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16. Abstract

This document provides guidelines and procedures for the retiming of arterial street networks, including procedures for data collection, and the types and amount of data to be collected; the analytical procedures and software packages that are available for signal retiming projects; and examples of step-by-step applications for each type of signal retiming project.

Section One, Introduction, provides background information and discusses how to determine if a signal should be retimed. Section Two, Arterial Street Networks, discusses the characteristics of arterial street networks, including the types of phasing, controllers, measures of effectiveness, and signal timing methods. Section Three, Data Requirements, discusses the procedures and requirements for data collection in an arterial street network.

Section Four, Evaluation, provides information needed for the simulation of existing network operations, including the use of various software programs currently available. Section Five, Optimization, provides the guidelines to optimize timings in a typical arterial street network. Section Six, Implementation, explains the interpretation of optimized signal plans and implementation in the field. Section Seven, Documentation, explains how the benefits of signal retiming can be calculated, and provides examples of possible benefits.

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IMPLEMENTATION GUIDELINES FOR

RETIMING ARTERIAL NETWORKS

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TEXAS TRANSPORTATION INSTITUTE
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College Station, Texas 77843-3135

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	2.54	centimeters	cm
ft	feet	0.3048	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	6.452	centimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.395	hectares	ha
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	millimeters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0328	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3

Note: Volumes greater than 1000 L shall be shown in m^3.

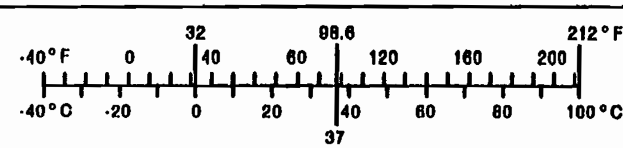
Symbol	When You Know	Multiply By	To Find	Symbol
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

These factors conform to the requirement of FHWA Order 5190.1A

*SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
yd	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
yd^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.53	acres	ac
		MASS (weight)		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	millimeters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



IMPLEMENTATION STATEMENT

The objective of this study is to place in a single set of documents, implementation guidelines for traffic signal retiming projects in Texas. These documents include the types and amounts of data to be collected, and the procedures for doing so; the analytic procedures and software packages that are available and the types of projects for which they are suited; and examples featuring step-by-step applications for several typical signal retiming projects in Texas. This set of documents also would include field implementation and evaluation guidelines. Specific types of signal retiming projects addressed by this study are as follows:

1164-1	Implementation Guidelines for Retiming Isolated Intersections;
1164-2	Implementation Guidelines for Retiming Arterial Streets;
1164-3	Implementation Guidelines for Retiming Diamond Interchanges;
1164-4	Implementation Guidelines for Retiming Arterial Networks; and
1164-5	Implementation Guidelines for Retiming Freeway Corridors.

The objective of this document is to provide implementation guidelines and procedures for retiming signalized arterial networks.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation and is NOT INTENDED FOR CONSTRUCTION, BIDDING, OR PERMIT PURPOSES.

ACKNOWLEDGEMENT

The research reported herein was performed as part of a study entitled "Implementation Guidelines for Traffic Signal Retiming Projects" by the Texas Transportation Institute and sponsored by the Texas Department of Transportation in cooperation with the U. S. Department of Transportation, Federal Highway Administration. Dr. Daniel B. Fambro, P.E. No. 47535 (Texas) of the Texas Transportation Institute served as the research supervisor, and Mr. Herman H. Haenel and Mr. Charles Riou of the Texas Department of Transportation served as technical coordinators.

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1.0 INTRODUCTION

1.1 Background

With urban congestion increasing and available funding decreasing in Texas cities, Texas Department of Transportation (TxDOT) personnel face the growing problem of developing low-cost solutions to increase the capacity of signalized intersections and arterial streets. This problem is compounded by both the state's assumption of the maintenance of traffic signals in cities between 15 and 50 thousand in population and at freeway-frontage road interchanges and the initiation of the Primary Arterial Street System (PASS) program for larger cities.

Some of the lowest cost methods of dealing with capacity problems are traffic signal retiming projects. Signal optimization and retiming projects have received increased attention as a cost-effective and transportation systems management (TSM) measure. Results from several studies demonstrate that substantial energy savings can be achieved through the development of improved timing plans on existing signal systems. Also, unnecessary delays and stops at traffic signals are eliminated, resulting in travel time savings for the public.

The development of efficient signal settings requires detailed data collection of traffic and geometric conditions, application of improved methods to optimize signal timing plans, and field implementation and evaluation of the improved signal timings. Several techniques and computer programs have been developed, and are available to traffic signal analysts to analyze existing conditions and optimize signal timing to minimize delays and stops and improve traffic progression.

Because of the diversity of retiming project types and the number of techniques and tools available, however, no single procedure or set of guidelines exists which applies to all projects. Field implementation and evaluation guidelines also are virtually nonexistent in the literature. In addition, most districts do not undertake such projects on a routine basis. For these reasons, it would be beneficial if a set of guidelines and procedures for several types of typical traffic signal retiming projects were available to each district. These guidelines should cover not only the development of new timing plans, but also their subsequent implementation and evaluation.

1.2 Objectives

This study places implementation guidelines for traffic signal retiming projects in a single set of documents. These documents would include the types and amounts of data to be collected, the procedures for doing so, the analytic procedures and software packages available, the types of projects for which they are suited, and examples featuring step-by-step applications for several typical traffic signal retiming projects in Texas. This set of documents also would include field implementation and evaluation guidelines. Specific types of retiming projects addressed are as follows:

1164-1	Implementation Guidelines for Retiming Isolated Intersections;
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1164-3	Implementation Guidelines for Retiming Diamond Interchanges;
1164-4	Implementation Guidelines for Retiming Arterial Networks; and
1165-5	Implementation Guidelines for Retiming Freeway Corridors.

This document provides individual guidelines and procedures for retiming arterial networks. This document includes the procedures for data collection, the types and amounts of data to be collected, and the analytical procedures and software packages available for each type of arterial network traffic signal retiming project.

1.3 Organization

This document provides guidelines and procedures for developing and implementing traffic signal retiming plans for signalized intersections in an arterial network. Separate documents address other types of traffic signal retiming projects. The guidelines and procedures for retiming signalized intersections in an arterial network are organized as follows:

1.0 Introduction
- 1.1 Background
- 1.2 Objectives
- 1.3 Organization
- 1.4 When to Retime Signals in an Arterial Network

2.0 Arterial Networks
- 2.1 Introduction
- 2.2 Types of Networks
- 2.3 Types of Phasing
- 2.4 Types of Control
- 2.5 Signal Timing Methods
- 2.6 Coordination Methods
- 2.7 Measures of Effectiveness

1.4 When to Retime Signals in an Arterial Network

Public complaints are usually the first signs of signal operational problems. Traffic signal retiming cannot address all complaints, but the complaints indicate a need for at least a field observation and/or possibly an engineering study. Some common complaints include: excessive approach delay, left-turn delay, poor progression, and excessive queues. One can make field observations to determine the legitimacy of the complaints. Major problems will be obvious to the observer, such as long queues, ineffective use of green times, and excessive cycle lengths (greater than 150 seconds). In some cases, equipment, such as detectors, may need repair. If one rules out these problems, retiming may be a solution to improving the signal's operational efficiency. As a rule of thumb, field observations or studies should be made every three to five years to determine if signal retiming program is necessary.

Changes in traffic flow caused by land use and population changes, addition or deletion of signals in the area, changes in major traffic generators and changes in the geometrics of the roadway or intersection may also create the need for retiming signals. Some jurisdictions recommend yearly inspection and documentation, by field data and/or video, of their traffic signal operations. This type of documentation will help identify operational problems before they become severe.

2.0 ARTERIAL NETWORKS

2.1 Introduction

A number of signalized intersections connected by one or more closely spaced arterial streets and/or one-way streets comprise an arterial network system. The primary function of any street system is to provide mobility. Given adequate design and access features, mobility in a network can be provided through signal coordination that allows vehicles to progress through a series of signals without stopping. Some of the problems that occur in an arterial network as a result of poor or outdated signal timing and increasing or changing traffic demand include:

1. Lack of progression causing excessive stops and low average travel speed;

2. Queue spillback into upstream intersections because of close spacing of intersections, causing gridlock to occur;

3. Inadequate phase capacity at intersections causing an additional amount of overflow traffic delay to occur and creating a bottleneck in the system; and

4. Heavy pedestrian demand at intersections requiring long minimum greens and impeding right turning traffic.

The following sections describe the types of arterial street networks; types of phasing and controllers used at intersections in an arterial street network; methods of timing networks and coordinating the signals in an arterial network; and the measures of effectiveness used to evaluate an arterial network's performance.

2.2 Types of Networks

Traffic signal analysts classify arterial street networks into various categories based on the structure and/or complexity of the network. Networks can consist of a single arterial street intersecting another arterial street (simple open network), a single arterial street intersecting several other arterial streets (multiple open network), an arterial system consisting of a pair of one-way streets (one-way pair), and a grid of closely spaced arterial streets (closed network). Figure 3-1 illustrates each of these classifications.

Simple Open Network. A simple open network consists of two arterials or major streets crossing each other. Such systems are either operated in a pretimed mode or in a semi-actuated coordinated mode. In order to provide progression on both arterials, analysts must select a common cycle length. The common cycle length selected should be suitable for the critical intersection(s) in the system, which is typically the intersection of the two arterials.

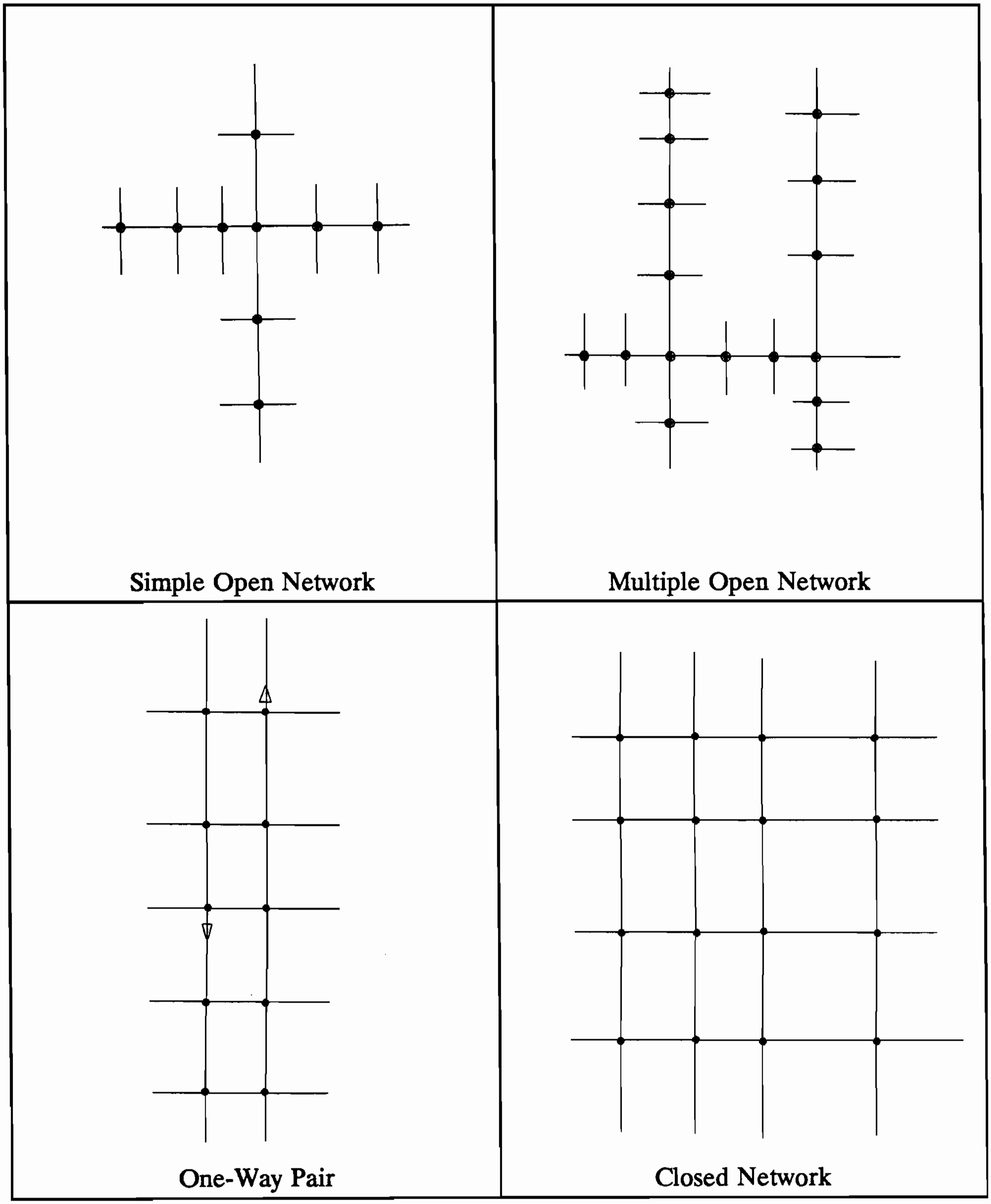


Figure 2-1. Example of Types of Network

Multiple Open Network. A multiple open arterial network consists of several arterials crossing each other. Like simple open arterial networks, such systems operate either in a pretimed or a semi-actuated coordinated mode. In order to provide progression on the arterials, one selects a common cycle length for all the intersections in the system. The traffic demand at the critical intersection in the system usually provides the basis for the selection of the common cycle length.

One-Way Pair Network. One-way pair networks consist of an arterial running on two streets, with each street having one-way operation; i.e., progression is provided only in one direction on each street. These two parallel streets stand a very short distance apart. Thus, minimizing the queue lengths at the intersection approaches between the two streets is of utmost importance. One-way operation may increase the overall vehicle miles of travel; however, it simplifies progression solutions and reduces stops due to the absence of opposing flow for the left turns, and generally results in an overall improved system performance.

Closed Network. A closed arterial network consists of a number of two-way and/or one-way streets forming a grid-like structure. One can find such networks in central business districts. They are normally characterized by closely spaced intersections and usually operate in a pretimed coordinated mode. Some important streets in such networks also operate in flashing mode during off-peak condition (night time), by flashing yellow on the main street and flashing red on the cross-streets. As mentioned earlier for a one-way pair network, a closed network if properly operated can result in an overall improved system performance.

2.3 Types of Phasing

One can divide the descriptions of the type of phasing at each intersection in the arterial street network into three parts: individual movement numbers, type of left-turn treatment, and phasing sequence. The following paragraphs describe each of these parts.

Movement Numbers. Most methods of signal timing analysis use the NEMA configuration for numbering movements, as shown in Figure 2-2. Each NEMA movement corresponds to a separate phase in an Eight-phase dual ring NEMA controller. Combinations of these movements are also considered as phases. To number the movements, start with Movement 1, (usually a left turn movement) and move clockwise numbering each left turn 3, 5, and 7. Movement 2 (usually a through movement) always lies across from Movement 1, and is usually chosen to represent the forward direction along the arterial (i.e., the direction in which the intersections are numbered or sequenced). After selecting the direction for Movement 2, proceed clockwise to number the remaining through movements 4, 6, and 8. For arterial street networks, movements 2 and 6 represent coordinated movements on one arterial, and movements 4 and 8 represent coordinated movements on crossing arterials.

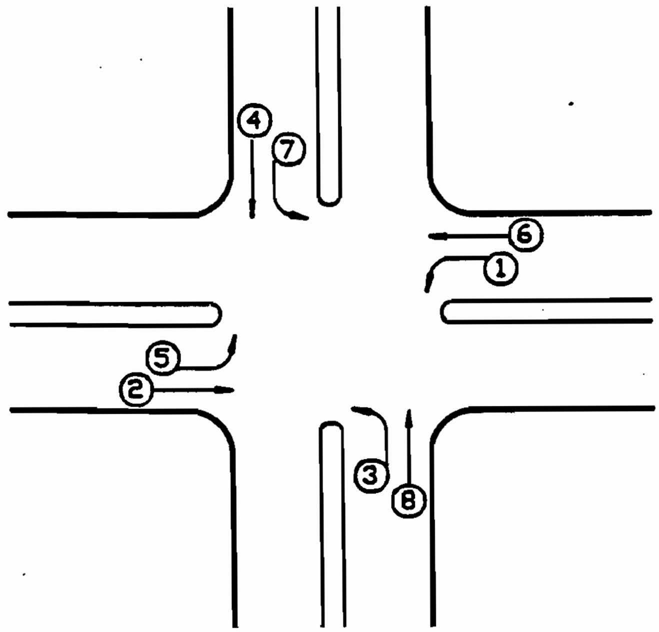


Figure 2-2. Movement Numbering Scheme for an 8-Phase NEMA Controller

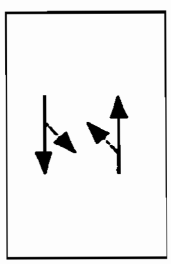
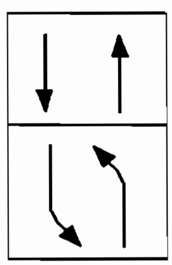
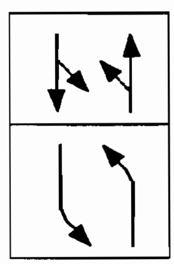
Geometry	Permitted Phasing (PM)	Protected Phasing (PR)	Combined Phasing (PP)
No Bay	1	2	3
Bay	4	5	6
Phasing			

Figure 2-3. Left-Turn Treatment Alternatives

Note that Movement 1 conflicts with Movement 2, Movement 3 conflicts with Movement 4, Movement 5 conflicts with Movement 6, and Movement 7 conflicts with Movement 8. Thus, these movement pairs are called conflicting movements, and as a result of this conflict, they cannot have a green indication at the same time. This general rule serves as the basis for the signal timing methodologies and hardware described in this report.

Left-Turn Phasing. Phasing schemes can be classified by the type of left-turn treatment that exists at the intersection. Left-turn movements can be permitted only, protected only, or protected-plus-permitted (combined), as illustrated in Figure 2-3 and described below:

Permitted - Left-turns must yield to opposing traffic. Drivers may proceed on a green ball after yielding to oncoming traffic.

Protected - Left-turns proceed separately from opposing traffic. Drivers may proceed either during a green left-turn arrow phase or during the time that opposing movements are stopped (i.e., the split phase).

Protected/Permitted - Left-turns are protected during part of the cycle and permitted in another part of the cycle. Drivers may proceed either during the protected left-turn phase or on a green ball after yielding to oncoming traffic.

Phase Sequence. The order in which the phases are displayed at a signalized intersection is called the phase sequence. Protected left-turn phases may be leading, lagging, lag-lead or lead-lag for the arterials and the cross-streets in the network. It is fairly common for the phasing sequence on the arterial streets to be different from the phasing sequence on the cross-streets. It also is not unusual for different intersections to have different phasing sequences on an arterial in order to improve progression.

Leading lefts - Both protected left-turn movements proceed before the through movements.

Lagging lefts - Both protected left-turn movements proceed after the through movements.

Lag-lead/lead-lag - One protected left-turn movement and its adjacent through movement proceed before or after the opposing protected left-turn movement and its adjacent through movement.

If the duration of the phases serving the two concurrent movements equal one another (i.e., the concurrent phases start and end at the same time), analysts describe the phasing as "without overlap" phasing. If the duration of the phases serving the two concurrent movements are not equal (i.e., the concurrent phases start at the same time, but end at a different time), one describes the phasing as "with overlap" phasing. These two phasing sequence descriptors are analogous to single and dual ring control, respectively. One should note that the terminology for describing phase sequences may vary between signal timing software and traffic controller hardware. Thus, it is important in signal retiming projects to check phasing output and controller input descriptors for differences in terminology.

2.4 Types of Control

The type of controllers at intersections in an arterial street network affect the number of timing plans that can be implemented, as well as the number of allowable phases and sequences at individual intersections. One typically operates a coordinated arterial network in one of two ways. First, analysts may control the arterial street network system by predetermined signalization schemes designed to accommodate anticipated traffic demands. This type of control is referred to as pretimed operation. Second, one may control the arterial street network system through signalization strategies that maintain progression, but respond to current traffic demands at the intersections. This type of control is known as actuated or semi-actuated operation.

Pretimed Coordinated Control. Under pretimed control, analysts assign right-of-way in a predetermined manner and coordinate signal timings and phases at intersections to provide for progression on arterial streets in the network. The major elements of pretimed control are fixed cycle length, fixed phase sequence, fixed phase length, and fixed offsets. Depending on the type of equipment available, one may use several different signal timing plans; the appropriate timing plan is implemented automatically at fixed times of the day, usually with one timing plan for the a.m. peak period, one timing plan for the p.m. peak period, and one timing plan for the off-peak period.

Pretimed operation is recommended for certain types of design and operational conditions. Design conditions that benefit from coordination are predominantly associated with intersection spacing. Generally, as the distance between traffic signals decreases, the need for coordination increases. Signal spacing may range from 150 to 5000 feet, but spacings between 800 and 1000 feet have proven ideal for coordination.

Traffic conditions that benefit from pretimed arterial coordination include ones where a limited number of traffic patterns exist, and there is no significant changes in these traffic patterns. Peak periods with heavy directional traffic volumes provide additional conditions where pretimed coordinated control proves advantageous. If more than three phases are required, however, pretimed control generally is not recommended.

For pretimed operations, two types of controllers exist: electromechanical (which are still in use but no longer manufactured) and solid state. The electromechanical controller is comprised of one or more dials (usually no more than three) driven by a synchronous motor. Each dial corresponds to a different cycle length; for example, one dial for the a.m. period, one dial for the p.m. period, and one dial for the off-peak period. A solid state controller is similar to an electromechanical controller, except the mechanical parts (the dial units, camshafts, and keys) are replaced by solid state components. Operations are controlled by a microprocessor. For more details about the hardware, refer to the *Traffic Control Systems Handbook* (1). One should note that the Texas Department of Transportation (TxDOT) no longer purchases pretimed controllers. Rather, full actuated controllers are purchased and then used as pretimed controllers when conditions warrant.

Semi-Actuated Coordinated Control. Semi-actuated coordinated control is suited for arterial streets where traffic patterns are unpredictable and demand varies. Traffic actuated control attempts to adjust green times, and in some cases skip minor phases to provide additional green time where vehicular demand warrants it. Detectors placed in the approach lanes provide demand information to the controller. The basic timing parameters are yellow plus red clearance times, minimum green times, green extension interval, and maximum green interval. Definitions for these basic timing parameters follow:

Yellow plus red clearance time - The portion of time that occurs at the end of the phase and provides adequate time for all vehicles to safely exit the intersection. This parameter is based upon the speed of the vehicles traveling through the intersection, the width of the intersection, and/or driver expectancy.

Minimum green time - The length of time considered to be the shortest amount of time that a signal display is allowed to be green. This parameter is usually based upon pedestrian walk time or the location of the detector. The actual green time cannot be less than the "minimum green" time.

Extension interval - The portion of time that the green interval can be extended is based on detector location. A minimum extension time should allow a vehicle sufficient time to travel from the point of detection to the stop line or in the case of multiple detection, time to travel from the point of detection to the next detector.

Maximum green interval - The maximum green interval is the longest time a green indication will be displayed in the presence of a call on a conflicting phase.

When specifying controller settings for coordinated semi-actuated controllers, the following signal timing parameters may be encountered:

Yield Point - The yield point is the earliest point at which the coordinated phase can end to give right of way to one or more of the conflicting phases. The yield point normally occurs at the beginning of the yellow interval (end of the green interval) of the coordinated phase.

Force-off - The force-off point is the fixed point/points in the background cycle length used to give right of way to one or more of the conflicting phases. Force-off points are calculated by adding the splits for each phase beginning with the start of the interval to which the yield point is referenced.

Figure 2-4 illustrates the above definitions of yield and force-off points.

There are two basic hardware designs for actuated controllers: the Type 170 and the NEMA standard. NEMA (National Electrical Manufacturers Association) controllers meet specifications whose standards reflect input from traffic engineers, installers of traffic signal equipment, and professionals in the field of traffic control. The NEMA specifications describe physical and functional requirements for fully actuated signal controllers. Type 170 controllers were jointly developed by the states of California and New York. These controllers require software to operate. Updating the inputs in the software accommodate changes in traffic conditions. For more information on these controllers, refer to *Traffic Control Systems Handbook* (1). It should be noted that TxDOT only purchases full actuated controllers conforming to NEMA standards, and that they have developed a set of standard specifications for their controllers.

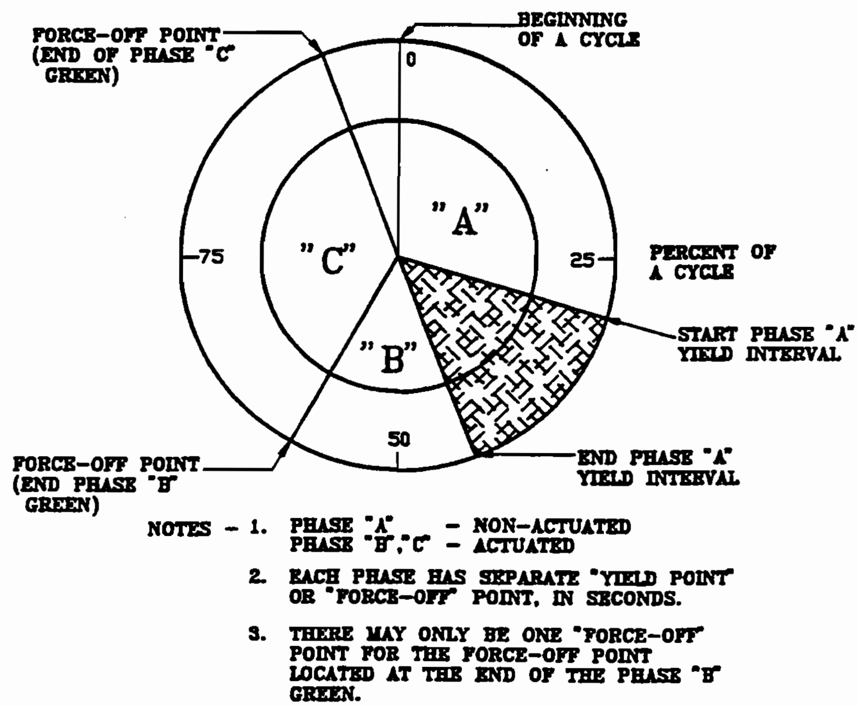


Figure 2-4. Yield Point and Force-Off Point for Semi-Actuated Controller

Actuated coordinated control of arterial streets in networks is predominantly at the semi-actuated operational type. The fundamental premise of semi-actuated arterial control provides the main streets with as much green as possible and only service the minor intersecting cross-streets and left-turn phases in response to traffic demand. Actuated arterial signals operate on a common background cycle, and force-off points provide synchronization. Coordination is provided for the arterial street phase (sync phase), which is commonly not actuated. Actuated phases tend to consist of those serving the minor cross-street and the main street left-turn movements.

Actuated controllers can either be single-ring (sequential) or dual-ring (concurrent), and can provide different combinations of phase sequences. Single-ring controllers are four-phase controllers that, handle each phase sequentially and return to the first phase at the end of the series. A specific preferred phasing sequence is used, and phases cannot occur simultaneously (overlap cannot be used). Figure 2-5 illustrates single-ring control with leading lefts on both the arterial and cross-streets.

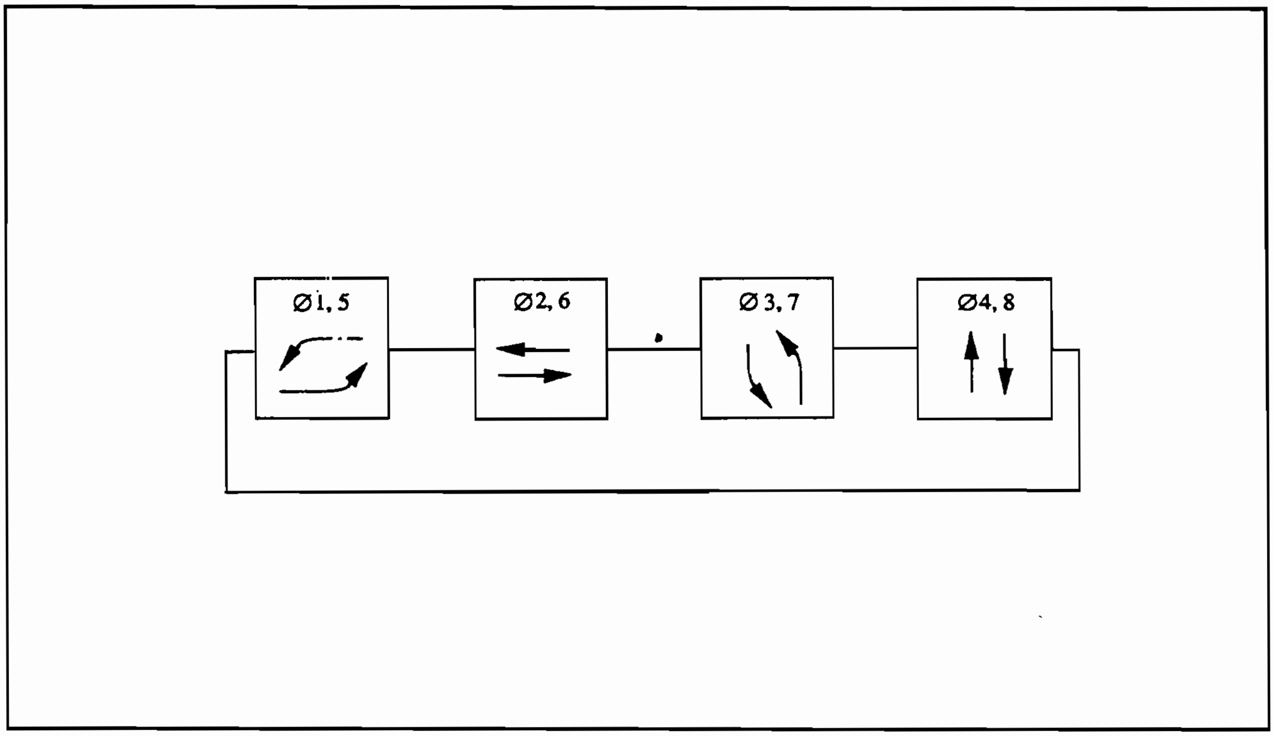


Figure 2-5. Phase Sequence for Single-Ring Control

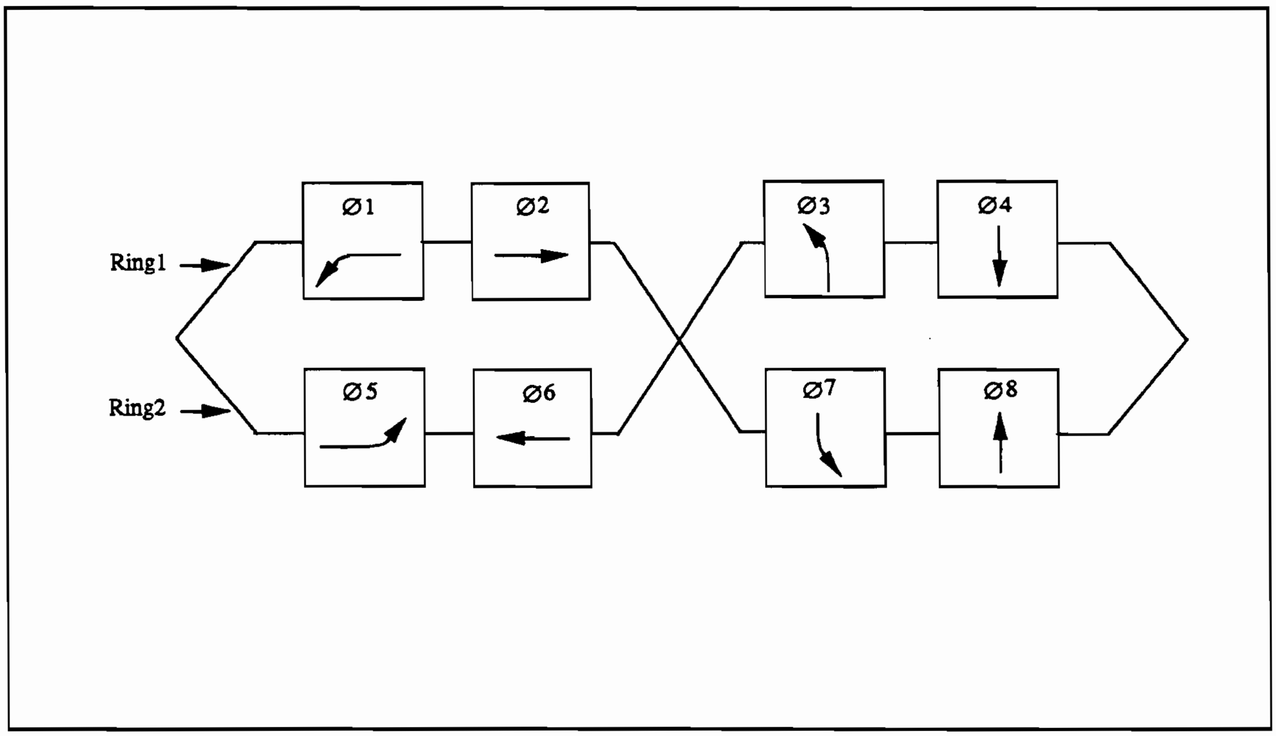


Figure 2-6. Phase Sequence for Dual-Ring Control

Dual-ring controllers can accommodate eight-phases corresponding to the eight movements at an intersection. One may use concurrent timing which allows a traffic phase to be selected and timed simultaneously and/or independently with another phase. Phases may be skipped and overlap phasing can be used. Figure 2-6 illustrates dual-ring control, with leading lefts on both the arterial and cross streets. Note that any phase to the left of the barrier in Ring 1 can be displayed simultaneously with any phase to the left of the barrier in Ring 2; i.e., they are non-conflicting phases. The same relationship holds true for phases in Ring 1 and Ring 2 to the right of the barrier.

The type of control selected may affect intersection operation. At low to moderate volume to capacity ratios, actuated controllers are almost always more efficient than pretimed controllers because of the capability of adjusting green times and/or skipping phases in response to variations in vehicular demands. In fact, even at conditions approaching capacity, there is still enough variation in vehicular demands, particularly relative to left-turn phases, that actuated controllers can be more efficient than pretimed controllers. In addition, actuated controllers are more responsive to high volume conditions because their maximum cycle lengths are generally longer than optimal pretimed controller cycle lengths.

2.5 Signal Timing Methods

For a network to operate effectively, the signal timing at the individual intersections in the network must be optimized. Signal timing at individual intersections attempts to find a "best" solution, characterized by a cycle length and green splits that accomplish a traffic signal retiming objective such as minimizing delay, fuel consumption, or excessive queuing. Analysts must coordinate the timing for individual intersections to achieve the same objective for the major streets in the network (i.e., an optimum timing plan for all intersections on major arterials). One should note that the common cycle length for all intersections may not be the best cycle length for each individual intersection.

One must consider the traffic characteristics at different times of the day when coordinating the signals. During peak hours, a directional distribution of the traffic may exist; i.e, during the morning peak, most of the traffic could move in one direction, while in the afternoon peak, most of the traffic could move in the opposite direction. In such cases, progression can be provided exclusively for the traffic moving in the peak direction. During off-peak conditions, analysts may provide progression in both directions. The best solution depends on the characteristics of the networks, intersection spacing, commercial developments in the vicinity, traffic characteristics, and the objective of the traffic signal analyst.

One signal timing method often used for retiming intersections is based on equations developed by Webster (2). Equations for estimating minimum delay cycle length and green splits are based on Webster's original work. The following questions discuss each of these equations.

Minimum Delay Cycle. Analysts often use delay as a measure of effectiveness to determine the efficiency of a signalized intersection's operation. Figure 2-7 illustrates the variation in delay with cycle length and the equation and location for Webster's minimum and minimum delay cycle lengths. Figure 2-8 illustrates the variation in minimum delay cycle lengths at various volume levels. Note that a minimum delay cycle exists for each and every volume level, and if traffic volumes fluctuate during the day, an intersection may have a different minimum delay cycle length, and the optimum phasing sequence may vary. Note also that adjacent intersections with different traffic volumes may have different minimum delay cycle lengths. Webster's equation for calculating the minimum delay cycle is as follows:

$$C_o = (1.5\ \Sigma L + 5) / (1 - \Sigma Y) \qquad [2\text{-}1]$$

where:
- C_o = minimum delay cycle length in seconds;
- ΣL = sum of the lost times for critical phases in seconds; and
- ΣY = sum of the critical flow ratios, $y_1 + y_2 + ... + y_i$ (y_i = volume for critical movement i divided by the saturation flow rate for critical movement i).

The range of cycle lengths that provides acceptable average delays (near minimum delay) at a typical intersection equals $0.8\ C_o < C < 1.5\ C_o$. Cycle lengths shorter than this range generally prove too short to handle the traffic volumes, and cycle failures (oversaturation) will occur. Cycle lengths longer than this range generally prove longer than necessary to handle the traffic volumes and wasted time resulting in long delays will occur.

After calculating the minimum delay cycle length for all intersections in the arterial street network, the largest minimum delay cycle length (i.e., the maximum of the minimums) is selected as the shortest cycle length for the system (the cycle length for all the intersections in the network). Although this cycle length may measure too long for the other intersections in the system, shortening the cycle length at the critical intersection may result in oversaturation and a bottleneck on the arterial. The longest allowable cycle length should equal no more than 10 to 15 seconds longer than the shortest allowable cycle length, to minimize the excess delay at the non-critical intersections. If the maximum minimum delay cycle length equals double that of the non-critical intersections, one should consider the possibility of double cycling the low volume intersections.

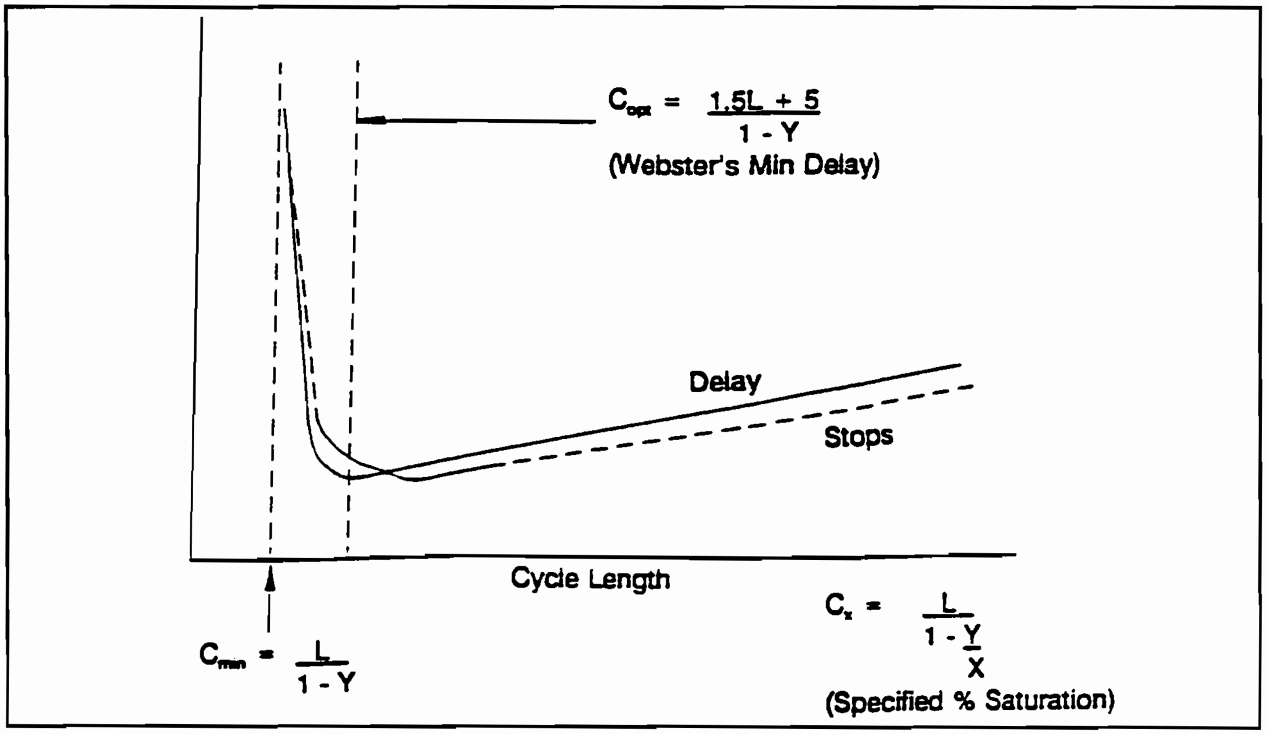


Figure 2-7. Minimum Delay Cycle Length

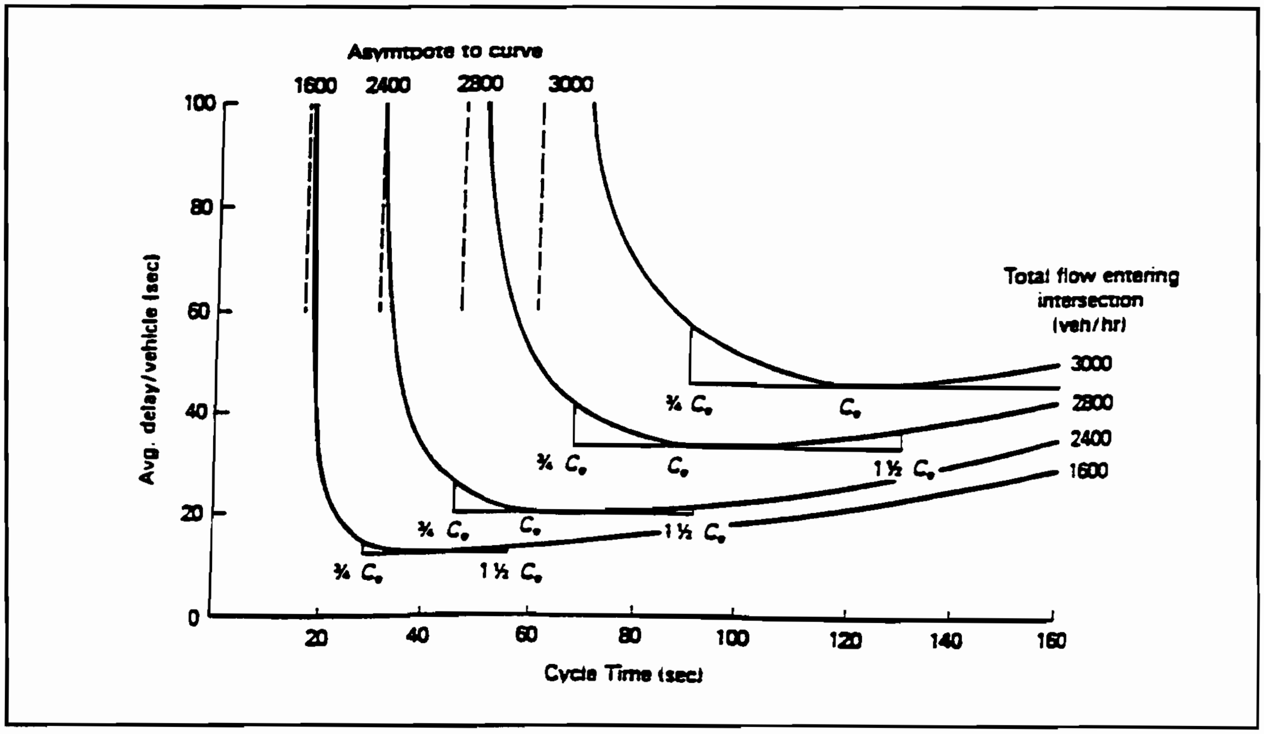


Figure 2-8. Variation in Delay with Cycle Length

Green Splits. After determining the cycle length to be used, green time must be allocated to each phase. To determine the optimum green splits at a particular intersection, the analyst has to identify the critical movements, and calculate their flow ratios. The sum of the critical flow ratio is denoted by the variable Y. The first step in calculating the green splits is the calculation of the overall volume to capacity ratio, X_I. Webster's method assumes X_I to be the volume to capacity ratio for each critical movement (the volume to capacity ratio being the same for each movement, as well as for the entire intersection). The equation for calculating the intersection volume to capacity ratio is as follows:

$$X_I = (\Sigma Y * C) / (C - \Sigma L) \qquad [2\text{-}2]$$

where: X_I = intersection volume to capacity ratio;
ΣY = sum of the critical flow ratios;
C = cycle length in seconds; and
ΣL = total lost time at the intersection in seconds; the lost time per phase generally ranges from 3 to 5 seconds.

The equation for determining the green time for each critical movement is as follows:

$$g_i = (y_i * C) / X_I \qquad [2\text{-}3]$$

where: g_i = phase time G + Y + RC - lost time in seconds;
y_i = flow ratio for movement, i;
C = cycle length in seconds; and
X_i = intersection volume to capacity ratio.

2.6 Coordination Methods

Two basic approaches (or objectives to achieve) exist when coordinating signals in an arterial street network. For simple open arterial networks and multiple open arterial networks, the objective often is to provide good progression along arterials by maximizing bandwidth. The delays and stops incurred by traffic on minor cross-streets is not considered significant; i.e., the smooth flow of traffic on arterials is given top priority. An optimum solution also should maximize the average travel speed along the arterials by providing progression (minimizing stops and delay) along the arterials. Closely spaced intersections and heavy non-directional traffic movement at all times characterize one way arterial pair and closed networks. Thus, the traffic performance on cross-streets is equally significant; i.e., queues at the intersections should not be long enough to back up into the upstream intersection, which would result in a grid-lock. Retiming signals in such cases often minimizes stops, delays, queue lengths, and improves the overall system performance.

To provide an efficient coordinated system, analysts must develop cycle lengths, phase sequences, and green splits for each intersection in the system, as well as determine offsets to progress vehicles along the system. To achieve coordination, the initiation of green phases should be altered at each intersection such that the phase changes correspond with the arrival of a platoon of vehicles.

One must determine optimal values for the following components to develop a coordinated arterial network signal timing plan.

System cycle length - This cycle length is based on the intersection within the system that has the longest cycle length required to satisfy the demand for that intersection. For coordinated operation, each parallel arterial must operate at one cycle length and usually is constrained by the individual intersection with the maximum (longest) minimum delay cycle length.

Phasing and splits - The phase sequences and lengths must be determined for each intersection in the system.

Offsets - Offsets relative to a master intersection must be calculated for each intersection. Offset also can be defined as the difference between the green initiation times at two adjacent intersections, and is usually expressed as a positive number between zero and cycle length.

Time-Space Diagram. A time-space diagram represents a plot of signal indications as a function of time for two or more signals. The diagram is scaled with respect to distance, in order to plot vehicle positions as a function of time. Figure 2-9 shows a time-space diagram for an arterial with four intersections (3). The time-space diagram illustrates a northbound vehicle travelling at a speed of 40 feet per second. Analysts used standard conventions to illustrate the various indications of the signals, a simple line indicates a green signal, a shaded line indicates an amber (yellow) signal, and a thick solid line indicates a red signal.

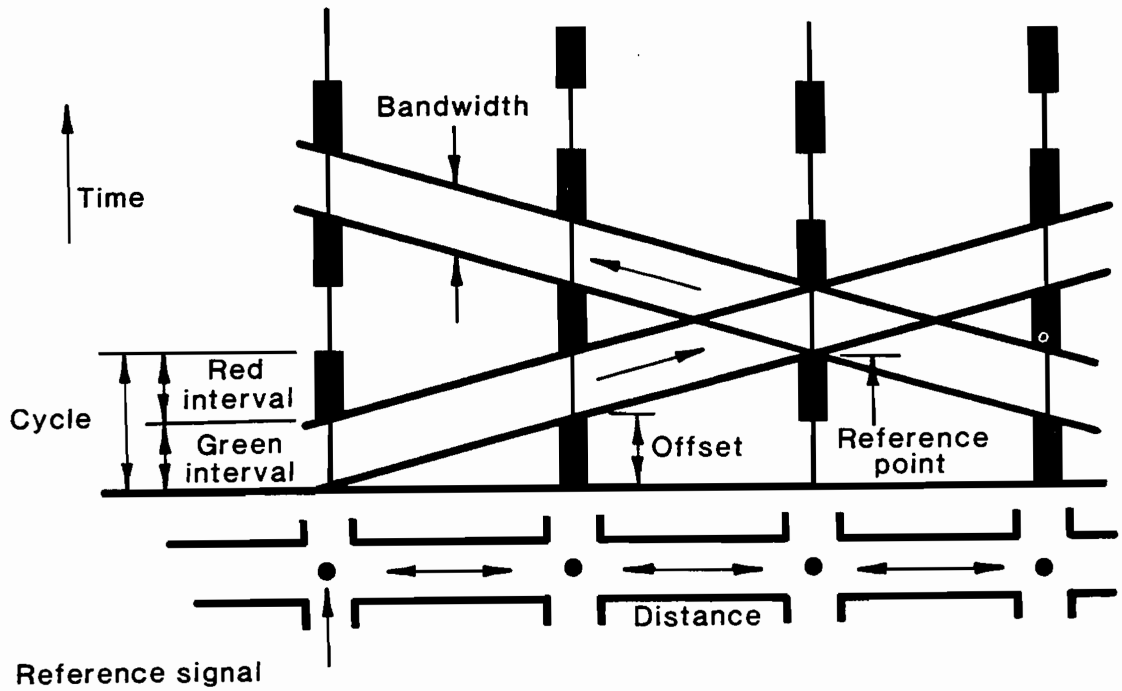


Figure 2-9. Typical Time-Space Diagram

Offset, as defined earlier, is the green initiation time (of the phase of interest) at the downstream intersection minus the green initiation time (of the phase of interest) at the master intersection. *Ideal offset* is defined as the offset that will achieve the specified objective. Often, the ideal offset equals the offset such that, as the first vehicle of a platoon arrives at the downstream signal, the downstream signal turns green. Equation 2-4 shows one how to calculate the ideal offset:

$$o_{id} = \frac{L}{v} \qquad [2\text{-}4]$$

where: o_{id} = ideal offset in seconds;
L = block length in feet; and
v = vehicle speed in feet per second.

If vehicles had to stop and then accelerate after some initial start-up delay, the ideal offset could be represented by the above equation plus some term representing start-up lost time at the first intersection; however, analysts generally use Equation 2-4 without an added term.

Progression Bandwidth. From Figure 2-9, one can see that a window, or band of green available for the movement of through vehicles exists. The size of this window is called the bandwidth and indicates how large a platoon of vehicles can pass through the arterial system without having to stop. The bandwidth is limited by the minimum green in the direction of interest. Traffic signal analysts like the concept of bandwidth, as it provides easy visual images of the signal system; however, a significant shortcoming of designing offset plans to maximize bandwidth is that one may overlook internal queues. If internal queues exist, bandwidth-based solutions can prove misleading and erroneous.

Analysts obtain good progression for through movements by maximizing the bandwidth in the direction of the peak traffic movement. For off-peak periods, emphasis is placed on providing equal bandwidth for both directions. One can achieve this latter objective through the process of half-integer synchronization. Half-integer synchronization generally assumes that speeds remain equal in both directions and results in equal bandwidths for both directions. Bandwidth can be maximized by centering either the green indications or the red indications and by minimizing bandwidth reduction effects, known as interferences (4).

Alternative Methodologies. Numerous methods of providing progression exist with the selection of the best method depending on traffic conditions, geometric conditions, and the spacing between intersections. The analyst generally determines the optimum cycle length for a system based on the demand at the critical (high volume) intersections. After determining the system cycle length, the appropriate method of providing progression is selected for implementation.

Simultaneous System Progression. For blocks with very short spacing and for rather high vehicle speeds, it may be best to have all the signals along a street always give the same indication at the same time. Figure 2-10 illustrates such a system. Systems with simultaneous progression also prove very useful in saturated congested conditions. In a very closely spaced network, such an operation will simultaneously release the vehicles in the queues and prevent the formation of gridlock. The major streets can have most of the green time resulting in extremely high traffic flow.

Alternate Progression. A signal system in which alternate signals give opposite indications to a given street at the same time is called alternate progression. Such progression is provided for uniform block lengths with 50-50 cycle splits and is usually operated from a single controller. One selects a cycle length as indicated in Equation 2-5 and obtains the progression as indicated in Figure 2-10. The figure indicates that the block travel time for each platoon equals exactly half a cycle. The efficiency of such a signal system is 50 percent because all of the green is used in each direction.

$$t = \frac{L}{v} = \frac{C}{2} \qquad [2\text{-}5]$$

where:
- t = travel time;
- L = block length in feet;
- v = vehicle speed in feet per second; and
- C = cycle length in seconds.

Double Alternate Progression. A signal system in which every alternate two signals display either green or red indications at the same time on a given street is called double alternate progression. Thus, one selects a cycle length, as specified in Equation 2-6. Figure 2-10 illustrates the progression obtained for such an offset. The figure indicates that the platoon travel time between each block equals to one fourth of the cycle length. The efficiency of such a system equals 25 percent in each direction because each direction only uses half the green. This system is best suited in downtown areas with square blocks, where analysts obtain some progression in all directions.

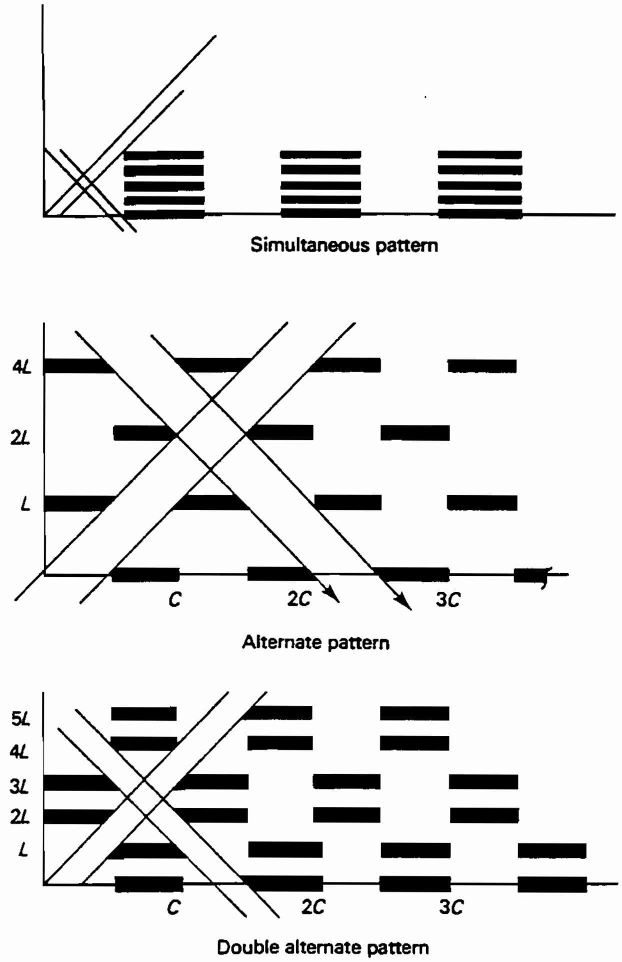


Figure 2-10. Types of Progression

$$t = \frac{L}{v} = \frac{C}{4} \qquad [2\text{-}6]$$

where: t = travel time;
L = block length in feet;
v = vehicle speed in feet per second; and
C = cycle length in seconds.

Delay-Offset Method. Hilliar of the Transportation and Road Research Laboratory in the United Kingdom developed the delay-offset method of selecting optimal offsets for pretimed signals (5). This method minimizes the overall delay but does not necessarily provide uninterrupted progression or minimize stops. The delay-offset method also does not exclusively favor the arterial through movement or a maximum progression solution. The delay-offset method attempts to minimize the overall delay of the system, and, therefore, individual movements as well as the overall system performance should concern analysts (6). Figure 2-11 illustrates the variation in delay with change in offset.

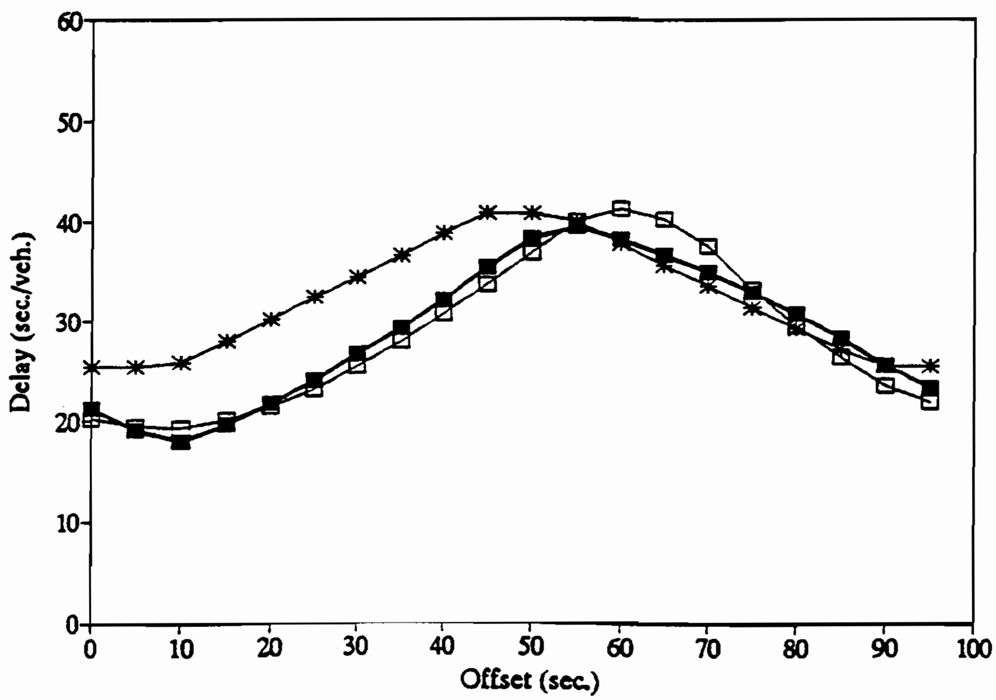


Figure 2-11. Variation in Delay with Change in Offset

Maximum Bandwidth Method. One of the most popular methods of timing arterials uses the philosophy of maximizing the progression bandwidth. Preference is given to the through movements on the arterial streets which may cause more delay to the cross streets. The maximum bandwidth solution attempts to develop a signal timing plan that will allow a queue of vehicles to leave an intersection and progress through the green of downstream intersections without stopping. The maximum bandwidth concept that one can obtain depends on the minimum green times for the inbound and outbound directions, and the minimum interference. The maximum bandwidth is calculated as follows (7):

$$B_{max} = G_{o\,min} + G_{i\,min} - I_{i\,min} \qquad [2\text{-}7]$$

where: B_{max} = maximum bandwidth, in seconds;
$G_{o\,min}$ = minimum green in the outbound direction, in seconds;
$G_{i\,min}$ = minimum green in the inbound direction, in seconds; and
$I_{i\,min}$ = minimum interference in seconds.

The primary measures of effectiveness to evaluate arterial progression are efficiency and attainability. Efficiency (E) describes the proportion of the cycle length used for progression of through movements. Attainability (A) equals the ratio between the sum of the bandwidths and the sum of the minimum green times in both direction; that is, the percentage of the shortest arterial through green time in each direction occupied by the band. Several studies have been documented by various authors that discuss the theory of maximum bandwidth; for further reference, see Little et al. (8), Brooks (4), and Messer (7). Efficiency and attainability are calculated as follows:

$$E = \frac{B_a + B_b}{2C} \qquad [2\text{-}8]$$

where: E = progression bandwidth efficiency ratio;
B_a = progression bandwidth in "A" direction, in seconds;
B_b = progression bandwidth in "B" direction, in seconds; and
C = cycle length, in seconds.

$$A = \frac{B_a + B_b}{G_{\min(a)} + G_{\min(b)}} \qquad [2\text{-}9]$$

where: A = progression bandwidth attainability ratio;
$G_{\min(a)}$ = minimum green time in "A" direction, in seconds; and
$G_{\min(b)}$ = minimum green time in "B" direction, in seconds.

2.7 Measures of Effectiveness

The measures of effectiveness (MOEs) used in the evaluation of signal timing alternatives on arterial street networks include average travel speed, critical volume to capacity ratio, total system delay, queue length, and fuel consumption. Each of these MOEs are discussed below.

Average Travel Speed. The *1985 Highway Capacity Manual* (HCM) (9) uses average travel speed as the basic measure of effectiveness for arterial streets. Such factors as the number of signalized intersections per mile and the average delay at these intersections greatly influence the average travel speed on an arterial segment. Table 2-1 presents the arterial level of service ranges in terms of the average travel speed of all through vehicles on the segment. The "arterial classification" concept utilized in Table 2-1 is based upon the functional and design category of the arterial under evaluation and further described in the 1985 HCM (9).

To compute average travel speed, take the distance between Points A and B and divide by the travel time between the same two points. Travel time includes the average delay at each of the signalized intersections and the running time between intersections. The basic relationship between average travel speed and intersection spacing is as follows: short spacings between intersections result in running time being a lesser percentage of the travel time, and as a result, lower average speeds and levels of service. Longer spacings between intersections result in running time being a higher percentage of travel time, and as a result higher average speeds and level of service. When computing average travel speed, however, one should realize that if one or more of the intersections on the arterial is oversaturated, the arterial will operate at Level of Service F, even if the calculated average travel speed indicates otherwise.

Table 2-1. Level of Service Ranges for Arterial Streets

ARTERIAL CLASS	I	II	III
Range of Free Flow Speeds (mph)	45 to 35	35 to 30	35 to 25
Typical Free Flow Speed (mph)	40 mph	33 mph	27 mph
LEVEL OF SERVICE	AVERAGE TRAVEL SPEED (MPH)		
A	≥35	≥30	≥25
B	≥28	≥24	≥19
C	≥22	≥18	≥13
D	≥17	≥14	≥ 9
E	≥13	≥10	≥ 7
F	<13	<10	< 7

Critical Volume to Capacity Ratio (v/c). The volume to capacity ratio for the critical signalized intersections in an arterial network provides a measure of effectiveness for assessing operations along an arterial system. According to the *Highway Capacity Manual* (9), the volume to capacity ratio equals the actual or projected rate of flow on an approach or designated group of lanes during a peak 15 minute interval divided by the capacity of the approach or designated lane group. One can compute the volume to capacity ratio (X_i) for a specific approach as follows:

$$X_i = V_i/c_i = V_i /[(g_i/C) * S_i] \qquad [2\text{-}10]$$

where:
- X_i = volume to capacity ratio of lane group or approach i;
- V_i = volume of approach i or lane group in vehicles/hour;
- c_i = capacity of lane group or approach;
- g_i = effective green time for lane group or approach i in seconds;
- C = cycle length in seconds; and
- S_i = saturation flow rate for lane group or approach i in vehicles/hour of green.

Capacity at intersections is defined as the maximum rate of flow (for the subject approach), which may pass through the intersection under prevailing traffic, roadway, and signalization conditions. A volume to capacity ratio of less than 1.0 indicates that the approach probably operates at an acceptable level; a volume to capacity ratio near 1.0 indicates that the approach operates near its capacity and operational problems may occur; and a volume to capacity ratio of greater than 1.0 indicates that more demand than capacity exists. If the capacity has not been underestimated, the approach does not operate at an acceptable level and operational problems will occur for as long as this condition persists.

The critical volume to capacity ratio for an arterial is considered to be the highest volume to capacity ratio found among the intersections in the arterial street network. It is important to realize, however, that arterial analysis can provide misleading results if the operational conditions resulting from the critical volume to capacity ratio are not taken into consideration. In other words, if one or more of the intersections operates at an unacceptable level, the arterial street network also will operate at an unacceptable level, even if the average speed indicates an acceptable level of service. **Thus, it is extremely important in the analysis of arterial street networks to check both average travel speed and volume to capacity ratios for arterial movements at each of the intersections.**

Total System Delay. Analysts consider the sum of the delay for each individual movement at each of the intersections in the network the total delay for the arterial network. Note that because total system delay represents the delay for the total number of vehicles in the system, it is not comparable to other systems with a different number of total vehicles. One can estimate the delay at individual intersections with delay equations based on Webster's delay theory (2), or one can measure delay directly in the field.

Delay is a measure of effectiveness commonly used to estimate the level of service at signalized intersections. Two types of delay that can be estimated are: stopped delay and total delay. Stopped delay is the amount of time a vehicle is actually stopped waiting for a green indication and/or the queue of vehicles to clear. Stopped delay is more easily measured than total delay. Total delay estimates the time lost to stops and speed reductions due to acceleration, deceleration, and interference from other vehicles. One typically determines the total system delay for an arterial using estimates for total delays.

The *Highway Capacity Manual* (9) contains the most widely used model to compute stopped delay. Two parts make up the equation: delay due to uniform arrivals and delay due to random and overflow arrivals. Delay for uniform arrivals is based on the assumption that vehicles arrive at a constant rate and are fully discharged during the cycle. Hence, no vehicles wait for more than one cycle to pass through the intersection. The first part of the equation for stopped delay with uniform arrivals is as follows:

$$d_1 = \frac{0.38C[1 - (g/C)]^2}{[1 - (g/C)(Min(X,1.0))]} \qquad [2\text{-}11]$$

where: d_1 = uniform delay in seconds per vehicle;
C = cycle length in seconds;
g = green time per phase in seconds;
Min (X,1) = the lesser value of either X (v/c ratio for lane group) or 1.0; and
X = volume to capacity ratio for that phase.

Vehicle arrival patterns, however, are not uniform. They are more likely to be random in nature. The second part of the equation for delay due to random arrivals and queue overflow (incremental delay) is as follows:

$$d_2 = 173X^2 \ [(X - 1) + \sqrt{[(X - 1)^2 + mX/c]}\ ] \qquad [2\text{-}12]$$

where: d_2 = incremental delay in seconds per vehicle;
X = volume to capacity ratio for that phase;
m = a calibration term representing the effect of arrival type and degree of platooning; and
c = capacity of lane group, in vehicles per hour.

The intersection stopped delay is as follows:

$$d = d_1 * DF + d_2 \qquad [2\text{-}13]$$

Total delay can be related to stopped delay as follows (10):

$$D = 1.3 * d \qquad [2\text{-}14]$$

where: D = total delay, in seconds per vehicle;
d = stopped delay, in seconds per vehicle; and
DF = delay adjustment factor for either quality of progression or control type.

Queue Length. Queue length provides another basic measure of performance. This is of particular importance when a limited queue storage space exists. A heavy left-turn demand or a short left-turn lane can cause queues of left-turn vehicles to back into the through lanes and block them. Similarly, long queues in the through lanes can block the entrance to the left-turn lanes and in some cases can block upstream intersections. This problem proves particularly significant at closely spaced intersections in an arterial network. The presence of queues at the intersection impedes the smooth flow of platooned traffic; causes more stops, delays, and driver frustration; and, in turn, could lead to safety problems.

According to Akcelik (11), the average number of vehicles in the queue at the start of the green period can be calculated as follows:

$$N = qr + N_o \qquad [2\text{-}15]$$

where: N = average number of vehicles in queue in vehicles;
q = arrival flow rate in vehicles per second in vehicles per second;
r = effective red time in seconds in seconds; and
N_o = average overflow queue in vehicles and given by:

$$N_o = \frac{QT_f}{4}\left(z + \sqrt{z^2 + \frac{12(x-x_o)}{QT_f}}\right) \qquad [2\text{-}16]$$

where: Q = capacity in vehicles per hour;
T_f = flow period in hours;
z = (x - 1);
x = degree of saturation (q/Q); and
x_o = (0.67 + sg/600), where s = saturation flow in vehicles per second, and g = effective green time for the lane group, in seconds.

The earlier mentioned equation for queue length is based on the theoretical model, which assumes that vehicles join the queue when they reach the stop line. Since vehicles actually can join the queues before reaching the stop line, the equation underestimates the maximum queue length. Maximum queue length can be calculated as follows:

$$N_m = \frac{qr}{1 - y} + N_o \qquad [2\text{-}17]$$

where: N_m = maximum length of the queue;
q = arrival flow rate in vehicles per second;
r = effective red time in seconds; and
y = flow ratio (i.e., volume/saturation flow rate).

Stops. The average number of stops provides another basic measure of performance from which one can obtain other (secondary) measures of performance (like fuel consumption). Note that every vehicle which comes to a complete stop at an intersection experiences a small delay. According to Akcelik (11), the average number of stops per vehicle is called the stop rate and can be calculated as follows:

$$h = 0.9 \left(\frac{1 - u}{1 - y} + \frac{N_o}{qC}\right) \qquad [2\text{-}18]$$

where: h = average number of complete stops per vehicle (i.e., stop rate);
u = green time ratio (g/c);
y = flow ratio (q/s);
q = flow in vehicles per second;
C = cycle time in seconds; and
N_o = average overflow queue in vehicles.

One obtains the number of stops per movement (H) by multiplying the stop rate (h) by the demand volume (Q). Equation 2-19 gives the stops per movement.

$$H = h * Q \qquad [2\text{-}19]$$

where: H = number of stops per hour;
h = stop rate; and
Q = demand volume in vehicles per hour.

Fuel Consumption. Faced with fuel shortage and increased fuel prices, traffic signal analysts have become more interested in fuel consumption estimates. One can divide fuel consumption in an arterial system into three components: fuel consumed travelling from Point A to Point B, fuel consumed while stopped at an intersection, and fuel consumed while decelerating to a stop and accelerating back to a desired speed. The model given in Equation 2-20 calculates fuel consumption in both PASSER II-90 and TRANSYT-7F.

$$
\begin{aligned}
F = \; & (A_{11} + A_{12}*V + A_{13}*V^2) * TT \\
& + (A_{21} + A_{22}*V + A_{23}*V^2) * D \\
& + (A_{31} + A_{32}*V + A_{33}*V^2) * S
\end{aligned}
\qquad [2\text{-}20]
$$

where:

- F = estimated total system fuel consumption, in gallons per hour;
- TT = total travel, in vehicle mile per hour;
- D = total delay, in vehicle hour per hour;
- S = total stops, in stops per hour;
- V = cruise speed, in miles per hour; and
- A_{ij} = regression model beta coefficients, and is given by:

$$
A_{ij} = \begin{vmatrix} 0.75283 & -1.5892\text{ E-3} & 1.50655\text{ E-5} \\ 0.73239 & 0.0 & 0.0 \\ 0.0 & 0.0 & 6.14112\text{ E-6} \end{vmatrix}
$$

3.0 DATA REQUIREMENTS

A major component of good signal timing plans is adequate data for analysis and optimization purposes. Poor or incomplete data results in less than desirable timing plans. One can categorize the type of data required for arterial network systems into two groups: intersection data and arterial network data. Intersection data involves data collection at each individual intersection within the system, while arterial network data corresponds to the overall characteristics of the arterial network. Knowing what data is needed before going to the field will save time and extra trips to the project site for the traffic signal analyst.

The first question one must ask is how many timing plans will be needed? The number of timing plans necessary depends on the fluctuation of traffic demand throughout the day and the type of control equipment available. Analysts should collect data during the periods of interest. For example, one-way progression may be desirable in the inbound direction for the a.m. peak and in the outbound direction for the p.m. peak. Two-way progression may be desirable for the off peak, a.m. or p.m. peaks. One should collect data for developing the a.m. peak timing plan during the a.m. peak period; likewise data for developing an off-peak timing plan should be collected during the off-peak time period, etc.

The following sections discuss guidelines and suggestions for the complete and accurate collection of data needed for retiming signalized arterial networks. Analysts use these data in the development of timing plans for both pretimed and traffic actuated environments. Section 4.0, "Evaluation," Section 5.0, "Optimization," and Section 6.0, "Implementation" describe the recommended use of the data.

There are four types of data to be collected:

1. Traffic Data;
2. Signal Data;
3. Geometric Data; and
4. Travel Time Data.

The type of data needed for analyzing an arterial network varies somewhat for each network. A worksheet for recording individual intersection data, such as the one specified in the *1985 Highway Capacity Manual* (9) and illustrated in Figure 3-1, proves helpful as a starting point.

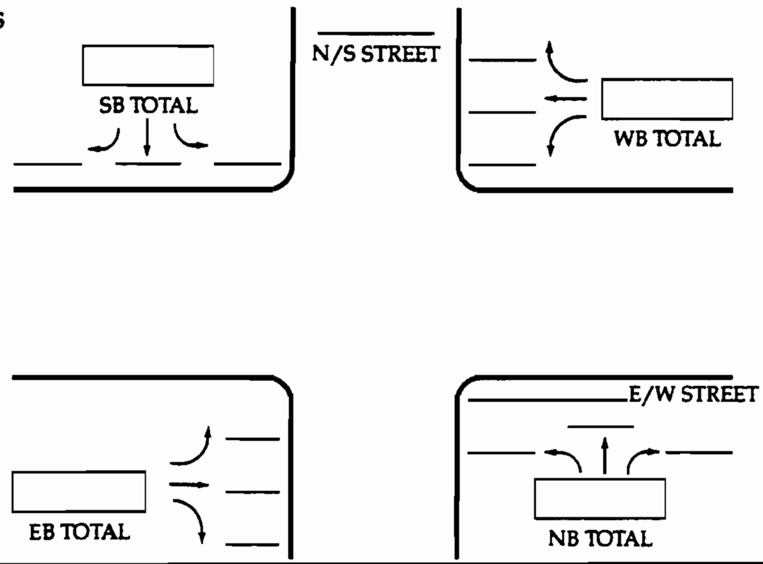
INPUT WORKSHEET

Intersection:______________________________ Date:______________

Analyst:______________ Time Period Analyzed:______________ Area Type: ☐ CBD ☐ Other

Project No.:______________________ City/State:______________________

VOLUME AND GEOMETRICS



IDENTIFY IN DIAGRAM:

1. Volumes
2. Lanes, lane widths
3. Movements by lane
4. Parking (PKG) locations
5. Bay storage lengths
6. Islands (physical or painted)
7. Bus stops

TRAFFIC AND ROADWAY CONDITIONS

Approach	Grade (%)	% HV	Adj. Pkg. Lane		Buses (N_B)	PHF	Conf. Peds. (peds./hr)	Pedestrian Button		Arr. Type
			Y or N	N_m				Y or N	Min. Timing	
EB										
WB										
NB										
SB										

Grade: + up, − down
HV: veh. with more than 4 wheels
N_m: pkg. maneuvers/hr
N_B: buses stopping/hr
PHF: peak-hour factor
Conf. Peds: Conflicting peds./hr
Min. Timing: min. green for pedestrian crossing
Arr. Type: Type 1-5

PHASING

DIAGRAM								
Timing	G = Y + R =	G = Y + R =	G = Y + R =	G = Y + R =	G = Y + R =	G = Y + R =	G = Y + R =	G = Y + R =
Pretimed or Actuated								

⟶ Protected turns	- - ⟶ Permitted turns	-------- Pedestrian	Cycle Length_____Sec

Figure 3-1. HCM Worksheet to Summarize Intersection Data

3.1 Traffic Data

Traffic data identifies both the demand and capacity of the intersections, as well as the factors affecting the smooth flow of traffic along the network. The quantification of demand requires observation of 24-hour traffic volumes at the intersections, the traffic volumes during the peak periods, and the traffic volumes for specific turning movements during the peak periods. The analyst also should identify the midblock traffic generators and their influence on the arterial network traffic. The capacity of an intersection is calculated based on the saturation flow rate and available green time for each movement. The number of heavy vehicles using the intersection, as well as bus stops and parking near the intersection, and the number of pedestrians that cross at the intersection all affect the saturation flow rates. The following text elaborates on the collection of traffic data.

Traffic Volumes. One should obtain traffic volumes for each intersection in the arterial network for the a.m., p.m., and off-peak time periods. The first step in this process, a 24-hour count, should be made at each intersection to determine the peak periods (or peak 15 minutes) and the fluctuation in traffic demand. One can take a 24-hour count by placing tube counters on all approaches at the intersection or by dumping detector counts from the controller.

Turning Movements. After determining the peak period, manual counts are necessary to record the volumes for individual movements (or lane groups during the peak period or period of interest). Twelve possible movements need to be counted at each signalized intersection, as shown in Figure 3-2. Generally, one should make turning movement counts in 15-minute intervals during the two hour a.m. or p.m. peak, and for one hour during the off-peak period.

The highest four consecutive 15-minute volumes are added together to determine the highest peak or off-peak hour flow rate. It may prove helpful to record intersection data on a worksheet, such as the one in the *Manual of Traffic Engineering Studies* (12) and shown in Figure 3-3. A sketch illustrating the arterial network and the orientation of its nodes and links will also prove helpful for recording system data (see Figure 3-4). A node is an intersection, and a link is a unidirectional traffic movement between two nodes. In some situations, more than one link may connect two nodes.

During congested periods, it is important that the volume counted be the demand rather than the discharge volume; i.e., the measured discharge volume will be less than the true demand volume if the queue fails to clear during the green indication. If this situation occurs, the actual volume counted should be those vehicles that arrive at the back of the queue rather than those vehicles that depart when the signal is green. One should note, however, that this procedure is for counting and not a recommended signal timing strategy; i.e., trying to clear the queue each and every cycle results in extremely long cycle lengths during congested conditions.

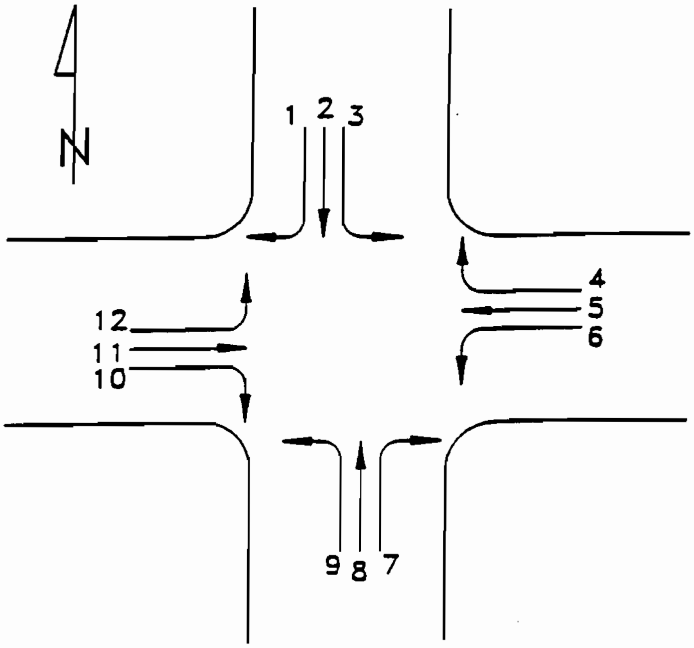


Figure 3-2. Turning Movements to be Counted at a Typical Intersection

TABULAR SUMMARY OF VEHICLE COUNTS

Observer ______ Date ______ Day ______ City ______

INTERSECTION OF ______ AND ______

R = Right turn
S = Straight
L = Left turn

TIME BEGINS	from NORTH				from SOUTH				TOTAL North South	from EAST				from WEST				TOTAL East West	TOTAL ALL
	R	S	L	Total	R	S	L	Total		R	S	L	Total	R	S	L	Total		

Figure 3-3. Worksheet to Record Intersection Data

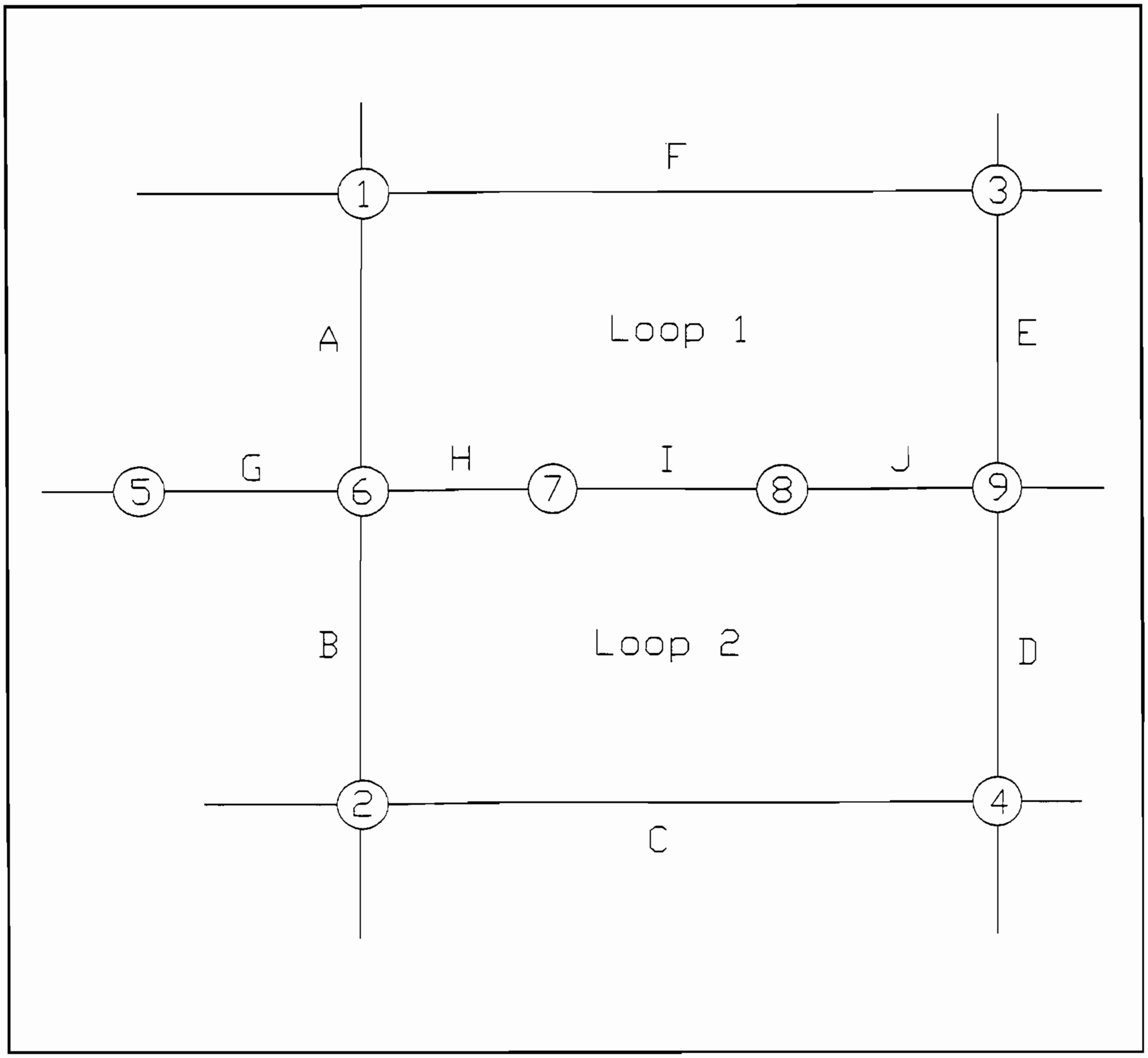


Figure 3-4. Typical Arterial Network

Right-Turn on Red (RTOR). In order to more accurately describe the existing conditions, recording the number of vehicles making right turns on the red interval is suggested. This number will be subtracted from the total right-turn volume when modeling (analyzing) the existing conditions at any intersection along the arterial network.

Mid-block Volumes. Heavy traffic generators may exist between intersections along the arterial network. These generators may include major shopping centers, large parking lots, etc. Analysts should use engineering judgment to determine the significance of the volumes generated. Most sources of large traffic generation have signalized access points; however, this generalization may not be so in all cases. Significant mid-block traffic affects the quality of progression.

Peak Hour Factor (PHF). After making turning movement counts, adjustments may be necessary to account for the peak period. According to the HCM, peak rates of flow relate to hourly volumes through the use of peak hour factors. The peak hour factor is defined as the ratio of total hourly volume to the maximum 15 minute rate of flow within the hour. If 15 minute counts are used, then:

$$PHF = \frac{V}{(4 * V_{15})} \qquad [3\text{-}1]$$

where: PHF = peak hour factor;
V = highest hourly volume, in vehicles per hour; and
V_{15} = highest 15 minute count within that hour, in vehicles per 15 min.

One generally states demand volumes in terms of vehicles per hour for a peak hour. For signal timing analysis, peak hour volumes are normally adjusted to flow rates in vehicles per hour for a 15-minute period. For example, a 24-hour count was made and the a.m. peak hour was determined to be between 7:00 a.m. and 8:00 a.m. The hourly volume equalled 900 vehicles per hour. The peak 15-minute flow rate within that hour equalled 300 vehicles in 15 minutes; thus, the denominator of the equation equals 1200 vehicles per hour.

$$PHF = \frac{900}{(300 * 4)} = 0.75 \qquad [3\text{-}2]$$

Thus, the peak hour factor for the a.m. peak equals 0.75 in this example. For timing purposes, one can calculate the peak hour flow rate either by dividing the hourly volume by the peak hour factor or by multiplying the peak 15-minute flow rate by four. In either case, the calculated peak flow rate multiplies to 1200 vehicles per hour. It is important to note that, if the peak 15-minute flow rate was multiplied by four to achieve a peak hour flow rate, the correct peak hour factor equals 1.0; i.e., the adjustment for peak flows within the hour have already been accounted for.

Saturation Flow Rate. The saturation flow rate is the maximum flow rate at which vehicles can pass through the intersection. One expresses this rate in vehicles per hour of green per lane during an hour with continuous demand and subject to prevailing roadway conditions. Traffic signal analysts use adjustment factors for roadway and traffic conditions, such as lane width and truck percentages, to reduce the ideal saturation flow rate to an adjusted rate appropriate for the location. One uses the following traffic data items to adjust the ideal saturation flow rate:

Percent heavy vehicles - The analyst should count the number of heavy vehicles operating within an intersection. A heavy vehicle is characterized as having at least 6 wheels in contact with the roadway. Heavy vehicles may be classified into three types: trucks, recreational vehicles, and buses. Heavy vehicles take up more lane space and operate differently than passenger vehicles, which contributes to a decrease in the saturation flow rate and capacity; e.g., heavy vehicles accelerate from a stop at a slower rate.

Parking - Parking in the vicinity of an intersection (within 200 feet of the stop line) also will affect flow in adjacent lanes either by frictional effect or occasional blockage of a lane.

Bus stops - If buses make scheduled stops at an established bus stop near an intersection (within 200 feet), restriction of flow and capacity may result in lanes adjacent to the bus stop. The analyst should record the time of day and frequency of bus stops. Most bus companies post their schedules at the bus stop and further information on bus frequency may be obtained from the bus company.

Pedestrians - The number and type of pedestrians crossing each intersection should be noted. Elderly pedestrians and children require more time to cross the street. This information is needed for the calculation of minimum green times, whether or not the intersections have pedestrians signals. The analyst should also note right-turn conflicts with pedestrians; if the right turn conflict is heavy, the capacity available for right turn movements may need reduction. Pedestrian volumes can be recorded as the actual number counted, or as a general range (less than 50, 50 to 200, or greater than 200). Either option is acceptable; however, it is important that one base the data on field observations.

Because saturation flow rate is such a critical factor, it should be measured in the field if possible. Figure 3-5 shows a worksheet for determining the saturation flow rate for an approach using field observations. If field measurements are unavailable, one can estimate the saturation flow rate using the procedure outlined in the *1985 Highway Capacity Manual* (9).

One should note that saturation flow rates are extremely important when determining the capacity and required splits for specific movements. For example, if one overestimates a particular movement's saturation flow rate, less green time than needed will be allocated to that movement. On the other hand, if one underestimates a particular movement's saturation flow rate, more green time than is needed will be allocated to that movement. Neither condition is efficient or desirable.

3.2 Signal Data

The analyst may take most information classified as signal data (cycle lengths; green, yellow, and red intervals; phasing; and offsets) directly from the controller for pretimed control plans. For actuated control plans, the fixed yellow and red intervals remain constant, and yield, hold, and force-off settings may be obtained from the actuated controller. Average green intervals may be obtained from field measurements. The following text elaborates on the necessary signal detail.

Cycle Length. The cycle length for the period of interest, a.m., p.m., or off peak, should be recorded. For pretimed control, the cycle length of each intersection will remain constant. Actuated control systems also must operate at the same cycle length or some multiple of the system cycle length which is normally called the background cycle length. One may obtain the system cycle length from existing timing plans, the controllers, or by field measurement with a stopwatch.

Green Splits. The analyst should record green splits for each intersection. The green split (the green, and yellow plus red clearance for each phase), will remain constant for pretimed control and can be obtained from controller settings, existing timing plans, or by field measurements. For actuated control, the green interval will be a variable length interval and should be determined by recording 10 to 30 measurements of the green interval in the field and calculating an average green interval length. The yellow and red intervals will remain constant for both pretimed and actuated control. This information may be obtained from timing plans or by field measurements with a stopwatch.

FIELD SHEET—SATURATION FLOW STUDY

Location:____

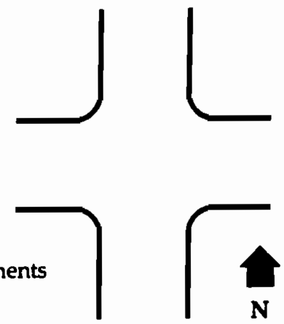
Date:____/____/____ Time:____________ City:____________

______Bound Traffic; Approaching From the_____________________

Observers:__________________ Weather:__________________

Movements Allowed
- ☐ Thru
- ☐ Right Turn
- ☐ Left Turn

Identify all Lane Movements & The Lane Studied



Veh. in Queue	Cycle 1			Cycle 2			Cycle 3			Cycle 4			Cycle 5			Cycle 6		
	Time	HV	T	Time	HV	T	Time	HV	T	Time	HV	T	Time	HV	T	Time	HV	T
1																		
2																		
3																		
4																		
5																		
6																		
7																		
8																		
9																		
10																		
11																		
12																		
13																		
14																		
15																		
16																		
17																		
18																		
19																		
20																		
End of Saturation																		
End of Green																		
No. Veh. > 20																		
No. Veh. on Yellow																		

HV = Heavy Vehicles (Vehicles with more than 4 tires)
T = Turning Vehicles (L = Left, R = Right)
Pedestrians and buses which block vehicles should be noted with the time that they block traffic, i.e.,
P12 = pedestrians blocked traffic for 12 sec
B15 = bus blocked traffic for 15 sec

Grade__________ Area Type__________

Figure 3-5. Worksheet for Measuring Saturation Flow Rates in the Field

Phasing. The analyst should record the existing phasing, including the type and sequence of phasing, for the intersection. As discussed in Section 2.2, the left-turn treatment determines the type of phasing, and the order that the left-turn phases occur describes the sequence. Types of phasing include permitted, protected, and protected/permitted.

Permitted -	Left-turn movements must yield to opposing traffic. They may proceed during green ball indication after yielding to opposing traffic.
Protected -	Left-turn movements proceed separately from opposing traffic. They are protected with a green arrow or a split phase. Left-turning vehicles cannot proceed otherwise.
Protected/Permitted -	Left-turn movements are protected during part of the cycle and permitted in another part of the cycle. They may proceed during the protected left-turn phase or on the green ball indication after yielding to opposing traffic.

Possible phase sequences at an intersection include leading lefts, lagging lefts, and lag/lead or lead/lag.

Leading Left -	Both left-turns proceed before the through movements.
Lagging Left -	Both left-turns proceed after the through movements.
Lag-lead/lead-lag -	One left-turn movement and its adjacent through movement proceed before or after the opposing left-turn and its adjacent through movement.

Offsets. In pretimed control, a parameter called the offset references signals to a master intersection. Offsets are usually referenced to the start or end of main street green; however, they may be referenced to the start or end of the phase for the coordinated movement. The analyst may obtain existing offsets from timing plans or controller settings. Actuated controllers use force-off, yield, and hold commands to provide progression. One may also obtain these settings from controller settings.

Type of Controller. Arterial network systems may be controlled by pretimed or actuated controllers. Section 2.3 discussed the characteristics and capabilities of these controllers, but in general, the following attributes should be noted for each type of controller.

Pretimed -	Is the controller electromechanical or digital? How many dials does it have?
Actuated -	Is the controller a single ring or dual ring? How many timing plans, cycle lengths, and split patterns will it accommodate?

Master Control Unit. A master controller coordinates the individual intersections in the arterial network. Local controllers may be interconnected with cable, or a time-base coordinator may provide coordination. Some local coordinators have the time clocks or master systems built into the cabinet, or the master controller may be a separate controller to which all other intersections are referenced. The analyst should record the existing arrangement and equipment.

3.3 Geometric Data

Geometric data may be determined from site plans or through field inspections. Geometric conditions can affect traffic operational data, such as the saturation flow rate. Additionally, signal data, particularly with regard to phasing and left-turn treatments, is dictated by the geometric conditions at the intersections in the arterial network.

Link/Node Structure. A link/node identification scheme represents the network of streets and intersections. The user designs the link/node identification, and once finalized, all other data are referenced to it. A node is an intersection, and a link is a unidirectional traffic movement between two nodes (in some situations, more than one link may connect two nodes). Figure 3-6 shows a typical link/node structure for a simple closed network.

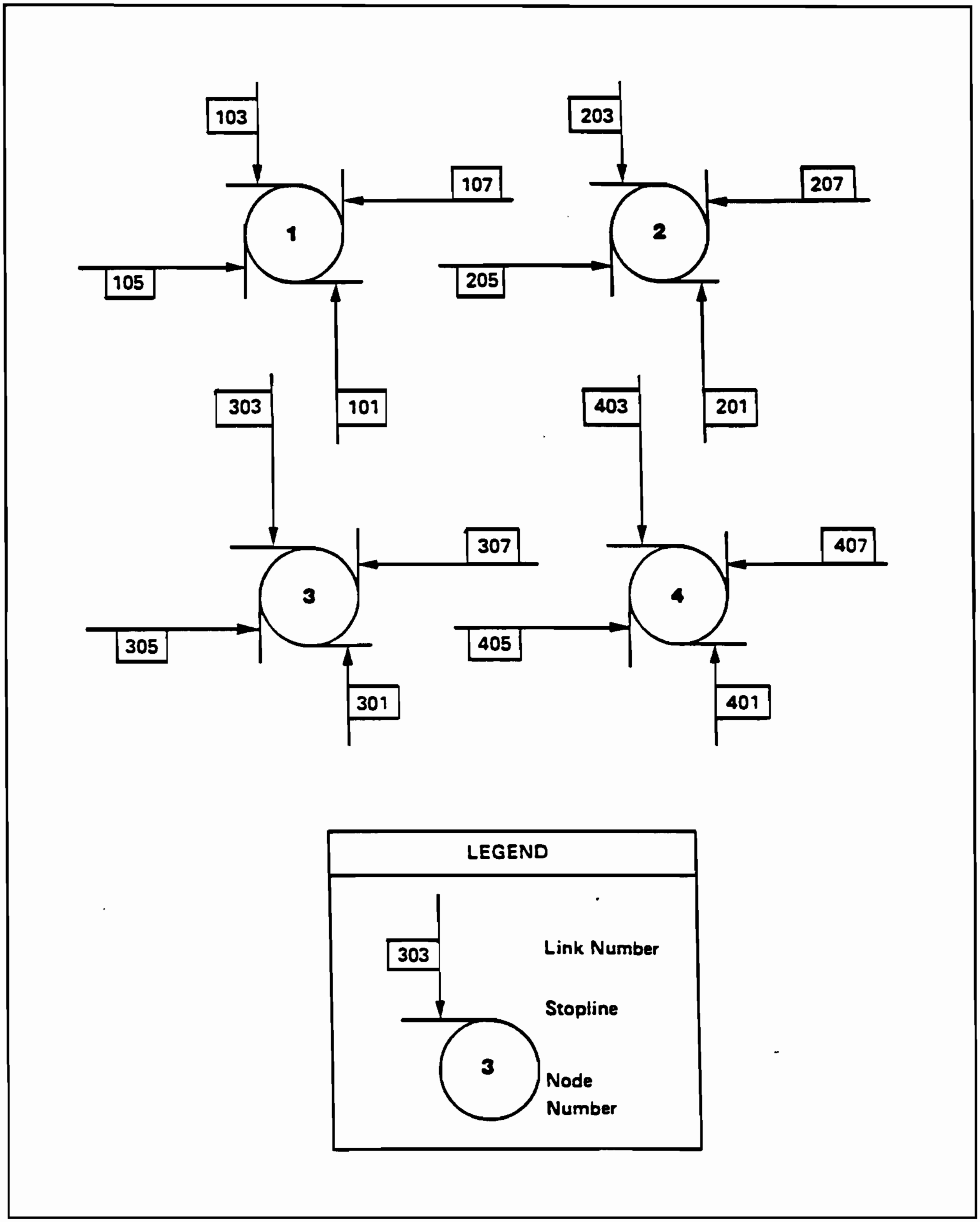


Figure 3-6. Typical Link/node Structure for a Simple Closed Network

Number of Lanes. The analyst should record the number of lanes per approach for each intersection. Note that the number of lanes is counted at the stop bar, not upstream or downstream of the intersection. One should also record the type of movements allowed from each lane, including exclusive turning lanes and shared lanes. The following information also should be noted for each type of lane and/or movement:

Left-turn lanes -	the number of lanes, whether left turns have an exclusive lane, the storage length, whether storage is adequate for the expected queue.
Through lanes -	the number of lanes, whether the through lanes accommodate left- or right-turns.
Right-turn lanes -	the number of lanes, whether right-turns have an exclusive lane.

Lane Widths. The analyst should measure the lane widths for each lane on the approach or obtain them from existing plan sheets. Lane width affects the saturation flow rate. Lanes less than 12 feet in width reduce saturation flow rate and, thus, the available capacity for that movement.

Percent Grade. One should record the percent grade at each approach. This information should be obtainable from existing plan sheets or could be measured in the field. Percent grade also affects the saturation flow and possibly causes lost time due to longer start-up times on an uphill grade.

Location. The analyst should note the location of the intersections with respect to the surrounding area. Is the intersection in a central business district (CBD)? An example of a CBD would be a downtown area, where arterial streets cross each other to form a grid system or network. Each arterial is of equal importance with regards to progression. The area is usually made up of businesses and shops and heavy pedestrian traffic, parking maneuvers, and turning movements exist.

Intersection Spacing. The distance from intersection to intersection in the arterial network is needed. One usually measures this distance from stop line to stop line, or from field measurements or plan sheets. Distances between intersections are usually the same in both directions; however, for skewed or offset intersections, distances between intersections may differ in different directions.

3.4 Travel Time Data

Analysts can use the test car method to determine the average speed between intersections in an arterial street network. The first step for conducting travel time studies is to make an inventory of the arterial street network's geometrics; identifying the segments, determining segment lengths, identifying the access control in each segment, determining the existing signal timing, and identifying the peak 15 minute flow periods and an off-peak period. Making runs in a test car equipped with a calibrated speedometer during low volume periods and noting the speeds at midblock locations determines the appropriate free flow speed along the arterial. These readings can be supplemented with spot speed studies at midblock locations. From the information obtained, one can determine the arterial street classification.

The next step is to conduct travel-time runs. The analyst should drive the test car as if it were a through vehicle. The analyst should note the location of all desired check points and their distances from the starting point. One starts the stop watch or timer at the first intersection, either at the instant the test vehicle comes to a stop or at the midpoint of the intersection if the vehicle does not stop at the intersection. The analyst should note cumulative travel time, stopped delay time, and the reason for the delay at each signalized intersections and other check points, like stop signs. The information obtained should be filled in on a tabular form as indicated in Figure 3-7.

For each arterial street in the system, the analyst makes six to twelve travel time runs for each study period. These runs are started at different times with respect to the cycle to avoid being a "first in the platoon vehicle" for all trips. The analyst should also note midblock speedometer readings and compare them with the free flow speeds measured earlier. The average travel time and travel speed for all links for open networks and arterial networks should be calculated. For a one way pair, the average travel speed should be calculated in both directions along the arterial, and for closed networks, along the primary links in the network. Note that one set of travel time data for each arterial street in the system will exist.

TRAVEL TIME FIELD WORKSHEET

Arterial____________________ Date__________

Driver__________ Recorder__________ Direction__________

		Run No. _ Time		Run No. _ Time		Run No. _ Time	
LOCATION	DIST (mi)	STOP TIME (sec)	CUM TT (sec)	STOP TIME (sec)	CUM TT (sec)	STOP TIME (sec)	CUM TT (sec)

S—Signal (lower box)
LT—Left Turn (upper box)
P—Pedestrian (upper box)
PK—Parking (upper box)
4W—4-Way Stop (upper box)

Figure 3-7. Travel Time Field Worksheet

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4.0 EVALUATION

After collecting the data, the next step toward retiming arterial street networks is to evaluate the existing conditions. Evaluation of an existing traffic control strategy requires field observation and analysis of existing conditions with computerized traffic models. A recommended methodology for assessing the operational efficiency of a traffic signal control strategy for an arterial street network is summarized below.

Field Evaluation

1. At critical intersections, check that the green intervals measure long enough to clear the stopped queues during most time periods. Although this objective may not be a desirable strategy with actuated control and oversaturated conditions, cycle failures over an extended period of time indicate signal timing or geometric problems. Such problems result in long delays, queue lengths, and excess fuel consumption.

2. At critical intersections, check that the green intervals are short enough to ensure that periods of time when vehicles are not moving through the intersection are not very long. Longer than necessary green intervals create wasted time and result in unnecessary delay and longer queue lengths for other movements; however, one should note that longer than necessary green intervals will occur at all non-critical intersections because of the need for a common cycle length for coordination.

3. Check that left-turn queues do not exceed left-turn storage. If so, left-turning vehicles may block through lanes and reduce their saturation flow rate; i.e., the available through capacity cannot be fully utilized. The opposite condition, long through queues blocking access to a left-turn lane, has a similar effect on left-turn capacity. Neither condition is desirable.

4. Check that the platoon arrives during the green interval so that through vehicles do not stop at the intersection. Unnecessary and sometimes excessive delay occurs if the platoon arrives during the red interval.

Computer Analysis

1. Check that individual movements are not delayed disproportionately. If so, green splits need adjustments and/or geometric modifications may be required.

2. Check that volume to capacity ratios for individual movements do not exceed 1.2. If so, the input data (usually capacity estimates) is probably in error, and needs correction. If not, the green splits and/or cycle length may be too short and needs lengthening. If through movements are oversaturated, a capacity bottleneck exists, and arterial progression through the intersection(s) is not possible.

3. Check that the estimated queue lengths do not exceed the available storage. If so, the intersection cannot operate at its full potential for moving traffic. Signal timing or geometric modifications may increase the intersection's operational efficiency.

4. Check that the progression bands are large enough to move a reasonable platoon of vehicles. This check is met if the efficiency and attainability are high and capacity bottlenecks do not exist. If the progression bands are small (i.e., if efficiency and attainability are small), then the offsets and phasing sequence needs changing.

4.1 Evaluation Software

One can perform evaluation or simulation of existing conditions using various computer simulation programs, such as the Highway Capacity Software (13), PASSER II-90 (14), PASSER III-90 (15), PASSER IV-94 (16) TRANSYT-7F (17, 18), and TRAF-NETSIM (20). One can use the measures of effectiveness calculated by these programs to locate problems within the arterial street network and pinpoint areas needing improvements. The following sections briefly describe each of the programs.

Highway Capacity Software (HCS). Courage and Wallace at the University of Florida developed the HCS software for the Federal Highway Administration. The program calculates saturation flow rates, average stopped delay, average travel speed, level of service, and other measures of effectiveness based on *Highway Capacity Manual* (HCM) (9) methodologies, the widely accepted standard for the analysis of signalized intersections, open networks, and arterial networks. The HCM program is straightforward and easy to use; however, one can only use the program for evaluating one intersection or one direction on the arterial at a time. For further information, consult the *Highway Capacity Software User's Manual* (13).

PASSER II-90. The Texas Transportation Institute at Texas A&M University developed the Progression Analysis and Signal System Evaluation Routine for the Texas Department of Transportation. The program analyzes and optimizes isolated intersections, arterial streets, and open arterial street networks. Features include provisions for actuated and pretimed control, an assistant function key for calculating saturation flow rates using HCM methods, and the capability to model permitted left turns. For evaluation purposes, PASSER II estimates the measures of effectiveness for movements corresponding to NEMA phases at individual intersections as well as overall measures of effectiveness for the entire arterial network. The measures of effectiveness used by the program include v/c ratios, delay, queues, stops, and fuel consumption. Additionally, PASSER II evaluates progression bandwidth efficiency and attainability for existing or optimum signal timing conditions. For further information on the program, refer to *Arterial Signal Timing Optimization Using PASSER II-90* (14).

PASSER III-90. The Progressive Analysis and Signal System Evaluation Routine, Model (PASSER) III is a fixed-time based traffic signal optimization model. The Texas Transportation Institute developed the program for the Texas Department of Transportation to determine and evaluate optimal signal timing plans at diamond interchanges. PASSER III analyzes isolated diamond interchanges (with or without frontage roads) and/or progression for a series of diamond interchanges connected by frontage roads. The program analyzes different phasing patterns and varies the offset to minimize delay within the interchange. Researchers designed PASSER III to analyze fixed time and fixed sequence control, but one can use the program to approximate actuated control. Input requirements include turning movements, distance between intersections, average link speeds, queue clearance interval, phasing sequence and minimum green times. PASSER III-90 has a built in assistant function to calculate saturation flow rates based on the Highway Capacity Manual methodology. Further information for running PASSER III may be obtained from the *PASSER III-90 User's Manual* (15).

PASSER IV-94. The Progressive Analysis and Signal System Evaluation Routine, Model (PASSER) IV is an advanced network signal timing optimization model. The program is being developed by the Texas Transportation Institute at Texas A&M University for the Texas Department of Transportation. This program is the only practical computer program that optimizes signal timings for large multi-arterial networks based on maximizing platoon progression. PASSER IV maximizes progression bandwidths on all arterials (one-way and two-way) in closed networks and explicitly handles one-way streets. The program complements PASSER II and TRANSYT-7F. In the present version of PASSER IV, it is possible to specify splits and phasing sequences. Offsets, however, cannot be specified; hence, one cannot simulate existing conditions. It is, however, expected that in future versions of PASSER IV, offsets will be specifiable and analysts will be able to use the program as a simulation tool.

The existing test version of PASSER IV determines the best cycle length, signal splits, signal offsets, and signal phasing sequences. Two versions of the program are under development: the standard version can handle networks having up to 20 arterials and 35 intersections, and an advanced version can handle even larger networks and is twice as fast as the standard version. A user-friendly graphic interface makes the program extremely easy to use. The features available in the current version include simultaneous maximization of uniform progression bands on all arterials in a network; arterial and directional priority options; determination of signal splits, optimal cycle lengths, optimal offsets, and optimal NEMA Phasing Sequences with overlap; and variation in link to link speeds.

TRANSYT-7F. Dennis Robertson of the Transport and Road Research Laboratory in England developed the **Traffic** Network Study **Tool** (17). Version 7 was modified to reflect North American nomenclature by the University of Florida for the Federal Highway Administration. Analysts use the program for the analysis and optimization of signal timing on coordinated arterials and grid networks. Features include provisions for actuated and pretimed control, the capability of modeling permitted left-turn movements, and provisions for including stopped controlled intersections along the arterial network. TRANSYT estimates measures of effectiveness for each of these movements at individual intersections, as well as overall measures of effectiveness for the arterial street network. The measures of effectiveness used by the program include delay, queues, stops, fuel consumption, total travel time, average travel speed, and total operating costs. Additionally, TRANSYT can graphically illustrate the flow profiles of the through and left-turn movements along the arterial network. For further information, refer to the *TRANSYT-7F Users Manual* (18).

A complementary program to TRANSYT, EZ-TRANSYT Plus (19), also will be addressed. This program is used to code the initial TRANSYT data base. EZ-TRANSYT is a more user-friendly method of coding TRANSYT, but it does not replace the need for reference to the TRANSYT-7F User's Manual. Not all coding options available in TRANSYT are accessible through EZ-TRANSYT, and after creating the initial data base, one must use TRANSYT to evaluate the system.

TRAF NETSIM. TRAF NETSIM is a microscopic traffic network simulation model developed by the Federal Highway Administration. This model simulates traffic control systems in great detail; however, it cannot be used to optimize signal timing. The TRAF NETSIM model handles both isolated intersections and coordinated arterial street networks. The model simulates uncontrolled, stop/yield controlled, pretimed and semi-actuated systems. Fully actuated signals can also be simulated in isolated mode. The output includes detailed statistics on delay, stops, queues, emissions, and other variables. For further information, refer to the *TRAF User Reference Guide* (20).

These guidelines will address PASSER IV and TRANSYT-7F due to their ability to both simulate (evaluate) and optimize arterial network timing plans. PASSER IV and TRANSYT can be used separately or in coordination for optimizing arterial network signal retiming plans. Both PASSER IV and TRANSYT run on IBM PC compatible micro-computers. As mentioned previously, one should make further reference to the user's manuals for both programs.

4.2 Input Requirements

This section discusses the coding and simulation procedures for PASSER IV and TRANSYT-7F. Table 4-1 presents some of the common input requirements utilized by PASSER IV and TRANSYT for coding existing conditions on an arterial street system. One must initially code a data set containing the existing traffic signal operational conditions for the arterial street network to be analyzed through one of the programs. After developing the initial data set, the selected program is utilized to simulate existing conditions. A simulation run models arterial conditions coded in the data set and generates a performance evaluation with respect to the modelling parameters of each program. The following sections outline the basic requirements for coding existing conditions for simulation with PASSER IV and TRANSYT.

PASSER IV-94. PASSER IV is composed of two components; a *User Interface* and *Optimization Module*. The *User Interface* module allows data editing and file manipulation functions, whereas the *Optimization Module* actually does bandwidth optimization for the given traffic network. The PASSER IV *User Interface* is extremely easy to use, requiring a minimum amount of practice. Figure 4-1 shows the first screen in this program, the *Main Menu*. The various options in the *Main Menu* allow the user to select the function that needs to be performed. The function keys in the *File* menu allow the user to select corresponding file functions outside the *File* menu. One may create an input data file, or load an existing data file into the current screen using these options.

The *Edit* function allows easy data entry/editing of a loaded data file. It uses a "free format" in the sense that the user can go to any *Arterial or Signal Data Entry Screen* in a selected order (that is, the program does not force the user to go through a fixed data entry sequence). Within the *Data Entry* hierarchy, the function keys (F2 and F3) can be used to move from one data entry scheme to another, as shown in Figure 4-2. An arterial in the network can be entered in any order (the program will attach a sequence number to each arterial in the order it is entered); however, one must enter signal data within an arterial starting from the first to the last intersection in the "Forward or A-Direction," without skipping any signal data. In addition, each signal must be assigned a unique node identification number, used by the program to find linkages in the network.

Table 4-1. Common Coding Requirements for PASSER IV and TRANSYT

ARTERIAL IDENTIFICATION	Name of Arterial Segment Orientation of Segment (NS or EW) Number of Intersections Distance Between Intersections
SYSTEM-WIDE PARAMETERS	Ideal Saturation Flow Rate Operational Defaults System Cycle Length
TRAFFIC/PHASING DATA	Speeds Volumes Phasing Sequences and Duration Additional Timing Intervals

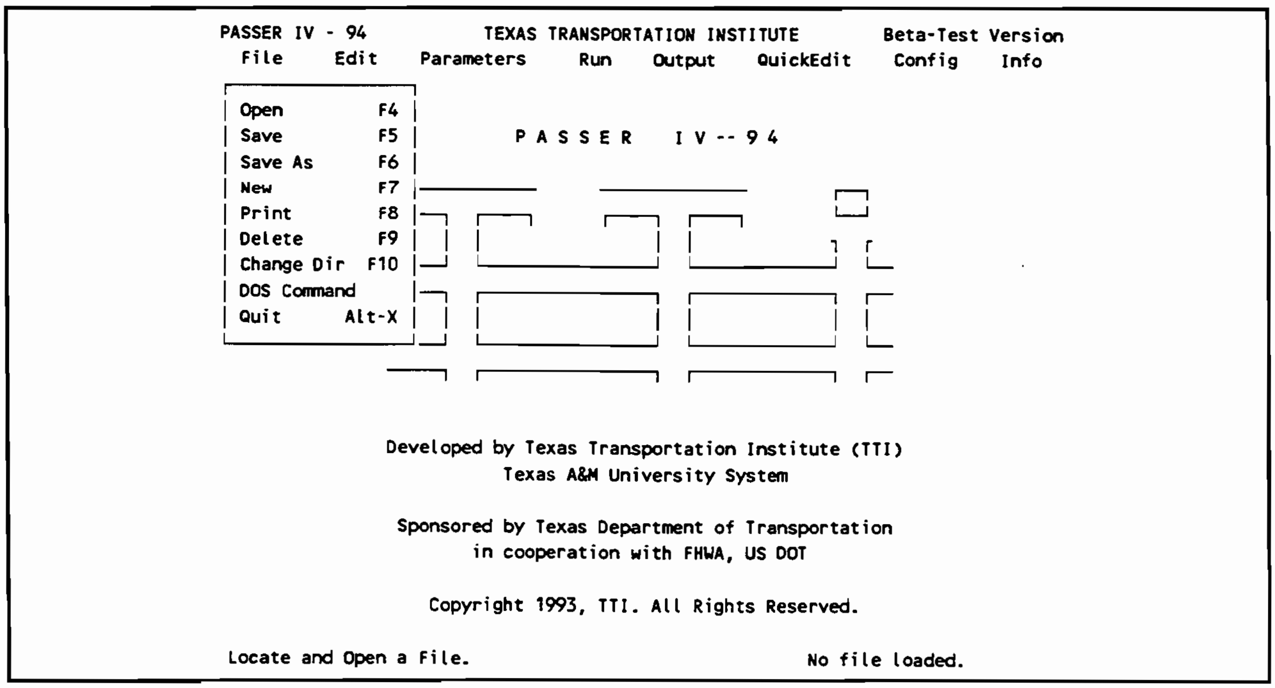


Figure 4-1. PASSER IV Main Menu Screen

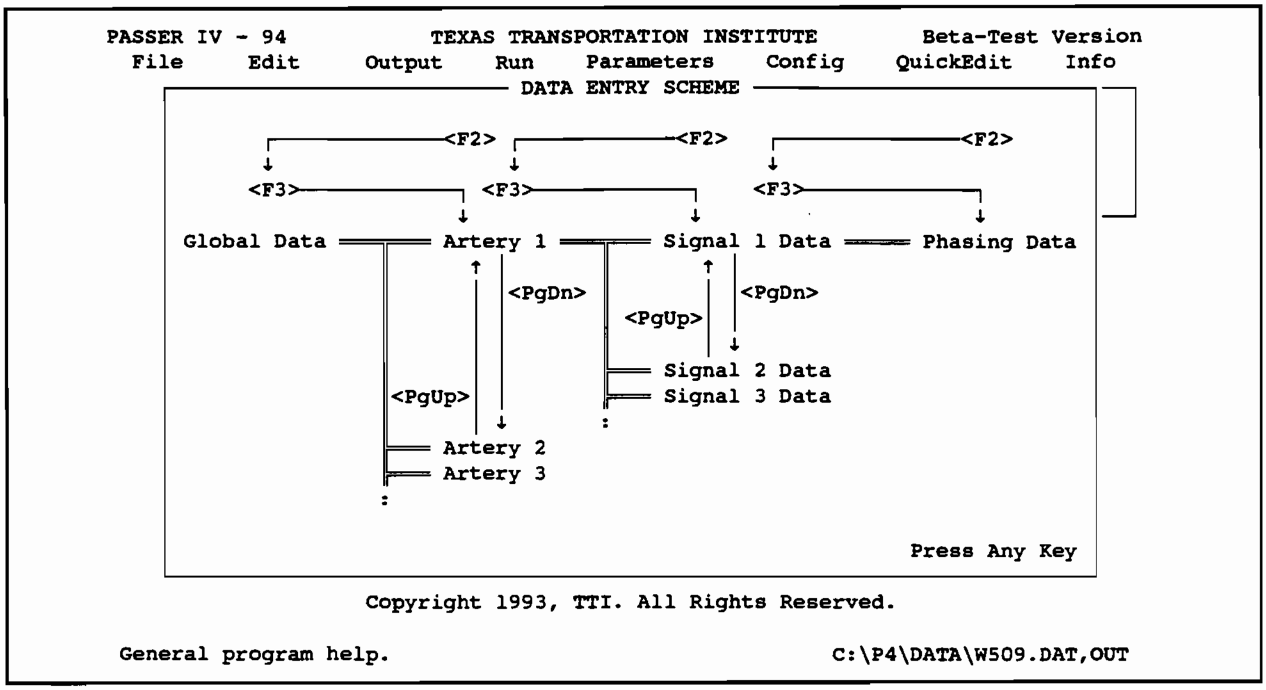


Figure 4-2. PASSER IV Data Entry Scheme

Data must be entered only once for an intersection falling on two arteries. For example, if Signal 1 on Arterial 2 and Signal 3 on Arterial 5 have the same node identification number, signal data need only be entered while entering Arterial 2 data. Figures 4-3 and 4-4 show the input screens for Global Data and Artery Data. Figures 4-5 and 4-6 show the input screens for *Signal Data* and *Left-Turn Pattern Selection Data.* The format is slightly restrictive as compared to other network programs available to the traffic community; however, this format is also very simple to code since the data entry sequence informs the program about the linkage of signals, which the user has no need to provide.

The *Parameters Screen* lets the user specify optimization data, including optimization steps, number of solutions to be saved at each step, and upper limit on the number of iterations and re-inversions for branch and bound procedure and linear programs. Figure 4-7 shows the *Input Data Screen for Optimization Parameters.* One-Step or global optimization gives the best possible solution but also is the slowest and applicable to all problems. Two and Three-Step optimization are heuristic procedures, which give very good solutions in a short amount of time. The Two-Step optimization process applies to arterial as well as closed loop networks. The Three-Step optimization procedure is only valid for multi-arterial-close-loop networks. The *Information* function allows the user to view the network on the screen, as illustrated in Figure 4-8.

```
PASSER IV - 94          TEXAS TRANSPORTATION INSTITUTE        Beta-Test Version
  File     Edit     Output    Run    Parameters    Config    QuickEdit     Info
 ================================ GLOBAL DATA ================================

  Run Number      :                       City Name    :
  District Number :                       Network Name : HAWTHORNE
  Date            :   /  /

  Number of Arteries         :  5         Number of Signals        :  9

  Lower Cycle Length (Sec)   : 90.0       Upper Cycle Length (Sec) : 90.0
  Minimize Cycle Length (Y/N) : N

  Measurement Unit (E/M)     : E          Warning Message (Y/N)    : N

         OUTPUT REPORT INCLUDES

  Input Data File (Y/N)                : Y
  Input Data Summary (Y/N)             : Y
  Optimization Performance Plot (Y/N)  : Y
  Solution Report (Y/N)                : Y

                                                         Esc:End F3:Artery

 City Name: Optional                                C:\P4\DATA\W509.DAT,OUT
```

Figure 4-3. PASSER IV Global Data Entry Screen

```
PASSER IV - 94          TEXAS TRANSPORTATION INSTITUTE        Beta-Test Version
  File     Edit     Output    Run    Parameters    Config    QuickEdit     Info
 ================================ ARTERY DATA ====================== Artery:2 =

  Artery Name    : HAWTHORNE              Number of Signals  :  5

  Time Scale     :    3                   A-Direction        : E-Bound

  Distance Scale :  150                   Artery Priority    :    0

                      A-DIRECTION              B-DIRECTION

  Priority       :         1                        1

  Average Speed  :        45                       45

  Speed Range    :         3                        3

  Speed Change   :         3                        3


                  Esc:End PgUp:Prev PgDn:Next F2:Global F3:Signals

 Artery Name:                                       C:\P4\DATA\W509.DAT,OUT
```

Figure 4-4. PASSER IV Artery Data Entry Screen

```
PASSER IV - 94           TEXAS TRANSPORTATION INSTITUTE        Beta-Test Version
  File     Edit      Output    Run    Parameters    Config    QuickEdit    Info
 HAWTHORNE ==================== SIGNAL DATA ====================== Signal:1

  Signal ID 6        NEMA 2 Movement E-Bound                                N ↑

  A-Direction on This  Artery E-Bound
  A-Direction on Cross Street  -Bound

                NB       SB       EB       WB
  Link Length                    1050     1120
  Link Speed                       45       45
  Speed Var                         3        3
  Queue Clear

              NORTHBOUND     SOUTHBOUND     EASTBOUND      WESTBOUND
            Left Thru Rgt  Left Thru Rgt  Left Thru Rgt  Left Thru Rgt
  Volume          292            166       132 1400       154  786
  Sat Flow       1200           1000      2400 6000      1500 6000
  Min Phs          25             25        10   25        10   25
  Grn Split
                             Esc:End PgUp:Prev PgDn:Next F2:Artery F3:LeftPat

 Signal ID: Unique integer must be supplied.          C:\P4\DATA\W509.DAT,OUT
```

Figure 4-5. PASSER IV Signal Data Entry Screen

```
PASSER IV - 94           TEXAS TRANSPORTATION INSTITUTE        Beta-Test Version
  File     Edit      Output    Run    Parameters    Config    QuickEdit    Info
 HAWTHORNE ==================== SIGNAL DATA ====================== Signal:1

  Signal ID 6        NEMA 2 Movement E-Bound                                N ↑

  A-Direction on This  Artery E-Bound
  A-Direction on Cross Street  -Bound
                       ========== LEFT TURN-PATTERN SELECTION ============
              NB       |
  Link Length          | NEMA  Phases           This Artery  Cross Street
  Link Speed           | With Overlap
  Speed Var            |
  Queue Clear          | A-Left Leads - B-Left Lags    Y             N
                       | A-Left Lags  - B-Left Leads   Y             N
                       | A-Left Leads - B-Left Leads   Y             N
            NORTHBOUN  | A-Left Lags  - B-Left Lags    Y             N
          Left Thru R  |
  Volume          292  | Main-Cross Split (Circular) Phasing         N
  Sat Flow       1200  |
  Min Phs          25  |                              Esc:End F2:Signal
  Grn Split
                             Esc:End PgUp:Prev PgDn:Next F2:Artery F3:LeftPat

 Lead-Lag: Yes or No                                  C:\P4\DATA\W509.DAT,OUT
```

Figure 4-6. PASSER IV Left-Turn Pattern Selection Data Screen

```
PASSER IV - 94          TEXAS TRANSPORTATION INSTITUTE       Beta-Test Version
  File     Edit     Output    Run     Parameters    Config    QuickEdit    Info
                     OPTIMIZATION PARAMETERS

  Maximum BB Iterations    :    1000000    Maximum BB Reinversions     :   100
  Maximum LP Iterations    :   500         Maximum LP Reinversions     :   100

  Restart Problem (y/n)       : N          Print Performance Plot (y/n) : Y
  Optimization Steps (1,2,3)  : 3
  In-depth Search (y/n)       : N          Coefficient of Z : 0.50

                      STEP 1               STEP 2              STEP 3
  Solutions saved :   1                    1                   1
  Tolerance 1     :
  Tolerance 2     :
  Tolerance 3     :
  Tolerance 4     :
  Tolerance 5     :
  Tolerance 6     :
  Tolerance 7     :
  Tolf            :

                                                                    Esc:End
 Maximum BB Iterations: Default 1000000                 C:\P4\DATA\W509.DAT,OUT
```

Figure 4-7. PASSER IV Coding Screen for Optimization Parameters

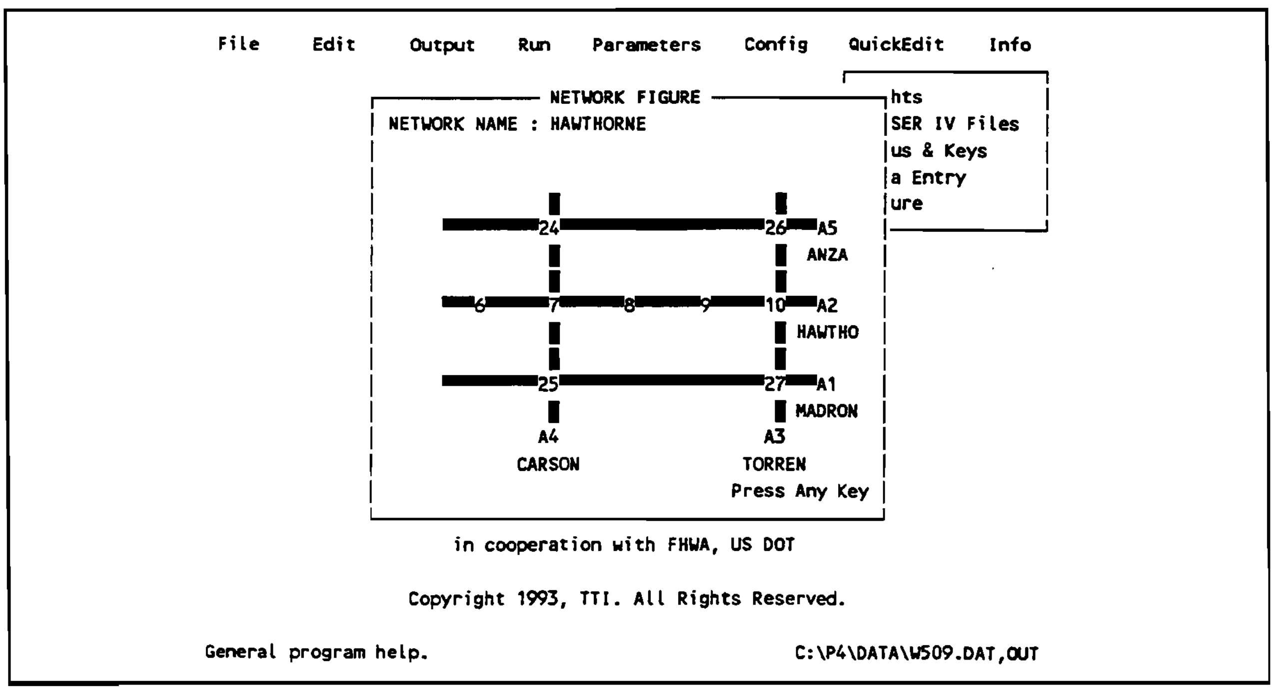


Figure 4-8. PASSER IV Screen for Network Layout

It is recommended that the number of steps for a given problem be the highest number possible, since that selection will require the least amount of CPU time. For example, use the Three-Step optimization procedure for a network with multi-phase signals. In addition, make sure that the number of solutions saved in the last step equals to one, except when an output report for more than one signal timing solution is needed.

TRANSYT-7F (EZ-TRANSYT). Coding initial arterial information through a supplementary program, such as EZ-TRANSYT, is a common approach for developing a data set for TRANSYT-7F. EZ-TRANSYT provides "pull-down" menus and coding screens for entering data, as illustrated in Figure 4-9. Arterial identification information is coded under the *Create* menu on the two coding screens illustrated in Figures 4-10 and 4-11. The *Grid Network Screen* illustrated in Figure 4-10 allows the user to enter the number of arterials in both the east/west direction and the north/south direction. The *Adjacent Nodes Screen*, illustrated in Figure 4-11, allows the user to code the names of the arterial and cross streets, along with the distances between each set of cross streets.

Having defined the arterial street network, the *Edit* menu is used to code the system-wide and traffic/phasing data. The *Network-Wide Parameters Screen*, illustrated in Figure 4-12, codes all the system-wide data for the arterial. The program codes operational defaults, system cycle length, and offset references on this screen. Other system parameters, such as base saturation flow rates and system lost-time, are defaults for the program, and one must alter them for each individual intersection or in the resultant TRANSYT data set.

Traffic and signal phasing data is coded on an *Intersection Screen* illustrated in Figure 4-13. The program provides a separate screen for each of the cross streets along the arterial segment, and volumes, number of lanes, adjusted saturation flow rates, speeds, and phasing intervals can be coded on each screen.

Once the initial coding has been completed with EZ-TRANSYT, a TRANSYT data deck is created. The TRANSYT program then uses this data deck for simulating existing conditions. The analyst can then use the program editing features of TRANSYT to edit the entire data deck and alter any of the coded information. One may access this editing feature by selecting *Alter Data File* on the TRANSYT shell menu.

```
[EZ7+ 6.0] Create Edit Route Print Generate Options Dos Quit
           Create new EZ-TRANSYT data base                        EX1
---------------------------------------------------------------------
              ==== NETWORK TYPE ====
              | Single intersection |
              | One arterial        |
              | Two arterials       |
              | Grid network        |
              | Other               |
              |                     |
              =====↑↓<Esc><Ret>======
```

Figure 4-9. EZ TRANSYT Main Menu Screen

```
[EZ7+ 6.0] Create Edit Route Print Generate Options Dos Quit
           Create new EZ-TRANSYT data base                        EX2
---------------------------------------------------------------------
        |                   GRID NETWORK                        |
        |-------------------------------------------------------|
        | Number of arterials in east/west   direction    2     |
        | Number of arterials in north/south direction    2     |
        ================↑↓<Esc><PgUp><PgDn>======================
```

Figure 4-10. EZ TRANSYT Coding Screen for a Grid Network

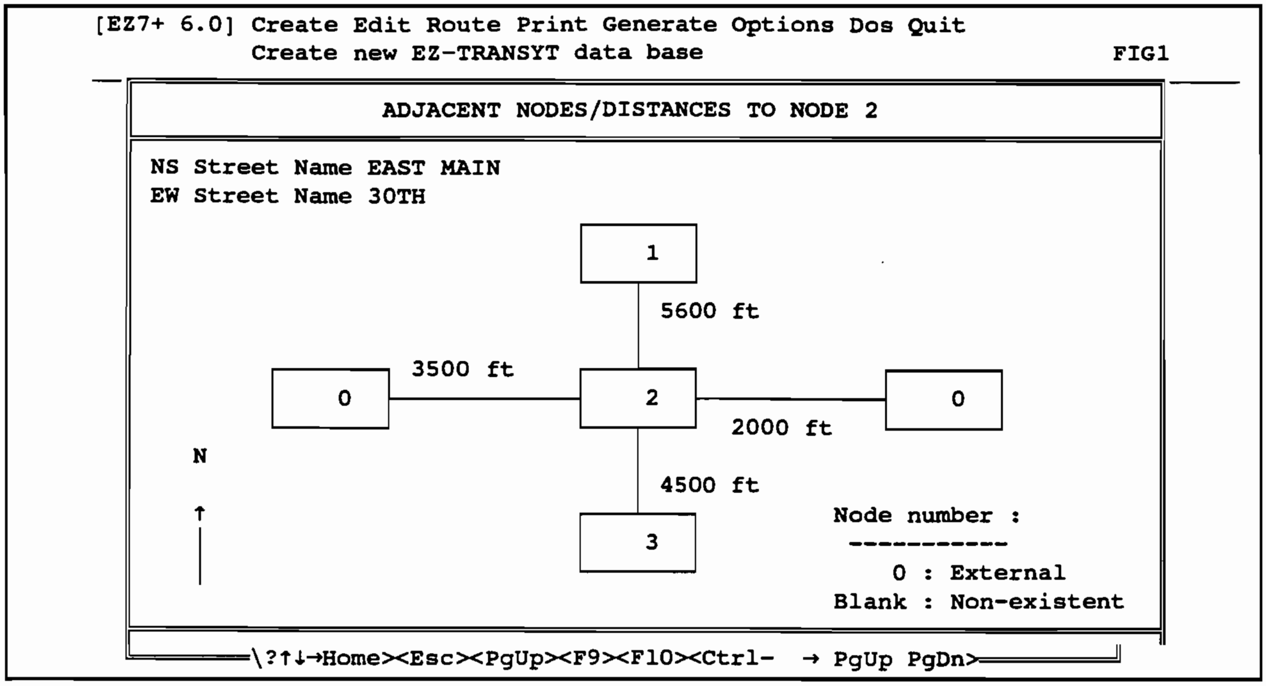


Figure 4-11. EZ TRANSYT Coding Screen for Adjacent Arterial Nodes

```
[EZ7+ 6.0] Create Edit Route Print Generate Options Dos Quit
           Edit existing EZ-TRANSYT data base                      FIG1

                       NETWORK-WIDE PARAMETERS

  Title : EAST MAIN ARTERIAL

  Run Action   : SIMULATION          PI Def.    : STOPS+DELAY
  Traffic      : MODERATE            Driver     : NORMAL
  Init. Timing:  NO                  Master Node:   0

  Cycle Length(sec) Min.:  70        Max.: 120     Increment :  5

  Yellow Time(sec):  3    All Red(sec):   1     Speed(mph): 30

  Fuel Cost($/gal) :    1.25         Avg. Veh. Occupancy    :   1.20
  Inflation Rate(%):    1.00         Excess Queue Weight.(%):     40
  Stop Penalty     :      -1         Double Cycle Threshold :     25

  Sneaker/Cycle, Permitted Only : 2.00   Permitted+Protected : 1.50

                 ?↑↓→Home><Esc><PgUp><PgDn>
```

Figure 4-12. EZ TRANSYT Coding Screen for Network-Wide Parameters

INTERSECTION 1 EAST MAIN & East-West Arterial

	Northbound			Southbound			Eastbound			Westbound		
	LT	TH	RT	LT	TH	RT	LT	TH	RT	LT	TH	RT
Volume(vph)	248	1903	86	178	1509	78	102	1300	19	116	1346	28
# of Lanes	1	2	0	1	2	0	0	2	0	0	2	0
Sat Flow/Ln	1600	1700	1600	1600	1700	1600	1600	1700	1600	1600	1700	1600
Mid-Block	0	0	0	0	0	0	0	0	0	0	0	0
Speed (mph)	45	45	45	45	45	45	30	30	30	30	30	30
Max. Queue	0	0	0	0	0	0	0	0	0	0	0	0
Lost Adjust	0	0	0	0	0	0	0	0	0	0	0	0
Ext. Adjust	0	0	0	0	0	0	0	0	0	0	0	0

Phase	Walk	FDW	Amb.	A-R	Min.	Act.
1. NB&SB Green	0	0	Net.	Net.	10	NO
2. EB&WB Green	0	0	Net.	Net.	10	NO
3.	0	0	Net.	Net.	10	NO
4.	0	0	Net.	Net.	10	NO
5.	0	0	Net.	Net.	10	NO
6.	0	0	Net.	Net.	10	NO

Excluded in PT	NO
Offset (sec)	0
Reference Interval	1
Double Cycle	NO
Exclude from Opt.	NO
Fix Split in Opt.	NO
Grouped with Node	0

\?/↑↓→Home<Esc><PgUp><F9><F10><Ctrl- → PgUp PgDn><F2>

Figure 4-13. EZ TRANSYT Coding Screen for Intersections

TRANSYT-7F. One enters arterial street network data through coding screens and windows accessible from TRANSYT's main menu, shown in Figure 4-14. The correct menu choice to create or edit an arterial street network data set is the TRANSYT *Data Input Manager* (DIM). After making this selection, a blank screen appears in the create mode, and a screen containing data appears if an existing data set was loaded. Figure 4-15 shows an example of an existing data set; however; one should note that the figure shows only the first 21 lines of data. The remainder of the data set is accessed by moving the cursor down to the bottom of the screen.

Note that a TRANSYT data set is made up of several lines of data, with each line containing 16 five column fields. To view column headings or enter data, move the cursor to the line of interest and press the [Esc] key. This key will cause a window with column headings and current data to appear on the right side of the screen. One can edit the data within the window, and update the data file when exiting the window. Figure 4-16 shows a data entry window for Card Type 1 (second line of data). Note that cycle length and analysis period length are entered on this data card.

Card Type 2 is an optimization node list card used to list the nodes for which the signal timing is to be optimized during an optimization run. Card type 7 is the shared stop line card which is used to list the sets of links that share the same stop line in the network. One must use this card whenever more than one link will end at a single downstream node, and it can be used for any grouping of links that share the same saturation flow rate and signal timing. Card Type 10 is the network master controller card and is used to code information about the system controllers at all nodes and/or links in the network. If the analyst uses the default values, then the network master card need not be included in the input data deck. Figures 4-17, 4-18, and 4-19 illustrate the data entry windows for Card Types 2, 7, and 10 respectively.

Cards Types 15 through 28 contain intersection information, such as phase lengths and sequences, traffic volumes, link speed, and distance data. This type of information will be repeated for each intersection in the arterial system. Figures 4-20, 4-21, and 4-22 illustrate the *Interval Timing*, *Signal Phasing*, and *Link Data*. It is apparent that, TRANSYT requires more detailed data and a more complex data entry scheme than PASSER IV.

```
                 McT7F - TRANSYT-7F MAIN MENU

            T ---> TRANSYT-7F Program
            R ---> Read Input/Output Files
            A ---> Alter Data Files (T7FDIM).
            N ---> New File (T7FGEN)
            S ---> Send Output File to Printer
            Y ---> Your Special Program
            T ---> TRANSYT-7F Program
            + ---> EZ-TRANSYT PLUS
            7 ---> 7F PPD Program
            F ---> File Management

           Copyright 1988, University of Florida

          Enter your Choice [Quit, eXit  or Esc]
```

Figure 4-14. TRANSYT-7F Main Menu

```
TRANSYT-7F DATA INPUT MANAGER                                          Version 4.1
  1    2    3    4    5    6    7    8    9   10   11   12   13   14   15   16
-RIDGEWOOD AVE     CHAP 7 BWC EX     BANDWIDTH CONSTRAINED OPTIMIZATION         -
[  1  120  120    0    0    0    3    3   -1    0    0   60    0    0    0    0]
[  2    1    2    3    4    0    0    0    0    0    0    0    0    0    0    0]
[  7  105  106    0    0    0  107  108    0    0    0  205  206    0    0    0]
[  7  207  208    0    0    0  405  406    0    0    0  407  408    0    0    0]
[ 10    0    0    0    0    0    0    0    0    1    0    0    0    0    0    0]
[ 13    1    0    1   14    4   56    4   38    4    0    0    0    0    0    0]
[ 21    1    1    1    2    0   10  102  104    0    0    0    0    0    0    0]
[ 22    1    3    3    4    0   15  101  103    0    0    0    0    0    0    0]
[ 23    1    5    5    6    0   15  105 -106  107 -108    0    0    0    0    0]
[ 28  101  100 3400  640    0    0    0   35    0    0    0    0    0    0    0]
[ 28  102  100 1600   46    0    0    0   35    0    0    0    0    0    0    0]
[ 28  103  766 3400  856    0  203  738   35  208   90   35  205   27   35    0]
[ 28  104  766 1600  110    0  203  110   35    0    0    0    0    0    0    0]
[ 28  105    0 3400  426    0    0    0    0    0    0    0    0    0    0    0]
[ 28  106    0    0   48    0    0    0    0    0    0    0    0    0    0    0]
[ 29  106    0    0    0    2    0    0    0  107    0    0    0    0    0    0]
[ 28  107    0 3400  214    0    0    0    0    0    0    0    0    0    0    0]
[ 28  108    0    0   86    0    0    0    0    0    0    0    0    0    0    0]
[ 29  108    0    0    0    2    0    0    0  105    0    0    0    0    0    0]
     [F1] for Command Mode , [Esc] for Window mode. [?] for card list
 File Name:    CHAP7.DAT             BROWSE MODE        Card No. 1  OF 72
```

Figure 4-15. Example of an Existing Data Set

```
TRANSYT-7F DATA INPUT MANAGER                                     Version 4.1
   1    2    3    4    5    6    7    8    9   10   11   12   13   14   15   16
-RIDGEWOOD AVE     CHAP 7 BWC EX     BA
[  1  120  120    0    0    0    3    CARD TYPE   1        SYSTEM CONTROLS
[  2    1    2    3    4    0    0
[  7  105  106    0    0    0  107   10  MINIMUM CYCLE..................[120   ]
[  7  207  208    0    0    0  405   40  MAXIMUM CYCLE..................[120   ]
[ 10    0    0    0    0    0    0       CYCLE INCREMENT................[0     ]
[ 13    1    0    1   14    4   56       SEC/STEP (CYC).................[0     ]
[ 21    1    1    1    2    0   10   10  SEC/STEP (OPT).................[0     ]
[ 22    1    3    3    4    0   15   10  START LOST TIME................[3     ]
[ 23    1    5    5    6    0   15   10  EXT. EFFECTIVE GREEN...........[3     ]
[ 28  101  100 3400  640    0    0       STOP PENALTY...................[-1    ]
[ 28  102  100 1600   46    0    0       OUTPUT LEVEL...................[0     ]
[ 28  103  766 3400  856    0  203   73  INITIAL TIMING (Y=1)...........[0     ]
[ 28  104  766 1600  110    0  203   11  PERIOD LENGTH..................[60    ]
[ 28  105    0 3400  426    0    0       SEC(0) / PERCENT(1)............[0     ]
[ 28  106    0    0   48    0    0       SPEED(0) / TIME(1).............[0     ]
[ 29  106    0    0    0    2    0       U.S.(0) / METRIC(1)............[0     ]
[ 28  107    0 3400  214    0    0       PUNCH (Y=1)....................[0     ]
[ 28  108    0    0   86    0    0
[ 29  108    0    0    0    2    0
     [PgUp] [PgDn] to change cards ... [Esc] to return to Browse Mode.
 File Name:    CHAP7.DAT           WINDOW MODE        Card No. 2  OF 72
```

Figure 4-16. Data Entry Window for Card Type 1

```
TRANSYT-7F DATA INPUT MANAGER                                     Version 4.1
   1    2    3    4    5    6    7    8    9   10   11   12   13   14   15   16
-EXTENDED HAWTHORNE. OPT OFF. MAX SEQ
[  1   90   90    5    5    1    2      CARD TYPE  2  OPTIMIZATION NODE LIST
[  2    3    4    5    6    7    8
-****4    2   15   40   15    2         *******************************[3    ]
-****6  500  500  500  100    1         *                             *[4    ]
[  4   15   40   -2   15   40    2   -  *    LIST THE NODES TO        *[5    ]
[  6 1000 1000  100  100  100   10      *    BE OPTIMIZED ON          *[6    ]
[  7  401  402  409    0    0  305   31 *    THIS SCREEN.             *[7    ]
[  7  407  412                 501   50 *                             *[8    ]
[  7  601  609                 603   61 *    NEGATIVE NODES           *[9    ]
[  7  705  711                 707   71 *    WILL BE GROUPED          *[10   ]
[  7  801  802  809            803   81 *    WITH THE NEXT            *[11   ]
[  7  807  812                1005  101 *    POSITIVE NODE.           *[12   ]
[  7 1101 1102 1109           1103  110 *                             *[13   ]
[  7 1107 1112                1201  120 *    BLANKS ARE IGNORED.      *[14   ]
[  7 1205 1211                1207  121 *                             *[15   ]
[  7 1305 1311                1307  131 *                             *[     ]
[  7 1407 1412                1503  150 *******************************[     ]
[ 10    3    3    0    0   35   35   10
[ 15    3   84    1    7    3    5
     [PgUp] [PgDn] to change cards ... [Esc] to return to Browse Mode.
 File Name:    B:HAWT1.DAT         WINDOW MODE        Card No. 3  OF 219
```

Figure 4-17. Data Entry Window for Card Type 2

```
TRANSYT-7F DATA INPUT MANAGER                                          Version 4.1
  1    2    3    4    5    6    7    8    9   10   11   12   13   14   15   16
-RIDGEWOOD AVE      CHAP 7 BWC EX      BA
[  1  120  120    0    0    0    3      CARD TYPE   7   SHARED STOPLINE GROUPS
[  2    1    2    3    4    0    0
[  7  105  106    0    0    0  107   10  PRIMARY LINK..................[105   ]
[  7  207  208    0    0    0  405   40  SECONDARY LINKS:...............[106   ]
[ 10    0    0    0    0    0    0       ..............................[0     ]
[ 13    1    0    1   14    4   56       ..............................[0     ]
[ 21    1    1    1    2    0   10   10  ..............................[0     ]
[ 22    1    3    3    4    0   15   10  PRIMARY LINK..................[107   ]
[ 23    1    5    5    6    0   15   10  SECONDARY LINKS:...............[108   ]
[ 28  101  100 3400  640    0    0       ..............................[0     ]
[ 28  102  100 1600   46    0    0       ..............................[0     ]
[ 28  103  766 3400  856    0  203   73  ..............................[0     ]
[ 28  104  766 1600  110    0  203   11  PRIMARY LINK..................[205   ]
[ 28  105    0 3400  426    0    0       SECONDARY LINKS:...............[206   ]
[ 28  106    0    0   48    0    0       ..............................[0     ]
[ 29  106    0    0    0    2    0       ..............................[0     ]
[ 28  107    0 3400  214    0    0       ..............................[0     ]
[ 28  108    0    0   86    0    0
[ 29  108    0    0    0    2    0
     [PgUp] [PgDn] to change cards ... [Esc] to return to Browse Mode.
 File Name:    CHAP7.DAT            WINDOW MODE        Card No. 4  OF 72
```

Figure 4-18. Data Entry Window for Card Type 7

```
TRANSYT-7F DATA INPUT MANAGER                                          Version 4.1
  1    2    3    4    5    6    7    8    9   10   11   12   13   14   15   16
-EXTENDED HAWTHORNE. OPT OFF. MAX SEQ
[  1   90   90    5    5    1    2      CARD TYPE   10   OPERATING PARAMETERS
[  2    3    4    5    6    7    8
-****4    2   15   40   15    2          MASTER NODE NO..................[3     ]
-****6  500  500  500  100    1          YELLOW CHANGE INTERVAL.........[3     ]
[  4   15   40   -2   15   40    2    -  ALL-RED CLEARANCE..............[0     ]
[  6 1000 1000  100  100  100   10       SATURATION FLOW/LANE...........[0     ]
[  7  401  402  409    0    0  305   31  APPROACH SPEED.................[35    ]
[  7  407  412                 501   50  PLATOON DISPERSION FACTOR......[35    ]
[  7  601  609                 603   61  FUEL MULTIPLIER................[100   ]
[  7  705  711                 707   71  AVERAGE VEHICLE SPACING........[25    ]
[  7  801  802  809            803   81  ORIENTATION FLAG (0/1-4).......[0     ]
[  7  807  812                1005  101  DESIRED DEGREE OF SATURATION...[85    ]
[  7 1101 1102 1109           1103  110  DESIRED DOUBLE CYCLE D/S.......[25    ]
[  7 1107 1112                1201  120  MAX. BACK OF QUEUE PENALTY ....[40    ]
[  7 1205 1211                1207  121  INFLATION FACTOR (%)...........[100   ]
[  7 1305 1311                1307  131  FUEL COST/GAL (CENTS)..........[125   ]
[  7 1407 1412                1503  150  AVG. VEHICLE OCCUPANCY (*100)..[120   ]
[ 10    3    3    0    0   35
[ 15    3   84    1    7    3    5
     [PgUp] [PgDn] to change cards ... [Esc] to return to Browse Mode.
 File Name:    B:HAWT1.DAT          WINDOW MODE        Card No. 19  OF 219
```

Figure 4-19. Data Entry Window for Card Type 10

```
TRANSYT-7F DATA INPUT MANAGER                                        Version 4.1
   1    2    3    4    5    6    7    8    9   10   11   12   13   14   15   16
-EXTENDED HAWTHORNE. OPT OFF. MAX SEQ
[  1   90   90    5    5    1    2     CARD TYPE [ 15]        INTERVAL TIMING
[  2    3    4    5    6    7    8
-****4    2   15   40   15    2        NODE NUMBER...................[3    ]
-****6  500  500  500  100    1        OFFSET OR YIELD PT............[84   ]
[  4   15   40   -2   15   40    2   - REFERENCE INTERVAL............[1    ]
[  6 1000 1000  100  100  100   10     INTERVAL LENGTH 1.............[7    ]
[  7  401  402  409    0    0  305   31 .               2.............[3    ]
[  7  407  412                 501   50 . (NOTE: IF THE 3.............[5    ]
[  7  601  609                 603   61 . '1X' IS NEG-  4.............[1    ]
[  7  705  711                 707   71 . ATIVE (-1X)   5.............[47   ]
[  7  801  802  809            803   81 . THE SPLITS    6.............[3    ]
[  7  807  812                1005  101 . WILL NOT BE   7.............[18   ]
[  7 1101 1102 1109           1103  110 . OPTIMIZED.)   8.............[1    ]
[  7 1107 1112                1201  120 .               9.............[12   ]
[  7 1205 1211                1207  121 .              10.............[3    ]
[  7 1305 1311                1307  131 .              11.............[     ]
[  7 1407 1412                1503  150 DOUBLE CYCLE? (Y=1)...........[     ]
[ 10    3    3    0    0   35   35   10
[ 15    3   84    1    7    3    5
     [PgUp] [PgDn] to change cards ... [Esc] to return to Browse Mode.
 File Name:   B:HAWT1.DAT          WINDOW MODE        Card No. 20  OF 219
```

Figure 4-20. TRANSYT Coding Screen for Interval Timing

```
TRANSYT-7F DATA INPUT MANAGER                                        Version 4.1
   1    2    3    4    5    6    7    8    9   10   11   12   13   14   15   16
[  1   90   90    5    5    1    2
[  2    3    4    5    6    7    8     CARD TYPE [ 21]         SIGNAL PHASING
-****4    2   15   40   15    2
-****6  500  500  500  100    1        NODE NUMBER...................[3    ]
[  4   15   40   -2   15   40    2   - START INTERVAL................[1    ]
[  6 1000 1000  100  100  100   10     VARIABLE INTERVAL.............[1    ]
[  7  401  402  409    0    0  305   31 YELLOW INTERVAL...............[2    ]
[  7  407  412                 501   50 ALL-RED INTERVAL..............[     ]
[  7  601  609                 603   61 MINIMUM PHASE LENGTH..........[9    ]
[  7  705  711                 707   71 LINKS SERVICED: 1.............[306  ]
[  7  801  802  809            803   81 .               2.............[308  ]
[  7  807  812                1005  101 .  (NEGATIVE   3.............[     ]
[  7 1101 1102 1109           1103  110 .   NUMBERS    4.............[     ]
[  7 1107 1112                1201  120 .     MEAN     5.............[     ]
[  7 1205 1211                1207  121 .  PERMITTED.) 6.............[     ]
[  7 1305 1311                1307  131 .               7.............[     ]
[  7 1407 1412                1503  150 .               8.............[     ]
[ 10    3    3    0    0   35   35   10 ACTUATED OR DESIRED D/S........[     ]
[ 15    3   84    1    7    3    5
[ 21    3    1    1    2         9   30
     [PgUp] [PgDn] to change cards ... [Esc] to return to Browse Mode.
 File Name:   B:HAWT1.DAT          WINDOW MODE        Card No. 21  OF 219
```

Figure 4-21. TRANSYT Coding Screen for Signal Phasing

```
TRANSYT-7F DATA INPUT MANAGER                                       Version 4.1
   1    2    3    4    5    6    7    8    9   10   11   12   13   14   15   16
[  7  401  402  409    0    0  305   31╔═══════════════════════════════════════╗
[  7  407  412                   501   50║ CARD TYPE   28              LINK DATA ║
[  7  601  609                   603   61║                                       ║
[  7  705  711                   707   71║ LINK NUMBER....................[301  ]║
[  7  801  802  809              803   81║ LINK LENGTH....................[500  ]║
[  7  807  812                  1005  101║ SATURATION FLOW................[1500 ]║
[  7 1101 1102 1109             1103  110║ TOTAL VOLUME...................[90   ]║
[  7 1107 1112                  1201  120║ MIDBLOCK ENTRY.................[     ]║
[  7 1205 1211                  1207  121║ 1ST INPUT LINK NO..............[     ]║
[  7 1305 1311                  1307  131║ .          VOLUME..............[     ]║
[  7 1407 1412                  1503  150║ .           SPEED..............[     ]║
[ 10    3    3    0    0   35   35   10║ 2ND INPUT LINK NO..............[     ]║
[ 15    3   84    1    7    3    5      ║ .          VOLUME..............[     ]║
[ 21    3    1    1    2    0    9   30║ .           SPEED..............[     ]║
[ 22    3    3    3    4    0    5   30║ 3RD INPUT LINK NO..............[     ]║
[ 23    3    5    5    6    0   22   30║ .          VOLUME..............[     ]║
[ 24    3    7    7    8    0    9   30║ .           SPEED..............[     ]║
[ 25    3    9    9   10    0    9   30║ QUEUEING CAPACITY..............[     ]║
[ 28  301  500 1500   90                ║                                       ║
[ 28  302  500 1500   80                ╚═══════════════════════════════════════╝
     [PgUp] [PgDn] to change cards ... [Esc] to return to Browse Mode.
 File Name:   B:HAWT1.DAT          WINDOW MODE        Card No. 26  OF 219
```

Figure 4-22. TRANSYT Coding Screen for Link Data

4.3 Output Evaluation

This section discusses the generation and interpretation of the output from simulation runs by PASSER IV-94 and TRANSYT-7F. After completing a simulation run, the program creates an output file of the simulation results. Because both PASSER IV and TRANSYT are signal optimization programs, the output generated by each program is oriented towards developing an optimal set of signal timing parameters. This section will focus upon the components of the output critical for evaluating existing conditions. In general, output files consist of an echo of the information coded in the initial input data file and a listing of the MOEs calculated for the existing or optimized traffic operational conditions.

PASSER IV Output. The initial selection of the output report for a PASSER IV optimization run includes input data file, input data summary, optimization performance plot, and the solution report. The input data summary consists of a report of the input conditions coded into the original data file. One typically refers to this input report as an input echo and includes the map, speed, length, and volume for each artery in the network. If coding errors are detected, they will be listed either with the input data or on the error message page generated after the input data, depending on when the error was detected.

Pages summarizing the optimization performance plots and optimization statistics follow the input echo. The optimization performance plot includes the optimization steps, number of solutions saved at each step, and the upper limit on the number of iterations and reinversions for branch and bound procedures and linear programs. Optimization statistics include the best objective function value of the final solution and the total number of iterations and reinversions performed. The objective function value is represented in fraction of cycle length, and equals twice the overall network efficiency. One obtains the average arterial efficiency by dividing the network efficiency by the number of arterials in the network.

The solution report includes the summary of intersection numbers at artery meetings, network wide cycle length, and the bandwidths for each artery in fraction of the cycle length as well as in seconds. Figure 4-23 illustrates the PASSER IV Solution report. For each artery, the solution report consists of artery-wide information (Figure 4-24), intersection information (Figure 4-25), phase settings for each node (Figure 4-26), and progression times and speeds (Figure 4-27). The time-space diagram provides a graphical illustration (Figure 4-28) of the timing sequence along each arterial and one can use it to plot progression bands for through movements along each arterial segment in the network. A summary of the best signal timing solution for each node in the network is also included in the solution report.

The present version of PASSER IV does not calculate MOEs for the network. One can calculate MOEs by using evaluation software like TRAF-NETSIM. This procedure will be further discussed relative to network optimization in Section 5.0.

```
                  **** PASSER-IV SOLUTION REPORT ****

RUN NUMBER               :     1

DISTRICT                 :
NAME OF CITY             : Los Angeles
NAME OF NETWORK          : HAWTHORNE
NUMBER OF ARTERIES       :     5
NUMBER OF SIGNALS        :     9

MEASUREMENT UNITS        : ENGLISH


             INTERSECTION NUMBERS AT ARTERY MEETINGS
             -------------------------------------
  ARTERIES  1 AND  4 INTERSECT AT SIGNALS  1 AND  3, RESPECTIVELY.
  ARTERIES  1 AND  3 INTERSECT AT SIGNALS  2 AND  3, RESPECTIVELY.
  ARTERIES  4 AND  2 INTERSECT AT SIGNALS  2 AND  2, RESPECTIVELY.
  ARTERIES  2 AND  3 INTERSECT AT SIGNALS  5 AND  2, RESPECTIVELY.
  ARTERIES  3 AND  5 INTERSECT AT SIGNALS  1 AND  2, RESPECTIVELY.
  ARTERIES  4 AND  5 INTERSECT AT SIGNALS  1 AND  1, RESPECTIVELY.


                    **** NETWORK SOLUTION ****


NETWORK WIDE CYCLE TIME:   80.00 SECS

          BANDWIDTHS - PERCENTAGE OF CYCLE LENGTH (SECONDS)
          ---------------------------------------------
ARTERY 1:     EASTBOUND: .5000 (40.00)    WESTBOUND: .5000 (40.00)
ARTERY 2:     EASTBOUND: .2919 (23.36)    WESTBOUND: .2919 (23.36)
ARTERY 3:    SOUTHBOUND: .3124 (24.99)   NORTHBOUND: .3124 (24.99)
ARTERY 4:    SOUTHBOUND: .2312 (18.49)   NORTHBOUND: .2312 (18.49)
ARTERY 5:     EASTBOUND: .4885 (39.08)    WESTBOUND: .4885 (39.08)

TOTAL BANDWIDTH:        3.648114
```

Figure 4-23. PASSER IV Solution Report

```
                         *** ARTERY  2 ***

NAME OF ARTERY:  HAWTHORNE               NUMBER OF SIGNALS: 5
A - DIRECTION :  EASTBOUND

                 *** ARTERY WIDE INFORMATION ***

       ARTERY DIRECTION   BAND (% of Cycle)   BAND (Seconds)
       ----------------   -----------------   --------------
           EASTBOUND            .2919              23.36
           WESTBOUND            .2919              23.36
       -----------------------------------------------------
       EFFICIENCY(%):   29.19     ATTAINABILITY(%):   75.70
```

Figure 4-24. PASSER IV Artery-Wide Information

```
                 *** INTERSECTION INFORMATION ***

        NODE    CROSS STREET   LEFT TURN PATTERN   SIGNAL
         NO.        NAME           SELECTED          NO.
       -----------------------------------------------------
          6                        LEAD- LAG          1
          7    CARSON              LEAD-LEAD          2
          8                        LAG -LEAD          3
          9                           N/A             4
         10    TORRENCE            LEAD-LEAD          5
       -----------------------------------------------------

ALL PHASE STARTING TIMES ARE RELATIVE TO THE START OF GREEN IN THE
 EASTBOUND DIRECTION AT SIGNAL 1 IN ARTERY 1.
```

Figure 4-25. PASSER IV Intersection Information

** PHASE SETTINGS -- SECONDS **

NODE NO.	DIR	GREEN BEGIN	GREEN END	GREEN LENGTH	LEFT BEGIN	LEFT END	LEFT LENGTH	BAND BEGIN	BAND END	BAND WIDTH	QUEUE TIME
6	EB	43.1	75.3	32.2	43.1	56.8	13.7	43.1	66.5	23.4	.0
	WB	56.8	9.5	32.7	75.3	9.5	14.2	66.1	9.5	23.4	.0
7	EB	48.1	2.5	34.4	38.1	48.1	10.0	59.0	2.4	23.4	.0
	WB	48.1	2.5	34.4	38.1	48.1	10.0	50.2	73.6	23.4	.0
8	EB	49.2	14.2	45.0	3.0	14.2	11.1	70.8	14.2	23.4	.0
	WB	39.2	3.0	43.9	39.2	49.2	10.0	39.2	62.5	23.4	.0
9	EB	79.0	54.0	55.0			.0	79.0	22.4	23.4	.0
	WB	79.0	54.0	55.0			.0	30.7	54.0	23.4	.0
10	EB	11.0	41.8	30.9	1.0	11.0	10.0	11.0	34.3	23.4	.0
	WB	11.0	41.8	30.9	1.0	11.0	10.0	18.5	41.8	23.4	.0

Figure 4-26. PASSER IV Output for Phase Settings

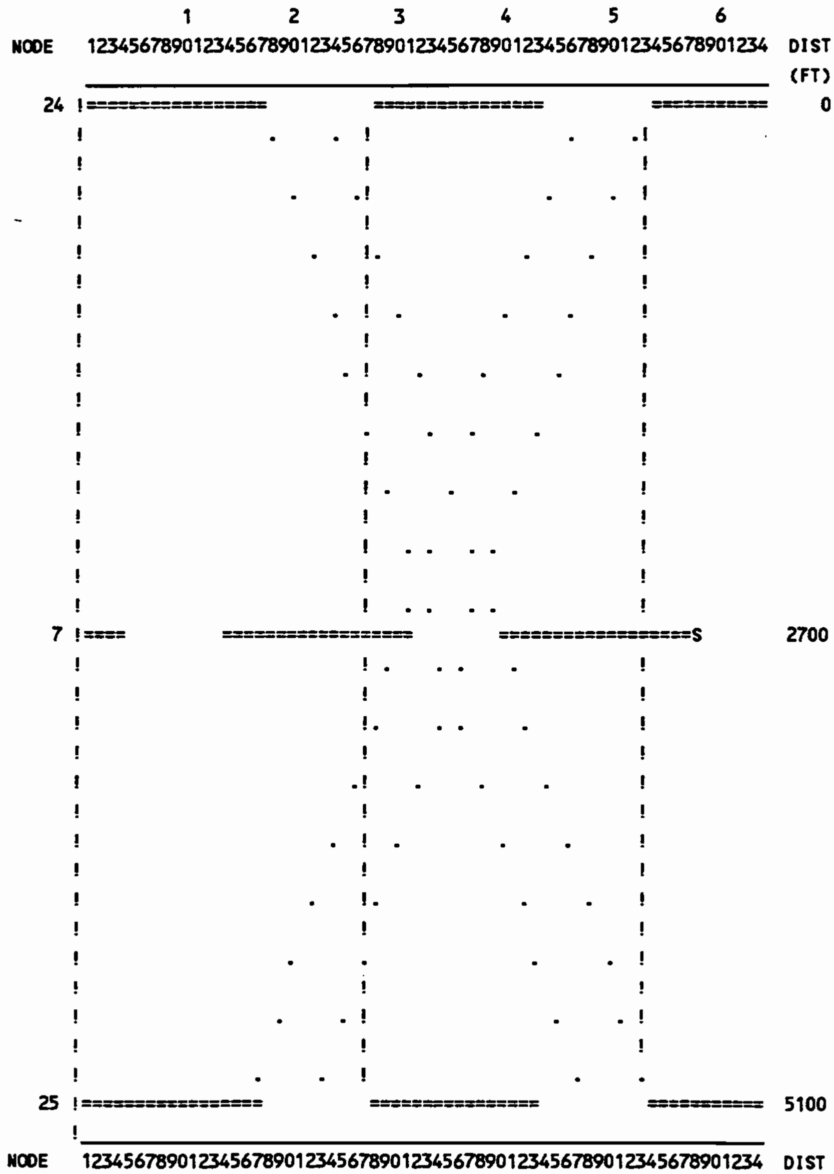
** PROGRESSION TIMES AND SPEEDS **

LINK NODE NO.	<-->	NODE NO.	EASTBOUND LINK LENGTH (FEET)	EASTBOUND TRAVEL TIME (SECS)	EASTBOUND AVERAGE SPEED (MPH)	WESTBOUND LINK LENGTH (FEET)	WESTBOUND TRAVEL TIME (SECS)	WESTBOUND AVERAGE SPEED (MPH)
6	<-->	7	1120.	15.9	48.0	1120.	15.9	48.0
7	<-->	8	830.	11.8	48.0	780.	11.1	48.0
8	<-->	9	560.	8.2	46.4	560.	8.5	45.0
9	<-->	10	840.	11.9	48.0	840.	12.2	46.9
ENTIRE ARTERY:			3350.	47.9	47.7	3300.	47.7	47.2

Figure 4-27. PASSER IV Output for Progression Times and Speeds

```
*** PASSER-IV TIME-SPACE DIAGRAM ***

NAME OF ARTERY: CARSON                    TIME  SCALE =   3 SEC/CHAR
CYCLE LENGTH  :  80.00 SECONDS            DIST. SCALE =  150 FT/LINE
```




```
NODE   24 ---> NODE   25: SOUTHBOUND: DIRECTION-DOWNWARDS : GREEN -  SSSSSS
NODE   25 ---> NODE   24: NORTHBOUND: DIRECTION-UPWARDS   : GREEN -  NNNNNN
SOUTHBOUND BAND =  18.5 SECS AT 38.0 MPH          GREEN  IN BOTH DIRECTIONS
NORTHBOUND BAND =  18.5 SECS AT 38.0 MPH   ======  RED    IN BOTH DIRECTIONS
```

Figure 4-28. PASSER IV Time-Space Diagram

TRANSYT-7F Output. When entering data using TRANSYT-7F, the user may designate a portion of the plots and diagrams to be included in the output. One can consult the TRANSYT-7F user's manual (18) for further information relative to the type of output information to be generated. In general, TRANSYT will produce an echo of the input data, intersection and system-wide performance evaluations, intersection controller settings, a time-space diagram, and flow profile diagrams (after completing a simulation run).

The table(s) of performance with initial settings provides a summary of the operational performance parameters associated with the individual movements at each intersection in the arterial street network. The program produces a separate table for each intersection in the network. For simulation and evaluation purposes, the initial settings table(s) can be used to identify specific bottlenecks and locations along the arterial where one could possibly make operational improvements. The performance measures for the entire arterial street network are reported in the system wide table, which also includes the performance index calculated by TRANSYT-7F. Flow profile diagrams illustrate the position of the platoon with respect to the arterial through green phase. Ideally, most vehicles would arrive during the green phase.

Figure 4-29 illustrates the individual intersection best solution and performance with initial setting reports generated by TRANSYT-7F. Figure 4-30 shows system-wide performance measures. Individual link performance measures also can be obtained for each arterial in the network (Figure 4-31). Time-space diagrams are generated, which provide a graphical illustration of the timing sequence at the intersections along the arterial. One can determine the bandwidth by extending two parallel lines through the green window at each intersection and then measuring its width. Flow profile diagrams for TRANSYT-7F, illustrated in Figure 4-32, can be generated for each intersection along the arterial. These diagrams graphically depict the arrival and departure pattern of vehicles during green and red. On the flow profile diagram, an "I" symbol indicates an arrival on red that queues, an "S" symbol indicates the departure of a queued vehicle, and an "O" symbol indicates an arrival as well as a departure on green.

```
WELLBORN SIMULATION
CYCLE:   88 SECONDS,    60 STEPS

<PERFORMANCE WITH INITIAL SETTINGS>

MOVEMENT/          TOTAL  TOTAL  TOTAL   AVG.   UNIFORM    MAX. BACK    FUEL
NODE NOS.   V/C  TRAVEL   TIME  DELAY  DELAY    STOPS    OF  QUEUE    CONS.
            (%)  (V-MI) (V-HR) (V-HR) (SEC/V)  NO. (%)   NO.  CAP.    (GA)
-----------------------------------------------------------------------------
  NB THRU : 74   180.40  12.96   8.99   42.3   557.( 73)   15   100    19.79
     LEFT : 14     8.50    .65    .47   46.6    24.( 68)    1    50      .94

  SB THRU :107*   15.14  37.29  36.96  163.9   756.( 93)   23>    8C   37.14
     LEFT : 69     1.49   1.26   1.23   55.2    74.( 93)    2     4     1.93

  EB THRU : 93     7.98   7.07   6.81   57.3   403.( 94)   10>    8C    7.61

  WB THRU : 90    10.59   7.59   7.25   45.9   530.( 93)   13>    8C    8.76

NODE      1:107* 224.09  66.83  61.69   82.6  2345.( 87)               76.17
```

Figure 4-29. TRANSYT-7F Intersection Performance Summary Table

```
WELLBORN SIMULATION
CYCLE:   88 SECONDS,    60 STEPS

<SYSTEM WIDE TOTALS INCLUDING ALL LINKS>

PERFORMANCE TOTAL  TOTAL  TOTAL  AVG.     UNIFORM     FUEL  SYSTEM TOTAL PERFOR-
MEASURES    TRAVEL TIME   DELAY  DELAY     STOPS      CONS. SPEED  COST  MANCE
             V-MI  V-HR   V-HR   SEC/V    NO. (%)      GA    MI/H         INDEX
--------------------------------------------------------------------------------

<TOTALS>     2644    276    214  82.6    6845( 73)     324    9.6  1089   228.1

--------------------------------------------------------------------------------

NOTE: PERFORMANCE INDEX IS DEFINED AS:

      PI = DELAY + STOPS

NO. OF SIMULATIONS =   1  NO. OF LINKS =  26  ELAPSED TIME =     4.3 SEC.
```

Figure 4-30. TRANSYT-7F Table of System Performance Measures

CYCLE: 90 SECONDS, 60 STEPS

<ROUTE SUMMARY REPORT>

7F HAWTHORNE (ARTERIAL 2)

MOVEMENT/ NODE NOS.	V/C (%)	TOTAL TRAVEL (V-MI)	TOTAL TIME (V-HR)	TOTAL DELAY (V-HR)	AVG. DELAY (SEC/V)	UNIFORM STOPS NO. (%)	MAX. BACK OF QUEUE NO.	CAP.	FUEL CONS. (GA)
605	: 37	278.37	12.55	3.22	8.3	620.(44)	17	168	17.24
705	: 53	343.68	18.01	6.49	14.4	991.(61)	26	179	24.36
805	: 38	264.74	10.76	1.89	4.0	510.(30)	14	133	15.10
905	: 42	215.91	8.53	1.29	2.3	448.(22)	14	90	12.31
1005	: 66	307.96	19.77	9.45	17.6	1354.(70)	35	134	27.03
DOWN	: 66	1410.66	69.63	22.33	9.3	3924.(45)			96.03
607	: 21	166.54	7.03	1.44	6.6	294.(37)	8	179	9.54
707	: 27	123.63	6.94	2.80	12.0	435.(52)	11	125	9.53
807	: 19	85.85	3.72	.85	3.8	221.(27)	6	90	5.37
907	: 18	142.85	5.22	.43	1.7	155.(17)	4	134	7.06
1007	: 34	231.68	11.94	4.17	16.8	556.(62)	14	219	15.65
UP	: 34	750.56	34.84	9.68	8.3	1661.(39)			47.15

Figure 4-31. TRANSYT-7F Table of Link Performance Measures

```
      LINK   203    MAX FLOW  3400 VEH/H     PLT. INDEX  .52
4000+
    :
    :
    :
    :           SSSSSS
    :           SSSSSS
3000+           SSSSSS
    :           SSSSSS
    :           SSSSSS
    :           SSSSSSS
    :           SSSSSSS
    :           SSSSSSS
2000+           SSSSSSS       OOOOO
    :           SSSSSSS     OOOOOOO
    :          SSSSSSSS   OOOOOOOOOO
    :          SSSSSSSS   OOOOOOOOOO
    :          SSSSSSSS  OOOOOOOOOOOO
    :          SSSSSSSS OOOOOOOOOOOOO
1000+          SSSSSSSS OOOOOOOOOOOOOI
    :IIII      SSSSSSSS OOOOOOOOOOOOOII             II         II
    :IIIIIII   SSSSSSSSOOOOOOOOOOOOOOIIIII          III    IIIIII
    :IIIIIIIII SSSSSSSSOOOOOOOOOOOOOOIIIIIIIIIIIII IIIII  IIIIIII
    :IIIIIIIIIIOOSSSSSSOOOOOOOOOOOOOOIIIIIIIIIIIIIIIIIIIIIIIIIIII
    :IIIIIIIIIIOOOOOSSSOOOOOOOOOOOOOOIIIIIIIIIIIIIIIIIIIIIIIIIIII
     **********                      ****************************
     123456789012345678901234567890123456789012345678901234567890
```

Figure 4-32. TRANSYT-7F Flow Profile Diagram

Output Verification. After using any traffic simulation program to evaluate conditions on an arterial segment, it is especially important to validate the output to insure the accuracy of the results. The timing parameters reported by the program, such as phase splits and sequences should equal the existing parameters recorded in the field. Additionally, operational measures such as v/c ratios and queue lengths should be measured and compared to the v/c ratios and queue lengths predicted by TRANSYT. While it is not always feasible to conduct a full-scale verification of the program output, analysts should always conduct some degree of validation. A simplified approach for verifying results could be to evaluate the total travel times along each arterial in the network by comparing the field measurements to the program estimates.

If large discrepancies between observed and estimated values are noted, check the input data again. After making corrections, rerun the program and check the results. If inaccuracies persist, evaluate the system-wide default variable to insure the assumed operational factors are reasonable. Inaccurate data cannot be used to simulate the existing conditions accurately and will result in optimization runs generating timing plans. The user should be sure that the simulation run is valid before going on to the optimization step.

4.4 Arterial Level of Service and Speed Profiles

Arterial level of service, as defined by the 1985 *Highway Capacity Manual* (9), is based on the average travel speed for the segment, section, or entire arterial under consideration. The average travel speed is computed from the running time on the arterial segments and the average intersection approach delay. One can estimate these two variables either from the field or by computer programs like the Highway Capacity Software, PASSER II, or TRANSYT-7F. Analysts should perform arterial level of service analyses for each major arterial street in the network.

Segment lengths and free flow speeds are estimated from existing data, running times can be computed using tabular values, and approach delays can be estimated using HCM delay equations. One obtains segment travel times by adding the approach delays and the running times. Figure 4-33 also shows the construction of a speed profile for the arterial. Figure 4-34 shows the necessary calculations to obtain arterial level of service. Delay estimates for the southbound through movement were obtained from the TRANSYT-7F output for NEMA movement 2. One should note that delay estimates from field measurements can be used in this analysis.

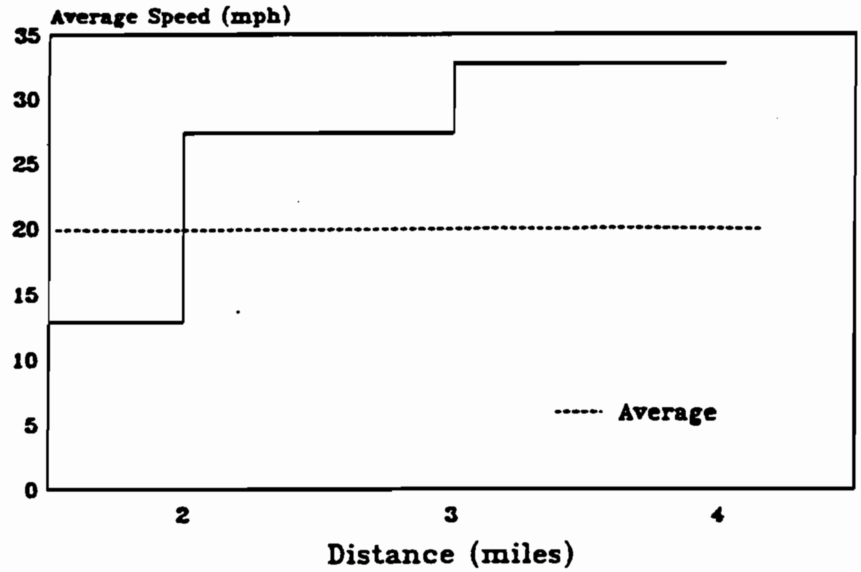


Figure 4-33. Speed Profile for the Arterial

COMPUTATION OF ARTERIAL LEVEL OF SERVICE WORKSHEET

Arterial: Hawthorne West-bound

File or Case #: Date: 2-20-93

Prepared by: Sunkari, Srinivasa

$$\text{ART SPD} = \frac{3600\ (\text{Sum of Length})}{\text{Sum of Time}}$$

Segment	Length (mi)	Arterial Class	Free Flow (mph)	Section	Running Time[a] (sec)	Intersec. Approach Delay[b]	Other Delay (sec)	Sum of Time by Section	Sum of Length by Section	Arterial SPD[c] (mph)	Arterial LOS by Section
1	0.199	I	45		15.9	45.9		62	0.199	11.5	F
2	0.212	I	45		17.0	32.9		50	0.212	15.3	E
3	0.157	I	45		12.6	2.3		15	0.157	37.7	A
4	0.106	I	45		8.5	83.4		92	0.106	4.2	F
5											
6											
7											
8											
9											
10											
11											
12											
13											
14											
15											

Grand Sum of Time = 219

Grand Sum of Length = 0.674

F

$$\frac{3{,}600 \times 0.674}{219} = 11.1 \text{ MPH}$$

[a]Use Table 11-4 and multiply by segment length
[b]From summary on Arterial Summary of Intersection Delay Estimates Worksheet
[c]See upper right corner of this Table for the Equation
Note: Round delay estimates to one place after decimal

Figure 4-34. Computation of Arterial Level of Service

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5.0 OPTIMIZATION

After making a simulation run to evaluate the existing conditions and checking output for accuracy, the next step toward retiming an arterial street network is to develop a signal timing plan that optimizes operations in the network. The objective of additional computer runs is to find cycle lengths, green splits, phase sequences, and offsets, which minimize delay, stops, and fuel consumption, increase capacity, and/or maximize bandwidth. The "best solution" depends on what the traffic signal analyst wants to accomplish. To quantify improvements, one should make comparisons between the best solution for the optimized runs and the evaluation run for the existing conditions.

Optimization runs can be made with PASSER IV or TRANSYT-7F. Most of the data needed for the optimization runs has already been coded for the evaluation of existing conditions. The parameters that differ can be changed by editing the data. One edits the data base in PASSER IV by accessing the EDIT screen and in TRANSYT-7F by accessing the Data Input Manager.

The following sections discuss procedures and guidelines for optimizing an arterial street network signal timing design using PASSER IV or TRANSYT-7F presented by Wallace and Courage (21). As already mentioned, the user will have previously entered most of the data required for optimization. The data should have been checked for accuracy and calibrated for local conditions. How this data will be edited depends on the type of optimization to be performed.

Before proceeding, one should note that the volume to capacity ratios and delays estimated by the computer models should remain consistent with existing conditions in the field (i.e., movements estimated to operate at oversaturated conditions should correspond to movements that fail to clear the entire queue during the green phase). If the model estimates prove inconsistent with existing conditions, the resultant signal timing design will be less than optimum.

5.1 Signal Timing Design

Signal timing design ultimately depends on the quality of the traffic data and the parameters that represent the nature of traffic flow. The most significant of these inputs to traffic signal optimization models are clearly the traffic volumes and saturation flow rates. These two classes of data prove so important to the process of traffic signal timing, they deserve special attention. The following are some general guidelines in selecting data for use in evaluating existing conditions and developing a good signal timing design.

1. One should use actual **demand** volumes, as measured in the field, for evaluation.

2. One should use adjusted volumes, which consider lane distribution and peak hour factors, for purposes of traffic signal timing. While adjusted volumes are proper for design, problems arise when artificial vehicles suffer "artificial" stops, delay, and fuel consumption, which is inappropriate for evaluation.

3. One should always use measured saturation flow rates if possible. If they must be estimated, the *Highway Capacity Manual* (9) saturation flow adjustment method should be used.

4. One should use measured cruise speeds for evaluating (and calibrating) existing conditions, but desired progression speeds should be used for traffic signal design.

5.2 Optimization Strategies

Both PASSER IV and TRANSYT-7F use their input data to decide how a signal system should operate. Their recommendations are expressed in terms of several control parameters, including phase sequence, cycle length, phase lengths and offsets. Several important points about the process deserve consideration in the design process. The following subsections give brief overviews of the considerations that go into determining signal design parameters.

Determining Phase Sequences. Selection of the best phase sequence (including how many phases are needed) hinges on the answers to (at least) the following questions:

1. What left-turn movements (if any) need to be protected?

2. Should left-turn protection (if required) be protected-only or both permitted and protected?

3. Assuming both left-turns on the arterial street must be protected, what benefits arise from overlap phasing?

4. Assuming both left-turn movements from the arterial street must be protected, what benefits arise from both left-turns leading or lagging versus lead-lag left-turn phasing?

The issue raised by the first question, the need for protection, stands more or less independent of the other three questions. While several factors are involved in this decision, including local preference, TRANSYT-7F can provide some guidance, by showing the effect of protected turning intervals on delay, stops, fuel consumption and left-turn conflicts. One may also use the program's output directly to provide insight into the other questions. PASSER IV does not directly estimate the MOEs of the network. The program only estimates the progression parameters, like bandwidth, efficiency, and attainability.

PASSER IV evaluates arterial street network operations from the point of view of progression, and, thus, care must be taken not to overlook the potential impact of residual queues blocking the through platoons. When PASSER IV considers both multiple phase sequences and overlap phasing, it generally recommends a mixture of phasing sequences. This mixture tends to give the best progression solution, and, thus, superior operation than the popular leading lefts phasing sequence. The point is, how willing is the analyst to trade off improved operation for potentially confusing signal operation? Many analysts are concerned about motorist behavior being too unpredictable and are unwilling to allow phasing variations. At the other extreme, some locations will allow complete flexibility (even to the extent of allowing the sequence at individual intersections to change during different times of the day).

A consistent phasing sequence at all intersections or allowing flexible phasing sequences at some locations is a matter of local preference. It should be noted, however, that varying the phase sequences among intersections will produce better progression along the arterials in the network.

Optimizing Cycle Lengths. PASSER IV bases cycle length selection on maximizing bandwidth efficiency, whereas TRANSYT-7F bases cycle length selection on minimizing some linear combination of stops and delay. The key issues involved in determining cycle lengths with PASSER IV are:

1. When evaluating a range of cycles, PASSER IV uses a less than a full scale optimization process (i.e., optimization is based solely on maximizing bandwidth efficiency); thus, this report suggests that no decision be made based on results from a single run with a wide range of cycle lengths.

2. One should carefully coordinate the cycle length with the phase sequences. A more flexible set of phase sequences may result in a different cycle length than a more constrained phasing plan.

Optimization of Offsets. PASSER IV bases its design of offsets on maximizing bandwidth efficiency progression on major arterials without real regard for traffic performance. PASSER IV also maximizes progression on major cross-streets depending on the weight given to the cross-street arterial compared to the major arterial(s). If the front of the through green is not in the progression band at the upstream intersection, if the left or right-turn volumes from the upstream intersection measure greater than 10 percent of the total volume, or if the downstream volume exceeds the upstream volume by more than 10 percent, stopped queues may block the platoon. TRANSYT-7F can prove very useful in this determination, particularly through inspection of its *Platoon Progression Diagrams*.

PASSER IV will produce its best results on sections when both the intersection spacing is such that the intersection proves critical to the progression scheme and the potential exists for significant progression bands. It also excels when most of the signals use multi-phase operation, provided that the analyst is prepared to implement a mixture of phasing schemes on the same arterial. If an arterial street in the network system is quite long and the through bands are very narrow, the analyst should consider splitting the system into two (or more) subsystems, where better operation may result within each of the shorter arterial subsystems.

5.3 Recommended Design Procedure

The analyst should see from earlier discussions that one should use an iterative procedure involving more than one run of a signal timing design program in optimizing and evaluating arterial street network signal system performance. This process involves evaluating existing conditions, optimizing splits, offsets, and phasing, fine-tuning the cycle length obtained, and developing a final design by increasing the stop penalty in TRANSYT-7F to place emphasis on progression. For purposes of this discussion, it is assumed that all steps will be pursued in detail.

Initial Evaluation. As described in Section 4.0, the analyst should perform initial evaluation using the existing cycle length, splits, phasing sequence, and offsets. Analysts often overlook this step; however, two important reasons to perform an initial evaluation exist:

1. To provide a basis for evaluation of the benefits from signal retiming; and

2. To insure that the system operation is being modeled correctly.

It should be self-evident that there is not much point in proceeding with a design using a model which does not describe the existing conditions adequately. Before proceeding further, therefore, one must decide whether the model has given credible results. A detailed evaluation would require the field measurements of delay, degrees of saturation, etc. The data collection requirements for a detailed evaluation lie beyond the resources of most traffic engineering agencies. As a minimum, however, one should examine all of the approaches at each of the intersections (especially those operating near full saturation) to insure that the model agrees at least qualitatively with the field observations.

The present version of PASSER IV does not predict any MOEs. Thus, TRANSYT-7F should be used to simulate and evaluate the existing conditions. For example, what if the TRANSYT-7F output indicates that an approach is oversaturated when, in fact, you know it is not? You must check and correct the capacity inputs, which are the saturation flow rates, lost time, or other factors determining capacity. If you fail to correct this inaccuracy, TRANSYT-7F will want to allocate an unreasonable amount of green time to that approach (at the expense of the other approaches), to cure a problem that never exists.

Optimizing Splits, Offsets, and Phasing Sequences. PASSER IV can select an appropriate cycle length, optimize splits and offsets, and select suitable phasing sequences for intersections in the system. As mentioned earlier, the objective function of PASSER IV is to maximize the overall bandwidth efficiency of the network.

TRANSYT-7F, however, requires specification of the phasing sequences in order to optimize splits and offsets. Hence, the phasing patterns are obtained from PASSER IV and TRANSYT-7F runs made for optimizing the splits and the offsets. First, a wide cycle length range is given, perhaps exceeding any range one would actually consider. One may use a large increment because the solution remains unimportant at this point. An output from this initial run will equal a rough estimate of the cycle length for optimum splits and offsets. The analyst also compares MOEs for the various cycle length increments and selects a cycle length. Then the timings obtained from TRANSYT-7F are further fine-tuned for implementation.

Fine-Tuning the Splits and Offsets. After selecting a cycle length, the timings are fine-tuned to minimize delays, stops, and improve the progression. Fine-tuning is done by selecting one cycle length and reducing the step size. Fine-tuning results in further reducing the delays and stops. A suggested range for closer scrutiny is as follows:

1. The minimum cycle length should measure no less than 0.85 times the maximin cycle length; and the maximum cycle length should measure no higher than 1.25 times the maximin cycle length.

2. These minimum and maximum values may need adjusting to the nearest five seconds to accommodate the cycle length resolution offered by some systems.

3. Although one may use this range as a general guide, one should really let the quality of progression and the resulting MOEs dictate which cycle length to use.

If at any step in the process, the "best" recommended cycle length falls on the minimum or maximum values, one should repeat the analysis while expanding the range to encompass the threshold value, unless the threshold value equals the absolute minimum.

Final Design. After obtaining the fine-tuned signal timings, the stop penalty in Card 1 is increased, and TRANSYT-7F is run for the fine-tuned timings in order to further fine-tune the splits and offsets and to improve the progression by reducing stops.

This step is an appropriate point in the design process to evaluate whether a bandwidth solution is suitable. The measure of interest is "attainability," previously defined as the bandwidth divided by the sum of the shortest green time in each direction. The rationale behind this measure is that it is not possible to obtain a through band which exceeds the critical green time. Theoretically, one can achieve an average attainability of approximately 50 percent by arbitrarily assigning all progression to one of the two directions (100 percent in one direction and 0 percent in the other direction). So, a bi-directional attainability less than 50 percent indicates that the compromise required to achieve an equitable bandwidth distribution of progression opportunities resulted in a generally poor design. Such a result often indicates that a solution based on stops and delay optimization by TRANSYT-7F would prove more appropriate.

An alternative solution for an arterial network where an acceptable progression solution is not attainable, would be to partition the arterial street network into two or more subsystems, with each free to operate on its own cycle length. The rationale behind this alternative is that the improvements resulting from sub-optimization may prove great enough to offset the problem of lost progression between subsystems. One should, of course, optimize each of the two sections for phasing, timing, and offsets.

5.4 Model Limitations

PASSER IV at present has a few limitations. The most obvious limitation of the present version of the PASSER IV is its inability to predict the MOEs for the runs made for evaluation and optimization. Several special modeling applications result from limitations of the PASSER IV model. The discussion below addresses how one can overcome these limitations.

Splits. PASSER IV bases its split calculations on maximizing bandwidth efficiency. It does not "optimize" splits as do, for example, SOAP or TRANSYT-7F. The design splits will likely prove relatively good as long as the intersection is not congested, particularly if the controller is semi-actuated. In the latter case, the operation will be locally optimized anyway, and the main concern is with sequence, cycle length, and offsets. If, on the other hand, good splits are more critical to the intersection operation, one may wish to consider enlisting the aid of another model, such as TRAF-NETSIM (20) or the TEXAS (22) model.

Other Timing Parameters. The major limitations of PASSER IV are those related to the maximal bandwidth approach, which tries to maximize the quality of progression as perceived by the driver. The main problem is that this approach deals most directly with progression opportunities which extend throughout the arteries and ignores opportunities occurring through only a portion of the route. Further, no explicit consideration is given to the effect of blocking queues. The potential problems can be identified by a visual inspection of the programs output; however, they emphasize the need to examine the optimum solution for hidden bottlenecks.

5.5 Example Problem

This section presents an example problem illustrating the development of an optimum arterial street network signal timing plan using both PASSER IV and TRANSYT-7F. This example seeks to lead the traffic signal analyst through the steps they might normally use in a signal timing or, more often, retiming project. New users may use the example as a learning tool. This objective is more easily accomplished with a relatively simple example, where results are reasonably predictable.

The example problem is a five arterial and nine intersection network called "Hawthorne." Figure 5-1 shows the basic schematic of the network. The purpose of this exercise is to develop a new, more efficient operating system for the Hawthorne arterial network system. The objectives of the study are as follows:

1. To simulate the existing timing plan, which one would in reality use to calibrate the models and to provide a basis for evaluating the new plans to be developed; and

2. To develop optimal timing plans for pretimed control. Phasing changes will be permitted only if strongly recommended by the process, since wiring changes would be required.

This example concentrates on a single peak period. All control periods require the same degree of attention in reality, but to avoid redundancy, discussions of **the process** for multiple periods will not be repeated. When the other time periods need mentioning, appropriate mention will be made. In an actual study, one must repeat the analysis and evaluation of differences, particularly in phasing, for each control period.

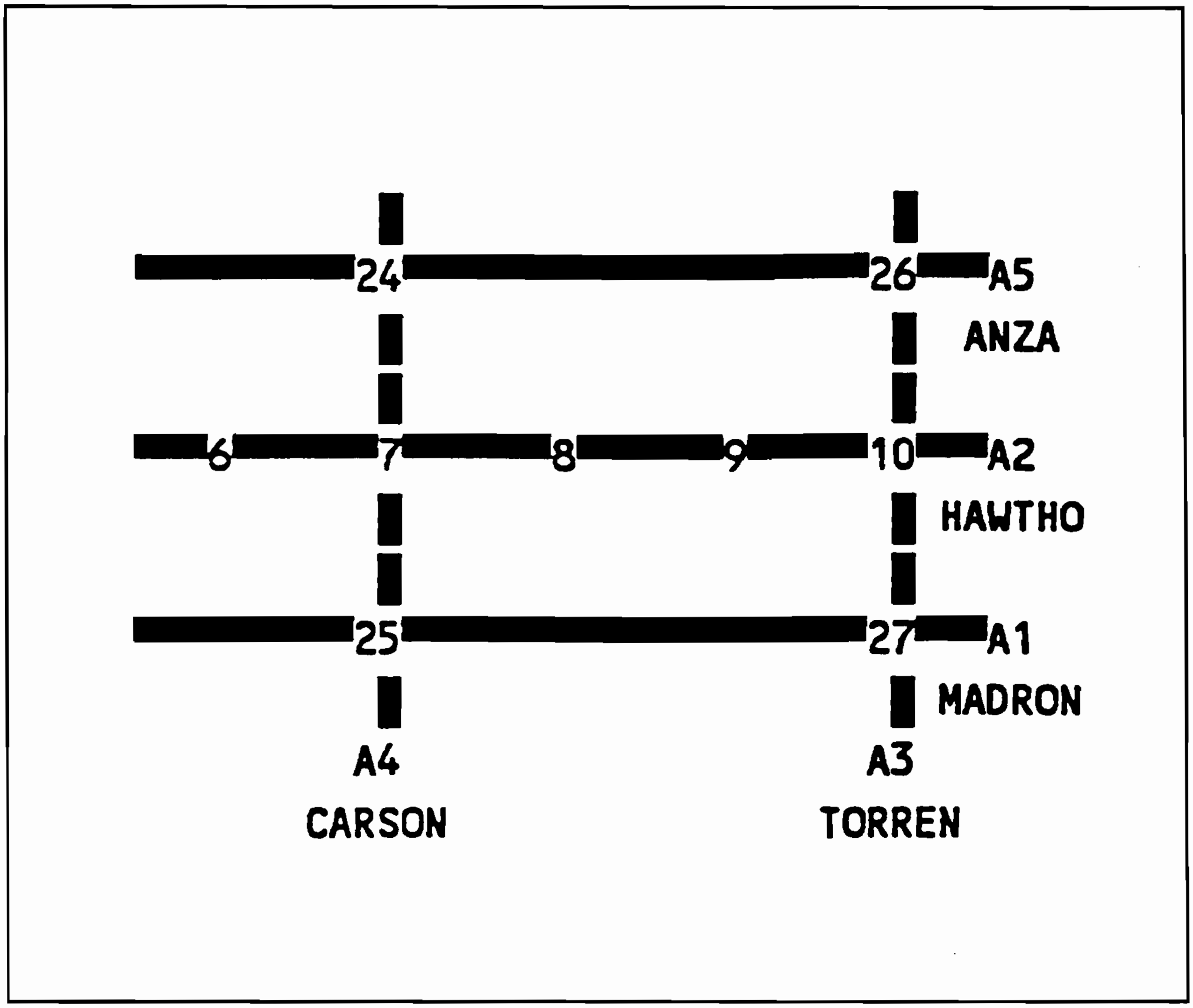

Figure 5-1. Schematic of the Hawthorne Network

Evaluating the Existing Conditions. One way to check the data is to print the Data Report, developed in the next step--evaluating the existing data. There are two major purposes for this step:

1. To check and verify the correctness of data; and

2. To calibrate the model parameters.

In this example, these checks will seem trivial. In reality, however, this step is perhaps the most important step in the design process. The final designs can only prove as "good" as the data and parameters that control the models--saturation flow rates, lost times, platoon dispersion factors, etc. Here, only the mechanics of the process will be reviewed.

The present version of PASSER IV does not predict any MOEs such as, v/c ratios, stops, delays, and fuel consumption. One can perform the most thorough evaluation of an existing timing plan using TRANSYT-7F to simulate the existing conditions. To run this model in the simulation mode, select *Edit* . . . *Run Instructions* to set up the run. One should accomplish the following at a minimum:

1. The initial run number (1) is okay for this run. Enter a "Run Title," such as "T7F on Existing," for TRANSYT-7F simulation/evaluation of existing conditions.

2. Enter the actual cycle length in both the "Min" and "Max Cycle." One can ignore the "Incr(ement)" for a simulation run.

3. It is important at this point to use "unadjusted" volumes so that the program can make a comparison with the known data.

To help double check all coded data, print the TRANSYT-7F Input Data Reports and review them carefully against the raw data sources. After checking the data and, at least from visual observation, they appear correct, one should begin the process of model calibration. This step involves examining the TRANSYT-7F results to ensure that degrees of saturation (volume to capacity ratios), delays, queue back ups, and platoon progression all conform with the actual operation; i.e., TRANSYT-7F's output is reasonable and matches observations made in the field.

One should note that traffic signal analysts should never assume they have finished reviewing the base data at the conclusion of this step. Often one needs to make corrections to the data even after making an optimization run. Thus, a need to make final evaluation runs for both Before and After conditions may exist as a last step in the design process after the optimization.

After completing the evaluation of the existing conditions, the next step is to optimize the arterial network signal timings. PASSER IV and TRANSYT-7F are the programs available for optimizing networks. The discussion below briefly describes the optimization process using each of these programs.

Optimization Using PASSER IV. The analyst enters the complete network data into PASSER IV using the input data screen. Optimization runs are made for each of the cycle lengths ranging from 80 seconds to 110 seconds in increments of 10 seconds. As mentioned earlier, the present version of PASSER IV does not give any values for MOEs. The program optimizes phasing sequence, splits, and offsets in order to maximize the overall network bandwidth efficiency.

Table 5-1 illustrates the network solutions for each of the four PASSER IV runs. The value for total bandwidth is the sum of the bandwidths in percentage of cycle in both directions for all the arterials and is a measure of the overall network operation. One can compute the overall network efficiency from total bandwidth, as shown in Equation 5-1.

$$\textit{Overall Network Efficiency} = \frac{\textit{Total Bandwidth}}{2 * (\textit{Total Number of Arterials})} \qquad [5\text{-}1]$$

From Table 5-1 one sees that a cycle length of 100 seconds resulted in maximum efficiency (0.398). Thus, according to PASSER IV, a cycle length of 100 seconds proves optimum for the network.

Table 5-1. Summary of the Network Solutions Using PASSER IV

Cycle Length (seconds)	Total Bandwidth (cycles)	Overall Network Efficiency
80	3.648	0.365
90	3.911	0.391
100	3.976	0.398
110	3.945	0.396

Optimization Using TRANSYT-7F. Analysts used TRANSYT-7F to evaluate the arterial network for a large range of cycle lengths using the phasing sequences obtained from PASSER IV. Table 5-2 illustrates a summary of the cycle length evaluation performance. Based on the MOEs predicted, a cycle length of 80 seconds appears to be the best cycle length. The value of "-1" for stop penalty was used for this run.

Analysts then made TRANSYT-7F runs for cycle lengths ranging from 80 seconds to 110 seconds at 10 second increments. TRANSYT-7F optimizes the arterial network timing to minimize a combination of stops and delays by optimizing splits and offsets. The program's priority is to minimize **stops** and **delays** without any significance given to the level of **progression** provided. Increasing the stop penalty for the network to "1000" (card "1") in order to minimize stops should improve progression along the arterials in the system. Analysts studied the arterial network and identified the major arterial (Hawthorne). In addition to increasing the stop penalty for the whole network, the stop penalty increases to "1000" for Hawthorne (card "38") to emphasize progression along the major arterial. This increase in stop penalty results in a stop penalty of "10,000" for the Hawthorne arterial.

Table 5-3 illustrates the results of TRANSYT-7F runs for various cycle lengths with an increased stop penalty. Comparing the MOEs in Table 5-3 with the MOEs in Table 5-2, a slight reduction in percentage stops, accompanied by a slight increase in delays, is evident. Note that a large increase in the performance index exists. This increase has occurred because analysts increased the stop penalty to "1000." Based on the overall performance index, TRANSYT-7F selects a cycle length of 100 seconds to provide an optimum solution for the arterial network.

Table 5-2. Cycle Length Evaluation Performance Summary

Cycle Length (seconds)	Average Delay (seconds/veh)	Percent Stops (%)	Fuel Consumption (gal/hr)	Performance Index
80	5.52	26	292.4	67.1
85	6.15	26	296.3	71.1
90	6.92	28	303.1	77.9
95	7.43	28	305.8	80.5
100	8.15	28	309.5	84.2
105	8.89	29	315.1	89.9
110	9.35	29	318.7	93.4
115	10.04	29	321.6	96.4
120	10.99	30	328.9	103.7

Table 5-3. Summary of the Network Solutions Using TRANSYT-7F

Cycle Length (seconds)	Average Delay (secs/veh)	Percent Stops (%)	Fuel Consumption (gal/hr)	Performance Index
80	5.74	25	293	5710
90	7.17	27	304	5894
100	8.53	27	311	5093
110	9.85	28	320	5584

Table 5-4. Fine Tuning the PASSER IV Solutions Using TRANSYT-7F

Cycle Length (seconds)	Average Delay (secs/veh)	Percent Stops (%)	Fuel Consumption (gal/hr)	Performance Index
80	24.5	66	453	228
90	22.3	63	437	212
100	21.1	60	427	202
110	22.0	59	430	205

Fine-Tuning the Optimized Timings. The optimized timings obtained from PASSER IV can be further fine-tuned using TRANSYT-7F. The phasing sequences, splits, and offsets obtained from the optimization runs for each cycle length are input into TRANSYT-7F. TRANSYT-7F optimization runs should then be made for these timings, with bandwidth constraints placed on them.

The MOEs predicted in Table 5-4 (fine-tuned solution) measure much higher than the MOEs in Table 5-3 (TRANSYT-7F solution). This result could be because bandwidth and the phasing sequences developed in PASSER IV's optimized solution may restrict TRANSYT-7F's ability to fine-tune and show significant improvement in the MOEs. While the MOEs for the fine-tuned solution appear worse than the MOEs predicted for TRANSYT-7F solution, such may not be the case. For example, the fine-tuned solution has good progression, while the TRANSYT-7F solution may not have good progression. Thus, the objective and judgment of the traffic signal analyst plays a significant role in deciding the necessary approach for obtaining optimal signal timings.

Visual Inspection of the Timing Plans. This example has illustrated the basic mechanics of using both TRANSYT-7F and PASSER IV to optimize an arterial network. Before implementing the timing plans, one should study the output to get an idea of how the timings measure up. One can perform this examination in the following ways:

1. Print the plot outputs to get visual evidence of likely operations:

   a. Time-space diagrams (TSDs), to study utilization of leading and/or lagging phases, particularly lead-lag subsequences;

   b. Flow profile diagrams (FPDs), to get a better view of probable traffic performance at the intersections; and, most useful,

   c. Platoon progression diagrams (PPDs), to evaluate the overall progression and the effect of queues.

2. Compare the timings generated by the computer programs (PASSER IV and TRANSYT-7F) to determine if the timings produced by one program prove superior than the other.

3. Whatever decision is made, fine-tune the plan, both in the office and in the field.

The last point is the most important--the traffic signal analyst should make the final decision about the best timing plan, not the computer programs.

Evaluation of Optimal Timing Plans. Two programs, PASSER IV and TRANSYT-7F are available for optimizing signalized arterial networks. It is not known how good the signal timings generated by PASSER IV are, since the program does not predict any MOEs. One should use a tool to simulate the PASSER IV timings and predict the MOEs to determine the worth of the timings.

Analysts can use TRANSYT-7F as a simulation tool. One can input the timings produced by PASSER IV into TRANSYT-7F and evaluate them. The MOEs predicted by TRANSYT-7F for PASSER IV timings can then be compared with the MOEs predicted by TRANSYT-7F for its own optimized timings. This procedure is not accurate because TRANSYT-7F tends to have a bias towards its own solution when evaluating the timings generated by PASSER IV and could predict very high MOEs for PASSER IV timings. TRANSYT-7F tends to minimize stops and delays, while PASSER IV tends to maximize bandwidth efficiency. A PASSER IV solution emphasizes progression and can experience higher stops and delays. While, this solution may appear an inferior solution based on the prediction of MOEs, such may not necessarily be the case. Thus, TRANSYT-7F is not an appropriate tool to evaluate PASSER IV timings.

TRAF-NETSIM is a microscopic simulation model, extensively used to simulate the timings generated by a number of programs. The program can simulate isolated intersections, arterials, and networks and predict the necessary MOEs. Thus, this report recommends that one use TRAF-NETSIM as the simulation tool to evaluate the timings generated by PASSER IV.

The analyst can input the timings obtained from PASSER IV into TRAF-NETSIM. TRAF-NETSIM is then run, and the predicted MOEs can be compared with their TRANSYT-7F counterparts for the timings generated by itself. This comparison, however, is not appropriate, as the methodologies used by TRAF-NETSIM and TRANSYT-7F to predict the MOEs differ. **Thus, one should not compare the TRAF-NETSIM output with TRANSYT-7F output.**

One can use TRAF-NETSIM to simulate the timings generated by PASSER IV and TRANSYT-7F. For the example problem (Hawthorn Network), analysts obtained six best solutions (six cases) from PASSER IV. The differences in the six best solutions ranged from different phasing sequences and/or different offsets. The cycle lengths and the splits remained constant. These timings were then input into TRAF-NETSIM, evaluated and the MOEs estimated. The timings for the same six best solutions obtained from PASSER IV were also input into TRANSYT-7F to further fine-tune these timings. The optimized timings from TRANSYT-7F were then input into TRAF-NETSIM, evaluated, and the MOEs estimated. Table 5-5 illustrates the MOEs estimated by TRAF-NETSIM for the timings obtained from PASSER IV and TRANSYT-7F.

Table 5-5. Timing Evaluation Using TRAF-NETSIM Simulation

Case Name	Model Name	Total Delay (veh-hr/hr)	Travel Time (min/mile)	Average Delay (min/veh)	No of Stops per Trip	Average Speed (mph)	Fuel Consumption (mpg)	Emissions (Kg/mile/hr)
HAW6	PASSER IV	423.6	4.9	2.8	1.8	12.3	9.7	4.0
(3.996)	TRANSYT-7F	436.5	5.0	2.9	1.8	12.0	9.6	4.0
HAW5	PASSER IV	402.6	4.6	2.7	1.6	13.0	10.1	3.8
(3.932)	TRANSYT-7F	420.2	4.9	2.8	1.5	12.3	9.9	3.7
HAW4	PASSER IV	414.6	4.7	2.7	1.7	12.6	9.9	3.9
(3.932)	TRANSYT-7F	418.7	4.8	2.8	1.6	12.5	9.8	3.8
HAW3	PASSER IV	421.4	4.8	2.8	1.6	12.4	9.8	3.9
(3.925)	TRANSYT-7F	437.0	5.1	2.9	1.6	11.8	9.7	3.8
HAW2	PASSER IV	422.8	4.8	2.8	1.7	12.4	9.8	4.0
(3.832)	TRANSYT-7F	423.8	4.9	2.8	1.7	12.3	9.8	3.9
HAW1	PASSER IV	437.5	5.0	2.9	1.7	11.9	9.6	4.0
(3.832)	TRANSYT-7F	435.1	5.0	2.9	1.7	12.0	9.7	3.9

From Table 5-5 the MOEs predicted by TRAF-NETSIM for the timings developed by PASSER IV prove slightly better than the MOEs predicted for the fine-tuned timings from TRANSYT-7F. This was expected, as one would generally expect the fine-tuned timings to indicate better MOEs; however, any improvement in the fine-tuning process depends on two factors. First, if a set of timings obtained from PASSER IV is very good, the scope for improvement proves limited. A good solution cannot be made much better. Second, the solution from PASSER IV should be conducive to fine-tuning by TRANSYT-7F; i.e., TRANSYT-7F has to fine-tune with a particular phasing sequence. With some phasing sequences, the fine-tuning may only deteriorate the optimized timings. From Table 5-5 the PASSER IV solution is evidently very good, even without fine-tuning. Thus, one should base any attempt to fine-tune on good engineering judgment.

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6.0 IMPLEMENTATION

The next step in the retiming of a traffic signal is implementation of the improved timing plan. After determining a "best solution" either from PASSER IV or TRANSYT-7F, one should transfer the results to a controller worksheet for use in the field. The text does not address all entries to the controller sheet, but only the entries directly related to the computer output. Different controller data sheets for electromechanical pretimed and actuated control exist; worksheets may vary with the brand of controller, or the analyst may use a self-made worksheet. These guidelines address current TxDOT controller standard specifications as much as possible.

The timing design from PASSER IV and TRANSYT-7F is generally not the design installed in the field. It is impossible for computer models to consider every element that must be considered in the real world. This limitation is where the fourth component, "the traffic engineer," comes in.

Regardless of the type of control--pretimed or actuated--the first step in timing implementation should be to fine-tune the model's design. One should examine the timing plan closely to adjust offsets and splits. A few seconds one way or the other may change the throughput of an intersection by hundreds of vehicles per hour.

Once satisfied with the design on paper, the next step is implementation of the timing plan in the field, a function of the type of control.

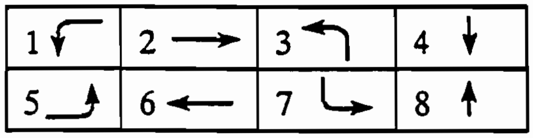
6.1 Terminology

Before discussing the implementation of the timing plans, it is important to define some terms commonly used in traffic signal timing (23):

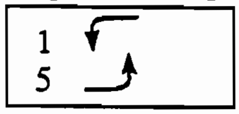
Split - The portion of the cycle length allocated to each of the various phases, expressed in seconds or as a percent of the entire cycle length.

Interval - A discrete portion of the signal cycle during which the signal indications do not change, including the green, yellow, and all red clearance intervals per movement.

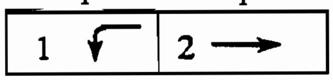
Phase - Individual movement; for example, at a typical intersection, eight movements are usually given some green time.



Concurrent phases are phases that are timed together:



Sequential phases are phases that follow one another:



6.2 Output Interpretation

The starting point is the format of the typical signal timing outputs. Each program produces a typical table summarizing the signal timing plan and contains the following information:

1. Cycle length;

2. Movements serviced on each phase;

3. Time allotted to each phase; and

4. Offset with respect to a specified phase or interval.

Different programs use different methods to describe timing plans. Figures 6-1 and 6-2 illustrate the typical signal timing design plans presented by PASSER IV and TRANSYT-7F. These plans illustrate the timing plans for the Example Problem demonstrated in Section 5.5. A comparison of the PASSER IV and TRANSYT-7F timing plans indicates some interesting similarities and differences.

PASSER IV Signal Timing Tables. The PASSER IV format attempts to represent dual-ring operation, even though the program itself models a single-ring sequence. This representation is achieved by assigning a phase number to each of the movements in the NEMA compatible scheme. The assignment is based on PASSER IV's internal definition and may not reflect actual assignments in the field.

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**** SUMMARY OF PASSER-IV BEST SIGNAL TIMING SOLUTION ****

*-[MASTER INTERSECTION] = NODE NO.   25   CYCLE LENGTH =  100.0 SEC

-------------
NODE NO.   25
-------------
                          MADRONA                  CARSON
                            (W-E)                           (N-S)
                      ARTERY  1 -- SIGNAL  1     ARTERY  4 -- SIGNAL  3
                      ----------------------     ----------------------
    PHASE NUMBER                 1                                2
    NEMA MOVEMENTS         -    2+6     -          -      -      4+8
    PHASE (SEC)            -    69.2    -          -      -     30.8
    PHASE   (%)            -    69.2    -          -      -     30.8
    PIN SET (%)   100 /  0.0      .0    -          -      -     69.2

OFFSET POINT =     .0 SEC (    .0%)
SYSTEM REFERENCE: START OF PHASE NO. 1 OF THE MASTER SIGNAL.


-------------
NODE NO.   27
-------------
                          MADRONA                  TORRENCE
                            (W-E)                           (N-S)
                      ARTERY  1 -- SIGNAL  2     ARTERY  3 -- SIGNAL  3
                      ----------------------     ----------------------
    PHASE NUMBER                 1               2                3
    NEMA MOVEMENTS         -    2+6     -       3+7       -      4+8
    PHASE (SEC)            -    60.0    -       10.0      -     30.0
    PHASE   (%)            -    60.0    -       10.0      -     30.0
    PIN SET (%)   100 /  0.0      .0    -       60.0      -     70.0

OFFSET POINT =   56.7 SEC (  56.7%)
SYSTEM REFERENCE: START OF PHASE NO. 1 OF THE MASTER SIGNAL.
```

Figure 6-1. PASSER IV Timing Design Table

INTERSECTION 1 PRETIMED - SPLITS ARE FIXED

INTERVAL NUMBER :	1	2	3	4	5	6	7	8	9	10
INTVL LENGTH(SEC):	8M	4	13	1	15	4	15	4	20	4
INTVL LENGTH (%):	9	5	15	1	17	5	17	5	21	5
PIN SETTINGS (%):	100/0	9	14	29	30	47	52	69	74	95
PHASE START (NO.):	1		2		3		4		5	
INTERVAL TYPE :	V	Y	V	Y	V	Y	V	Y	V	Y
SPLITS (SEC):	12		14		19		19		24	
SPLITS (%):	14		16		22		22		26	
LINKS MOVING :	103 104		101 103		101 102		105 106		107 108 112	

Figure 6-2. TRANSYT-7F Controller Setting Table

Figure 6-1 presents PASSER IV's recommended signal timing plan design in two columns. The left column shows the phase splits information for the arterial, while the right column shows the phase splits information for the cross-street. The PASSER IV signal design plan indicates the NEMA movements involved, their duration in seconds, and the percent of the cycle of each phase. The order of the phases presented in these two columns indicates the order in which the phases will operate in the field. The phase duration, as well as the "cycle count" indicating the cumulative cycle time prior to the beginning of each phase, are also indicated. The offset point with respect to the system reference point is shown in seconds as well as in percentage of the cycle.

TRANSYT-7F Signal Timing Tables. A table is presented with one column for each interval in the single-ring sequence. For each interval, the table provides the interval length and the pin settings. The table indicates the interval which begins each phase along with the type of interval in each phase. The interval types are as follows:

F	Fixed	The duration of the phase is not subject to change by TRANSYT-7F during the optimization process.
V	Variable	The duration of this interval may be modified by the optimizer. Only one variable interval is allowed per phase.
Y	Yellow	This interval represents the yellow portion of the change period.
R	Red	This interval represents the red portion of the change period.

For each phase, the splits are shown after the interval types. The table presents the link list next. TRANSYT-7F uses a link node concept to represent a network of traffic signals. A node represents each intersection, and a link generally represents each movement. TRANSYT-7F user's manual (18) suggests two such link numbering schemes. The first two digits of the four digit link number represent the intersection number. The last two digits represent the movement number. Figure 6-3 illustrates these two schemes.

6.3 Typical Traffic Control System Timing Inputs

Each traffic control system has its own unique requirements for timing plan data. Thus, it is essential that the specific equipment operating the control system be thoroughly understood before making any timing design changes in the field. Following are some categories of the type of control equipment:

1. Pretimed controllers which may operate either isolated or coordinated with other pretimed controllers in the same system.

2. Large scale computerized systems, like Urban Traffic Control System (UTCS), which take direct control of the field equipment.

3. Traffic responsive systems, in which standard NEMA dual ring traffic actuated controllers are supervised by external hardware to impose some aspects of a coordinated operation. This category is generally referred to as "externally coordinated systems."

4. Traffic responsive systems, in which the developers have gone a step beyond the NEMA standards and incorporated the coordination hardware and software internally within the controller. The timing plan resides in a system master controller and not in the local traffic actuated controllers themselves. This category is generally referred to as "internally coordinated systems."

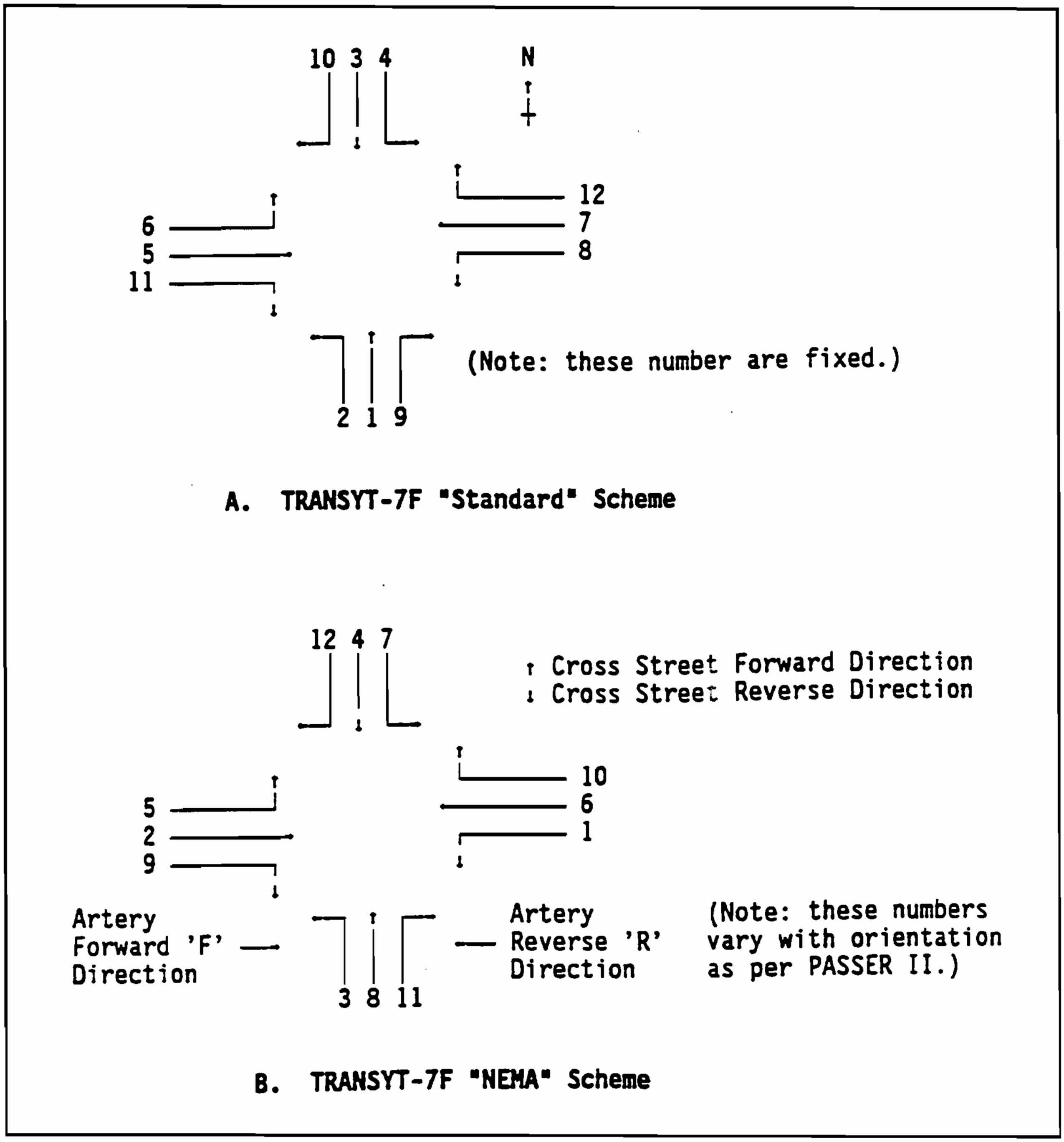

Figure 6-3. TRANSYT-7F Movement Numbering Schemes

6.4 Implementation in Pretimed Controllers

When implementing timing plans for pretimed control, both the splits and pin settings can be determined from the PASSER IV output. The splits, also referred to as green time, and Figure 6-1 indicates that the *PIN.SET* for concurrent and individual phases are given in the output table, entitled "Summary of PASSER IV Best Signal Timing Solution." One can read the pin settings directly under the phase times in percentages in Figure 6-1. The *PIN.SET* equals zero for the first phase; for every subsequent phase, the *PIN.SET* equals *PIN.SET* of the previous phase plus the total time for the previous phase. The term *PIN* in the output gives the green time (splits) for each concurrent phase. The phase times in PASSER IV output include the yellow and the red clearance for each phase.

The information about each artery in the network is illustrated in the PASSER IV output, entitled "Artery Wide Information" and is illustrated in Figure 6-4. Figure 6-4 illustrates the bandwidth for both directions and the phasing pattern for all the intersections along each arterial. The phase settings, in fractions of cycle and in seconds for the entire arterial at all intersections, and the progression times and speeds along each link are also illustrated. Figure 6-5 illustrates a typical time-space diagram for the arterial.

6.5. Implementation in Externally Coordinated Systems

Traffic actuated controllers do not recognize the concept of cycle length, phase splits, and offsets used by signal timing design programs. Without coordination, these programs would constantly adjust to fluctuations in demand and generate their own timing plans on each cycle. Thus, some means of imposing a constant cycle length with predictable time relationships is needed if a group of traffic actuated controllers is to function as a coordinated system. Analysts commonly use two external control functions to impose a background cycle and offset on an isolated traffic controller:

Hold Function -	This function causes the controller to hold at one point in the cycle until it is released, regardless of the detector demand.
Force-off Function -	This function causes the controller to terminate a phase, and move on to the next phase, again regardless of detector demand.

*** ARTERY 2 ***

NAME OF ARTERY: HAWTHORNE NUMBER OF SIGNALS: 5
A - DIRECTION : EASTBOUND

*** ARTERY WIDE INFORMATION ***

ARTERY DIRECTION	BAND (% of Cycle)	BAND (Seconds)
EASTBOUND	.3409	34.09
WESTBOUND	.3409	34.09

EFFICIENCY(%): 34.09 ATTAINABILITY(%): 84.05

*** INTERSECTION INFORMATION ***

NODE NO.	CROSS STREET NAME	LEFT TURN PATTERN SELECTED	SIGNAL NO.
6		LEAD- LAG	1
7	CARSON	LEAD-LEAD	2
8		LAG -LEAD	3
9		N/A	4
10	TORRENCE	LEAD- LAG	5

ALL PHASE STARTING TIMES ARE RELATIVE TO THE START OF GREEN IN THE EASTBOUND DIRECTION AT SIGNAL 1 IN ARTERY 1.

** PHASE SETTINGS -- FRACTIONS OF CYCLE **

		GREEN			LEFT			BAND			
NODE NO.	DIR	BEGIN	END	LENGTH	BEGIN	END	LENGTH	BEGIN	END	WIDTH	QUEUE TIME
6	EB	.553	.956	.403	.553	.725	.171	.587	.928	.341	.000
	WB	.725	.133	.408	.956	.133	.177	.792	.133	.341	.000
7	EB	.611	.108	.497	.511	.611	.100	.758	.099	.341	.000
	WB	.611	.108	.497	.511	.611	.100	.611	.951	.341	.000
8	EB	.584	.234	.650	.073	.234	.160	.893	.234	.341	.000
	WB	.484	.073	.590	.484	.584	.100	.484	.825	.341	.000
9	EB	.984	.734	.750			.000	.984	.325	.341	.000
	WB	.984	.734	.750			.000	.393	.734	.341	.000
10	EB	.052	.498	.446	.052	.183	.131	.112	.453	.341	.000
	WB	.183	.598	.414	.498	.598	.100	.257	.598	.341	.000

Figure 6-4. PASSER IV Artery-Wide Information

```
                    *** PASSER-IV TIME-SPACE DIAGRAM ***

    NAME OF ARTERY: HAWTHORNE                  TIME  SCALE =   3 SEC/CHAR
    CYCLE LENGTH  : 100.00 SECONDS             DIST. SCALE =  150 FT/LINE

                 1         2         3         4         5         6
NODE   1234567890123456789012345678901234567890123456789012345678901234  DIST
       ________________________________________________________________  (FT)
    6 !WWWW=============EEEEEE        WWWWWW=============EEEEE              0
      !                    .   .     .!   .
      !                             !
      !                     ..      !..
      !                             !
      !                     . .     . .
      !                             !
    7 !    ================           =================                  1120
      !     .                       !
      !                .        .  .!     .
      !                             !
      !               .        ..  !      .
      !                             !
    8 !  EEEEEE========WWW           EEEEE========WWWW                  1950
      !                             !
      !              .          .  .!         .
    9 !                          =========                   ======    2510
      !           .          .      !.          .
      !                             !
      !          .          .      ! .           .
      !                             !
      !        .          .        !  .          .
   10 !==EEEE          WWW================EEEE           WWW==========  3350
      !________________________________________________________________
NODE   1234567890123456789012345678901234567890123456789012345678901234  DIST

NODE     6 ---> NODE    10:  EASTBOUND: DIRECTION-DOWNWARDS : GREEN -  EEEEEE
NODE    10 ---> NODE     6:  WESTBOUND: DIRECTION-UPWARDS   : GREEN -  WWWWWW
 EASTBOUND BAND =  34.1 SECS AT 43.5 MPH              GREEN  IN BOTH DIRECTIONS
 WESTBOUND BAND =  34.1 SECS AT 42.0 MPH       ====== RED    IN BOTH DIRECTIONS
```

Figure 6-5. PASSER IV Time-Space Diagram

Elements of Coordination. Analysts use the external commands discussed earlier to modify the operation of a traffic actuated controller to impose a specific cycle length, splits and offsets. In an arterial network, progression is normally provided by coordinating the through movements because the proportion of the through traffic measures far greater than the turning traffic. Thus, according to the NEMA convention, phases 2 and 6 on the major streets, and phases 4 and 8 on the minor streets are coordinated. One can find a detailed discussion of the control concepts in the *Traffic Control Systems Handbook* (1). The typical elements in coordination are:

Non-Actuated Phase - This phase is generally the "main street" or arterial phase, displayed each cycle without the need for detector demand.

Subsequent Phase - This phase is referred to as the "non-actuated + 1," "non-actuated + 2," etc. A four-phase operation would generally consist of the non-actuated phase plus three actuated phases.

Yield Point - The point in the cycle at which the hold function is released is called the yield point. If the non-actuated phase has pedestrian provisions, the yield point would normally occur at the beginning of the Flashing Don't Walk. If no pedestrian provisions exist, it would occur at the end of the green. In a typical coordinator, all times are referenced to the yield point.

Offset - Offset is the elapsed time from an arbitrary system zero reference point to the beginning of the non-actuated phase. This point is the value normally reported by PASSER IV and TRANSYT-7F, although for an "actuated" controller, TRANSYT-7F refers to this as a yield point.

Figure 6-6 illustrates the computation of the yield point for a typical timing plan. A yield point can be calculated as:

$$\begin{aligned}\text{Yield point} &= \text{OFFSET} + \text{SPLIT} - (\text{FDW} + \text{CLEARANCE}) \\ &= 27 + 35 - (15 + 5) \\ &= 42\end{aligned}$$

The force-off point for any of the actuated phases may be calculated as:

Force off	=	(phase) Begin Time	+	Splits	-	Clearance
	=	(non-act + 1) 20	+	20	-	5
	=	35				

(non-act + 1) 20 + 25 - 5 = 35
(non-act + 2) 40 + 25 - 5 = 60
(non-act + 3) 65 + 20 - 5 = 80

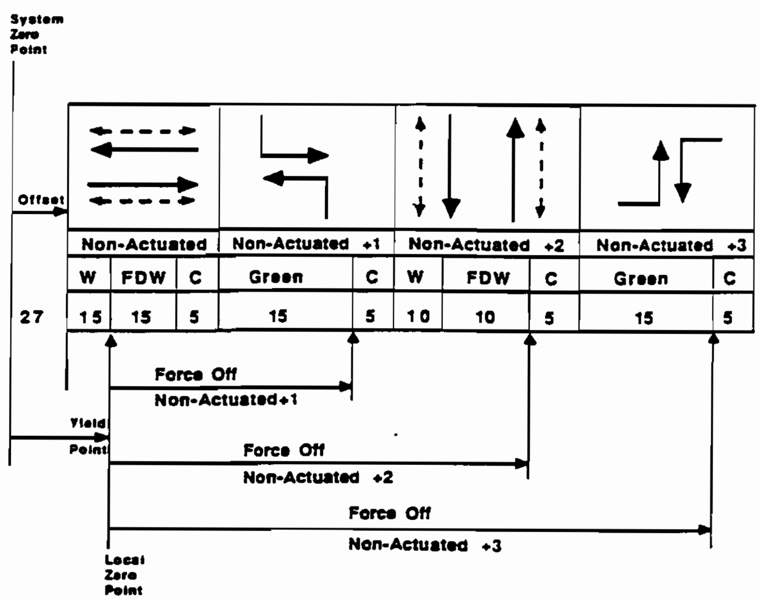

Figure 6-6. Sample Calculation of Force-Offs and Yield Point

Permissive Periods. If the operation as described earlier was implemented as it is, just one instant (yield point) would exist when the actuated phase (cross-street) could be initiated, if a vehicle places a call on the detector. During peak periods, a constant demand of traffic on the cross-street exists; however, during off-peak periods, if a cross-street vehicle arrives just after the yield point, it will have to wait the whole cycle to be serviced. Thus, the concept of the permissive period gains importance. Permissive periods are implemented to service the cross-street traffic, even after the onset of the yield point (as long as subsequent phases are not affected). This action will reduce delay to the cross-street without compromising arterial coordination. Figure 6-7 illustrates the calculation of the yield point, force-offs, and the permissive periods.

Note that the term "permissive period" is not related in any way to the left-turn treatment. The use of the word "permissive" or "permitted" in connection with left-turn protection is a totally different subject.

The following sections contain timing plan implementation guidelines suggested by Wallace and Courage (21).

6.6 Implementation in Internally Coordinated Systems

Due to complications involved with external coordination, more and more traffic control systems have incorporated internal coordination features. Internal coordination systems accept cycle length, splits, and offsets and perform computations. Computerized timing designs are, therefore, much easier to implement with internally coordinated systems. Some differences arise in the way offsets and reference points are referenced when using software control, as opposed to using hardware control. When using software control, the offset is usually referred to the start of the main street green. When using hardware control, the offset is usually referred to in three ways:

1. To simultaneous display of coordinated phases;
2. To the first coordinated phase; and
3. To the barrier following coordinated phases.

While NEMA intersection controllers are well standardized, coordination software and hardware vary considerably. Thus, one must carefully tailor the data transfer routines to each system.

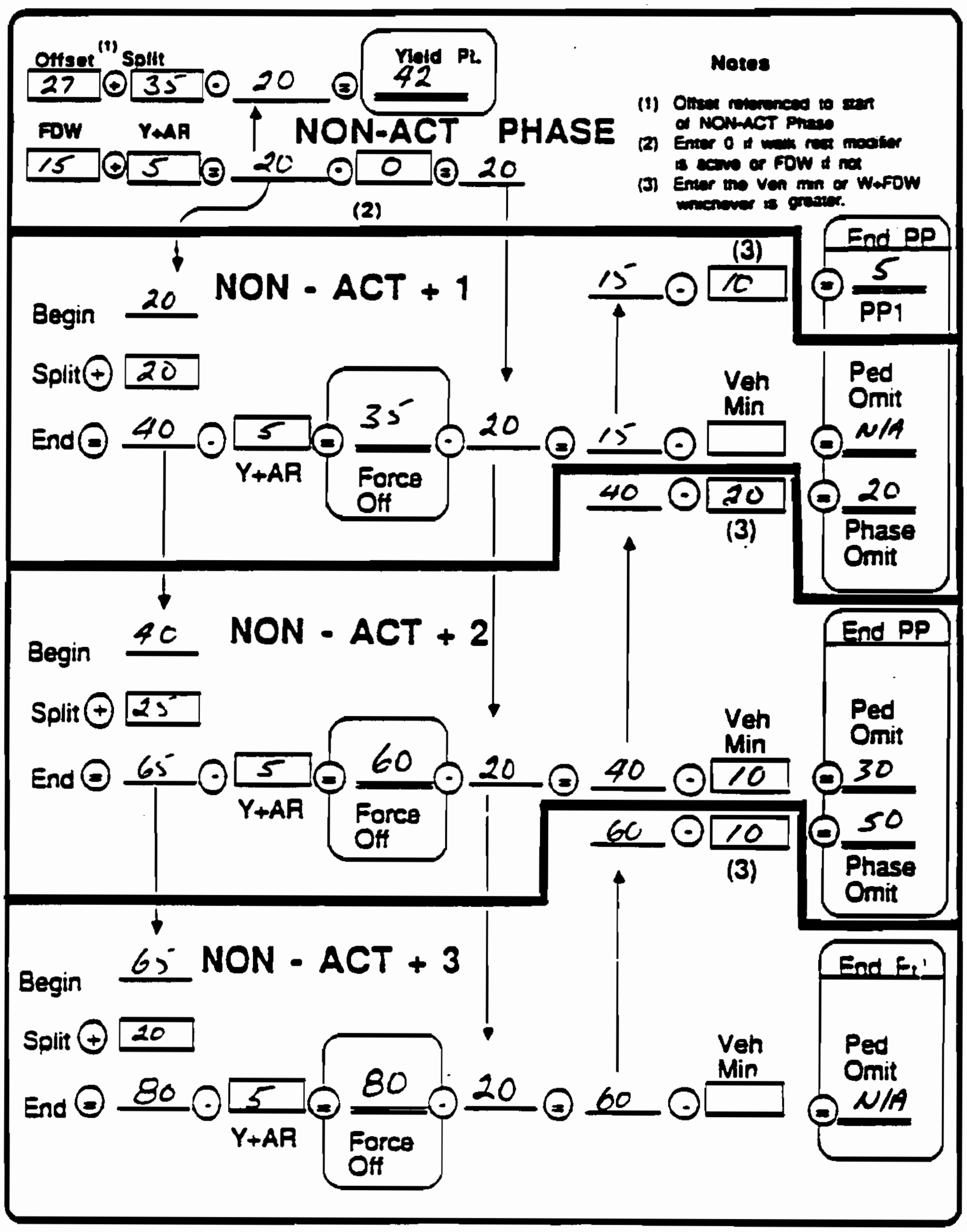

Figure 6-7. Sample Calculation of Yield Point, Force-Offs, and Permissive Periods

6.7 Multiple Period Considerations

For a given control period, the development of a timing plan involves more than simply running PASSER IV once. The steps presented in Section 5.0 should be followed to develop a recommended timing plan for each control period. Then the analyst must resolve the differences, as explained below.

Selection of a Timing Plan for a One-Dial System. If the signal system is capable of handling only one timing plan, the analyst may follow the procedure discussed below to determine an acceptable timing plan; however, no one signal timing plan will prove optimum for all periods throughout the day. Thus, the selection of the "best" signal timing plan necessarily requires engineering judgment.

To accomplish the objective of having good signal timing plans throughout the day, the development of more than one timing plan is recommended. One should evaluate each timing plan using the different traffic demand levels which exist during various periods throughout the day. Timing plans for the a.m. peak period traffic demands, the p.m. peak period traffic demands, and representative off-peak period traffic demands should be developed. The analyst should evaluate each timing plan using the traffic demand data for the a.m. peak, p.m. peak, and off-peak periods. The most appropriate signal timing plan should be selected based on engineering judgment, attempting to accommodate the majority of the traffic demand as well as possible.

One should also examine each plan for major problems such as oversaturation. In short, plan selection should be a thoughtful and objective process, not a purely quantitative assessment.

Selection of Timing Plans for Multiple Dials. If the system can deal in multiple control periods, the analyst is less constrained as to the control parameters; however, the parameter likely to be constrained is the phase sequences. An analysis similar to the example above should be performed, but using the "best" phase sequences from each control period to evaluate using others traffic conditions. As above, the best overall phase sequences should be selected, and those will be the phase sequences that will apply all day.

6.8 Fine-Tuning the Timing Plan

The following discussion follows suggestions and guidelines presented by Yauch and Gray (24). The final step in the implementation phase of retiming signals is fine-tuning the signal timing plan. Fine-tuning involves observing the signal timing plan in operation after its installation in the controller and determining if the new plan operates effectively. Based on observations, minor adjustments may be needed to improve the performance of the timing plan in the real world setting. Most adjustments will be made to the phase lengths or offsets.

The analyst should not consider results from signal timing optimization computer runs absolute or completely correct. Input data may not reflect the real world situation. Signal optimization software are tools to help produce a good timing plan. Engineering judgment and field observation must also be part of the implementation process.

Fine-Tuning In-house. Before actual field observation, one should check the data used in the analysis for errors. The analyst should then verify the simulation of existing conditions before making the optimization runs. Other reasons for field observation and fine-tuning are that scaled measurements may have been used for distances, or data may have been entered incorrectly into the controller. After reaching an optimized solution, one should thoroughly scrutinize data input and results. The transposed data from the computer output to controller settings should be reviewed for accuracy. If one takes these steps before field implementation, adjustments in the field will be minor.

The analyst should notify the public of proposed signal changes in advance. This modification may be accomplished via the media or appropriate signing. When actual field modifications begin, one should apply proper traffic control to protect the traveling public and workers implementing the new timing plans.

Fine-Tuning in the Field. Fine-tuning signal plans in the field involves the verification of plan implementation cycle length, phase splits, and offsets. Field fine-tuning also involves determining the effects of the new timing plan on traffic flow. Before determining the operational effects, one should first verify controller settings. Before actual field fine-tuning takes place, the analyst should allow the traffic to settle to make field observations and before making any changes to the controller. Drivers may react hesitantly or erratically due to the change in signal timing and/or phasing. The true effect of how the new control strategy affects traffic flow may not be immediately apparent due to driver behavior. Therefore, one should not make observations and measurements until drivers become familiar with the new changes.

Cycle Length and Phase Splits. After modifying the controller settings, one should make field observations to ensure that the proper settings have been implemented. Cycle lengths and phase lengths can be verified in the field with a stopwatch. For most full actuated controllers, the analyst may observe the maximum green for each phase by locking VEH DET or MAX RECALL for each phase. Once verifying the settings in the field, the analyst should lock functions "Off." Otherwise, the maximum time will be assigned to each phase, whether or not it is needed, and most benefits from actuated control will be lost.

Implementation of new timing plans, especially those involving new phase sequences, may cause drivers to hesitate, or drivers may refer back to the old phase sequence out of habit. One should take this into account when observing the overall effectiveness of the changes. If other problems observed in the field, such as excessive queues and poor green time allocation, are not predicted by PASSER IV or TRANSYT-7F, one should check the input data and controller settings again.

Fine-tuning timing plans in the field can have a significant effect on the performance of the signal timing plan. Minor changes, such as a two second increase for a phase, will result in 60 additional vehicles per phase discharging at the approach. One should follow this process for each timing plan implemented at the diamond interchange. **Engineering judgment, in combination with signal timing tools and public feedback is the key to developing a good retiming plan.**

7.0 PROJECT DOCUMENTATION

Assessing the benefits of the new signal timing plan is an important and final step in the signal retiming process. The following sections discuss two types of documentation. First, traffic signal analysts are interested in the benefits obtained from implementing a new timing plan because traffic control improvement plans often require justification to decision makers before expenditures are allocated. Verifying estimated improvements or better operations along the arterial, assists the engineer in future fund allocations for projects. Second, traffic signal analysts are interested in documenting any decisions pertinent to the signal timing process for future reference.

7.1 Estimation of Benefits

To evaluate the results of a new timing plan, Before and After studies often prove used. One uses measures of effectiveness, such as delay, stops, fuel consumption, queues, and v/c ratios as a basis of comparison. The analyst should first establish the objectives or goals of the project before undertaking the project. Some objectives may include:

1. Improved safety along the arterial network;
2. Reduced system delay on the arterial network;
3. Improved air quality;
4. Reduced fuel consumption; and
5. Increased arterial operational efficiency.

From these goals, measures of effectiveness are chosen for use in the Before and After analysis. One can use either TRANSYT-7F or TRAF-NETSIM to estimate chosen measures for both the Before (existing) and After (optimized) conditions. The same program, however, should be used for MOE estimation for both conditions; i.e., one should not use TRANSYT-7F in the Before condition and TRAF-NETSIM in the After condition. The differences in the Before and After conditions represent the benefits of the new signal timing plan. Because both arterial street networks programs' analysis periods equal one hour, one should multiply the benefits by unit costs and then convert them to daily and annual totals for the life of the project.

It is important to remember that, when estimating benefits, one should use actual traffic volumes rather than the adjusted traffic volumes used to determine optimum signal timings during the peak hour; i.e., one should only attribute benefits to the actual number of vehicles at the intersection. It is also desirable to have field data from the Before and After conditions that verify the magnitude of the estimated benefits.

It is important to note that TRANSYT-7F and TRAF-NETSIM can be used to estimate benefits for both pretimed and actuated control. In both cases, the benefits attributable to signal retiming represent the difference between the Before and After conditions. Actuated control, however, will result in better operation than that predicted by TRANSYT-7F, as long as the volume to capacity ratios at the intersection measure less than 0.95. The improvement due to actuated control equals an approximate 15 percent reduction in individual MOEs, when volume to capacity ratios measure less than 0.85, and a correspondingly lesser reduction as volume to capacity ratios approach capacity.

Example Calculations. In an example problem that represents a signal retiming project, analysts used PASSER II-87 to evaluate existing conditions at 71 signalized intersections in an arterial network and then to produce an optimized timing plan. PASSER II-87 reports the following measurements of effectiveness: stops, delay, and fuel consumption.

Example calculations show the Before and After conditions in an arterial network, as seen in Table 7-1. The difference in the Before (existing) and the After (optimized) conditions is:

Stops = 88005 stops/day (5.9 percent reduction);
Delay = 926 veh-hrs/day (6.45 percent reduction); and
Fuel = 1183.6 gallons/day (4.1 percent reduction).

Typically, benefits for retiming signals range from of 5 to 20 percent reductions in delay, stops, and fuel consumption, depending on the type of retiming strategy used (25). Generally, optimization of green splits or cycle length optimization will produce improvements of around 5 percent, while geometric and signal hardware improvements may show as much as a 20 percent overall improvement. The percentage of improvement also depends on how bad the signal timing plan was before it was optimized.

To estimate the total benefits of an optimized signal system, the delay reduction (or other improvements reported by an analysis tool such as PASSER II) should be multiplied by the number of hours a timing plan is in operation. If three timing plans are used in a day, typically the a.m. and p.m. peak timing plans will be used for one to two hours each, and the off-peak timing plan will be used for seven to ten hours for benefit analysis; i.e., ten to fifteen hours of the day was used for benefit analysis. The following steps show how one may calculate benefits per day, per year, and for the life of the project:

1. **Compute Hourly Benefits.** For each timing plan, calculate the improvement in measures of effectiveness, such as stops, delay, and fuel consumption. For example, the delay due to signalization for the optimized (After) timing plan is subtracted from the delay due to signalization for the existing (Before) timing plan.

Table 7-1. Benefits of a Signal Retiming Project

		STOPS		TOTAL SYSTEM DELAY (veh-hrs)		FUEL (gals)	
		BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER
HOURLY VALUES	AM	114711	107147	1008.8	945.8	2310.39	2174.84
	OFF	122687	117801	1053.3	993.5	2464.67	2387.51
	PM	194268	174261	2469.4	2277.9	3308.41	3107.62
DIFFERENCES	AM	7564		63		135.55	
	OFF	4886		59.8		77.16	
	PM	20007		191.5		200.79	
HRS/DAY	AM	1.5		1.5		1.5	
	OFF	7.5		7.5		7.5	
	PM	2.0		2.0		2.0	
DAILY	AM	11346		94.5		203.32	
	OFF	36645		448.5		578.7	
	PM	40014		383		401.58	
	TOTAL	88005		926		1183.60	
UNIT VALUES		$0.014		$10.00		$1.00	
ANNUAL SAVINGS		$369,621		$2,778,000		$355,081	
PROJECT COST :		$49,066		TOTAL ANNUAL SAVINGS :		$3,502,702	

2. **Compute Benefits for Each Timing Plan.** For each timing plan, multiply the savings (stops, delay, or fuel consumption) by the number of hours that the timing plan operates. As discussed previously, the a.m. peak reduction may be multiplied by 1.5 hours, the p.m. reduction by 2.0 hours, and the off-peak reduction by 7.5 hours.

3. **Compute Daily Benefits.** Next, sum the reductions (stops, delay, and fuel consumption) for each timing plan; (a.m. reduction * 1.5) + (p.m. reduction * 2.0) + (off-peak reduction * 7.5). This sum will equal the total reduction for each measure of effectiveness in stops per day for stops, vehicle-hours per day for delay, and gallons per day for fuel consumption.

4. **Compute Annual Benefits.** To estimate the annual benefit, these reductions per day are multiplied by 300 days per year (not counting weekends). Express the yearly reductions will be in stops per year for stops, vehicle-hours per year for delay, and gallons per year for fuel consumption.

5. **Compute Benefits for Life of Project.** Typically the life of a signal timing plan equals three to five years. To estimate the benefit of reductions over the life of a project, multiply the yearly reductions (stops, delay, and fuel consumption) by the life of the project. To allocate a dollar amount to the savings due to these reductions, select a cost from a reference, such as the AASHTO Manual on User Benefit Analysis of Highway and Bus-Transyt Improvement (26), per stop per vehicle-hour of delay, and per gallon of fuel.

Some cities have published information regarding the benefits of signal retiming to motorists. This information allows local citizens and public officials to recognize the benefits gained through traffic signal retiming projects. A previous study conducted on signal retiming in 44 Texas cities (2,243 signals retimed) resulted in annual reduction in fuel consumption, delay, and stops of 9.1 percent (30 million gallons), 24.6 percent (43 million hours), and 14.2 percent (1.7 billion stops) respectively (27). One should note that signal retiming benefits the citizens directly by reducing fuel consumption, delay time, and the number of stops at signalized intersections.

7.2. Benefit-Cost Analysis

When considering the question of how much to budget for signal retiming projects, one should consider total costs as well as potential benefits. For example, say a district has 450 signals and a total budget for the signal section of $1,387,000, such as that shown in Figure 7-1. If $160,000 of the total budget (approximately 10 percent) is used primarily for signal timing, this expenditure would equal $356 per signal per year, or $1067 per signal every three years. One can see that even a small reduction in stops, delay, and fuel consumption would easily pay for the cost of retiming.

Other considerations in determining benefits from a new timing plan involve the cost of preparing and implementing the new timing plan. The analyst may estimate costs by person-hours used to collect and prepare data for analysis, computer costs, and person-hours needed to implement the timing plan in the field. An example of an analyst's cost estimate may look like the example in Table 7-2. Note that this cost estimate is for retiming six intersections and includes the purchase of new hardware.

Some estimates of retiming costs given by various agencies range from $500 to $1800 per intersection (28). Another estimate figured one person-week for retiming a signal, which corresponds to one person timing 50 signals in a year; of course, several persons work on one project at a time. These estimates include data collection and development of timing plans. Costs will prove higher for geometric improvements or major signal hardware replacement.

After computing benefits and costs of the signal retiming project, it is a simple matter to calculate a benefit-cost ratio for the project. Typical costs from past projects have ranged from $20 to $100 dollars in motorist benefits for every dollar spent on the signal retiming projects. One should note, however, from the previous example (Table 7-1) that motorists saved 71.4 dollars for every dollar spent on signal timing projects.

After the new signal timing plan is implemented, fine-tuned and documented, the need for future field observation does not end. Further fine-tuning may prove necessary as time progresses. If events cause further traffic volume shifts, the process of evaluation, optimization, and implementation needs repeating. Careful planning of new signal design projects eases the problems of future traffic growth. If possible, one should install the most versatile controller equipment and signal hardware to accommodate future growth and fluctuations. As demonstrated by this example, retiming signals can be a cost effective means of improving intersection capacity and movement.

Salaries and Fringe Benefits	
Signal Engineering - $266,667 x 60% =	$160,000
Signal Shop - $900,000 x 60% =	$540,000
Overtime and Standby Pay for Signal Maintenance	$ 32,000
Motor Pool Charges for Signal Surveillance and Maintenance Vehicles	$120,000
Supplies	$ 25,000
Repairs of Equipment by Vendors (including Maintenance of Central Computer Equipment)	$ 15,000
Signal Parts and Components for Maintenance	
Funded from Operating Budget	$170,000
Capital Improvements Funds (knockdowns, replacement of controllers and detectors) estimated	$325,000
TOTAL	$1,387,000

Figure 7-1. Example District's Budget for a Signal Section

Table 7-2 Analyst's Cost Estimate for a Typical Retiming Project

COST ITEM	LEVEL/TYPE	TIME	COST	COMMENTS
Personal	Engineer	20 hrs	$715.60	$37.78 per hour
	Oprtns. Supt	32 hrs	$743.68	$23.24 per hour
		40 hrs	$990.00	$24.75 per hour
	Traffic Tech.	32 hrs	$427.52	$13.36 per hour
		115 hrs	$1,656.00	$14.40 per hour Hourly rates include salary plus 30 percent
	Total		$4532.80	overhead and fringe benefit allowance.
Expenses	Equipment		$33,000.00	6 Eagle EPAC 300 Controllers
	Vehicle	90 hrs	$585.00	Bucket Truck
	Training		$444.00	PASSER Training
Total Local Costs			$34,029.00	
Consulting	Timing Plans		$7,250.00	
	Install Controllers		$15,000.00	
Total			$22,250	
Total Project Cost			$56,279.00	

7.3 Documentation of Decisions

As in all other aspects of engineering and TxDOT projects, liability remains an important concern. The analyst should document the final signal timing plan agreed upon for implementation. This documentation includes citing all steps taken in developing the timing plan. Documentation of tasks performed and decisions made concerning signal retiming should be included, along with pedestrian considerations, clearance time calculations, left-turn phasing, etc. One should record and explain any unusual design procedures or engineering judgment decisions.

Documentation is recommended when timing plans are implemented and fine tuned, including the traffic control and safety procedures taken to protect the traveling public. It is recommended that one copy of the signal timing plans currently in operation be kept in the controller and at least one copy of the plans be kept in the office or project files. It also is recommended that two copies of the signal's maintenance records be kept, as these records are becoming increasingly important in tort liability cases. As with signal timing plans, one copy of the maintenance records should be kept in the controller and the second copy in the office files.

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