this effect will be subsequently demonstrated through a series of simulation studies.

Maximum possible flow rates for the two stop-sign controlled approaches to a four leg isolated intersection have been determined by using a computer simulation model called TEXAS Model for Intersection Traffic. Relationships between maximum hourly flows (per lane) through the stop-controlled approaches versus arterial (uncontrolled) flow rates are illustrated in Figs 4-1 and 4-2 for straight and right-turn maneuvers, respectively. Arterial street traffic represented in these figures is completely uncontrolled with platoons formed only by chance. It this same traffic flow occurred along an arterial street with coordinated signalization, platoons would be created by

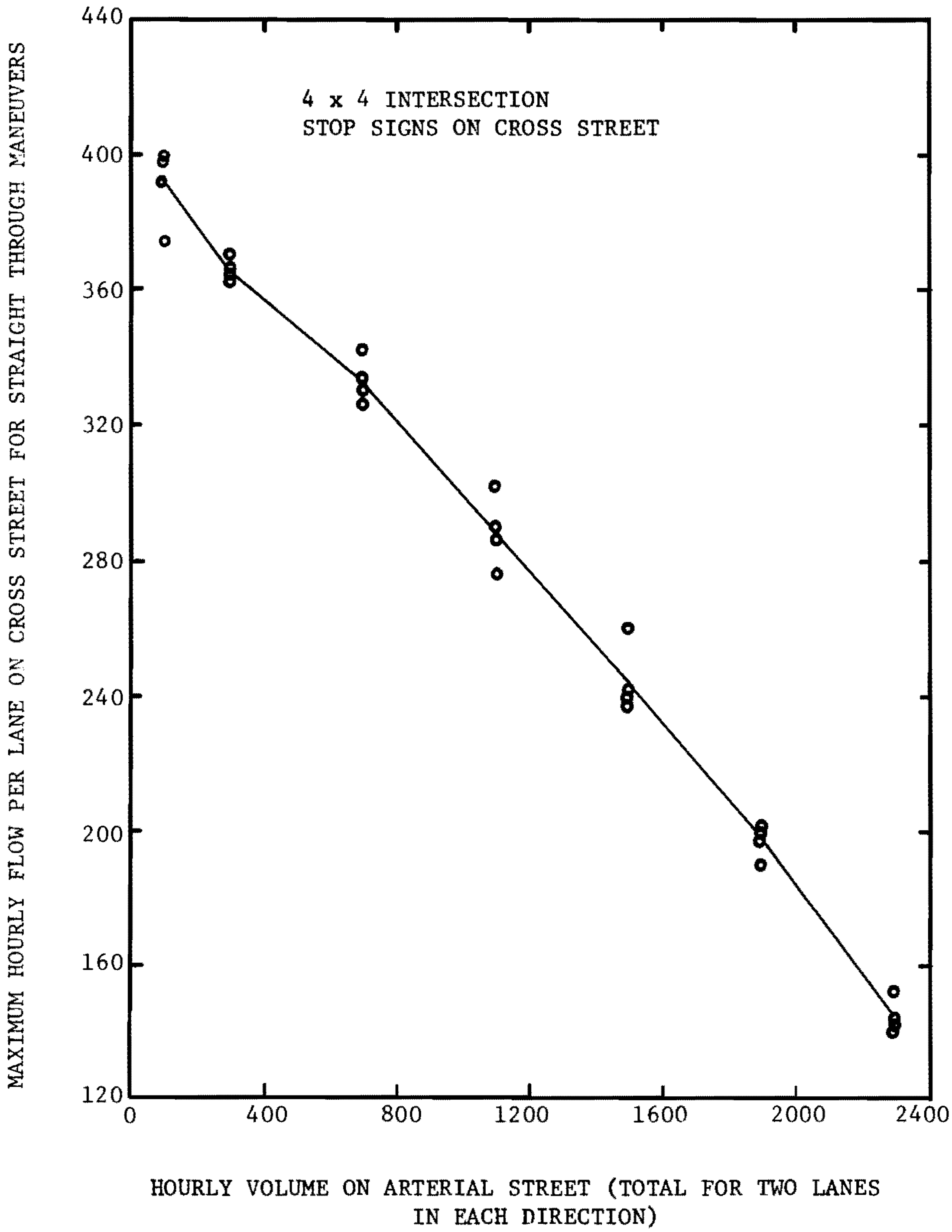


Fig 4-1. Maximum hourly flow per lane on cross street for straight through maneuvers with stop signs on cross street only.

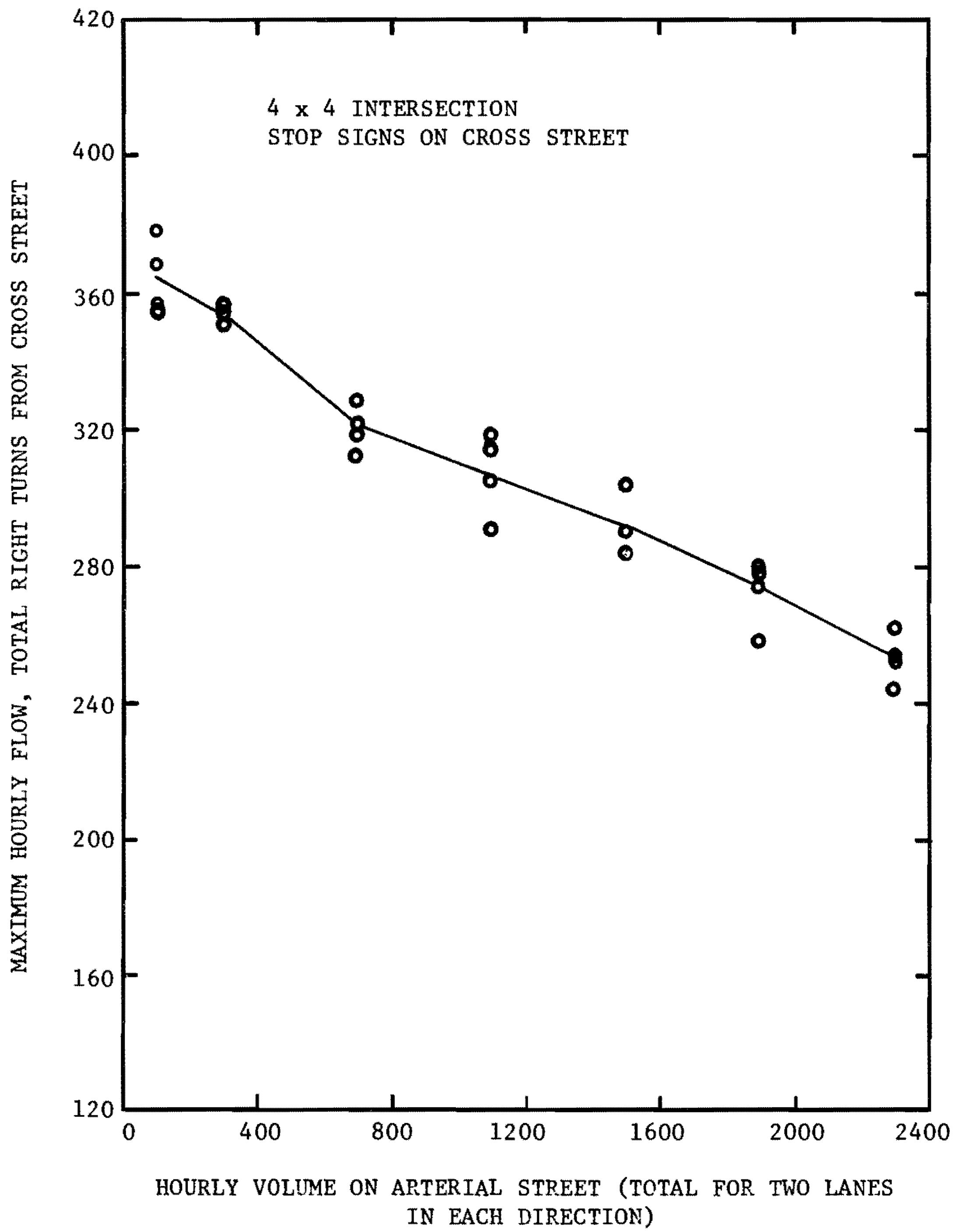


Fig 4-2. Maximum hourly flow, total right turns from cross street with stop signs on cross street only.

the signalization and the number of gaps perceived by crossing traffic would have a different pattern. Thus, the maximum flow rates through stop-sign controlled approaches to an arterial with coordinated signals will possibly exceed those shown in Figs 4-1 and 4-2.

A summary of nineteen sets of statistics gathered through the NETSIM Model [Ref 24] for arterial and cross street operations is presented in Table 4-1. Each test condition, which will be discussed in subsequent sections, is identified by a unique run number (except for replicate runs identified by the suffix R). In all cases the arterial street section was approximately one mile in length and had seven intersections. All signalized intersections were coordinated to provide various amounts of vehicle platooning and through-band width. A comparison of cross street demand (Column 5) with vehicles actually processed (Column 9) gives an indication of the relationship between the actual traffic demand and the potential maximum flow. The demand was generally satisfied by the flow through the stop signs.

In the previous paragraph, the concept of maximum flows through two-way stop-sign control was introduced for uncontrolled arterial flows. The maximum hourly flow rate for straight movements on a single-lane stop-controlled approach that can cross an arterial street with an hourly flow of 2000 vehicles per hour(1000 each direction on two lanes in each direction) is approximately 180 vehicles per hour (Fig 4-1). The equivalent flow rate for two lanes would thus be approximately 360 vehicles per hour. If the arterial traffic were controlled by a coordinated signal system with associated vehicle platooning, the stop-controlled flow could possibly be increased. Run 1 of Table 4-1 presents the statistics for a comparable case in which the arterial traffic is controlled by a coordinated signal system. In this example, the number of vehicles processed through a 2-lane

TABLE 4-1. SUMMARY STATISTICS FOR EXAMPLE RUNS

RUN	DIR.	BAND. (SEC)	DEMAND (VPH) (2 LANES/DIR.)		STATISTICS FOR FIFTEEN MINUTES SIMULATED OBSERVATION TIME				CROSS STREET CONTROL	CYCLE LENGTH (SEC)	CROSS STREET QUEUES LANE 1/ LANE 2 (MAX)	SECT.
					DELAY (MIN.)		VEHICLES PROCESSED					
			ARTERY	CROSS	TOTAL ALL ARTERY LINKS	CROSS STREET PER APPROACH	TOTAL ALL ARTERY LINKS	CROSS STREET PER APPROACH				
1	2	3	4	5	6	7	8	9	10	11	12	13
1	A	22.5	1000	400	172.0	110.1	1037	101	Stop	60	5/9	1
	B				162.0	122.5	1036	100			7/6	1
1R	A	22.5	1000	400	149.1	60.0	1046	92			5/6	1
	B				164.7	70.3	1036	99			6/7	1
1 mean	–	–	–	–	161.9	90.7	1039	98	–	–	–	–
2	A	12.0	1000	400	157.1	20.6	1055	100	Signal	60	2/2	1
	B				212.2	20.6	1031	100			1/2	1
2R	A	12.0	1000	400	167.1	21.9	1045	100			2/2	
	B				208.9	21.5	1040	100			2/1	1
2 mean	–	–	–	–	186.3	21.1	1042	100	–	–	–	–

(continued)

TABLE 4-1. CONTINUED.

RUN	DIR.	BAND. (SEC)	DEMAND (VPH) (2 LANES/DIR.)		STATISTICS FOR FIFTEEN MINUTES SIMULATED OBSERVATION TIME				CROSS STREET CONTROL	CYCLE LENGTH (SEC)	CROSS STREET QUEUES LANE 1/ LANE 2 (MAX)	SECT.
					DELAY (MIN.)		VEHICLES PROCESSED					
			ARTERY	CROSS	TOTAL ALL ARTERY LINKS	CROSS STREET PER APPROACH	TOTAL ALL ARTERY LINKS	CROSS STREET PER APPROACH				
1	2	3	4	5	6	7	8	9	10	11	12	13
3	A	0	1000	400	304.2	21.7	1035	100	Signal	60	2/1	1
	B				326.2	21.7	1025	100			2/1	1
3 mean	–	–	–	–	315.7	21.7	1030	100	–	–	–	–
4	A	22.5	1000	200	117.3	17.4	936	49	Stop	60	1/1	1
	B				127.7	18.1	913	50			2/1	1
4R	A	22.5	1000	200	108.1	16.1	912	51			1/1	1
	B				132.3	20.0	903	50			2/2	1
4 mean	–	–	–	–	121.3	17.9	916	50	–	–	–	–
4E	A	12.0	1000	200	124.5	9.3	896	49	Signal	60	1/1	1
	B				149.7	9.6	919	49			1/2	1
4ER	A	12.0	1000	200	252.7	9.5	905	51			1/1	1
	B				252.7	9.2	906	50			1/1	1
4 mean	–	–	–	–	194.9	9.4	906	50	–	–	–	1

(continued)

TABLE 4-1. CONTINUED.

RUN	DIR.	BAND. (SEC)	DEMAND (VPH) (2 LANES/DIR.)		STATISTICS FOR FIFTEEN MINUTES SIMULATED OBSERVATION TIME				CROSS STREET CONTROL	CYCLE LENGTH (SEC)	CROSS STREET QUEUES LANE 1/ LANE 2 (MAX)	SECT.
					DELAY (MIN.)		VEHICLES PROCESSED					
			ARTERY	CROSS	TOTAL ALL ARTERY LINKS	CROSS STREET PER APPROACH	TOTAL ALL ARTERY LINKS	CROSS STREET PER APPROACH				
1	2	3	4	5	6	7	8	9	10	11	12	13
5	A	30	1300	400	242.3	216.7	1147	78	Stop	80	10/13	2
	B				264.1	216.0	1198	78			11/12	2
5R	A	30	1300	400	292.4	320.5	1170	63			20/20	2
	B				238.8	359.5	1194	68			21/19	2
5 mean	-	-	-	-	259.4	278.2	1177	72	-	-	-	-
6	A	10	1300	400	350.9	25.9	1161	99	Signal	80	3/3	2
	B				418.4	26.0	1211	99			2/2	2
6R	A	10	1300	400	403.2	25.9	1145	98			2/2	2
	B				456.4	27.9	1206	98			2/2	2
6 mean	-	-	-	-	407.2	26.4	1180	99	-	-	-	-

(continued)

TABLE 4-1. CONTINUED.

RUN	DIR.	BAND. (SEC)	DEMAND (VPH) (2 LANES/DIR.)		STATISTICS FOR FIFTEEN MINUTES SIMULATED OBSERVATION TIME				CROSS STREET CONTROL	CYCLE LENGTH (SEC)	CROSS STREET QUEUES LANE 1/ LANE 2 (MAX)	SECT.
					DELAY (MIN.)		VEHICLES PROCESSED					
			ARTERY	CROSS	TOTAL ALL ARTERY LINKS	CROSS STREET PER APPROACH	TOTAL ALL ARTERY LINKS	CROSS STREET PER APPROACH				
1	2	3	4	5	6	7	8	9	10	11	12	13
7	A	20	1300	400	378.1	26.1	1162	100	Signal	80	2/2	2
	B				389.0	25.6	1171	100			1/2	2
7R	A	20	1300	400	338.5	25.4	1191	101			2/2	2
	B				391.5	25.1	1183	100			2/1	2
7 mean	-	-	-	-	374	25.6	1176	100	-	-	-	2
8	A	40	1300	400	266.5	237.1	1169	61	Stop	100	20/20	3
	B				233.6	241.5	1111	58			19/21	3
8R	A	40	1300	400	275.1	332.2	1207	72			16/21	3
	B				210.8	380.6	1101	73			17/20	3
8 mean	-	-	-	-	246.5	297.8	1147	66	-	-	-	-

(continued)

TABLE 4-1. CONTINUED.

RUN	DIR.	BAND. (SEC)	DEMAND (VPH) (2 LANES/DIR.)		STATISTICS FOR FIFTEEN MINUTES SIMULATED OBSERVATION TIME				CROSS STREET CONTROL	CYCLE LENGTH (SEC)	CROSS STREET QUEUES LANE 1/ LANE 2 (MAX)	SECT.
					DELAY (MIN.)		VEHICLES PROCESSED					
			ARTERY	CROSS	TOTAL ALL ARTERY LINKS	CROSS STREET PER APPROACH	TOTAL ALL ARTERY LINKS	CROSS STREET PER APPROACH				
1	2	3	4	5	6	7	8	9	10	11	12	13
9	A	15	1300	400	475.5	27.9	1179	99	Signal	100	2/1	3
	B				499.9	31.2	1178	100			2/2	3
9R	A	15	1300	400	390.7	32.6	1110	98			2/2	3
	B				507.1	30.7	1226	100			2/1	3
9 mean	-	-	-	-	468.3	30.6	1173	99	-	-	-	3

stop-controlled approach to the arterial (Column 9) in 15 minutes is approximately 100 or an equivalent hourly flow of 400 vehicles per hour. Since all the cross street demand (400 vph) was served the maximum flow rate is likely more than 400 vph. This number is comparable to the 360 vph maximum flow rate and demonstrates the beneficial effects of artery signal coordination to cross street traffic.

Another example of this effect can be demonstrated by comparing values in Fig 4-1 and Table 4-1 for arterial flow rates of 1300 vph in each direction. The indicated maximum flow on two stop-controlled lanes across an uncontrolled flow of 2600 vph (total both directions) from Fig 4-1 is approximately 160 vph. Run 5 of Table 4-1 illustrates a comparable case for coordinated arterial traffic, but produces maximum stop-controlled flows of approximately 280 vph (4 x the 15-minute rate shown in Column 9). In this case, the cross street demand (Column 5) is 400 vph which is roughly 40 percent more than the equivalent hourly processing rate. This indicates that a maximum flow rate through the stop sign was achieved.

The degree to which coordinated signalization will effect stop-controlled cross street flow is heavily dependent upon the width of the artery, through band, the extent of band utilization, and the relative position of the stop-controlled intersection in the section. These relationship among the factors can best be visualized through reference to the time-space diagrams shown in Figure 4-3. The diagrams show the same three sections for which simulation data are presented in Table 4-1. In each diagram, the artery through bands have been shaded to indicate those times in which cross street traffic cannot traverse the artery if both of the directional arterial through bands are fully utilized. Location of stop- controlled cross streets are shown in parentheses, and blocked crossing

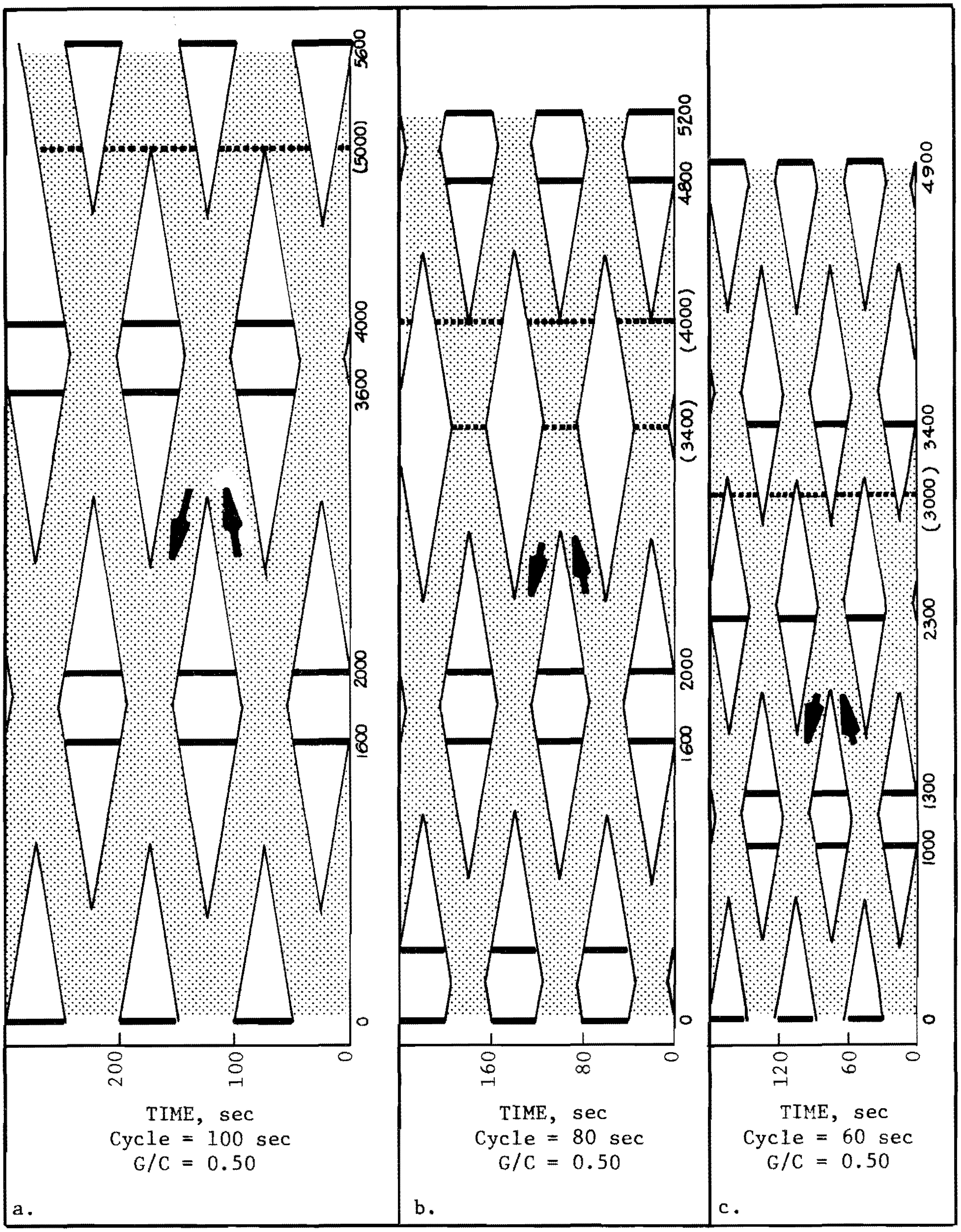


Fig 4-3. Time-space diagrams for three sections of arterial streets operating under coordinated signal control.

time is indicated by dotted lines. Approximately 20 seconds of clear crossing time are available between the shaded through bands each minute under the conditions of Figure 4-3a. This occurs in two 10-second intervals following each directional band. Due to the longer signal cycles, greater bandwidth, and different positioning of the stop-controlled intersections in Figs 4-3b and 4-3c the availability of clear crossing time between arterial through bands is somewhat greater and the opportunities appear less frequently. In Figure 4-3c, for example, a crossing time of 20 seconds, between through bands, is provided only once each 100 seconds which is the equivalent of about 12 seconds of crossing time per minute. It is interesting to note that a stop-controlled intersection located 3800 feet from the beginning of the section shown in Figure 4-2c would receive 60 seconds of crossing time per 100 second cycle or triple that provided at the 5000 feet location. For the cross street locations and signal timing conditions shown in Fig 4-3b available crossing time between arterial through bands at the 3400 feet location is 50 seconds out of the 80-second cycle (62.5 percent), and at the 4000 feet location it is 20 seconds out of the 80-second cycle (25 percent). Thus, it can be seen that intersection location relative to the arterial through bands can have a pronounced effect upon cross street potential flow rates.

The problem of little or no crossing time for stop-controlled cross streets obviously cannot be solved by "moving" the cross street. The relative position with respect to the through bands may, however, be changed by revising arterial signal timing. Minor changes in signal offsets, or particularly changes in red-green splits of the signal cycle, may be used to revise the time-space diagram to provide more clear crossing time. Simple time-space diagrams such as those shown in Fig 4-3 are recommended as essential tools for evaluating potential, clear crossing time and the effects of changes in arterial signal timing. A practical graphical technique for constructing time-space diagrams is presented in Appendix B.

CROSS STREET, QUEUES AND VEHICULAR DELAY

A variety of techniques may be used to verify the presence of cross street traffic demand which approaches or exceeds the maximum possible stop-control flow rates. The easiest and most reliable technique, however, is simple counting of existing queues and subsequent computation of average queue lengths. When queues of seven to ten vehicles are maintained almost continuously at a stop-controlled approach, vehicular delays frequently average three to five minutes per vehicle. Runs 5 and 8 of Table 4-1 illustrates such situations. Although the absence of significant queues, does not guarantee tolerable vehicular delays, the presence of long queues is strongly indicative of a significant demand flow imbalance and accompanying large vehicular delays.

At locations where significant queues are maintained for extended periods of time, the procedures outlined in the previous section should be applied in an attempt to provide more clear crossing time. If these attempts fail to reduce continuous queue lengths to acceptable levels, a signal should be installed. A ten fold decrease in total delay to cross street traffic on the previously stop-sign controlled approaches is not infeasible where appropriately timed coordinated signals are installed. Comparison of runs 5 and 6, and of runs 8 and 9 shown in Table 4-1 demonstrates the potential effects on cross street delay and queue lengths. Runs 5 and 8 illustrate situations in which cross street demands exceed the possible flow rates. Total delay to vehicles on each cross street approach, per 15 minutes, are 278 and 297 minutes (Column 7) for Runs 5 and 8, respectively. Runs 6 and 9 illustrate the results of signal installation with total approach delays reduced to 26 and 31 minutes, respectively.

ARTERIAL STREET OPERATIONS

Signalization of a two-way stop-sign controlled intersection within a coordinated arterial system may have a significant impact upon arterial operations. Once again, the best means of visualizing the potential magnitude of the impact is through the use of a basic time-space diagram. Principal effects will include changes in the width and/or slope (speed) of the artery through band. Both effects can be easily visualized with the time-space diagram. Signal timing optimization programs such as Passer II, Transyt, and Maxband may be used advantageously to evaluate the effects of proposed changes in signal timing to the artery through band.

The order of change in total delay to arterial traffic which might be expected is illustrated in Table 4-1. Runs 1, 2, and 3 demonstrate the magnitude of change in total arterial delay when the width of the artery through band is reduced from 22.5 to 12.0 seconds and finally to zero. For all runs shown in Table 4-1, the slope of the band was held constant at an equivalent progression speed of 27 mph so that delays were not influenced by changes in the progression speed. Since arterial and cross street traffic demand were also held constant throughout Runs 1, 2, and 3 the only systematic change which affected the artery traffic was bandwidth reduction. Total delay experienced by traffic along the full length of the artery section increased from 162 to 186 to 315 minutes (per 15 minutes of observation time) as bandwidth was decreased from 22.5 to 12 seconds to zero. The magnitude of arterial delay change per unit of bandwidth change is strongly affected by the arterial traffic demand. comparisons of Runs 5 and 7 shown in Table 4-1 illustrates how a higher traffic demand (1300 vph on two lanes per direction versus 1000 in the previous example) is affected more by bandwidth changes. In this case, a 10-second bandwidth change produced a 40 percent increase in total arterial delay.

COMPARISON OF ARTERIAL AND CROSS STREET EFFECTS

Within the context of the previous discussion, effects of cross street signalization have been presented separately for the artery and the cross street. A decision to install an additional cross street signal should be based upon separate analyses of both artery and cross street operations followed by a comparison of relative potential effects.

One guideline which has been proposed for deciding when to implement a new signal would be based upon the relative change in total delay. If the increase in total delay on the artery is less than the decrease on the cross street, then the signal should be implemented. Although this guideline is sound, the number of variables which may effect delay on both streets is very large. Any generalizations regarding the conditions which might produce such delay conditions is therefore highly problematic. Traffic demands and their relationship to maximum possible flow rates are, however, good indicators of potential delay effects to both streets.

Very small ratios of demand traffic to maximum flow rates on both streets are usually indicative of insignificant delay effects to both artery and cross streets. Warrant 2 of the MUTCD states that a cross street signal may be warranted if traffic demand on the higher volume cross street approach exceeds 100 vph and the total demand (sum of both directions) on the artery is 900 vph when the street geometry is two lanes in each direction on both streets. The warrant further states that these volume levels must be maintained for eight hours of a typical day. The attainable maximum flow rates on both such streets are considerably greater than those stated in the warrant; therefore, the ratios of signal warrant demand to maximum flow are small. A large quantity of simulation data collected for such low volume conditions indicates that changes to total delay on both streets due to cross street signalization are generally insignificant. The usual magnitudes of changes in delay are smaller than the magnitude of random or chance variations. As noted earlier, certain combinations of cross street location and artery through band configuration may create significant crossing problems, but these cases are very rare when traffic demands are small. When the ratios of demand to attainable maximum flow are small on both the artery and the cross street, adjustment of artery signalization is likely a preferred solution, rather than cross street signalization.

When traffic demands on the artery are large relative to attainable maximum flow rates and cross street demands are less than attainable, a fairly clear decision may be possible. Runs 4 and 5 of Table 4-1 exemplify such a situation. In this example, signalization of the cross street created 73 minutes of additional artery delay while saving only 8 minutes (per 15 minutes of observation) on the cross street. For such a case, signalization of the cross street would appear to be counterproductive. Such situations may be identified in the field by the presence of very small queues (one or two vehicles) on the cross street and by artery through bands that are full or nearly full.

On the other hand, when the cross street demand exceeds the attainable maximum flow rate, the relative delay guideline may dictate cross street signalization. As noted in previous sections, other solutions should certainly be attempted first, but if maximum flow cannot be increased through the stop-sign controlled approaches, a signal should be added. Runs 5, 6, and 7 on section two, and Runs 8 and 9 on section three of Table 4-1 illustrate this situation. For both these sections, cross street demands exceed maximum flow rates under stop control. In all these cases, despite severe reductions in artery bandwidth, the reductions in total delay to the cross street exceed the additional delay to traffic on the artery. The relative delay guideline would dictate cross street signalization in these cases.

SUMMARY

Based upon the discussion in the previous section, the following sequential procedure is suggested for making a cross-street signalization decision.

(1) The relationship of cross street traffic demand to the attainable maximum flow rates should be established through field counting of queue lengths or other appropriate means. If demand is found to approach or exceed maximum attainable levels, a feasible means of providing additional crossing time must be sought.

(2) A time-space diagram should be developed to help visualize the relationship of the cross street crossing opportunities to the artery through bands. Modifications to the artery signal timing should be attempted to provide additional crossing time, thus increasing maximum cross street flow rates. Signal optimization routines such as PASSER II, Transyt, and Maxband may be helpful in developing such signal timing modifications, but time-space diagrams should be used for final evaluation of the signal system.

(3) The relationship of arterial traffic demand to the maximum attainable flow should be established. This may be accomplished by observing platoon sizes and dispersion and by estimating the degree of utilization of available artery through bands.

(4) If neither the artery nor the cross street demands are large relative to their respective maximum flow rates, the cross street is not likely to be a good candidate for signalization. Neither is it likely to be a good candidate if cross street demands are very light and artery demands are very heavy relative to maximum flows.

(5) If a particular situation cannot be categorized as belonging to one of the above categories, computer simulation of the actual system using the NETSIM model is suggested.

CHAPTER 5. SUMMARY AND RECOMMENDATIONS

The objective of using a coordinated traffic control signal system on an arterial street network is generally to maximize flow at a reasonable speed on the major arterial street while at the same time limiting the stops and delays to tolerable values for traffic on both the major street and the cross streets. Several geometric and traffic operational factors, including the number and location of signalized intersections in the network, interact to determine the efficiency with which such a coordinated system functions. While there are quantitatively defined conditions under which signals can be warranted at single, isolated intersections, few guidelines exist for characterizing the conditions under which specific intersections in an arterial network can be signalized beneficially. A methodology for assessing the effects of signalizing particular intersections in a network is needed. This report describes a study in which simulation was used to quantify the effects of adding or removing one or more signals within a series of twelve representative street networks operating under coordinated signal control.

OPTIMIZATION AND SIMULATION

The study revealed that the best practicable evaluation of the effects of changing the number and spacing of signals in a network can be accomplished by applying signal timing optimization programs such as PASSER II and traffic simulation programs such as NETSIM directly to the specific before and after geometric and traffic control circumstances under consideration. The various indicators of traffic performance produced by simulation before signalization are comparable with those for the after case.

Overall effects on the network as well as those on an individual intersection approach can be evaluated quantitatively. This technique, of course, requires access to large computer facilities and experienced personnel.

An effort was therefore made to develop an evaluation technique which would not require the use of a large computer. An analysis methodology is presented which utilizes graphical time-space diagrams and small amounts of field data collection.

RECOMMENDATIONS

The analysis techniques that are presented in this report should be used to evaluate the effects of possible changes in the number of signalized intersections in an arterial street network. Various levels of quality in the quantitative estimates of the traffic performance which can be expected on a network are possible with the techniques described. The Optimization and Simulation technique produces a detailed evaluation of specific situations and should be used for final decision making and detailed design changes in a coordinated network control system.

Total delay to all traffic using the network should probably be considered as the basic indication of effectiveness for the traffic control system, but this one indicator is not sufficient. Consideration must also be given to the delay, length of queues, and number of stops experienced by traffic on each individual intersection approach. Tolerable values for these parameters must be maintained if the control scheme is to be judged effective. A coordinated signal control scheme which potentially satisfies most or all the critical requirements should be selected for implementation.

The scope of the analysis given in this report is somewhat limited, and further study is recommended in order to broaden the basis for decision-making about adding or removing signals in a network. Areas for additional consideration include:

(1) peak-hour directional traffic conditions,

(2) complex signal phasing arrangements,

(3) varied geometric configurations of intersections,

(4) pedestrian effects,

(5) bus-priority systems, and

(6) field validation studies.

Analysis methods which incorporate these considerations will extend the work described in this report and provide more versatile tools for designing and operating efficient traffic control schemes on signalized arterial street networks.

REFERENCES

1. Ackcelik, R., "TRANSYT 6/N and Its Use as a Network Evaluation Tool," Australian Road Research ARR No. 92, Australian Road Research Board, May 1979, pp. 33-59.

2. Baker, R. R., Handbook of Highway Engineering, Van Nostrand Reinhold Company, New York, 1975.

3. Baerwald, J. E., Transportation and Traffic Engineering Handbook, The Institution of Traffic Engineers, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1976, pp. 818-829.

4. Bowker, A. H. and G. J. Lieberman, Engineering Statistics, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1972.

5. Clark, C. T. and L. L. Schkade, Statistical Analysis for Administrative Decision, South-Western Publishing Co., Cincinnati, Ohio, 1979.

6. Copelle, D. G., "Traffic Signal System: Techniques for Optimization Operation," Itte. California University, Berkeley, 23rd California Transportation and Public Works Conference, March 1971, pp. 51-53.

7. Herman, R., Theory of Traffic Flow, Elsevier Publishing Co., New York-Princeton, 1961.

8. "Highway Capacity Manual," Special Report 87, Highway Research Board, 1965.

9. Kell, J. H. and R. B. Cody, "Method for Network Optimization: SIGOP," Proceedings, Institute of Traffic Engineers, September 1972, pp. 190-193.

10. Lee, C. E., Savur, U. S. and G. E. Grayson, "Application of the Texas Model for Analysis of Intersection Capacity and Evaluation of Traffic Control Warrants," Research Report 184-F, Center for Highway Research, The University of Texas at Austin, July 1978.

11. Kennedy, W. J., Ralph, M. Farr and D. Labrum Wilard, "Implementing Computer Simulation of Traffic Signal System," Traffic Engineering Vol. 45, No. 2, Institute of Traffic Engineers, 1975, pp. 44-50.

12. Lenthart, H. R., "Design of a Progressively Timed Signal System," Traffic Engineering Vol. 45, No. 2, Institute of Traffic Engineers, 1975, pp. 11-18.

13. Little, J. D. C., Kelson, M. D. and N. H. Gartner, "MAXBAND - A Versatile Program for Setting Signals on Arteries and Triangular Network," Department of Transportation, Federal Highway Administration, Report for project through contract DOT-FH-11-9562, December 1980.

14. Manual on Uniform Traffic Control Device for Streets and Highways, Department of Transportation, Federal Highway Administration, Washington, D.C., 1971.

15. Messer, C. J., Whitson, R. H., Dudek, C. L. and E. J. Romano, "A Variable Sequence Multi-Phase Progression Optimization Program," Transportation Research Record No. 445, Transportation Research Board, 1973, pp. 24-33.

16. "NETSIM MODEL" Report No. FHWA-RD-77-44, Vol. 4, User's Guide, Federal Highway Administration, April 1977.

17. Pignataro, L. J., Traffic Engineering Theory and Practice, Prentice-Hall, Inc., Englewood Cliff, New Jersey, 1973.

18. Rach, L., Lam, J. K., Richardson, D. B. and D. C. Kanfman, "Evaluation of Off-Line Traffic Signal Optimization Techniques,," Transportation Research Record No. 538, Transportation Research Board, 1975, pp. 48-58.

19. Robertson, D. I., "Transyt: A Traffic Network Study Tool," Road Research Laboratory RRL Report LR253, Ministry of Transport, 1969.

20. Ross, P. and D. Gibson, "Review of Road Traffic Network Simulation Model," Transportation Research Record No. 644, Transportation Research Board, 1977, pp. 36-41.

21. "Signal Timing Optimization to Maximize Traffic Flow," Workshop Notebook,Office of Traffic Safety, Texas State Department of Highways and Public Transportation, August 1978.

22. "Traffic Control Systems Handbook," Department of Transportation, Federal Highway Administration, June 1976.

23. "Traffic Engineering Computer Programs PASSER II (Multi-phase Arterial Progression Program)," Texas Highway Department, Division of Automation. 1974.

24. "Traffic Network Analysis with NETSIM, A User's Guide," Department of Transportation, Federal Highway Administration, January 1980.

25. United States Department of Commerce, Bureau of Statistical Analysis, Survey of Current Business, November 1981, p. S-4.

26. Wohl, M. and B. V. Martin, Traffic System Analysis for Engineers and Planners, McGraw-Hill, New York, 1972.

27. Yagoda, H. N., Steven, E. E., and P. R. Mogridge, "Computer and Signal Timing," Traffic Engineering Vol. 42, No. 5, Institute of Traffic Engineers, 1972, pp. 12-16.

28. Zaniewski, J. P., et. al., Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors, Final Draft Report, Federal Highway Administration, Washington, D.C., December 1981.

APPENDIX A

METHODS FOR ESTIMATING THE EFFECTS OF ADDING SIGNALS

Procedures for evaluating the effects of adding new signals to a given coordinated signal system are summarized in Chapters 3 and 4. These procedures may be successfully applied to a very wide range of different situations. In addition to the general procedures of Chapters 3 and 4 considerable effort was devoted to development of very quick, shortcut methods. Results of these efforts are presented in this Appendix.

Potential users are strongly cautioned however regarding the use of the methods of this Appendix. The equations presented are valid only for a very narrow range of possible cases and extrapolation beyond the range of experimentation will likely yield erroneous results. Two alternative methods for estimating these effects without using a simulation model are presented. The methods are based on analyses of the data which resulted from simulating traffic on the twelve representative street networks described in Chapter 2.

In the first method, data classification has been used to arrange the results of about 100 NETSIM traffic simulation runs for twelve representative arterial street networks (see Fig 2-6) into a format which allows a rough approximation to be made of the expected change in delay and number of stops per vehicle on both the major street and the cross streets and in the number of vehicular trips accommodated on the cross streets when one or more intersections in an arterial street network is converted from sign control to signal control. These changes are presented as average values for those networks which have been grouped according to ranges of vehicular trips on the major street and ranges of cumulative queue lengths on the cross streets before adding signals when change in bandwidth attributable to the signalization is considered.

For the second method, regression analysis has been used to analyze the same results and develop equations for relating the operational characteristics (independent variables) of all the networks before adding signals to the expected effects (dependent variables) of converting from sign control to signal control at one or more intersections. These equations provide a somewhat more refined estimate of the average changes which can be expected after signalization.

SELECTION OF VARIABLES

Independent Variables

The independent variables which were selected for developing the methods presented here which were found to be helpful in explaining the observed changes in the dependent variables. The chosen independent variables are listed in Table A-1.

Actual field data concerning the number of vehicle trips, X_{TA}, that can be accommodated on a cross street after a signal has been installed to replace stop signs obviously can not be obtained unless new signals are in fact added. But, by simulating a number of different situations and applying regression analysis techniques it is possible to estimate this number from the number of vehicle trips, X_{TB}, and the accumulative queue length, X_{AQ}, before the signal is added. The estimation formula that has been derived from simulation results in this study is $X_{TA} = 1.011X_{TB} + 1.36X_{AQ}$. For this regression equation, the R^2 is 0.9908, the standard error for residual is 10.5 percent and the F ratio is 5169.4. The variable X_{TA} is treated as an independent variable in the regression analysis.

Except for bandwidth, the value of all other independent variables listed in Table A-1 can be determined either by field observation or by estimation before the installation of new signals. Attainable bandwidths for both the before case and the after case can be obtained either by running

TABLE A-1. DEFINITION OF INDEPENDENT VARIABLES

Symbol	Variable	Unit
X_{MT}	Average number of vehicle trips on Major Street in the before case, per 15 minutes	number
X_{SB}	Number of signals per mile in the before case	number
X_{SA}	Number of signals per mile in the after case	number
X_{MB}	Mean of signal spacings in the before case	feet
X_{MA}	Mean of signal spacings in the after case	feet
X_{BB}	Bandwidth in the before case	seconds
X_{BA}	Bandwidth in the after case	seconds
X_{TB}	Average number of vehicle trips on Cross Street in the before case, per 15 minutes	number
X_{TA}	Average number of vehicle trips on Cross Street in the after case, per 15 minutes	number
X_{AQ}	Accumulative queue length on Cross Street in the before case, per 15 minutes	number

optimization computer programs or by manual calculation methods. Values for all the stated independent variables are prerequisites for the analysis.

Except for three time-independent variables (number of signals, mean of signal spacings, and bandwidth), all other variables, both dependent and independent, use values which appear in the NETSIM output for simulation interval of 15 minutes.

Dependent Variables

"Total Delay", "Average Delay per Vehicle", and "Number of Stops per Vehicle", are taken as measures of disutility for both the major street and the cross street. These variables are defined in the previous chapter. "Number of Additional Vehicle Trips on the Cross Street" is introduced here as a new dependent variable which provides information about how many additional vehicle trips can be handled on the cross street with signal control rather than with stop sign control.

In Chapter 4, the values of each dependent variable were summed according to the direction in which traffic flowed. For example, in Table 4-2, there are two different values for major street total delay - one for the "A direction", and one for the "B direction". In this chapter, the value of each dependent variable is taken as the average value for the two directions.

METHODS FOR EVALUATING THE EFFECT OF NEW SIGNALS

After the independent variables and dependent variables had been defined, the next step in developing an evaluation method was to find a relationship between them so that values of the dependent variables could be estimated from the independent variables. Various effects of signalization could then be assessed quantitatively by comparing the magnitude of the dependent variable before signalization with those after signalization. A decision as to whether or not signals should be installed or removed from a coordinated network could be based on the overall effects to traffic on the major street and on the cross street(s).

Data Classification Method

A series of tables, Tables A-2 through A-8, are given to provide a convenient form for obtaining the mean value of several dependent variables within given ranges of the independent variables.

Major Street. Three independent variables are used in each table for major street, they are:

(1) Average vehicle trips for fifteen minutes on major streets,

(2) Delta bandwidth, which equals optimal bandwidth before the installation of new signal(s) minus the optimal bandwidth after the installation of new signal(s), and

(3) Delta number of signals, which is the number of new signals.

One table is provided for each of the three major street dependent variables. The number of observations, mean, standard deviation, and coefficient of variation (standard deviation divided by the mean) are listed on each table, category by category. Three tables were developed for the major street dependent variables: Table A-2 for increased total delay, Table A-3 for increased average delay per vehicle and Table A-4 for increased number of stops per vehicle.

Cross Street. The basic idea of tables for cross street is the same as for major street tables. Two independent variables are used in these tables. The first, accumulative queue length on cross street, is defined as the total number of vehicles on cross street which stopped one or more times and waited in a queue to enter the intersection. The second independent variable is

TABLE A-2. INCREASE IN TOTAL DELAY TO TRAFFIC ON MAJOR STREET (VEHICLE-MINUTES)

DELTA BANDWIDTH (SEC)	DELTA NUMBER OF SIGNALS	FACTOR	MAJOR STREET AVERAGE VEHICLE TRIPS PER 15 MIN. (PER DIRECTION)		
			175 and Less	From 176 to 194	195 and More
1 or less	1	OBSERVATIONS	16	17	9
		MEAN	18	28	87
		STD. DEVIATION	16.8	22.0	71.5
		COEF. OF VARIATION	0.91	0.78	0.90
	2 or more	OBSERVATIONS	0	4	7
		MEAN	-	143	187
		STD. DEVIATION	-	55.2	80.7
		COEF. OF VARIATION	-	0.39	0.43
2 or more	1	OBSERVATIONS	8	9	12
		MEAN	74	93	200
		STD. DEVIATION	44.1	47.2	80.6
		COEF. OF VARIATION	0.60	0.51	0.40
	2 or more	OBSERVATIONS	6	4	4
		MEAN	110	159	270
		STD. DEVIATION	25.1	15.3	25.6
		COEF. OF VARIATION	0.23	0.10	0.09

TABLE A-3. INCREASE IN AVERAGE DELAY PER VEHICLE ON MAJOR STREET (SECONDS/VEHICLE)

DELTA BANDWIDTH (SEC)	DELTA NUMBER OF SIGNALS	FACTOR	MAJOR STREET AVERAGE VEHICLE TRIPS PER 15 MIN. (PER DIRECTION)		
			175 and Less	From 176 to 194	195 and More
1 or less	1	OBSERVATIONS	16	17	9
		MEAN	12	11	29
		STD. DEVIATION	15.7	6.1	23.4
		COEF. OF VARIATION	1.34	0.54	0.82
	2 or more	OBSERVATIONS	0	4	7
		MEAN	-	35	34
		STD. DEVIATION	-	24.6	15.9
		COEF. OF VARIATION	-	0.71	0.47
2 or more	1	OBSERVATIONS	8	9	12
		MEAN	27	30	51
		STD. DEVIATION	10.4	8.9	13.1
		COEF. OF VARIATION	0.39	0.30	0.26
	2 or more	OBSERVATIONS	6	4	4
		MEAN	34	42	58
		STD. DEVIATION	5.9	5.0	7.2
		COEF. OF VARIATION	0.17	0.12	0.12

TABLE A-4. INCREASE IN THE AVERAGE NUMBER OF STOPS PER VEHICLE ON MAJOR STREET (STOPS/VEHICLE)

DELTA BANDWIDTH (SEC)	DELTA NUMBER OF SIGNALS	FACTOR	MAJOR STREET AVERAGE VEHICLE TRIPS PER 14 MIN. (PER DIRECTION)		
			175 and Less	From 176 to 194	195 and More
1 or less	1	OBSERVATIONS MEAN STD. DEVIATION COEF. OF VARIATION	16 0.40 0.27 0.75	17 0.50 0.18 0.37	9 0.70 0.27 0.44
	2 or more	OBSERVATIONS MEAN STD. DEVIATION COEF. OF VARIATION	0 - - -	4 1.8 0.54 0.29	7 1.8 0.45 0.27
2 or more	1	OBSERVATIONS MEAN STD. DEVIATION COEF. OF VARIATION	8 1.0 0.36 0.34	9 1.1 0.27 0.23	12 1.4 0.18 0.12
	2 or more	OBSERVATIONS MEAN STD. DEVIATION COEF. OF VARIATION	6 1.4 0.18 0.11	4 1.5 0.27 0.18	4 1.2 0.18 0.18

TABLE A-5. DECREASE IN TOTAL DELAY TO TRAFFIC ON CROSS STREET (VEHICLE-MINUTES)

MINOR STREET ACCUMULATIVE QUEUE LENGTH PER 15 MINUTES	FACTOR	MAJOR STREET AVERAGE VEHICLE TRIPS PER 15 MINUTES (PER DIRECTION)				
		169 and Less	170 to 179	180 to 189	190 to 209	210 and More
29 and Less	OBSERVATION	23	16	11	6	0
	MEAN	22	57	119	255	-
	STD. DEVIATION	10.5	57.4	114.0	163.9	-
	COEF. OF VARIATION	0.48	1.0	0.96	0.64	-
30 to 79	OBSERVATION	0	0	6	7	2
	MEAN	-	-	723	922	-
	STD. DEVIATION	-	-	231.9	160.7	-
	COEF. OF VARIATION	-	-	0.32	0.17	-
80 to 99	OBSERVATIONS	0	0	0	3	9
	MEAN	-	-	-	1090	1125
	STD. DEVIATION	-	-	-	56.3	72.4
	COEF. OF VARIATION	-	-	-	0.05	0.06
100 and more	OBSERVATIONS	0	0	1	2	12
	MEAN	-	-	-	-	1291
	STD. DEVIATION	-	-	-	-	177.7
	COEF. OF VARIATION	-	-	-	-	0.14

TABLE A-6. DECREASE IN AVERAGE DELAY PER VEHICLE ON CROSS STREET (SECONDS/VEHICLE)

MINOR STREET ACCUMULATIVE QUEUE LENGTH PER 15 MINUTES	FACTOR	MAJOR STREET AVERAGE VEHICLE TRIPS PER 15 MINUTES (PER DIRECTION)				
		169 and Less	170 to 179	180 to 189	190 to 209	210 and More
29 and Less	OBSERVATIONS	23	16	11	6	0
	MEAN	13	34	76	149	-
	STD. DEVIATION	5.2	33.0	79.7	115.1	-
	COEF. OF VARIATION	0.40	0.98	1.1	0.77	-
30 to 79	OBSERVATIONS	0	0	6	7	2
	MEAN	-	-	372	561	-
	STD. DEVIATION	-	-	141.3	172.5	-
	COEF. OF VARIATION	-	-	0.38	0.31	-
80 to 99	OBSERVATIONS	0	0	0	3	9
	MEAN	-	-	-	630	670
	STD. DEVIATION	-	-	-	120.8	166.1
	COEF. OF VARIATION	-	-	-	0.19	0.25
100 and more	OBSERVATIONS	0	0	1	2	12
	MEAN	-	-	-	-	885
	STD. DEVIATION	-	-	-	-	200.4
	COEF. OF VARIATION	-	-	-	-	0.23

TABLE A-7. DECREASE IN AVERAGE NUMBER OF STOPS PER VEHICLE ON CROSS STREET (STOPS/VEHICLE)

MINOR STREET ACCUMULATIVE QUEUE LENGTH PER 15 MINUTES	FACTOR	MAJOR STREET AVERAGE VEHICLE TRIPS PER 15 MINUTES (PER DIRECTION)				
		169 and Less	170 to 179	180 to 189	190 to 209	210 and More
29 and Less	OBSERVATIONS	23	16	11	6	0
	MEAN	0.54	0.56	0.60	0.74	-
	STD. DEVIATION	0.04	0.04	0.12	0.19	-
	COEF. OF VARIATION	0.08	0.08	0.21	0.26	-
30 to 79	OBSERVATIONS	0	0	6	7	2
	MEAN	-	-	0.80	0.97	-
	STD. DEVIATION	-	-	0.07	0.19	-
	COEF. OF VARIATION	-	-	0.09	0.19	-
80 to 99	OBSERVATIONS	0	0	0	3	9
	MEAN	-	-	-	0.70	0.71
	STD. DEVIATION	-	-	-	0.01	0.10
	COEF. OF VARIATION	-	-	-	0.02	0.14
100 and more	OBSERVATIONS	0	0	1	2	12
	MEAN	-	-	-	-	0.74
	STD. DEVIATION	-	-	-	-	0.16
	COEF. OF VARIATION	-	-	-	-	0.22

TABLE A-8. INCREASE IN TOTAL NUMBER OF TRIPS ON CROSS STREET

MINOR STREET ACCUMULATIVE QUEUE LENGTH PER 15 MINUTES	FACTOR	MAJOR STREET AVERAGE VEHICLE TRIPS PER 15 MINUTES (PER DIRECTION)				
		169 and Less	170 to 179	180 to 189	190 to 209	210 and More
29 and Less	OBSERVATIONS MEAN STD. DEVIATION COEF. OF VARIATION	23 1 1.7 16.11	16 1 4.5 3.77	11 7 12.0 1.59	6 23 16.1 0.69	0 - - -
30 to 79	OBSERVATIONS MEAN STD. DEVIATION COEF. OF VARIATION	0 - - -	0 - - -	6 86 41.9 0.48	7 94 20.1 0.21	2 - - -
80 to 99	OBSERVATIONS MEAN STD. DEVIATION COEF. OF VARIATION	0 - - -	0 - - -	0 - - -	3 135 11.3 0.08	9 139 12.4 0.09
100 and more	OBSERVATIONS MEAN STD. DEVIATION COEF. OF VARIATION	0 - - -	0 - - -	1 - - -	2 - - -	12 155 18.9 0.12

major street average vehicle trips. The relationship between these independent variables and four dependent variables are shown in Tables A-5 through A-8. Table A-5 shows decreased total delay, Table A-6 shows decreased average delay per vehicle, Table A-7 shows decreased number of stops per vehicle, and Table A-8 shows increased number of vehicle trips.

From Table A-8, it can be seen that when accumulative queue length on cross street is less than 29 and when major street average vehicle trips are less than 190, the values of dispersion for increased number of trips on minor street are greater than one. These conditions exist when the existing minor street vehicular volume is less than the capacity of the stop-sign controlled approaches. Under these conditions, the average number of vehicle trips on cross street is always the same no matter what the control strategy is. The "mean value" listed in these categories are results caused by the stochastic features of the simulation program, it does not indicate the actual increase in the number of vehicle trips on the minor street.

Regression Analysis Method

The data classification technique used in analyzing the simulation data for various categorized operating conditions on twelve street networks as described above gives average values for the selected effects as described by the dependent variables. The same simulation data have been further analyzed in order to develop a series of regression equations which permit a somewhat more refined estimate of the expected value of the effects (dependent variables) that will be produced by adding or removing signals from one or more intersections in a street network.

Major Street. For major street, the dependent variables which are used are taken as measures of disutility for the whole major street, that is, from the first intersection to the last intersection. "Total Delay" is the summation of the delays of all the vehicles when they were traveling on the major street within the simulation time (15 minutes). "Total Average Delay per Vehicle" is the total delay time of all vehicles traveling through the whole series of intersections on the major street divided by the number of vehicle trips. "Total Number of Stops per Vehicle" is calculated on the same basis.

Two tables were developed for a summary presentation of the regression equations developed from simulation results. Table A-9 is provided for the condition in which only one new signal is added to the system and Table A-10 is for two or more new signals. The regression equations are given in each table in pairs. For each dependent variable, the user should apply one equation from the table for the before case and one equation for the after case. The effect on major street traffic of adding signals to a coordinated system can be assessed quantitatively by comparing the values of the dependent variables for the before and the after cases.

Cross Street. Assessing the effects of signal control on the cross street traffic is not as complex as for traffic on the major street because there is only one link on each cross street. The values derived from the regression equations are average values for all the cross street links which were converted from sign control to signal control in the series of NETSIM runs. If consideration is being given to adding signals at more than one intersection in a network, the total increase or decrease in delay or number of stops on the cross streets is simply the average values derived from the equations times the number of newly signalized intersections. Table A-11 is provided for evaluating the effects of signalization on cross street traffic. Values for the amount of decrease in delay to cross street traffic can be obtained directly from the equations shown, but changes in the number of

TABLE A-9. REGRESSION EQUATIONS FOR EFFECTS ON MAJOR STREET WHEN ONE TRAFFIC SIGNAL IS ADDED

DEPENDENT VARIABLE \ CASE	BEFORE CASE	AFTER CASE
Y_{TD}: Total Delay on the Major Street (vehicles minutes)	$Y_{TD} = -1231.0 + 3.652X_{MT} + 87.379X_{SB} + 0.434X_{MB} - 12.39X_{BB} - 0.56X_{TB}$ $R^2 = 0.9235$ F ratio = 156.8941 Standard Error = 9.9%	$Y_{TD} = -922.1 + 5.925X_{MT} + 66.874X_{SA} + 0.798X_{MA} - 84.57X_{BA} - 1.57X_{TB}$ $R^2 = 0.8663$ F ratio = 84.2247 Standard Error = 11.8%
Y_{AD}: Total Average Delay Per Vehicle on the Major Street (seconds/vehicle)	$Y_{AD} = -321.4 + 0.689X_{MT} + 29.31X_{SB} + 0.134X_{MB} - 3.25X_{BB} - 0.174X_{TB}$ $R^2 = 0.9258$ F ratio = 162.2304 Standard Error = 7.6%	$Y_{AD} = -133.8 + 1.08X_{MT} + 18.56X_{SA} + 0.254X_{MA} - 28.06X_{BA} - 0.30X_{TB}$ $R^2 = 0.9009$ F ratio = 118.1483 Standard Error = 11.5%
Y_{NS}: Total Number of Stops Per Vehicle on the Major Street (stops/vehicle)	$Y_{NS} = -5.344 + 0.0199X_{MT} + 0.712X_{SB} + 0.002X_{MB} - 0.174X_{BB}$ $R^2 = 0.9647$ F ratio = 450.3223 Standard Error = 5.0%	$Y_{NS} = -2.565 + 0.0265X_{MT} + 0.609X_{SA} + 0.0047X_{MA} - 0.725X_{BA}$ $R^2 = 0.9487$ F ratio = 305.0130 Standard Error = 7.0%

TABLE A-10. REGRESSION EQUATIONS FOR EFFECTS ON MAJOR STREET WHEN TWO OR MORE TRAFFIC SIGNALS ARE ADDED

DEPENDENT VARIABLE \ CASE	BEFORE CASE	AFTER CASE
Y_{TD}: Total Delay on the Major Street (vehicles minutes)	$\log Y_{TD} = 2.5634 + 0.00461X_{MT} - 0.000638X_{MB} - 0.002969X_{TB}$ $R^2 = 0.7133$ F ratio = 19.0767 Standard Error = 10.5%	$\log Y_{TD} = 2.3960 + 0.00383X_{MT} - 0.000907X_{MA} + 0.000687X_{TA}$ $R^2 = 0.8090$ F ratio = 32.4675 Standard Error = 7.3%
Y_{AD}: Total Average Delay Per Vehicle on the Major Street (seconds/vehicle)	$\log Y_{AD} = 2.491 + 0.00248X_{MT} - 0.000713X_{MB} - 0.00305X_{TB}$ $R^2 = 0.6141$ F ratio = 12.1997 Standard Error = 9.7%	$\log Y_{AD} = 1.228 + 0.00193X_{MT} - 0.0519X_{MA} - 0.000599X_{TA}$ $R^2 = 0.7033$ F ratio = 18.1725 Standard Error = 6.7%
Y_{NS}: Total Number of Stops Per Vehicle on the Major Street (stops/vehicle)	$Y_{NS} = 9.841 + 0.01466X_{MT} - 0.00892X_{MB} - 0.2123X_{BB}$ $R^2 = 0.8924$ F ratio = 63.5727 Standard Error = 6.6%	$Y_{NS} = 40.83 + 0.0205X_{MT} - 1.215X_{SA} - 0.03645X_{MA} - 0.8683X_{BA}$ $R^2 = 0.8382$ F ratio = 28.4845 Standard Error = 7.2%

TABLE A-11. REGRESSION EQUATIONS FOR EFFECTS ON CROSS STREET WHEN STOP-SIGN CONTROL IS REPLACED BY SIGNAL

Y = Decreased total delay (vehicle minutes)

$$Y^{0.2} = -3.666 + 0.00923X_{MT} + 1.972 \log X_{TA} + 0.559 \log X_{AQ}$$

$R^2 = 0.9271$ $F = 398.68$ Standard Error for Residual = 9.4%

Y = Decreased average delay per vehicle (seconds/vehicle)

$$Y^{0.2} = -2.525 + 0.00952X_{MT} + 1.272 \log X_{TA} + 0.594 \log X_{AQ}$$

$R^2 = 0.9076$ $F = 307.85$ Standard Error for Residual = 10.7%

Y = Number of stops per vehicle for the before case

$$Y^{0.2} = 0.938 + 0.00344X_{MT} + 0.0296 \log X_{AQ}$$

$R^2 = 0.6919$ $F = 106.68$ Standard Error for Residual = 2.0%

Y = Number of stops per vehicle for the after case

$$Y^{0.2} = 0.773 + 0.000325X_{MT} + 0.000296X_{AQ}$$

$R^2 = 0.6910$ $F = 106.23$ Standard Error for Residual = 2.0%

NOTE: $X_{TA} = 1.011X_{TB} + 1.36X_{AQ}$

stops per vehicle that will result from replacing stop signs with signals must be obtained by applying the respective regression equations shown in the lower half of the table for the before and the after case.

SUMMARY

Two methods for evaluating the effect of adding new signals in a coordinated system without using simulation are presented in this chapter. One method, which is intended to provide an easy-to-use technique for quick response in evaluating the possible effects of signalizing one or more intersections in a network, involves defining the network configuration and the traffic operating characteristics listed in Table A-1 for the before-signalization and after-signalization cases. The approximate delay, number of stops per vehicle, or increased number of vehicle trips for appropriate categories of conditions are located in Tables A-2 through A-8. This method requires no calculation; only table lookup.

The other method requires that a series of regression equations be solved in order to get a more refined estimate of the effects of signalizing one or more intersections in a network. A relatively small amount of computation is required to transform the variables and evaluate the equations.

Both methods give approximate quantitative values of the effects of selected types of traffic control. The methods are not recommended for general use since they encompass only a very narrow range of conditions and extrapolation may be very unreliable.

APPENDIX B

CONSTRUCTION OF TIME-SPACE DIAGRAMS FOR COORDINATED ARTERIAL SIGNAL SYSTEMS

A time-space diagram is a valuable aid for developing a workable timing plan for a coordinated arterial signal system and an essential tool for making an engineering evaluation of any selected scheme. The diagram gives a comprehensive view of the relationship among (1) intersection spacing, (2) signal cycle time, (3) artery and cross-street green phases, (4) offset of the beginning of the artery green indication at each signalized intersection, (5) potential crossing time for traffic on unsignalized cross streets, (6) duration of the through-traffic band (if any) in each direction of travel on the artery, i.e. size of platoons, and (7) speed of progression for the through-traffic platoons in the band. A sufficiently accurate diagram for virtually any practical situation involving less than about a dozen signalized intersections along a traffic artery can be drawn in a few minutes on an 8 1/2 x 11 inch or a 11 x 14 inch sheet of paper using only an engineer's scale, two triangles (or a parallel rule), and the cycle split aid shown in Fig B-1.

Before constructing a time-space diagram, basic computations must be made concerning (1) cycle length, and (2) percent of the cycle which will be allocated to the artery green phase at each signalized intersection. The same cycle length, or a multiple thereof, must be used at all intersections in order to maintain synchronization throughout the system. Normally, the cycle length used is the longest needed to handle the traffic at any of the signalized intersections in the system. The percent of the cycle which will be allocated to the artery green phase is computed as a function of the relative traffic demands on the artery and on the cross street. It is usually desirable to have as much green time as is feasible on the artery. Two-phase operation is frequently used for coordinated systems, but multiple-phase control can be used and indicated on the diagrams.

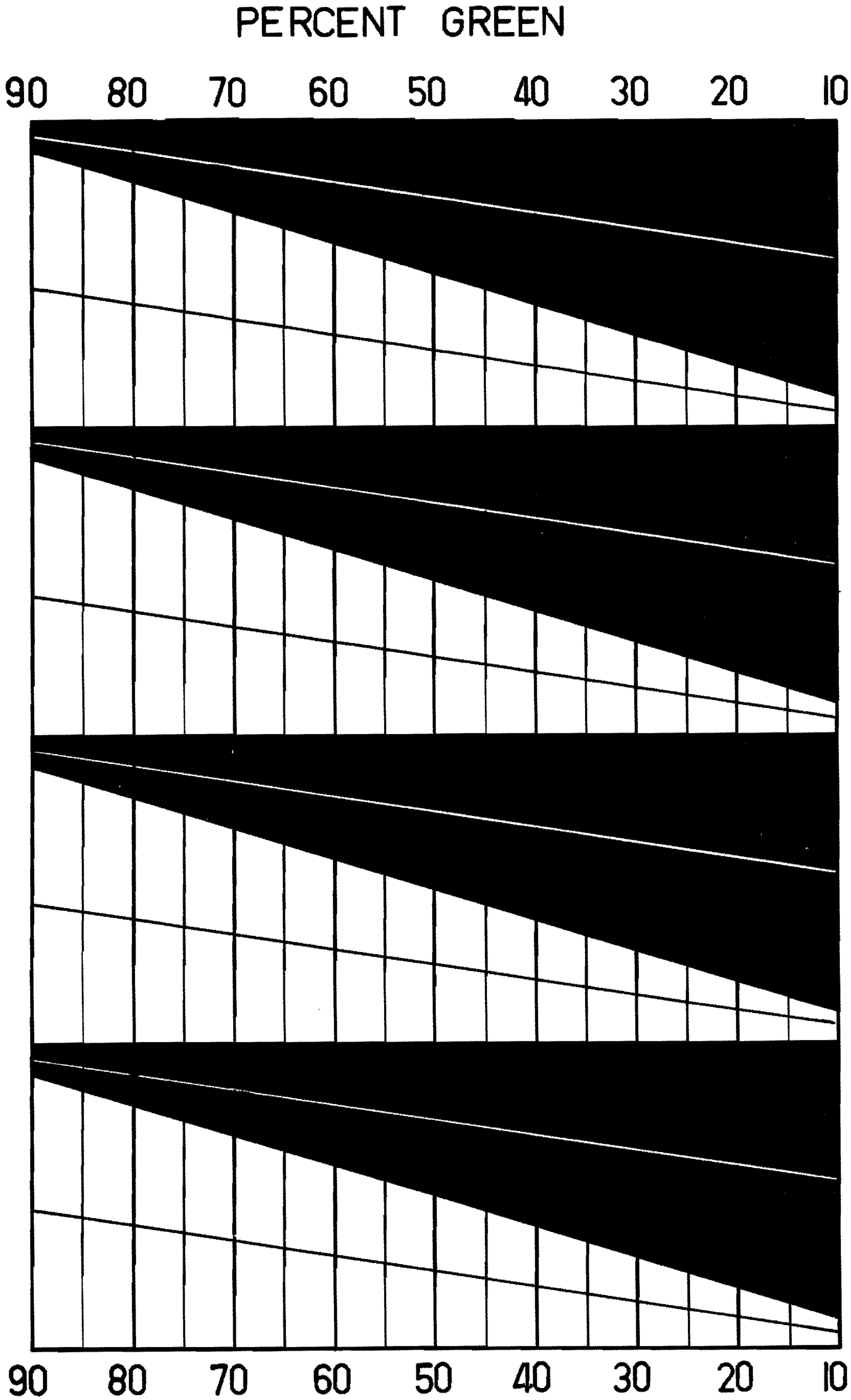


Figure B-1 Cycle Split Aid

Also, before developing the time-space diagram, two objectives must be decided upon. First, a desired speed of progression and the tolerable variations from this speed must be specified. The character of the arterial street and its surrounding will guide the decision concerning reasonable speeds. Second, whether preference will be given to traffic flowing in one direction on the artery or whether both directions of flow will have equal opportunities must be decided. The former case might apply to heavy directional demand on the artery in the morning or evening peak periods while the latter might be best suited for use in off-peak periods when demand is about the same in both directions. Once these decisions are made, a time-space diagram can be constructed.

For the former case, the objective can be obtained simply by offsetting the beginning of the artery green at each intersection so that it coincides with the arrival of the lead vehicle in a platoon traveling on the artery at the desired progression speed in the preferred direction. Traffic in the other direction may or may not experience progression through the system at a reasonable speed without slowing or stopping. A time-space diagram constructed in this way will permit immediate evaluation of the effects of such signal timing on traffic flow in both directions, however.

For the later case, often called the off-peak signal timing pattern, the objective can be met by having equal speed of progression and equal width of the through-traffic band in both directions. A general graphical solution to this problem was developed in the 1950's by James H. Kell when he was teaching at the University of California, Berkeley. His method of constructing a time-space diagram was first presented in traffic engineering course notes there and later summarized in the <u>Transportation and Traffic Engineering Handbook</u>, Institute of Traffic Engineers, Third Edition, 1965, Prentice-hall, Inc., Englewood Cliffs, New Jersey, pp. 818-829. In Kell's Method, the required conditions of symmetry in the slope and width of the through-traffic bands on the time-space diagram is attained by centering either the red or the green arterial signal interval on a reference point (a horizontal line on the time-space diagram shown in Fig B-2) in such a way that the beginning of artery green will be offset properly for a speed of progression within the tolerable range.

The procedure for constructing a time-space diagram for an off-peak timing plan by Kell's Method is illustrated in the following steps for the series of intersections spaced as shown in Fig B-2. For this example, the required cycle length is 80 seconds, and the percent of cycle time that will be allocated to artery green is given at the top of the diagram. The tolerance range for progression speed is 25 to 30 mph. The yellow phase-change interval is included in the artery green.

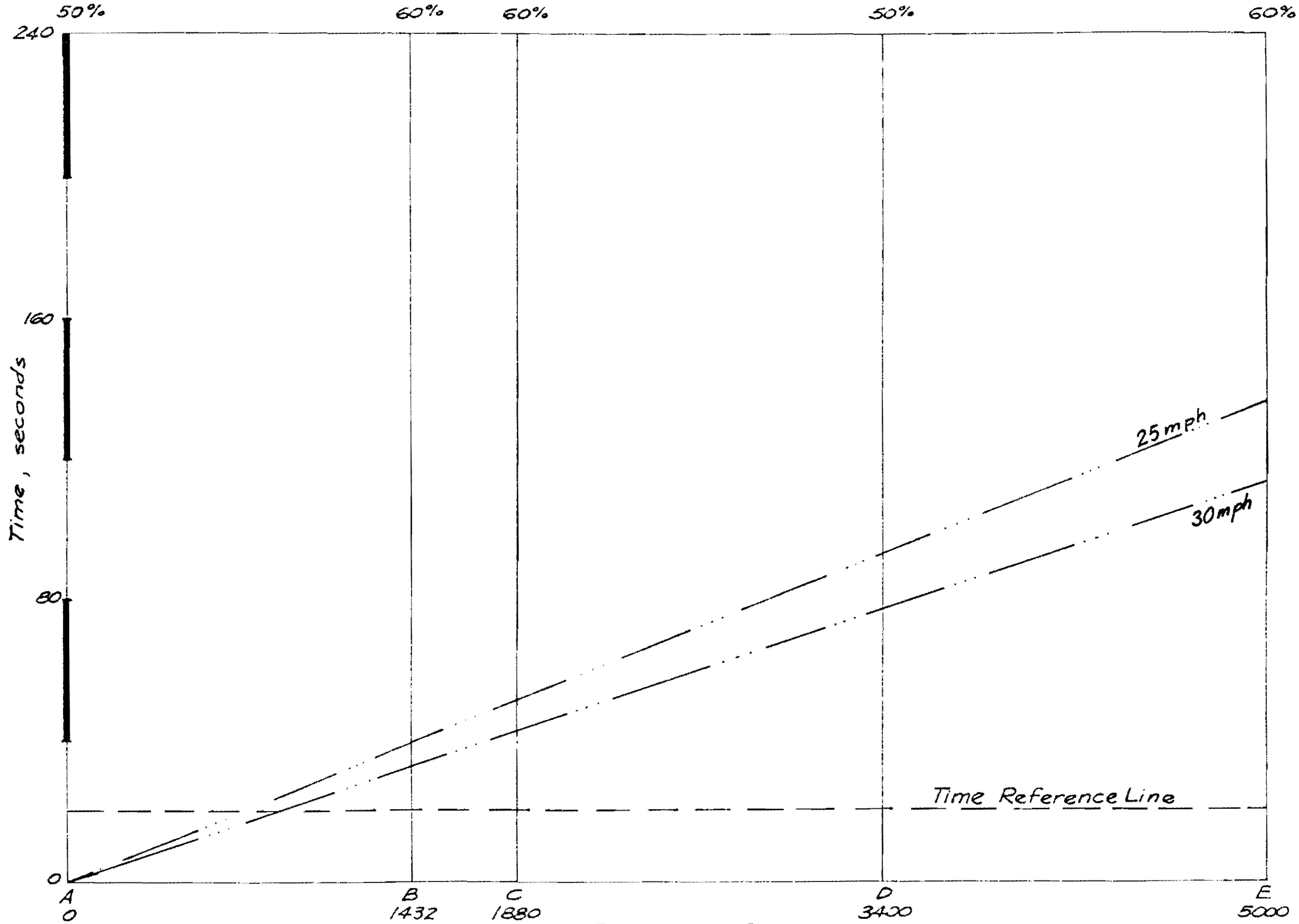
(1) Locate each signalized intersection along the horizontal axis using a scale such that all intersections in the section will fir on the long axis of the sheet (1 inch = 60 feet) and draw a vertical line at each location. Identify each intersection (A through) and note the cumulative distance from the beginning of the section to each intersection. Write the percent of cycle time allocated to artery green at the top of each vertical line which locates the intersection.

(2) Select a vertical scale which makes 2 inches equal to 80 seconds (40 divisions per inch) and graduate the vertical line at the first intersection into 80-second time intervals. (See Fig B-2)

(3) Calculate the time, T, required to travel the full length of the section (5,000 feet) at 25 mph and at 30 mph.

$$T_{25} = (5000)(3600)/(25)(5280) = 136 \text{ sec}$$

$$T_{30} = (5000)(3600)/(30)(5280) = 114 \text{ sec}$$



50%
60%
60%
50%
60%
240
160
80
0
Time, seconds
25 mph
30 mph
Time Reference Line
A
0
B
1432
C
1880
D
3400
E
5000
Distance, feet

Figure B-2

Draw a speed-of-progression line from the origin to each of these times measured along the vertical time line at the 5,000 feet location. Note the speed on each line. (See Fig B-2)

(4) Carefully fold the cycle split aid, Fig B-1, vertically and crease the paper at each percent green value shown at the top of the diagram. This aid was developed by Professor Clyde E. Lee at The University of Texas at Austin in the 1960's for constructing time-space diagrams. With the aid folded, the shading along the crease indicates artery green time by white and artery red time by black. The center of each of these intervals is marked on the aid.

(5) Place the folded aid (at 50 percent) adjacent to the vertical time line at the first intersection (A) with the beginning of artery green (white on aid) at the origin. Mark heavy bars on the diagram along the vertical time line to show artery reds (black on aid), being careful to start and end these bars accurately. also mark the center of the first green interval and draw a horizontal line on the diagram to serve as a reference time at the other intersections. NOTE: The aid may be used at the 5,000 feet intersection to locate the horizontal reference time line accurately on the diagram. The successive green and red signal indications that will be viewed by drivers on the artery as they approach Intersection A are thus shown on the vertical time axis of the diagram.

(6) Next, fold the aid to the percent artery green at Intersection B and align the crease beside the vertical time line at this intersection location. Adjust the aid vertically to center the artery red indication on the horizontal time reference line and notice that the beginning of artery green is offset for a speed of progression of approximately 26 mph and most of the artery green remains to accommodate a platoon from A. This is within the tolerable speed range; therefore, centering artery red is accepted from defining offset at this intersection. Draw bars on the diagram at B with red centered on the time reference line to indicate the red intervals on the artery. If green is centered on the time reference line, only a few seconds of artery green will remain for the platoon from A and a very narrow bandwidth would result. This is, therefore, not an acceptable offset. (See Figs B-3 and B-4)

(7) Repeat the procedure described in 6 above for each signalized intersection in the system. Either artery red or artery green must be centered on the time reference line. The decision as to which is judged with respect to allowing an acceptable speed of progression and maximizing bandwidth (a function of the end of artery green). (See Fig B-5)

(8) Now, the uniform speed of progression for a platoon moving from A to E is determined by fitting a sloping straight line through the beginning of the two artery greens that will provide the highest speed of progression. In the example, B and E control this speed.

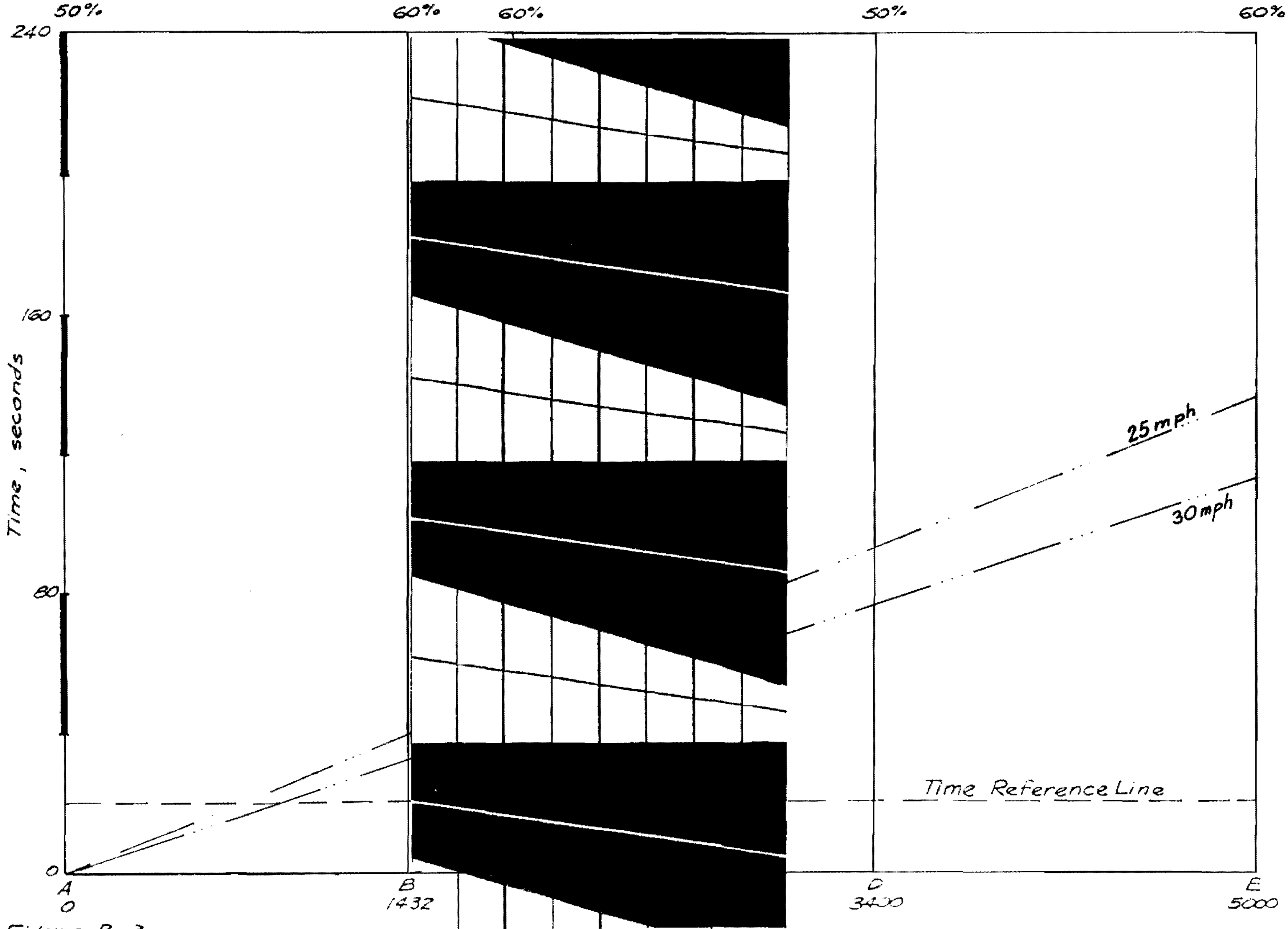

50%
60%
60%
50%
60%
240
160
80
0
Time, seconds
25 mph
30 mph
Time Reference Line
A
0
B
1432
C
3400
E
5000

Figure B-3

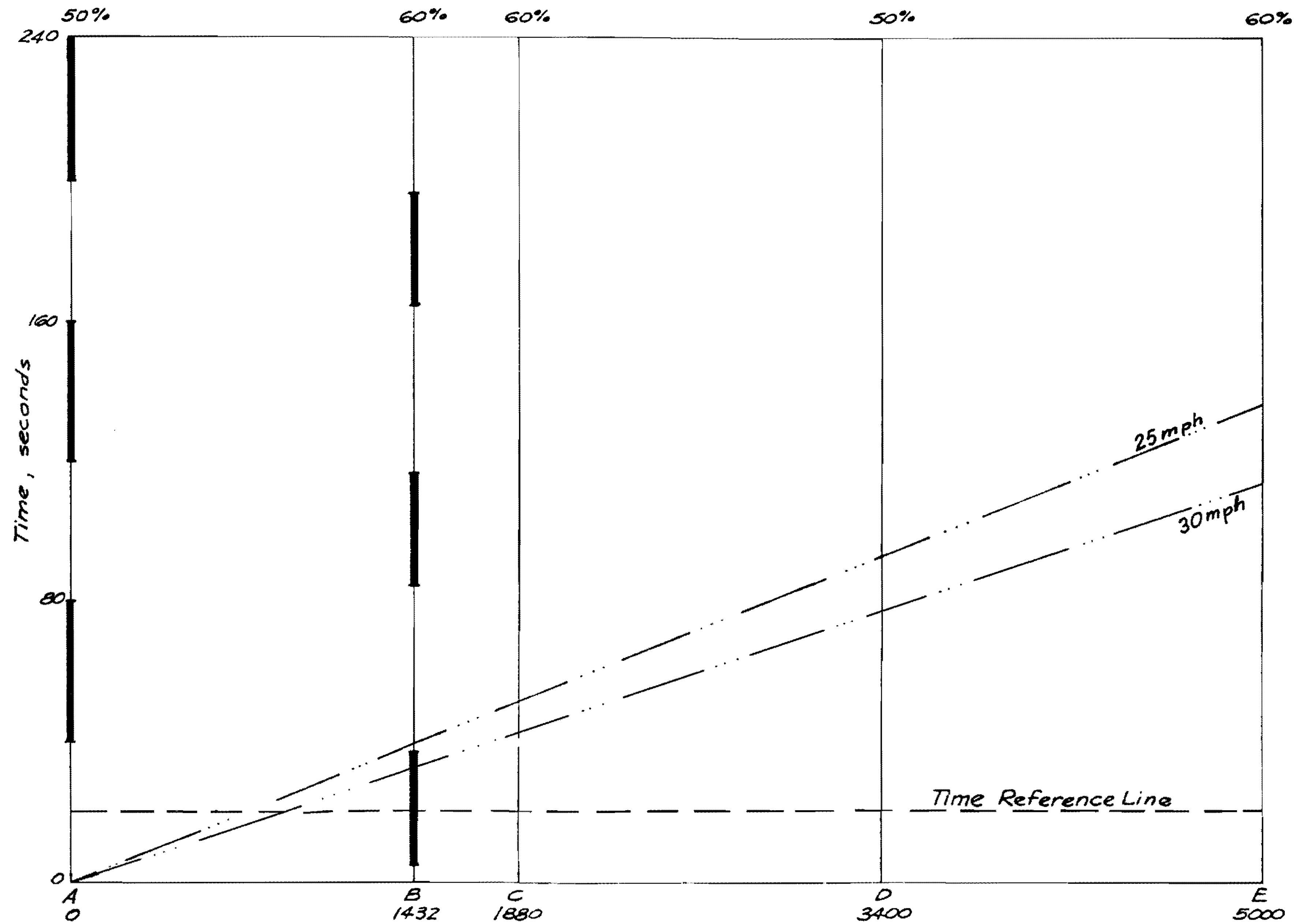

50%
60%
60%
50%
60%
240
160
80
0
Time , seconds
25 mph
30 mph
Time Reference Line
A
0
B
1432
C
1880
D
3400
E
5000
Distance , feet

Figure B-4

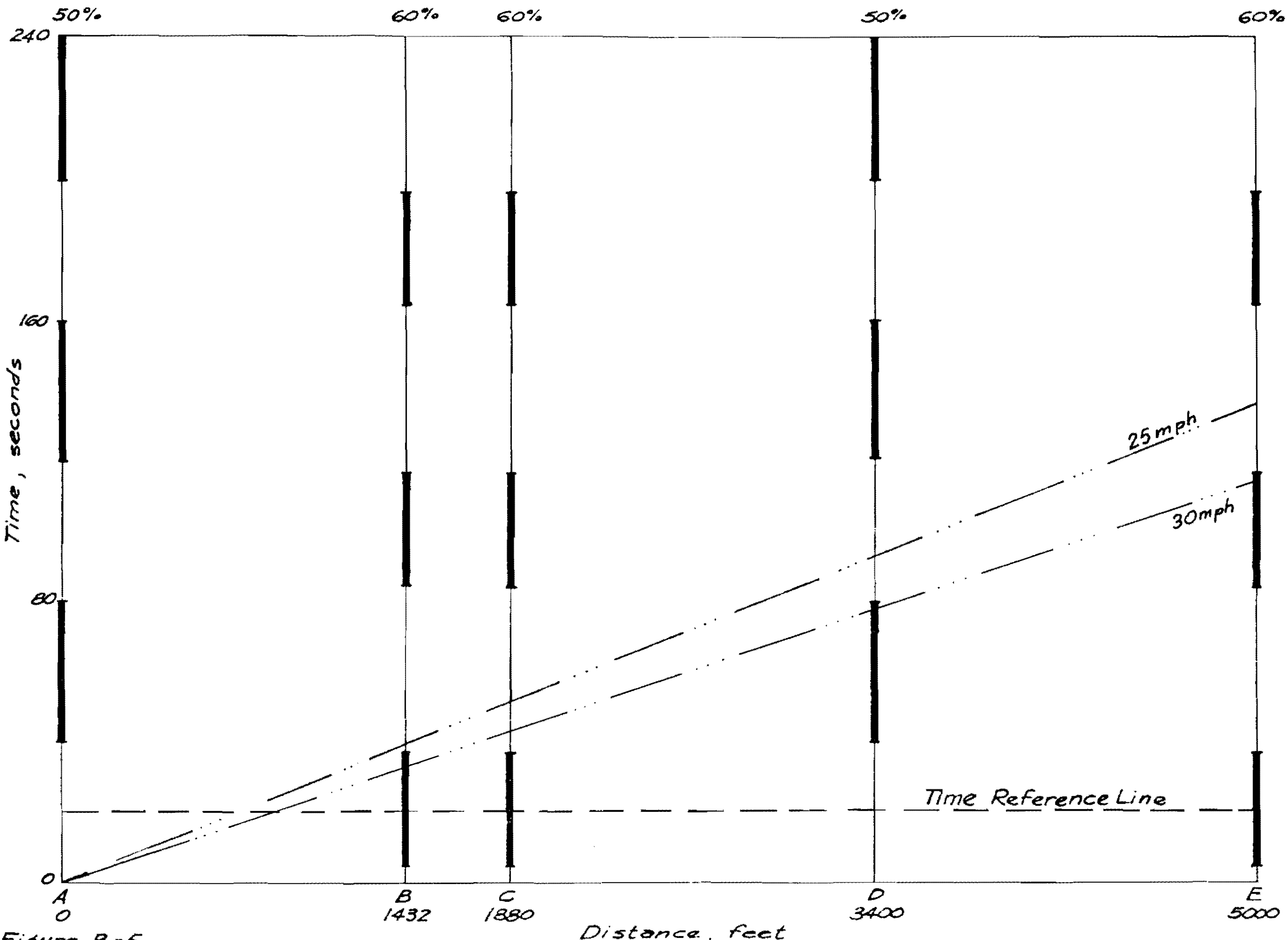

50%
60%
60%
50%
60%
240
160
80
0
Time, seconds
25 mph
30 mph
Time Reference Line
A
0
B
1432
C
1880
D
3400
E
5000
Distance, feet

Figure B-5

(9) Bandwidth is the time allowed for a platoon of vehicles to move completely through the system at uniform speed and is measured on the diagram along the time (vertical) axis. On the diagram, bandwidth is determined graphically by fitting a line parallel to the speed of progression line through the end of the artery green that limits bandwidth most. In the example bandwidth for the platoon from A to E is controlled by the end of green at A. Draw the parallel line to define bandwidth. Actual bandwidth can be measured in seconds on the diagram with a scale (1 inch = 40 seconds). Bandwidth is 35 seconds in the example.

(10) An exact mirror image of the through-traffic band from A to E can e drawn on the diagram for traffic moving from E to A. The controlling times are indicated by circles on the diagram (Fig B-6). This completes the construction of the time-space diagram.

(11) Offsets for setting the signal controller at each intersection can be scaled from the diagram with adequate precision for practical purposes, but they can also be calculated from the relative time values shown on the diagram.

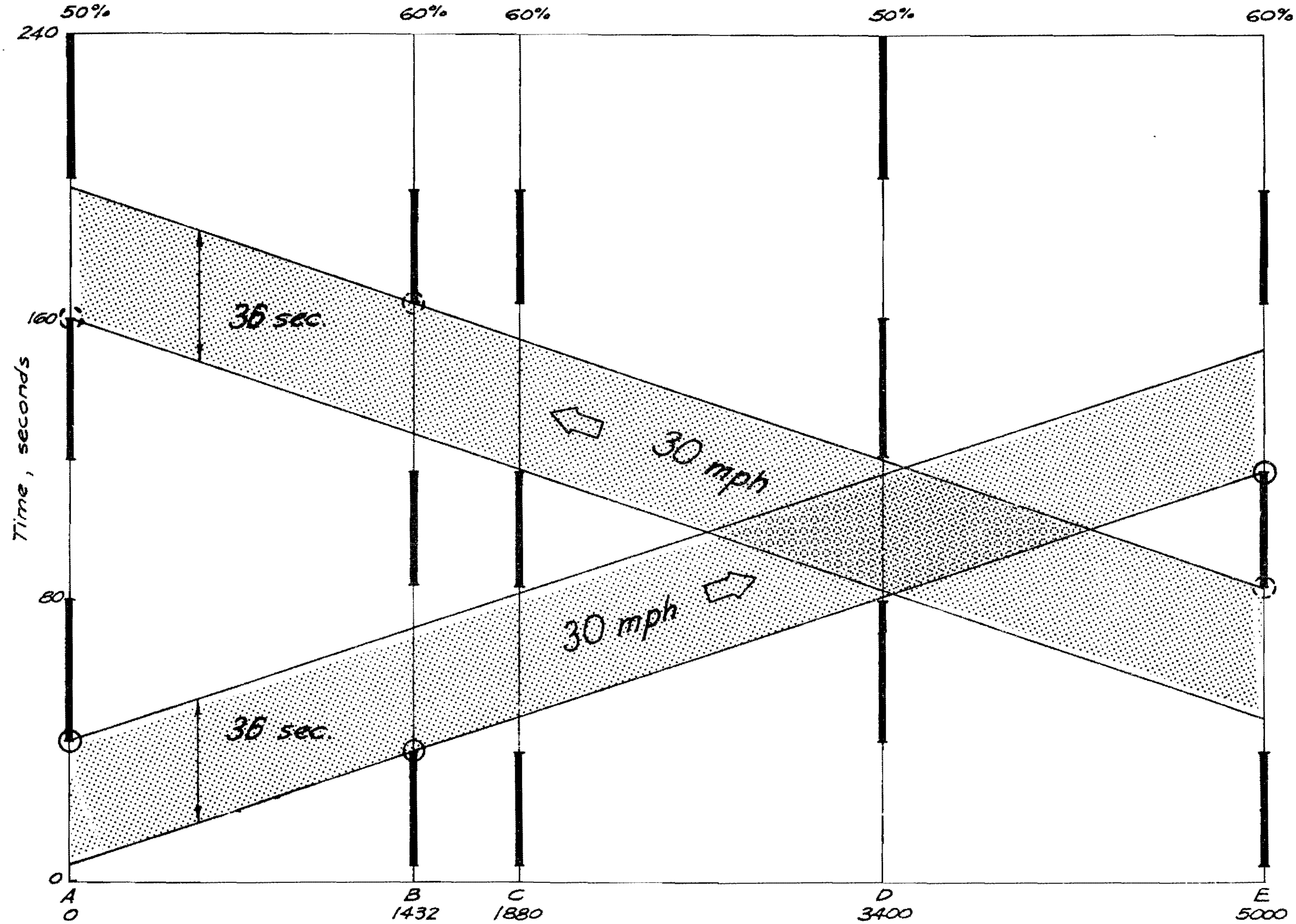

50%
60%
60%
50%
60%
240
160
80
0
Time, seconds
36 sec.
36 sec.
30 mph
30 mph
A
0
B
1432
C
1880
D
3400
E
5000
Distance, feet

Figure B-6