THE UNIVERSITY OF ALBERTA

An Evaluation System for Signal Coordination

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled An Evaluation System For Signal Coordination submitted by Gary D. Evans in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

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ABSTRACT

The objective of this research project is the development of a practical system to evaluate signal coordination at an individual intersection. It appears that delay can be employed to this end.

"Delay" is not a simple or exact term. It is defined as the difference between the actual travel time and the unimpeded travel time on a roadway section. Nevertheless, delay is an important indicator of the quality of signal coordination. The basic idea is simple: when coordination through a traffic signal is good, most vehicles will encounter no delay. On the other hand, if most platooned vehicles are delayed, the coordination is suspect.

The relationship between delay and coordination underlies the survey system developed by this research project.

Portable field equipment and subsequent computer programs assist in the measurement of delays. The survey method is based on the re - creation of a time - space diagram for a signalized intersection approach lane. Spatial reference extends from an arbitrary point upstream of signal queues to the stopline. The difference between the actual and unimpeded travel time determines individual vehicle delays. Individual vehicle information is summarized in the form of delay distributions and cyclic flow profiles.

This document describes the system, and examines the utility of it.

ACKNOWLEDGEMENT

The author would like to express his gratitude for the assistance provided by numerous individuals from The Transportation Group of the Civil Engineering Department, University of Alberta. The guidance, technical direction, patience, and moral support provided by Professor Stan Teply, throughout this research is gratefully acknowledged.

Without this support and help the research objectives could not have been met.

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CHAPTER I, INTRODUCTION

A) PROBLEM STATEMENT

During periods of low traffic volumes, individual vehicles experience different durations of delay. Vehicles arriving on green will experience minimal delays while those arriving on red will be impeded. Typical urban environments result in traffic movement along a specified route through a series of adjacent intersections. As vehicles are discharged on green their behavior becomes aggregate in the formation of a platoon. The task of coordination involves the offset of green intervals such that the greatest portion of a platoon is unimpeded by the signal. To aid in the selection of the appropriate offset the traffic engineer has traditionally used vehicle trajectory bands, cyclic flow profiles , or a combination of both methods. Post design evaluation of signal coordination is accomplished with a before / after comparison of the design assumptions or through the use of computer models.

Present signal coordination procedures focus on the macroscopic or aggregate movement of vehicles through two or more adjacent intersections. Inherent to all macroscopic models is the exclusion of individual vehicle behavior. The deficiency of microscopic information is addressed by the individual vehicle perspective used in this paper. This research considers microscopic vehicle behavior as the basis for coordination analysis. Previous coordination techniques omitted individual vehicle behavior to the benefit of assumed aggregate behavior.

Major objectives of coordination include increasing intersection capacity, control of queue patterns, or decreasing stops, delays and travel times. Common to each objective is the vehicle delay. It follows logically that delay can be employed as an indicator of the quality of signal performance.

The combined concerns of insufficient microscopic information and individual vehicle coordination potential provide the motivation for this research. Individual vehicle delays form the foundation for a coordination analysis. A quantitative display of individual vehicle delays in the form of a probability function provides a useful design and / or evaluation tool. The cumulation of these efforts is the development of a system to evaluate the quality of signal performance.

B) PROBLEM SOLUTION

Vehicle delay is dependent on the progression of a platoon through the signal. This relationship implies a correlation between delay and coordination. Short delays indicate good coordination while longer delays indicate poor coordination. In the same manner, it can also be implied the frequency of a delay duration may indicate the coordination potential. If a high proportion of vehicles are not delayed coordination is good. Large frequencies of long delays indicate the opposite, i.e., poor coordination. To combine the parameters of delay duration and frequency a probability distribution is employed.

In the case of ideal coordination a free flowing platoon would arrive on the green phase with all vehicles experiencing minimal delays. Figure 1.a illustrates. The delay probability distribution would consist of all vehicles in the smallest delay class as illustrated by Figure 1.b.

The opposite of perfect coordination occurs when the signal offset is altered such that the platoon arrives on the red phase. All vehicles will experience delays proportional to their arrival on red. Figure 1.c illustrates. The delay probability function shifts towards longer delays to the detriment of zero delays. Figure 1.d illustrates.

A typical intersection contains a combination of both cases; free flowing vehicles experience minimal delays while vehicles arriving on red experience a variety of delay durations. As the coordination ability improves or deteriorates the delay probability distribution should shift towards shorter or longer delays accordingly.

The correlation between delay and coordination implies that the relative shape of the delay distribution could provide insight towards the cause of vehicle delays. Increased knowledge of the delay characteristics could provide a starting point for both further study and possible remedial actions. To present the delay distribution graphically, a computer program entitled DELAY was

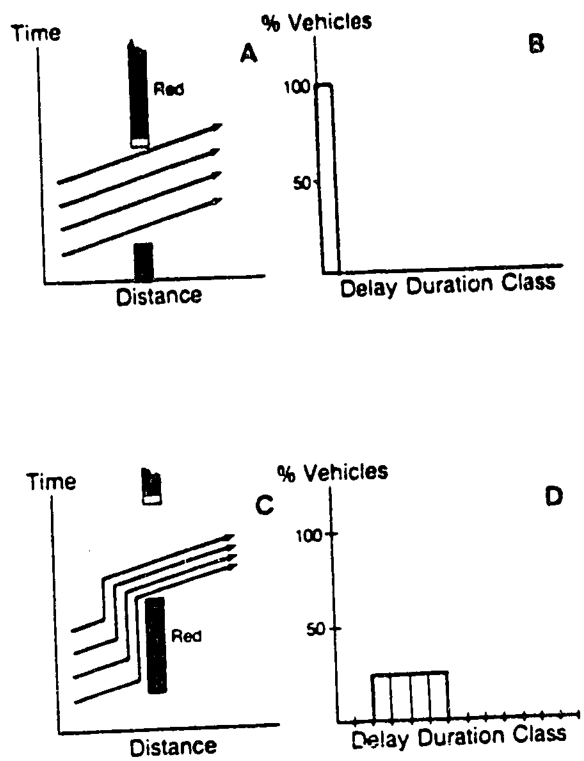

Figure 1.1: The Influence of Arrival Pattern on Delay (Ref 1)

developed. The DELAY program includes a time - space diagram of vehicle movements, cyclic flow profiles, and a delay distribution with statistics.

C) OBJECTIVE

The objective of this research is the development of a practical system to evaluate the quality of signal coordination at an individual intersection. Individual vehicle delays are combined in a probability distribution to provide an indicator of coordination potential. Traffic and signal characteristics are illustrated in the form of a time - space diagram and cyclic flow profiles. The cumulation of these efforts are presented in the computer program entitled DELAY.

D) SCOPE

The scope of this research project entails the development of a system to evaluate signal performance at an individual intersection. The overall research goal is obtained through the completion of the following subordinate tasks:

1) The collection of data (Ref 2) showing the spatial relationship of individual vehicles. Field data was collected by a traffic analyzer and transferred to a personal computer.

2) Analysis of individual vehicle spatial information in the form of a time - space diagram. This aspect of the research is

accomplished with the computer program entitled TSD (Ref 3,4,5).

3) Analysis of an intersection approach time - space diagram to determine individual vehicle delays, a delay distribution with statistics and cyclic flow profiles. These tasks are inclusive in the computer program entitled DELAY (Ref 6).

4) The testing of the DELAY program through the interpretation of results from a variety of traffic conditions. Based on these results the validity of the initial assumptions will be commented upon and the effectiveness of the methodology is discussed.

The flow chart of Figure 1.2 illustrates the scope of the research.

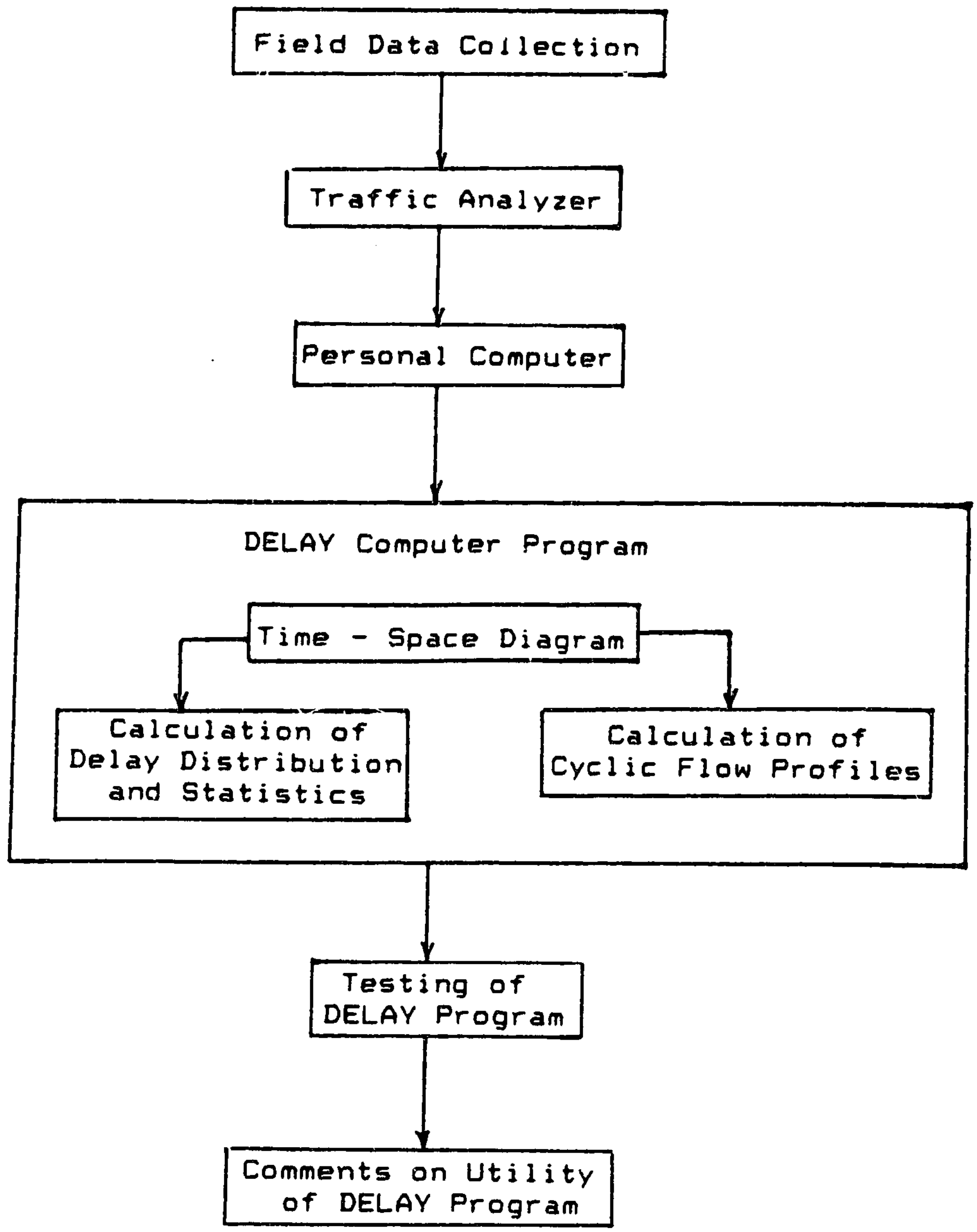

Figure 1.2: Scope of the Research

CHAPTER II, BACKGROUND

A) COORDINATION

Coordination involves the setting of signal offsets to minimize delay encountered along a specified route. The traffic engineer must consider fixed parameters such as roadway geometry, traffic volumes, speeds, vehicle patterns, and driver behavior. Given each fixed parameter the designer must then determine a pattern within a group of signals which optimizes the coordination objectives. Typical coordination objectives include the minimization of stops, delays, or travel time; to maximize intersection capacity; or the control of queue patterns.

The designer must first determine the allocation of green time for each phase within the cycle. Allocation of green time is based on the traffic volume for each intersection movement. Movements within the phase(s) containing the greatest percentage of traffic receive a greater proportion of green time. If pedestrian movements are present green intervals may also be subject to minimal pedestrian clearance intervals. Upon completion of green time allocation the signal designer determines how the signal effects adjacent signals. Traffic patterns on a route are considered for coordination. The start of green is offset within the cycle such that the optimal coordination is provided. The task of signal coordination involves the determination of cycle times, the calculation of phasing within the cycle, and finally the offset of green time for a group of signals.

Various different methods or tools for the evaluation of signal coordination have been developed. These include throughbands, greenbands, cyclic flow profiles, progression factors, and delay calculations. The remainder of this chapter outlines signal coordination procedures.

A.1) Time - Space Diagram Techniques

Historically coordination design is calculated from vehicle trajectories on a time - space diagram. This technique combines a group of trajectories into a band and then shift green offsets to accommodate the largest band possible. The two prominent methods developed are throughbands and greenbands. They are outlined below.

A.1.a) Throughbands

Throughbands (Ref 7) involve the illustration of a band of vehicle trajectories passing through a series of adjacent intersections. The free flow velocity along the route is determined as a reference vehicle trajectory. Adjacent green offsets are then adjusted to provide a maximum band width of free flow velocity. An example of throughbands is illustrated in Figure 2.1.

Throughbands do not consider the effects of platoon dispersion

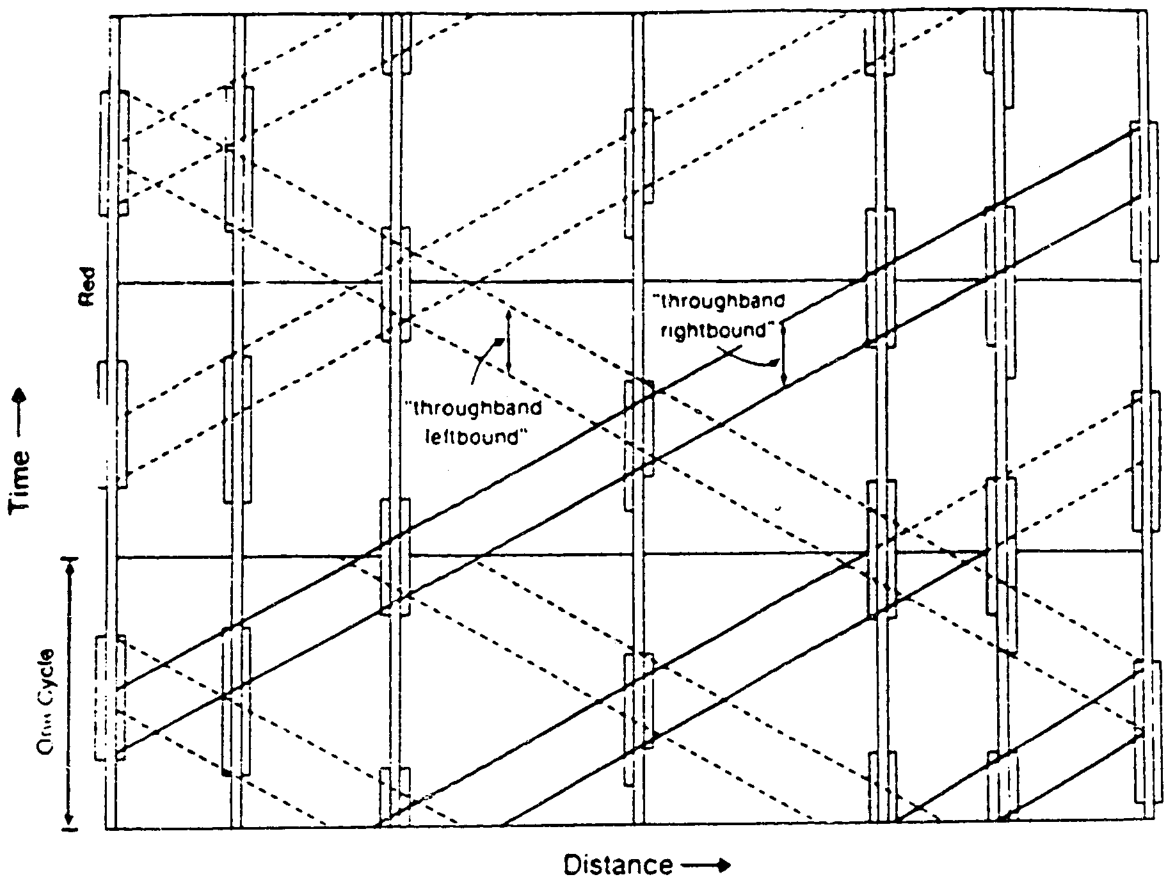

Figure 2.1: Example of an Offset Design Using Throughbands (Ref 7)

or queued vehicles caused by onturning traffic. This method assumes platoon departure at the start of green at an upstream intersection, and platoon arrival at beginning of green at the downstream intersection. If vehicles are queued at the downstream intersection the platoon must wait for their dispersal before it proceeds. This situation is illustrated in Figure 2.2.

Throughbands do not accurately reflect the flow of traffic. The omission of queued vehicles neglects delays incurred by the platoon. This inconsistency has led to the use of greenbands.

A.1.b) Greenbands

Greenbands (Ref 7) consider the arrival of a platoon when queued vehicles are present. The designer first determines the length of queue accumulated during the red phase. The signal is then offset such that the queue has dispersed upon arrival of the lead vehicle in the platoon. A greenband represents the region of free flowing vehicle trajectories that are unimpeded at each signal. Design of greenbands is best illustrated in Figure 2.3.

Greenbands are smaller in width than a throughband due to a portion of green utilized to disperse queued vehicles. However, the band width accurately reflects an unimpeded platoon movement.

A.2) Cyclic Flow Profiles

Cyclic Flow Profiles (Ref 8) illustrate the average arrival or

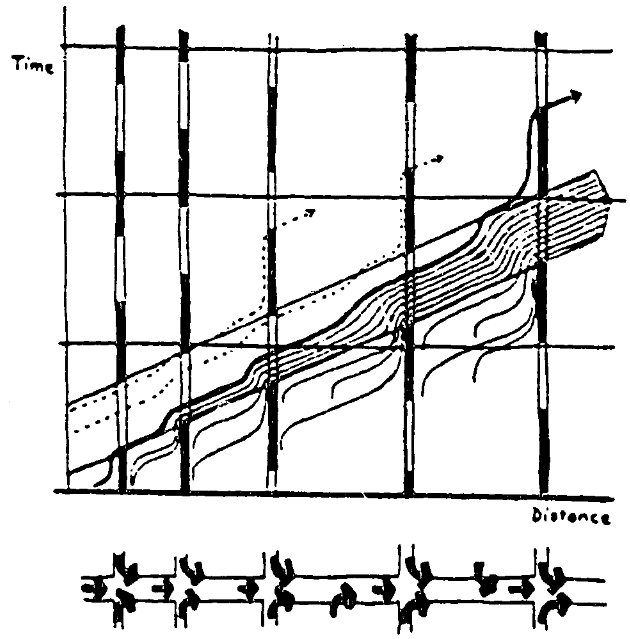

Figure 2.2: Effects of Onturning Traffic on Throughbands (Ref 7)

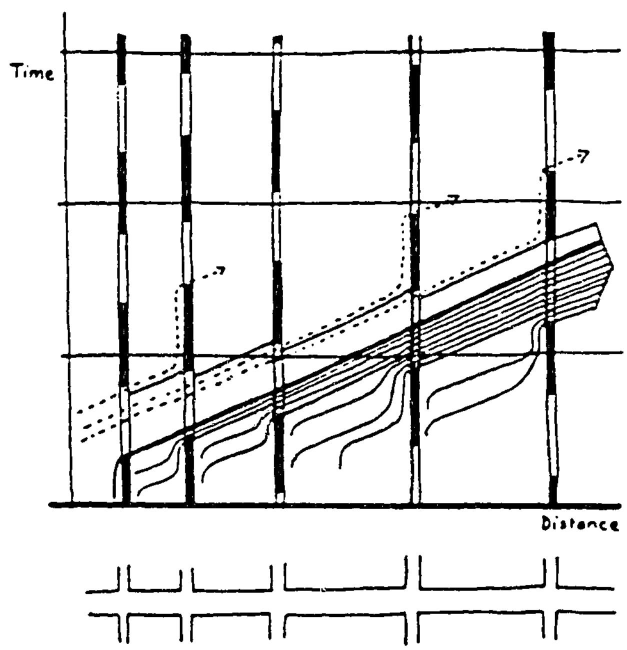

Figure 2.3: Design of Greenbands (Ref 7)

discharge rate at an intersection over the duration of one cycle. Cyclic flow profiles require prior knowledge of the saturation flow, the number of onturning vehicles, and the signal pattern at the intersection. The upstream discharge pattern combined with both midlink sources and upstream turning vehicles are projected to an arrival pattern at a downstream intersection. Platoon dispersion is taken into account between intersections. The intersection is then discharged at saturation flow until the queue has dissipated. In undersaturated conditions the remainder of green then has an equivalent arrival and discharge rate. This process is then repeated throughout the route or network.

In general, cyclic flow profiles require extensive calculations and are usually calculated by a computer model. Computer programs such as TRANSYT (Ref 9) use cyclic flow profiles to set green intervals and offsets in a network. Examples of TRANSYT cyclic flow profiles are illustrated in Figure 2.4.

Cyclic flow profiles are often used in conjunction with time - space diagram methods to describe traffic conditions.

B) DELAY

Delay is often used as an overall indicator of the quality of coordination. Short delays reflect good coordination while long delays reflect poor coordination. As delay can increase exponentially in oversaturated conditions caution must be exercised in comparing delay values. Figure 2.5 illustrates.

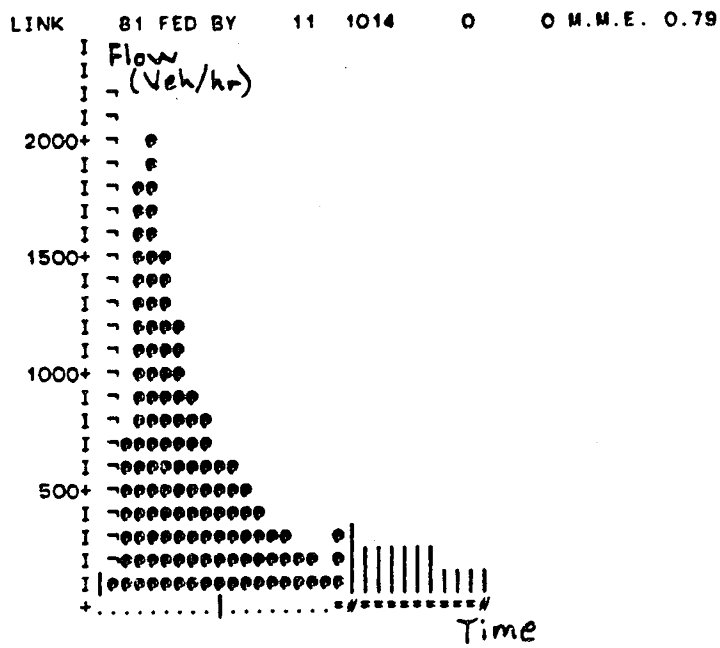

Figure 2.4: Example of a Cyclic Flow Profile Produced by TRANSYT

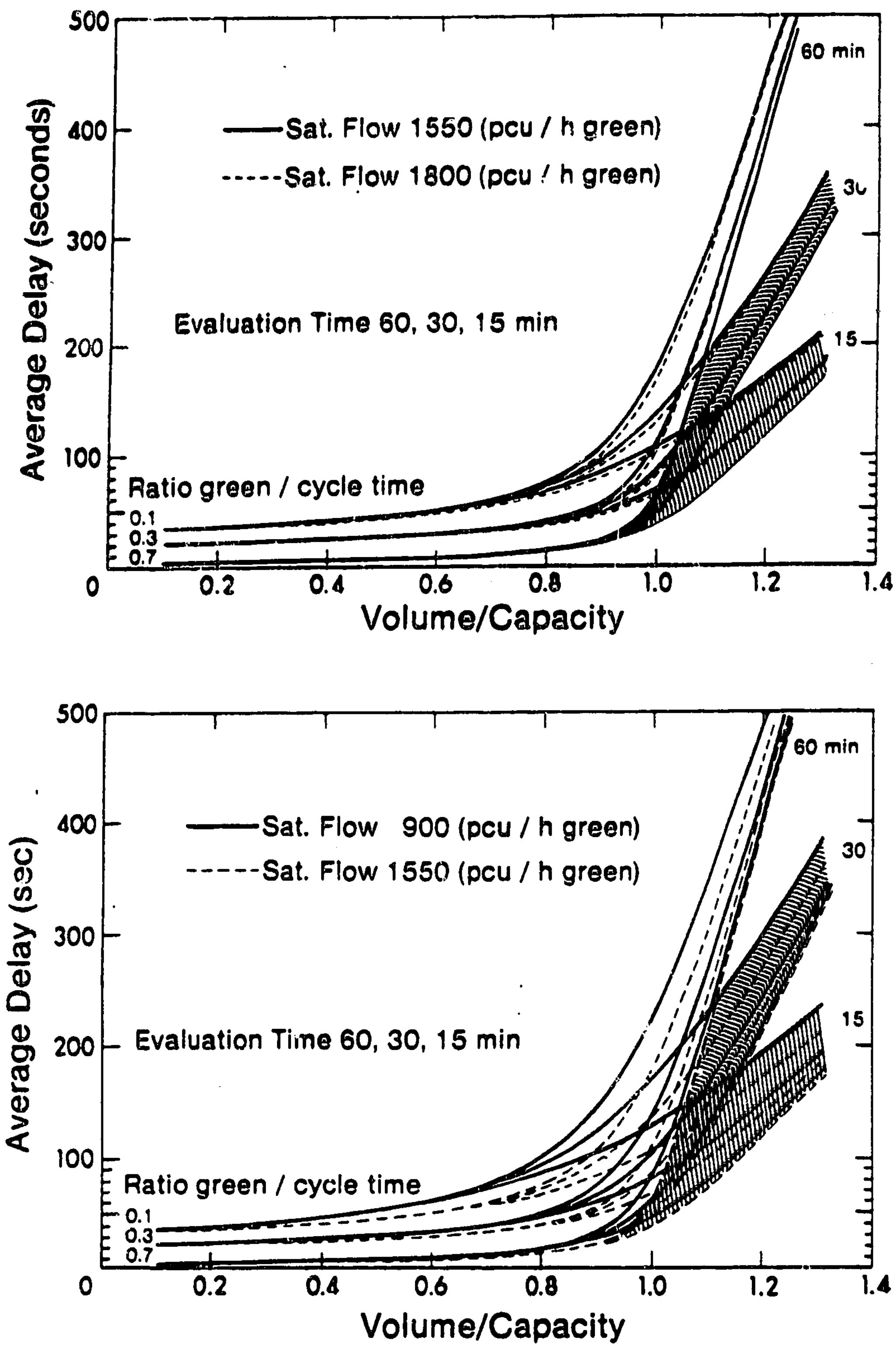

Figure 2.5: Delay vs Degree of Saturation (Ref 10)

Delay remains constant if the volume to capacity ratio is less than 0.9. As a result delay comparisons should consider intersections with similar Volume to Capacity ratios. To avoid unreliable comparisons this research considers only undersaturated conditions in which the saturation levels are less than 0.8.

Delay at an intersection can be further divided into Uniform delay and Overflow (or Incremental) delay. Uniform delay is the time within a cycle encountered by waiting for a green signal. Overflow or incremental delay occurs when vehicles are unable to discharge within one cycle. Overflow delay may occur if flows are less than the saturation level. When the volume / capacity ratio is greater than 0.9, fluctuations in vehicle arrivals may cause overflow delays. Uniform and overflow delays are illustrated in Figure 2.6.

Mathematically, delays can be expressed in terms of the following formula:

$$D = du + di$$

Where du = Uniform Delay

di = Incremental Delay

Delay may be considered as stopped delay or overall delay. Stopped delay is the time that a vehicle is completely stopped at an approach. Overall delay is the time that a vehicle decelerates, stops, and accelerates back to free flow velocity. Figure 2.7 illustrates stopped and overall delay in terms of vehicle trajectories. Since the acceleration and deceleration times are positive, overall delay will always be greater than stopped delay. However, a vehicle with zero stopped delay could have an overall

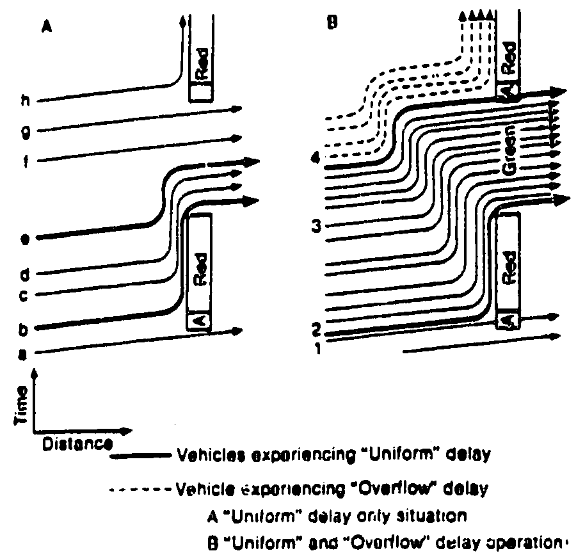

Figure 2.6: Uniform and Overflow Delays (Ref 10)

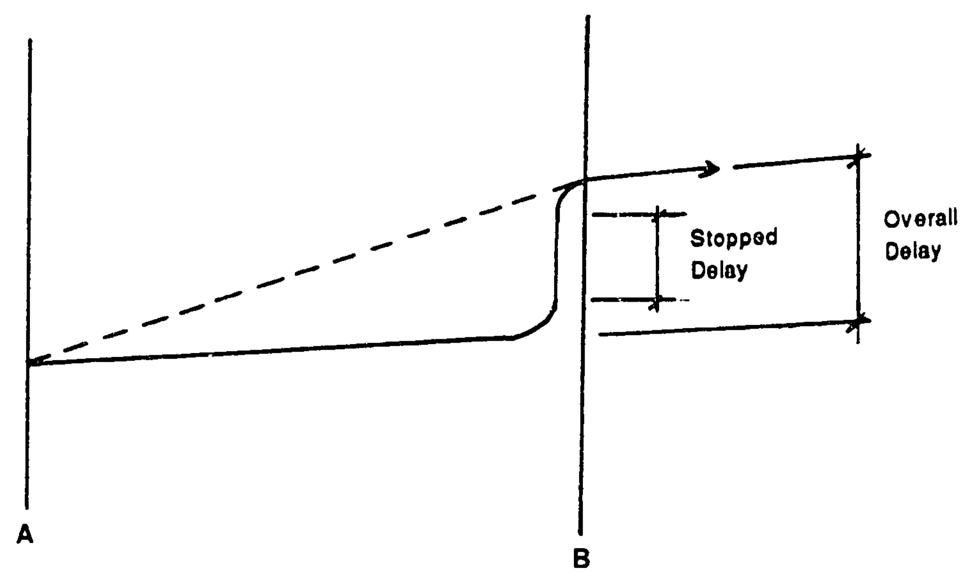

Figure 2.7: Uniform and Overall Delay

delay.

Delay is at best an indeterminate term. To avoid discrepancies this document utilizes the unqualified word delay when the type of delay is not relevant to the discussion. Uniform or incremental delay is not specified as the research is limited to undersaturated conditions and assumes that all delays are uniform. Specific types of delay are qualified in terms of stopped delays and overall delays.

B.1) Delay Calculations

Different methodologies have been developed to calculate delays (Ref 11,12). The American approach is to consider stopped delay while Canadian standards consider overall delay. Delay calculation methods are outlined as follows.

B.1.a) Highway Capacity Manual (Ref 13)

The American method calculates individual land delays in terms of the cycle length, green ratio, volume to capacity ratio, and the capacity of the lane. The stopped delay formula (Ref 13) is expressed as follows:

$$Ds = 0.38c \frac{(1 - g/c)^2}{\{1-(g/c)X\}}$$

where Ds = Stopped Delay
g = Effective green time in seconds.
X = Volume to Capacity ratio.
c = Cycle time in seconds.

The Highway Capacity Manual considers coordination when designing the phase timings of a signalized intersection. The quality of signal coordination at an approach is classified based on five arrival types. The arrival type is determined directly from the calculation of the Platoon Ratio (Ref 13) as follows:

$$Rp = \frac{PVG}{PTG}$$

where Rp = Platoon Ratio
PVG = Percentage of vehicles arriving on green
PTG = Percentage of green time within the cycle

Based on the platoon ratio and the signal type a progression adjustment factor is determined. This factor is then used to modify the previously calculated lane delay. Lane delays are averaged into an approach delay which in turn is averaged into a stopped delay for the intersection. Based on stopped delay the overall performance of the intersection is determined as the Level of Service. Thus coordination is considered to effect delay which in turn determines the overall level of service at the intersection.

B.1.b) Canadian Capacity Guide

The Canadian capacity Guide (Ref 10) calculates delay in a formula similar to the American Highway Capacity Manual. Overall delay is calculated using the same terms of cycle length, green duration, lane volumes and lane capacity. The Canadian Capacity Guide uses the following formula (Ref 10).

$$Dt = 0.50c \frac{(1 - g/c)^2}{\{1-(g/c)X\}}$$

Where Dt = Uniform Total Delay
g = Effective green time in seconds.
X = Volume to Capacity ratio of the lane.
c = Cycle time in seconds.

In calculating uniform delay the Canadian Capacity Guide differs from the Highway Capacity Manual only in the coefficient of the equation, i.e. the Canadian method uses 0.5 as opposed to 0.38 in the American Equation. This discrepancy can be explained in terms of the Canadian method measuring overall delay as compared to the American method measuring stopped delay.

B.2) Field Measurement of Delay

B.2.a) American Highway Capacity Manual

The Highway Capacity Manual (Ref 13) outlines a procedure to determine the stopped delay directly from field observations. The number of vehicles stopped prior to the signal are counted at regular intervals of 10 to 20 seconds in duration. The interval length is not divisible by the cycle time to avoid repetitive counting of stopped vehicles at the same position of the cycle.

To perform the survey the length of a queue in the observed lane is recorded manually at the interval time. Concurrently with this recording is an observation of the total vehicle count that passes through the intersection. In this manner the intersection volume is determined.

The average stopped delay is calculated with the following formula (Ref 13).

$$Ds = \frac{Vs * I}{V}$$

Where Ds = Field measured stopped delay
Vs = Total number of stopped vehicles
I = Interval between stopped vehicles
V = Total volume during study period

B.2.b) License Plate Survey

License plate surveys (Ref 14) can be used to determine the overall travel speed of vehicles on a specific route. A route is selected with an upstream (or entrance) and a downstream (or exit) reference point. Observers are located at each reference point using a synchronized reference time. As vehicles cross each reference point the license plate number and time is recorded. The length of the route between reference points is also measured.

Data analysis consists of matching the license plate numbers for each reference point. Travel time for each vehicle is determined by subtracting the route entrance time from the route exit time. Travel speed is calculated as the route length divided by the individual vehicle travel time. Individual vehicle speeds can then be subject to statistical analysis in order to determine the route travel speed characteristics.

The license plate survey can be modified to include major intersections between the entrance and exit points. The midpoints are referenced in the same manner as the boundry points.

Vehicles leaving the route are noted at each midpoint. Inclusion of the vehicles exiting the route helps to determine travel priorities within the route. Additional mid route survey points also indicate the travel patterns for sub sections of the route.

License plate surveys alone do not give an indication of delay, they simply determine travel time or speed along a specific route. Comparing license plate surveys on a route before and after an external influence is implemented can indicate the delay. The difference in before and after travel times indicates the impact of the external influence (Ref 15).

B.2.c) Floating Car Survey

The floating car survey technique (Ref 14) utilizes a test vehicle driven along the route in study. Safe driving procedures are maintained through reasonable acceleration and deceleration rates and the observation of proper passing distances. The vehicle is typically driven at the posted speed limit unless impeded by traffic conditions.

The survey is performed on a predetermined route with entrance, exit, and mid route control points. The test vehicle is driven past the entrance point to initiate the reference time. The vehicle is then driven the length of the study route with time readings recorded at control points. When the test vehicle is delayed a second clock is initiated to measure the duration of each delay. The location, duration, and cause of each delay is then noted. The survey is then ended with the recording of a reference time at the exit point. The survey produces a chronological event record of the study route consisting of control point information and delay descriptions.

Floating car surveys allow considerable flexibility in evaluating the traffic flow conditions. Similar to the license plate survey, vehicle speeds are determined from control point passage times and route distances. Accumulation of these values on the route results in a travel speed profile along the route. Delay durations and causes are measured directly and can be statistically analyzed. Accumulation of the travel speeds and delay values result in a informative profile of the travel characteristic along the route.

CHAPTER III, RESEARCH METHOD

Present delay calculation methods use the aggregate variables of volume and capacity as their basis. The DELAY program differs from current methods. The DELAY program uses individual vehicle information to form the basis of the delay calculation. As a result, this research proposes a new data acquisition procedure and corresponding delay calculation method. The remainder of this chapter describes the research methodology utilized by the DELAY program.

A) Field Observations

Information was recorded with a University of Alberta modified traffic analyzer (Ref 16,17). The observer simply presses a pre-determined button to record the occurrence of an event. Recorded evnets include the passage of a vehicle over each reference point and the appropriate signal changes. Figure 3.1 illustrates the field data collection process.

Individual vehicles are flagged as they pass over the initial reference point A, located upstream of the signal. Point A is arbitrarily determined in an area of free flowing traffic beyond the effects of a signal queue. The vehicle then proceeds towards the signal and is recorded a second time as it passes over the second

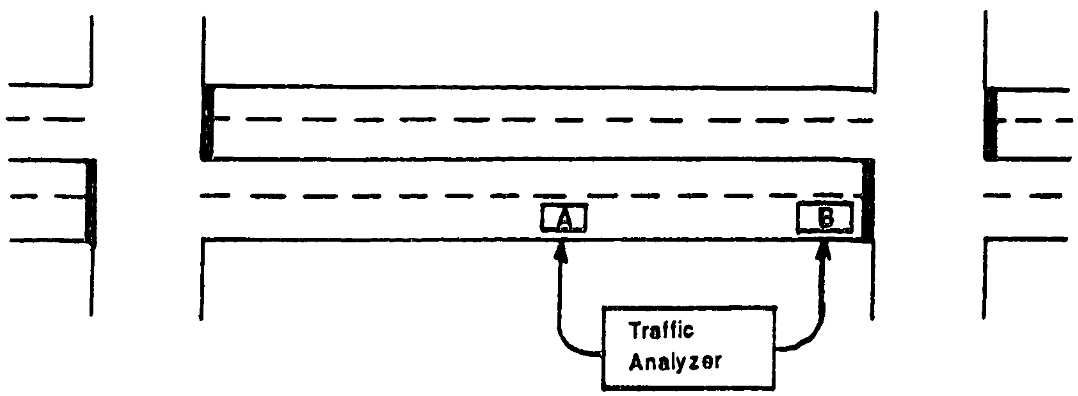

Figure 3.1: Field Data Collection

reference point B, located at the stopline. If the vehicle is stopped by a red signal the event is not recorded until the vehicle passes over the stopline. The process of flagging individual vehicle movements is continued concurrently with a similar indication of the signal changes. This is repeated until the appropriate amount of data is collected. Typical surveys required a minimum of 10 cycles or 20 minutes for the data to be statistically significant.

Field information is stored on the traffic analyzer and transferred to a personal computer by the computer program DATAIN (Ref 18). Data is then converted from hexadecimal to decimal format with the aid of the conversion program PROCESS (Ref 18). The net result of the field observations is a computer file consisting of a chronological list of events at the survey location.

B) Determination of Delay

B.1) Data Preparation

Field information is reorganized within the DELAY program such that individual vehicle movements can be determined. With the aid of internal subroutines the DELAY program produces a time series of vehicle movements at each reference point and a second list of the signal changes. As field data collection is not an exact process, errors often exist in the matching of vehicles at the upstream reference point with vehicles at the stopline. To correct this problem a time - space diagram is displayed on the screen and a copy of the vehicle movements is printed. The user can match the vehicle data using these two outputs. The input file can then be edited until all vehicles have the appropriate arrival and discharge pattern. Figure 3.2 illustrates a typical time - space diagram. Figure 3.3 illustrates the vehicle movement information.

B.2) Delay Calculations

To calculate overall delay the vehicle at each reference point and signal changes are required. Figure 3.4 illustrates.

The DELAY program requires a user input free flow speed for the lane in study. This value can be the posted speed limit, an external calculation of free flow speed, or a suggested value calculated by the DELAY program. Regardless of the source, the DELAY program uses the free flow speed to extrapolate a vehicle trajectory from the upstream reference point. The extrapolated arrival time represents the time that an unimpeded vehicle would arrive at the stopline. Figure 3.5 illustrates. The difference between the extrapolated arrival time and the actual departure time of the vehicle is the overall vehicle delay. Figure 3.6 illustrates the theoretical values of delays and vehicle trajectories used by the DELAY program.

Because the DELAY program uses assumed free flow velocities it is possible to calculate a negative delay. An example of such a problem occurs when a vehicle is travelling faster than the assumed free flow velocity with an arrival and departure on the green

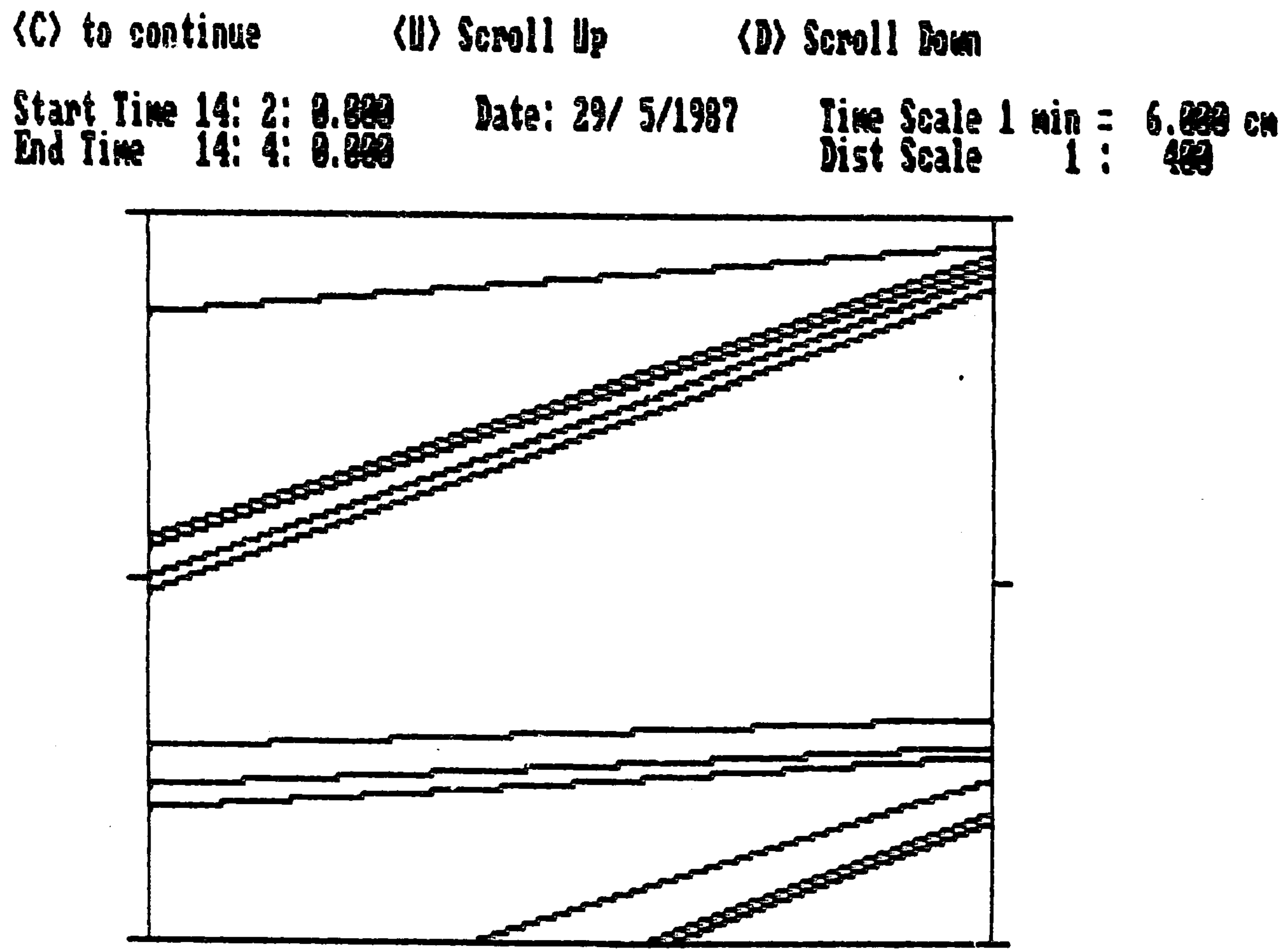

Figure 3.2: Typical Time-Space Diagram From the DELAY Program

VEHICLE MOVEMENT INFORMATION

OK	Loc	Name	Time HH:MM:Sec	ExtTime HH:MM:Sec	GTime HH:MM:Sec	ActTime HH:MM:Sec
T	A	Car	14: 1:25.745			
	B	AnyVehicle	14: 2:20.571			
		StopLine		14: 1:31.161	14: 2:19.184	14: 2:20.571
		Velocity =	4.35 Km/hr			
T	A	Car	14: 1:27.392			
	B	AnyVehicle	14: 2:22.063			
		StopLine		14: 1:32.808	14: 2:19.184	14: 2:22.063
		Velocity =	4.36 Km/hr			
F	A	Car	14: 1:28.825			
	B	Error	14: 2:23.134			
		StopLine		14: 1:34.241	14: 2:19.184	14: 2:23.134
		Velocity =	4.39 Km/hr			
T	A	Car	14: 1:41.949			
	B	AnyVehicle	14: 2:27.877			
		StopLine		14: 1:47.365	14: 2:19.184	14: 2:27.877
		Velocity =	5.19 Km/hr			
T	A	Car	14: 2:22.251			
	B	AnyVehicle	14: 2:31.214			
		StopLine		14: 2:27.667	14: 2:19.184	14: 2:31.214
		Velocity =	26.59 Km/hr			
T	A	Car	14: 2:26.053			
	B	AnyVehicle	14: 2:33.513			
		StopLine		14: 2:31.469	14: 2:19.184	14: 2:33.513
		Velocity =	31.95 Km/hr			
T	A	Car	14: 2:32.404			
	B	AnyVehicle	14: 2:37.967			
		StopLine		14: 2:37.820	14: 2:19.184	14: 2:37.967
		Velocity =	42.84 Km/hr			
T	A	Car	14: 2:58.257			
	B	AnyVehicle	14: 3:48.373			
		StopLine		14: 3: 3.673	14: 3:45.702	14: 3:48.373
		Velocity =	4.76 Km/hr			
T	A	Car	14: 3: 0.132			
	B	AnyVehicle	14: 3:50.581			
		StopLine		14: 3: 5.548	14: 3:45.702	14: 3:50.581
		Velocity =	4.72 Km/hr			
F	A	Car	14: 3: 2.035			
	B	Error	14: 3:51.411			
		StopLine		14: 3: 7.451	14: 3:45.702	14: 3:51.411
			3 Km/hr			

Figure 3.3: Vehicle Information From the DELAY Program

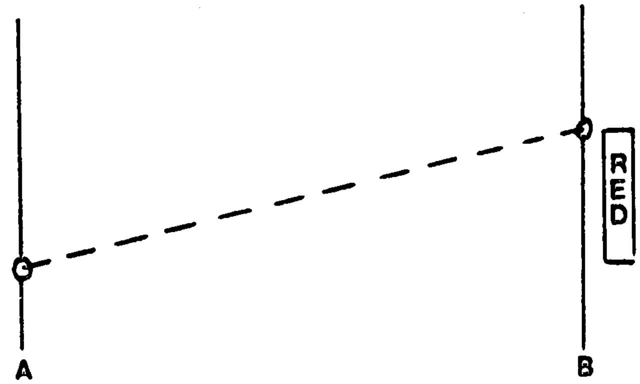

Figure 3.4: Information Required For Calculations

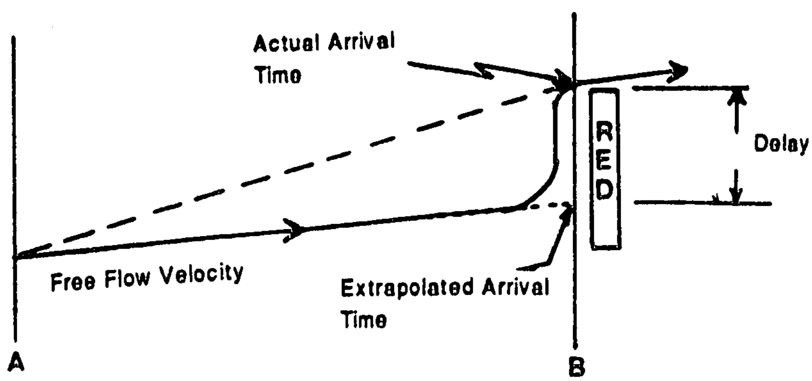

Figure 3.5: Calculation of Delay

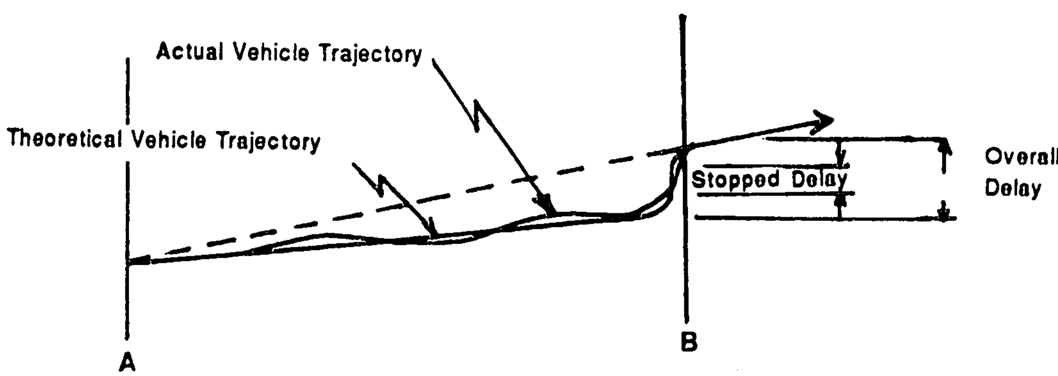

Figure 3.6: Theoretical and Actual Vehicle Trajectories

interval. Figure 3.7 illustrates. In this case the extrapolated arrival time occurs after the actual arrival time. As delay is calculated by subtracting the extrapolated arrival time from the actual arrival time this would result in a negative delay. The DELAY program assumes all delay values are non negative and would assign this vehicle a zero delay.

The DELAY program does not determine the cause of a short delay. This occurs when a vehicle arrives and departs on green but has a velocity slightly slower than the free flow velocity. Although the vehicle was not delayed by the signal it will have a small positive delay value as illustrated in Figure 3.8.a. However, a vehicle could also experience a similar type of delay if it was to join the back of a moving queue. Figure 3.8.b illustrates. As the DELAY program recognizes the value of overall delay only, it cannot differentiate between these two occurrences. This problem is reduced by the fact that the delay distribution groups delays in terms of intervals. Thus the shorter delays are usually grouped in the same interval as zero delays.

C) Delay Distributions

Delay distributions are determined directly from the individual vehicle delays. The DELAY program first groups delays according to a user specified interval. The number of individual vehicle delays within each interval is then counted. This information is presented in the form of a delay histogram. The

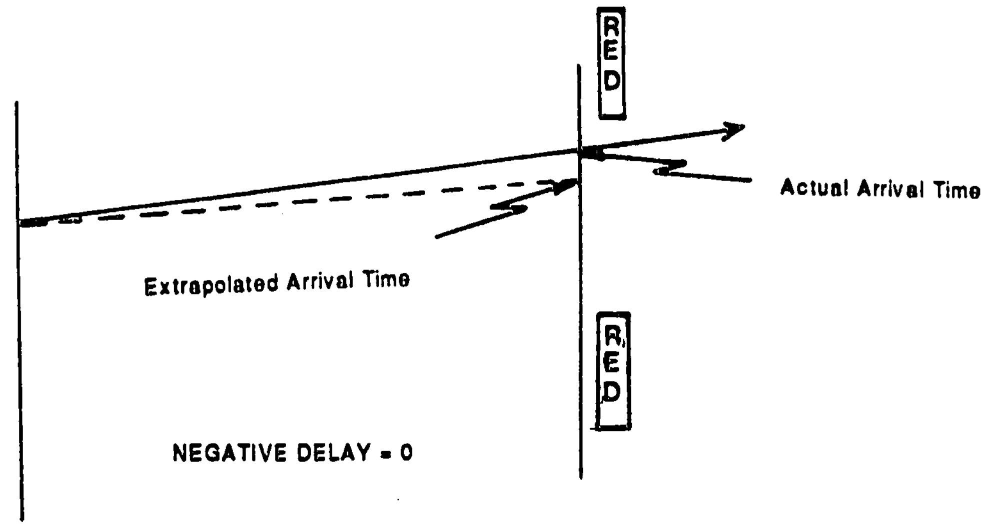

Figure 3.7: Example of Negative Delay

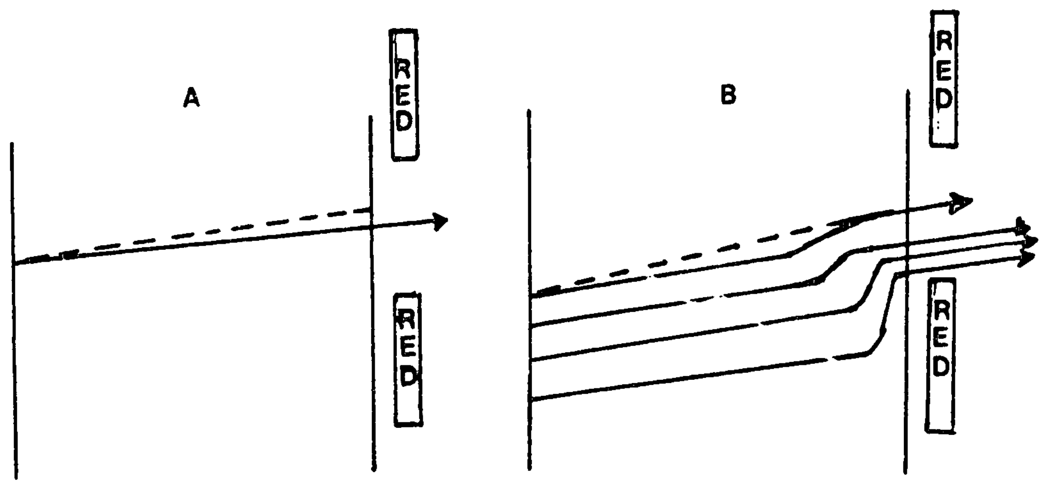

Figure 3.8: A) Short delay for a free flowing vehicle.
B) Short delay caused by queue.

histogram normalized to produce a delay distribution. Delay histograms and distributions from the DELAY program are illustrated in Figure 3.9 and Figure 3.10 respectively.

The delay mean and standard deviation are calculated from the individual vehicle delays. The mode value of delay is calculated from the delay histogram as the interval with the greatest number of occurrences.

D) Cyclic Flow Profiles

To calculate a cyclic flow profile the cycle time is first divided into user specified intervals. Intervals may vary from one to ten seconds with a typical value of 5 seconds. All cyclic flow profiles assume that the cycle starts at the beginning of green.

To calculate an inflow cyclic flow profile the vehicle time at the upstream reference point is related to the start of the green. The arrival time is noted and the appropriate interval is incremented. This process is repeated for each vehicle in the survey. The inflow volume for each interval is then determined by converting vehicle counts to an hourly volume. Figure 3.11 illustrates a typical inflow cyclic flow profile.

To calculate an outflow cyclic flow profile the vehicle departure time from the stopline is referenced from the start of the green phase. As with an inflow profile the appropriate interval is then incremented. Vehicle counts within each interval are then converted to an hourly volume. Figure 3.12 illustrates a typical

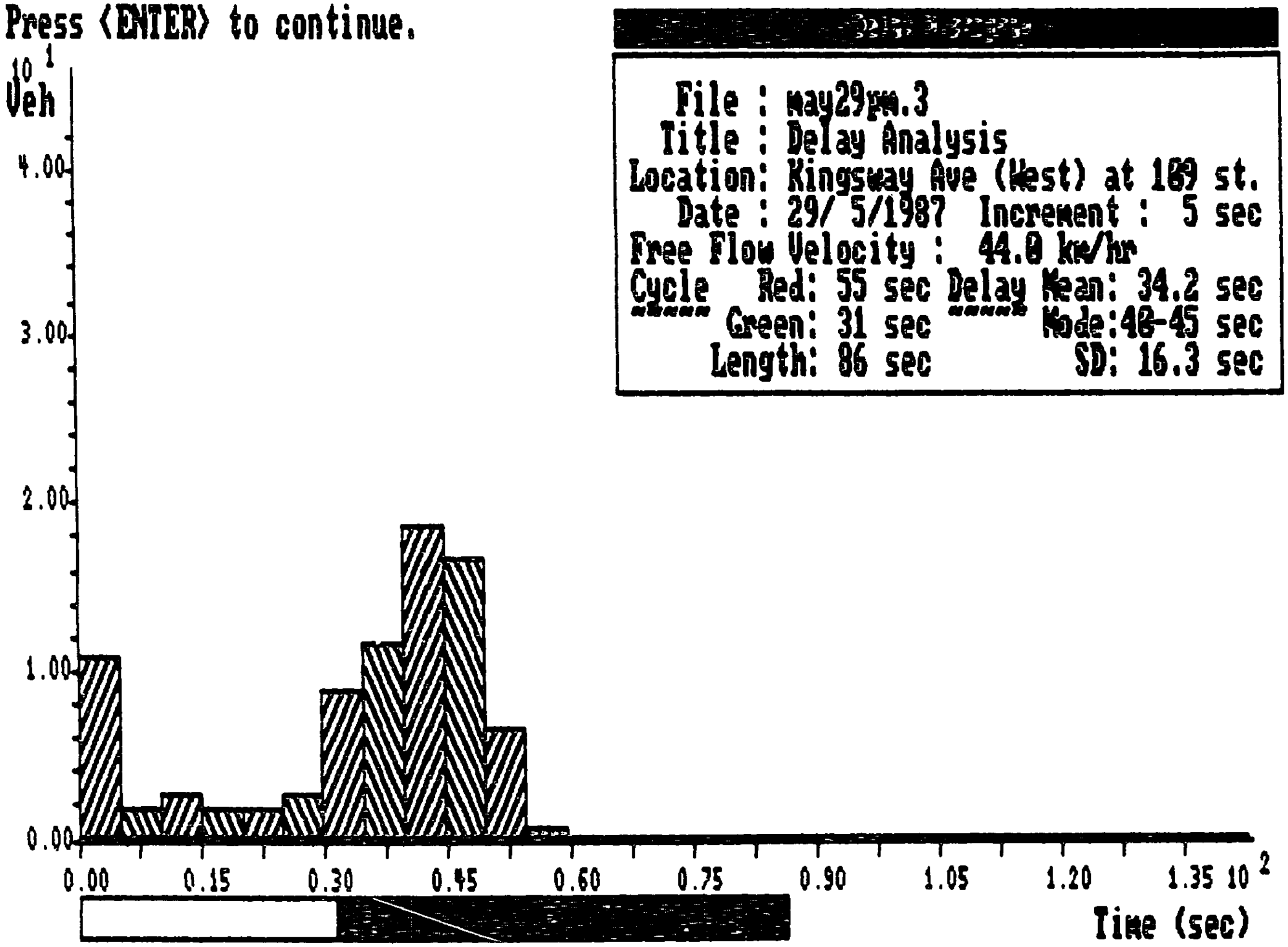

Figure 3.9: Example of a Delay Histogram

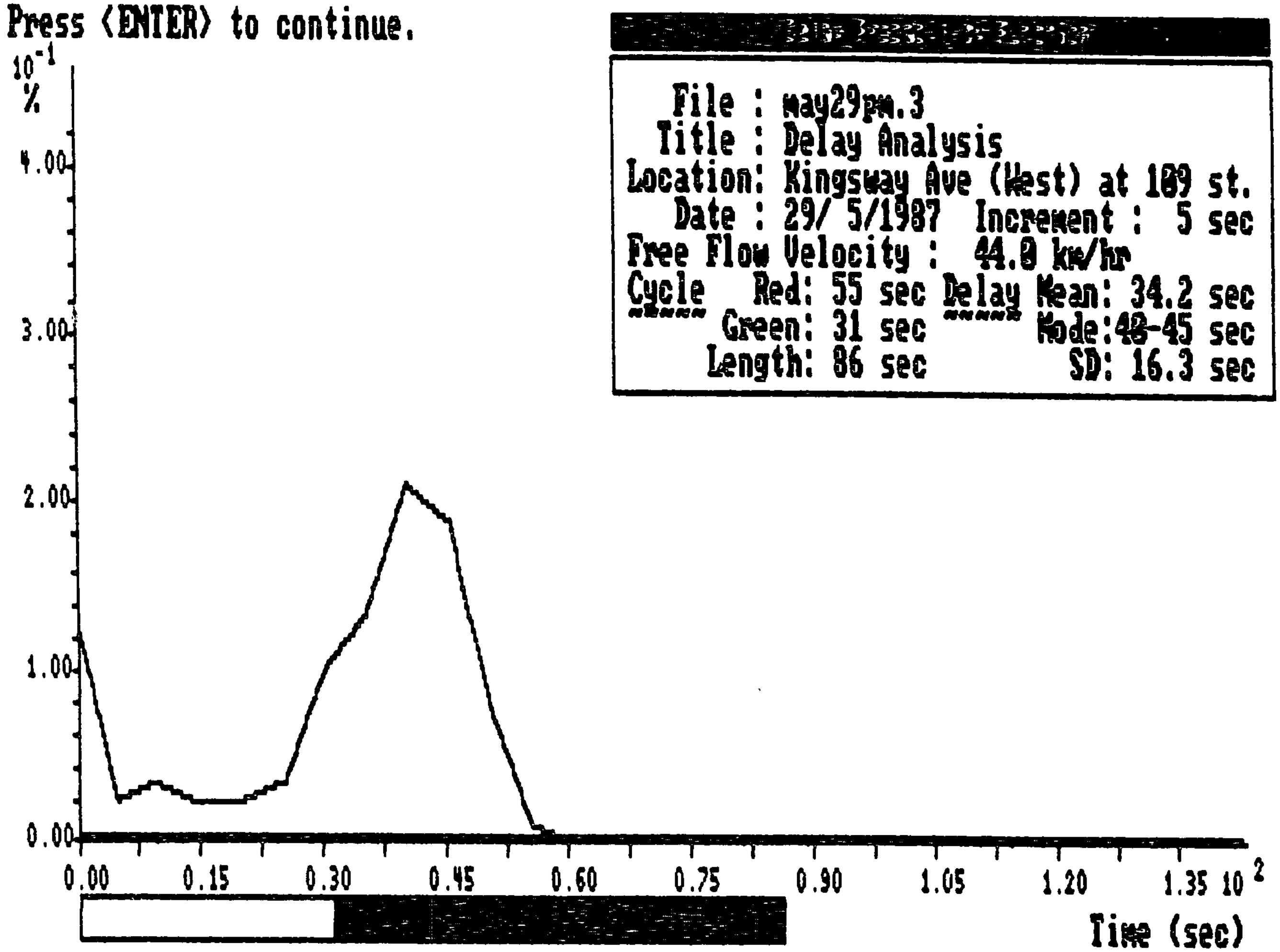

Figure 3.10: Example of Delay Probability Function

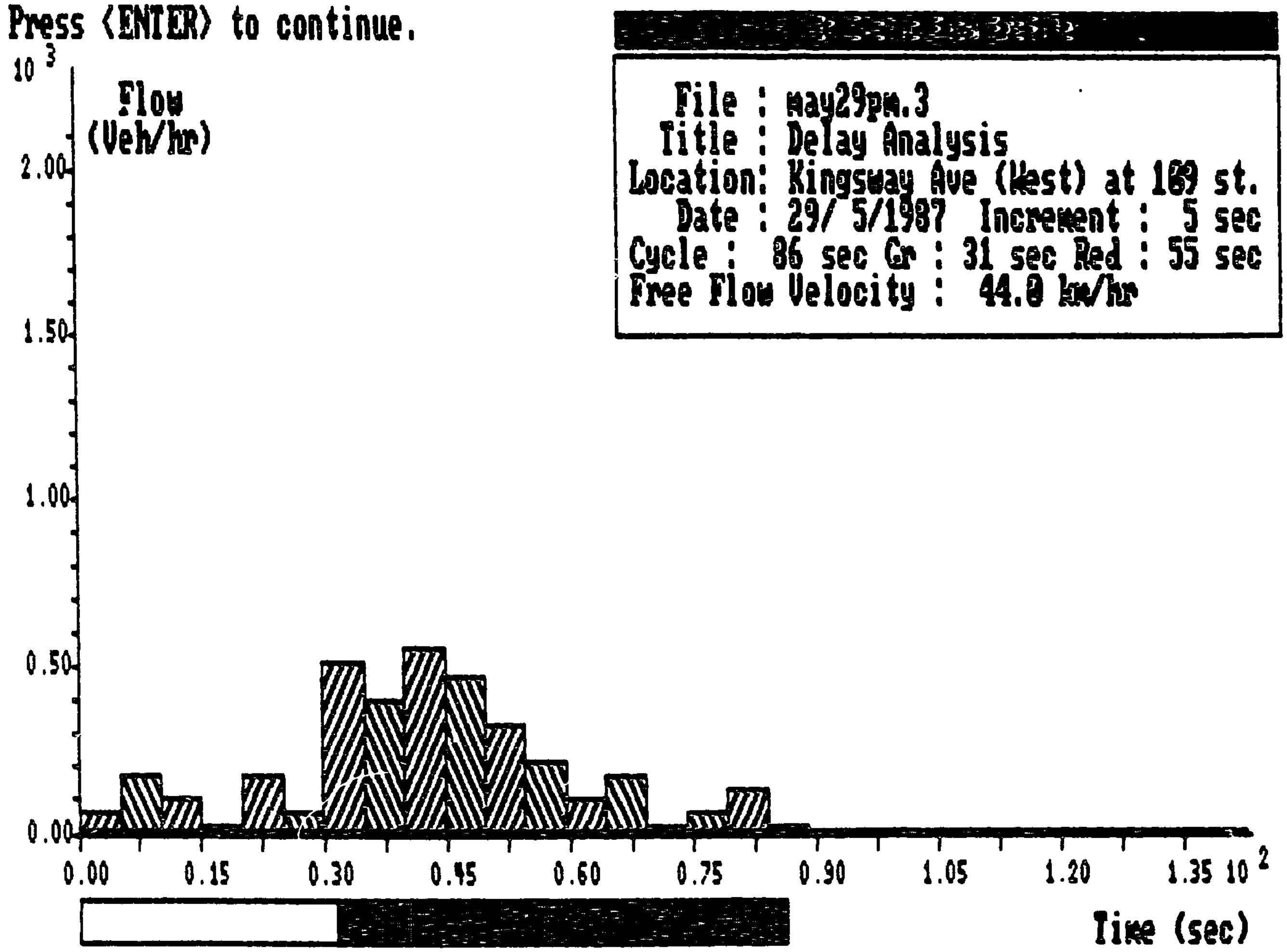

Figure 3.11: Example of a Typical Inflow Cyclic Flow Profile

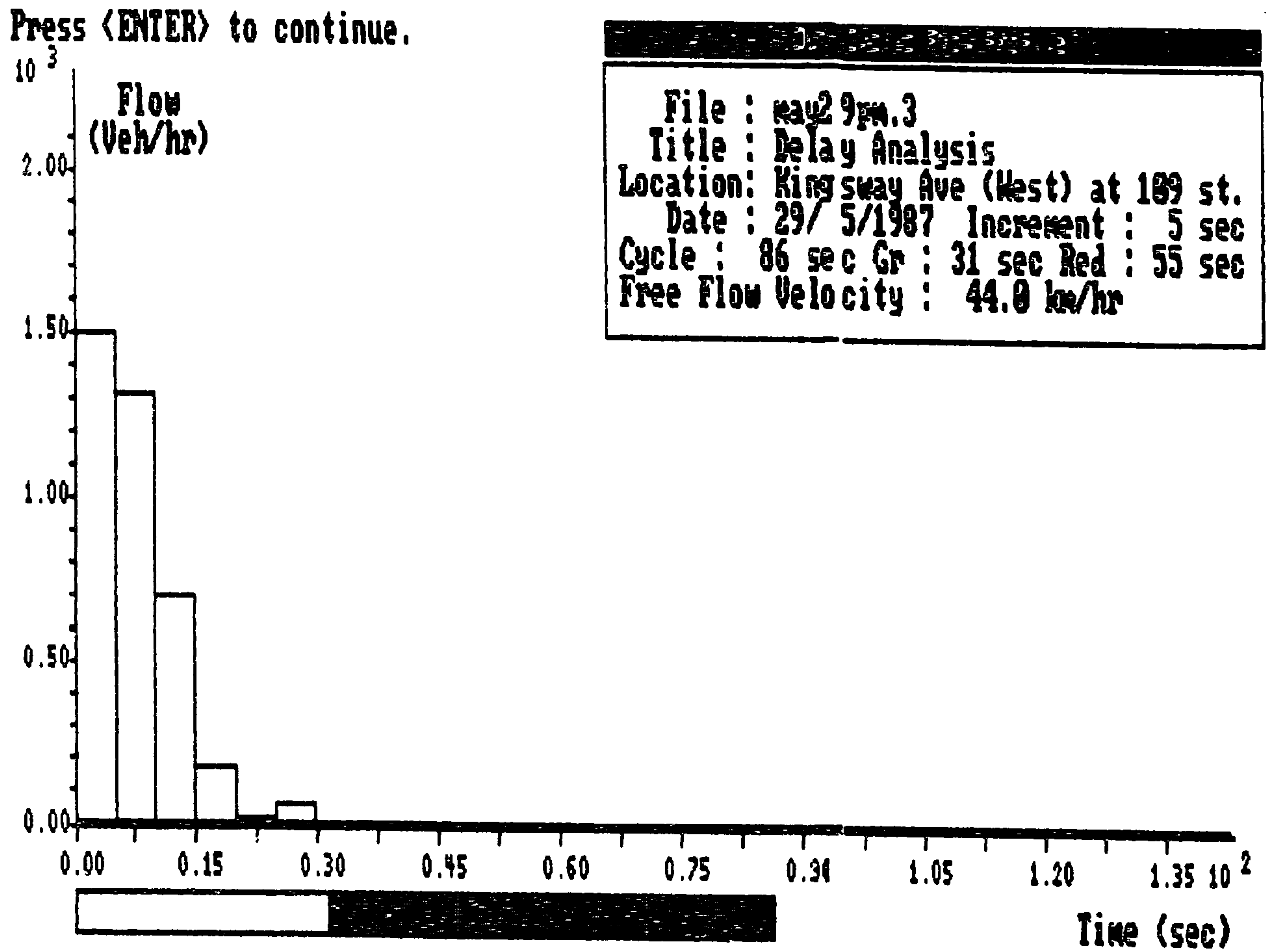

Figure 3.12: Example of a Typical Outflow Cyclic Flow Profile

inflow cyclic flow profile.

The DELAY program also combines the inflow and outflow cyclic flow profiles into a single cyclic flow profile. Figure 3.13 illustrates a typical in / out cyclic flow profile.

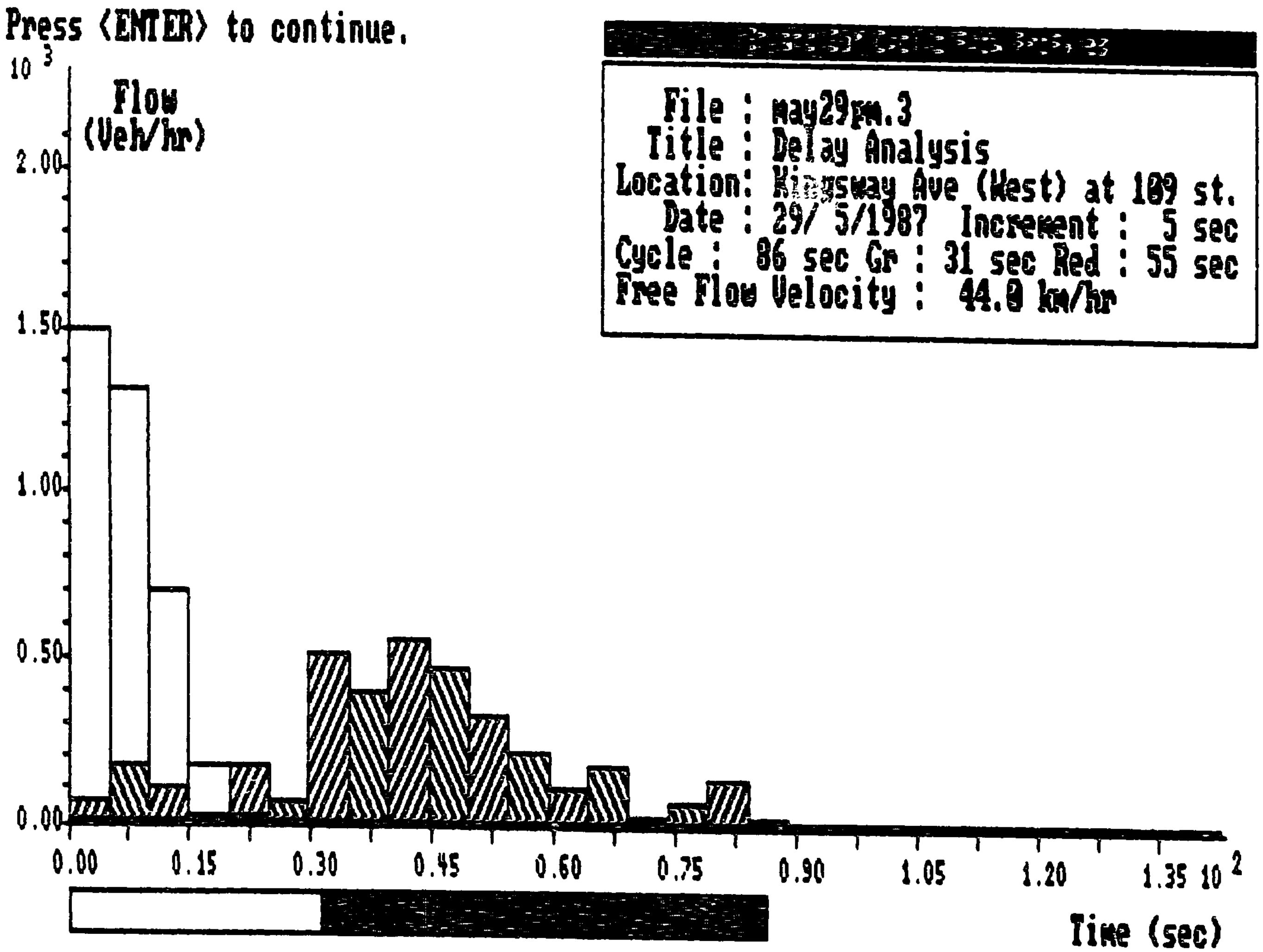

Figure 3.13: Example of a Typical In/Out Cyclic Flow Profile

CHAPTER IV, ANALYSIS TOOLS

The computer program development portion of the research was divided into two tasks. The first consisted of the development of a computer program to graphically represent a time space diagram (TSD) for two free flowing reference points. This was used as a building block for the intersection delay analysis, and a stand alone analysis tool for free flowing conditions. The second task was to translate the free flowing time - space diagram to a signalized intersection approach. Based on the modified time space diagram, delay statistics and cyclic flow profiles were calculated. The final result is an intersection analysis tool in the form of a computer program. The paragraphs of this chapter outline the features and usage of each of these two computer programs.

A) Time - Space Diagram Computer Program (TSD)

A.1) Data Collection

Data is collected from two reference points in a manner similar to the DELAY program. Individual vehicles are flags as they pass over each reference point. The information is recorded on a traffic analyzer and transferred to a personal computer.

A.2) Program Operation

To initiate the TSD program the compiled code is loaded into the computer and the command "TSD" is typed at the system prompt. The program is interactive and requires user responses to initiate actions. The operation of the TSD program is illustrated by the flow chart of Figure 4.1.

A.3) Program Calculations

A.3.a) Time-Space Diagram

The ordinate of the diagram represents time while the abscissas represents distance. The vehicle movement is plotted using the vehicle time stamps and the distance between reference points. A line connecting the time coordinates of the reference points represents the vehicle trajectory. Repeating this process for each vehicle produces a time - space diagram for the survey location. Information from the diagram is then used to calculate the following traffic flow variables:

A.3.a.i) Headways

Headway is the time separation between two subsequent vehicles at one reference point (Ref 19). A statistical analysis of individual headways can be performed to calculate the mean, variance, and standard deviation at each reference point.

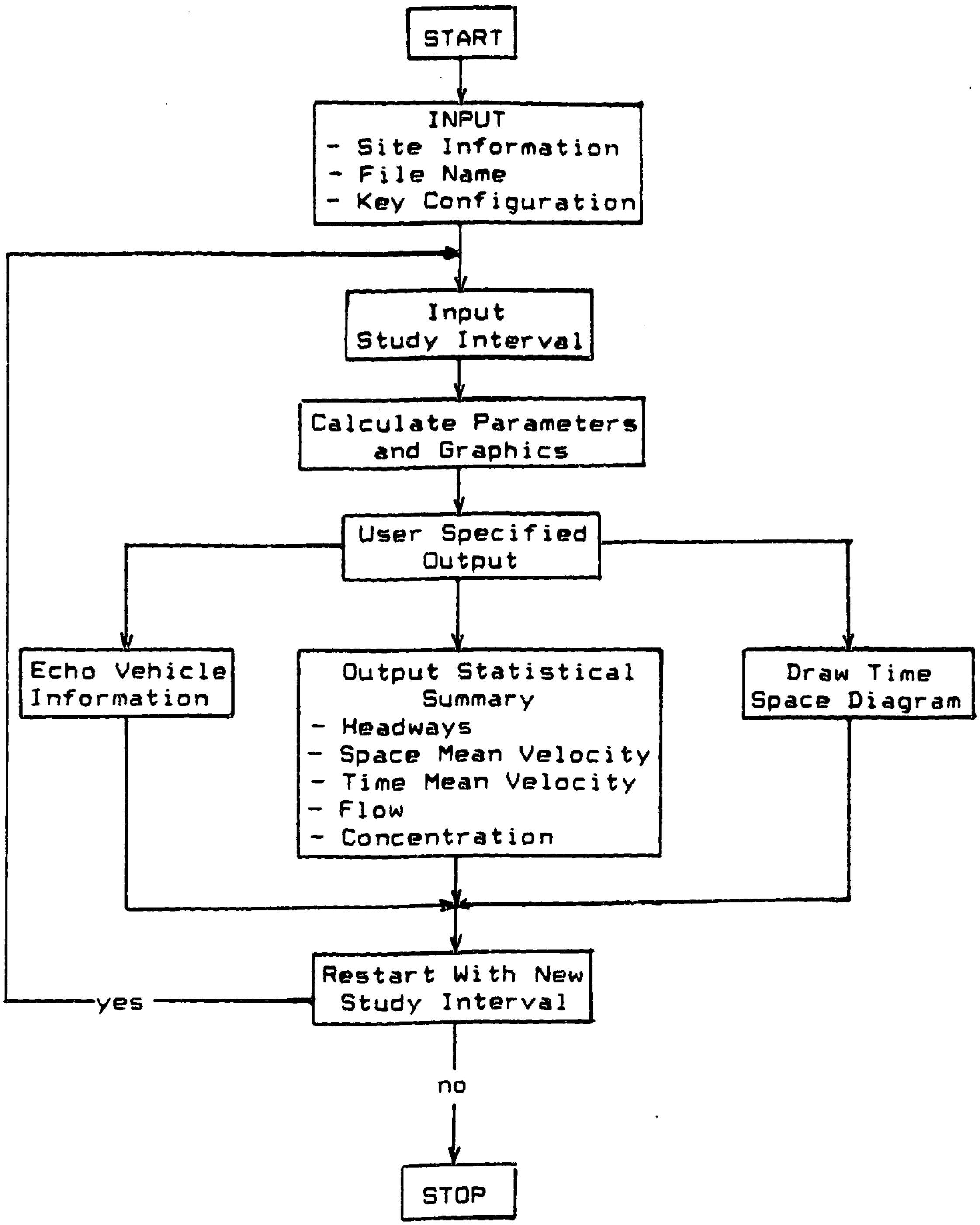

Figure 4.1: Flow Chart for the TSD Program

A.3.a.ii) Time - Mean Velocity

The distance between reference points divided by the time that an individual vehicle spends between the reference points yields the vehicle's velocity. The mean of these velocities over a specified time is the Time-mean velocity (Ref 19). The time - mean velocity is part of the TSD program statistical summary.

A.3.a.iii) Space - Mean Velocity

The total distance travelled by all vehicles in a time interval can be calculated by multiplying the total number of vehicles by the distance between reference points. The time each vehicle spends between reference points can be calculated from individual vehicle time stamps. The summation of each vehicle's time will result in total time required by all vehicles to travel between reference points. Dividing the total distance travelled by the total time required by the vehicles gives the space-mean velocity (Ref 19). The Space - mean velocity is part of the statistical summary output by the TSD program.

A.3.a.iv) Flow

Flow is the number of vehicles that pass a given reference point over a period of time. This is calculated by counting the number of valid time stamps at a reference point for a user specified time period. The flow is part of the TSD program statistical summary.

A.3.a.v) Concentration

Concentration is the number of vehicles between two reference points at any given instant. The concentration is determined by dividing the flow by either the space-mean or time-mean velocity. The concentration is part of the TSD statistical summary.

A.4) Programmers Guide

The TSD program was written and compiled in the Pascal computer language. The use of graphics within the program requires that the system have graphics capability. Programming considerations and software algorithms are not within the direct scope of this document, however the users Guide (Ref 2) contains a detailed program description.

B) DELAY program

B.1) Data Collection

In a manner outlined previously both vehicle and signal data was collected on a traffic analyzer. This information is then transferred to a personal computer where it is subject to analysis by the DELAY program.

B.2) Program Operation

To initiate the DELAY program the compiled code is loaded into the computer and the command "DELAY" is typed at the system prompt. The program is interactive and requires user responses to initiate actions. Input to the program consists of the data file name, site geometry, and the free flow velocity. Cycle patterns may be user specified or input from the data file. Output varies depending on the user requirements. The flow chart of Figure 4.2 illustrates the possible actions of the DELAY program.

B.3) Program Calculations

B.3.a) Time - Space Diagram

Individual vehicle trajectories are produced by connecting the time coordinates of the two reference points. The present form of the diagram does not display the signal timings at the stopline. However, the green intervals are known for each vehicle. Both the true vehicle trajectory and the signal timings are features that would greatly supplement the clearness of the time - space diagram. An algorithm as to their implementation is presented in the Future Enhancements section of the Users Guide (Ref 6). Information from the diagram is then used to calculate the following traffic flow variables:

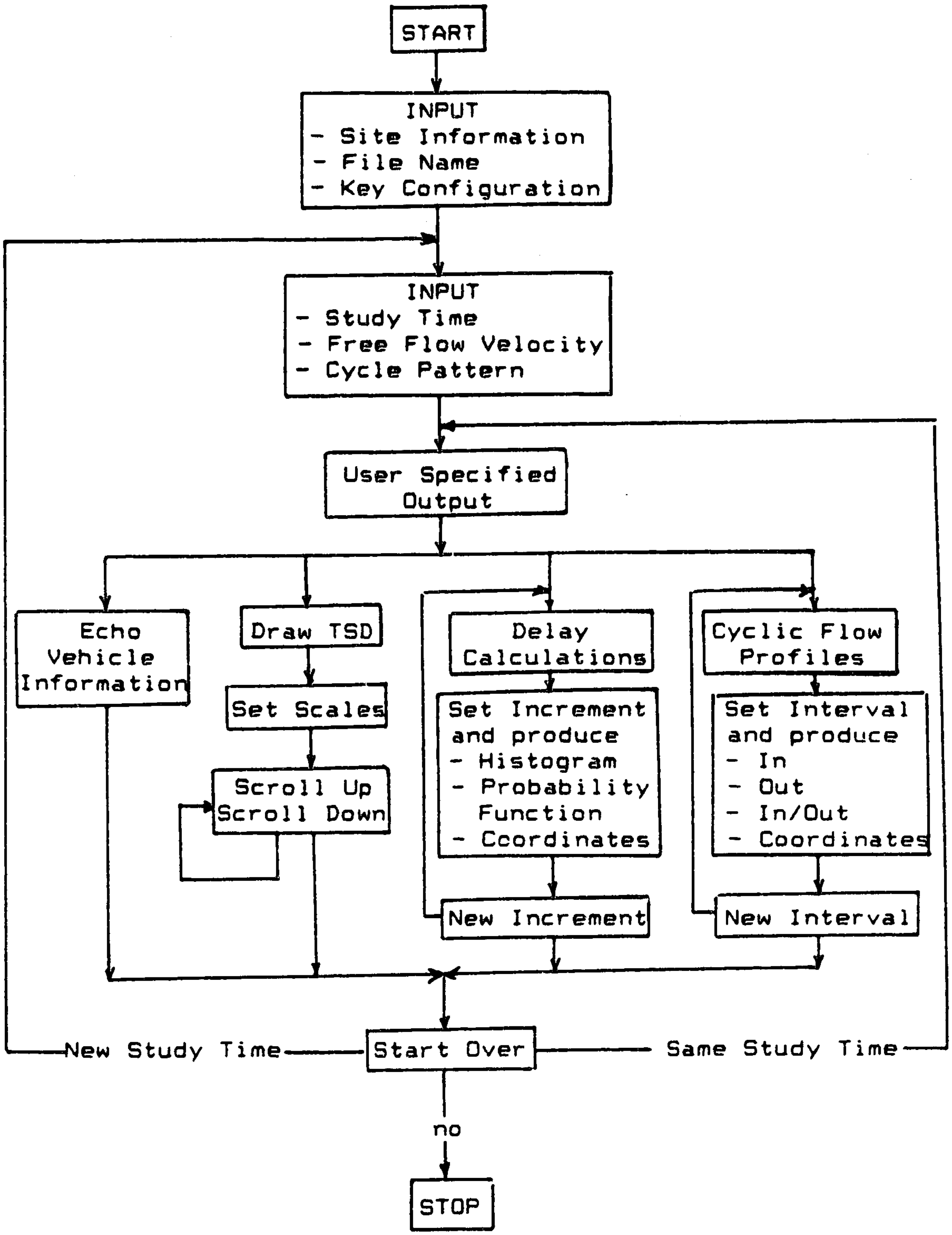

Figure 4.2: Flow Chart for the DELAY Program

B.3.b) Delay Calculations

The vehicle delay is the difference between the extrapolated arrival time at the stopline and the actual departure time at the stopline. The user must now specify one of three types of delay calculations; a histogram of vehicle delays, a probability function of delayed vehicles, or the coordinates used to plot either the histogram or the probability function. Delay options are outlined as follows:

B.3.b.i) Delay Histogram

The delay histogram is a graphical representation of the histogram coordinates. The default output location of the histogram is the screen, however the <PrtSc> key may be used to obtain a hard copy. Both the ordinate and abscissas are preset and cannot be changed by the user. Should the data produce a histogram incompatible with the preset axis the histogram will extend beyond the preset boundaries.

B.3.b.ii) Delay Probability Function

The delay probability function is a graphical representation of the probability function coordinates. The default output location is the screen, however the <PrtSc> key may be used to obtain a hard copy. Both the ordinate and abscissas are preset and cannot be changed by the user. Should the data produce a probability function incompatible with the preset axis the probability function will clip data outside the boundaries.

B.3.b.iii) Delay Statistics

When the delay option is chosen the user will also obtain the mean, mode, and standard deviation of the individual vehicle delays. These parameters are displayed in the title box section of the histogram or the probability function.

B.3.c) Cyclic Flow Profiles

The user may choose as one of the output options the calculation of cyclic flow profiles. These profiles are calculated as either an inflow or an outflow profile at the intersection. The user must specify one of four types of cyclic flow profiles calculations; an Inflow, and Outflow, both In and OutFlow profiles, or the coordinates of both profiles. These options are outlined as follows.

B.3.c.i) Inflow Cyclic Flow Profile

The arrival time of a vehicle within a cycle is determined at the stopline. If a vehicle is delayed by the signal the arrival time is taken as the extrapolated time at the stopline. Vehicles that are unimpeded by the signal use the actual time at the stopline to calculate an inflow. Once a vehicle's stopline arrival time is determined it is counted in the appropriate time slice of the cycle time. The number of cycles analyzed and the vehicle count for each increment are then used to calculate a flow rate per hour. The concatenation of these rates over the cycle yields the Inflow Cyclic Flow Profile.

B.3.c.ii) OutFlow Cyclic Flow Profile

The departure time from the signal is determined by subtracting the cycle start or vehicle green time from the actual vehicle departure time at the intersection. This departure time is then counted in the appropriate time slice of the cycle. From this vehicle count and the number of cycles, a flow rate per hour is calculated. The concatenation of these rates yields the Outflow Cyclic Flow Profile.

B.3.c.iii) Both Inflow and Outflow Cyclic Flow Profiles

When the user specifies this option the DELAY program will calculate both in and out profiles, and superimpose the profiles upon each other. The result is output to the screen.

B.3.c.iv) Coordinates of the Cyclic Flow Profiles

This option allows the user to view the actual flow rates for each time interval. The results may be output at the screen, a printer, or written to a file.

B.4) Programmers Guide

The DELAY program reads the input file and sorts the data into three linked lists corresponding to each reference point and the signal changes. Based on the three lists information on each vehicle is stored in a record. The records are then combined to form a linked chronological list of vehicle information. The vehicle list is utilized to calculate the user specified parameters or graphics.

The DELAY program was written and compiled in the Pascal computer language. The use of graphics within the program requires that the system have graphics capability. Programming considerations and software algorithms are not within the direct scope of this document, however the users Guide (Ref 6) contains a detailed program description.

CHAPTER V, PROGRAM VERIFICATION

A) DATA COLLECTION

Naturally the development of a delay evaluation system included the testing and calibration of the computer programs. This was accomplished by testing the DELAY program under a variety of traffic flow conditions. The remainder of the chapter outlines the data collection, data interpretation, and calibration of the DELAY program. The DELAY program methodology is compared to other methods and its application as a coordination tool is commented upon.

A.1) SITE CONSIDERATIONS

Survey locations consist of a signalized intersection approach lane with two reference points. The upstream reference point represents a unimpeded travel speed and thus is located prior to the effects of signal queues. The downstream reference point is located at the stopline. Field observations consist of individual vehicle time stamps at each reference point and a time indicator of each signal change. Figure 3.1 illustrates a typical survey location.

Comparison of delay data required the traffic volumes to be below saturation levels. In this manner the delay calculation would measure uniform delays only. Although the data collection for this research was limited to undersaturated conditions, this is not a limitation of the DELAY program. Traffic studies in the City of Saint Albert (Ref 20,21) utilized the DELAY program for saturated conditions.

Survey lanes where traffic was not interfered with by turning movements or heavy vehicle traffic were selected for this research. As well, bus and truck traffic was avoided because of possible driver perception of a slow moving lane.

Whenever possible surveyors were located so that their presence could not be detected by the traffic. Inconspicious observation avoids the possibility of diverted driver attention through either curiosity or the perception of a police speed trap.

A.2) TRAFFIC ANALYZER

Field information was gathered with the aid of a University of Alberta modified Traffic Analyzer. Each vehicle movement and signal change may be recorded through either automatic or manual input. The automatic hardware includes inductive loops or pneumatic tubes, and the signal controller may be accessed directly. However, automatic operation did not prove practical due to long set up times for short surveys and the omission of error indicators available through manual input. Manual data entry by two observers proved to be the quickest and most accurate method of data collection. The observers simply press the appropriate key as the vehicle passes over each reference point or when the signal changes.

The field data collection produces a computer file containing a chronological list of events The raw data is then processed by the DELAY program.

A.3) SURVEY LOCATIONS

To ensure a variety of delay patterns, intersections with a wide range of traffic characteristics were required. In consultation with the City of Edmonton's Traffic Planning Department ninteen locations where identified. Each intersection was then subject to detailed analysis by the DELAY program. Figure 5.1 illustrates the survey locations.

In order to evaluate intersections with short delays three potentially well coordinated routes were selected. These routes consisted of 111the Avenue and the Central Business District one-ways or 102nd and 103rd Avenues (Locations G,H,I,J,K,P,Q,R,S). Neutral coordination characteristics where evaluated at the isolated intersection of 107th Avenue and 170th Street (Location L). Long delays where analyzed at four locations in the area of Kingsway Avenue between 109th and 111th Streets (Locations C,D,E,F). The remaining locations where chosen to ensure a variety of traffic conditions.

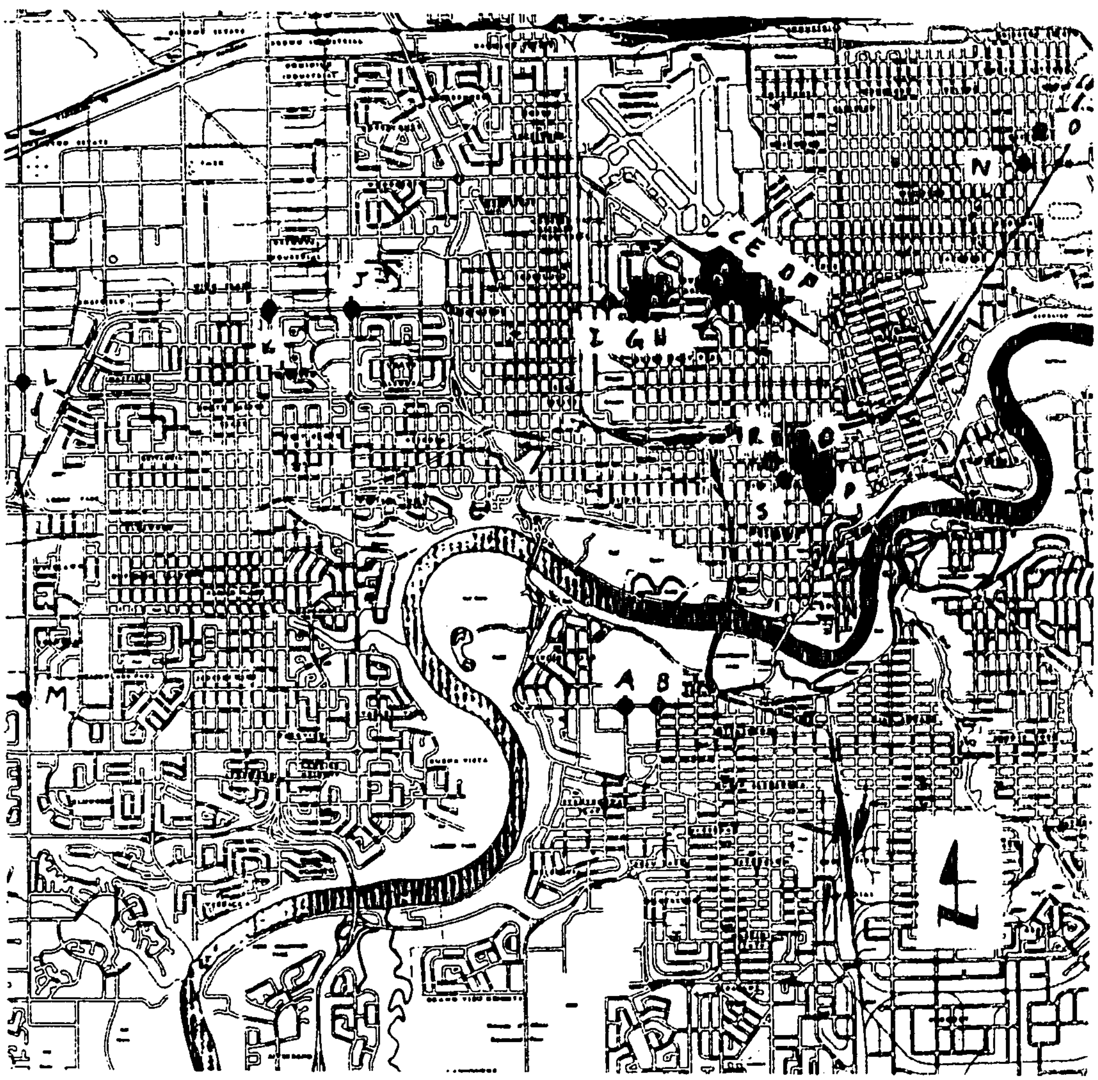

Figure 5.1: Survey Locations

B) ANALYSIS

B.1) OVERALL INTERSECTION PERFORMANCE

The correlation between delay and coordination implies that a typical delay probability function can be used as a general indicator of the quality of signal performance. This hypothesis was evaluated with the nineteen test locations subject to analysis by the DELAY program. Figure 5.2 illustrates a series of nine delay probability functions produced by the DELAY program. The probability functions progress from the shortest to the longest mean delay and follow patterns similar to that expected for varying coordination potential. As expected the low values for mean delay are shifted to the left with a large probability for zero delay. As the coordination ability deteriorates the mean delay value increases, the zero delay probability decreases, and the probability function shifts towards longer delays. In the worst cases the zero delay probability is minimal, with typical delays increasing in both duration and frequency.

It appears that the relative shape of the delay probability function provides a starting point for further study of the approach lane traffic flow characteristics. To further expand on the information produced by the DELAY program individual intersections are characterized by delay length and discussed in greater detail.

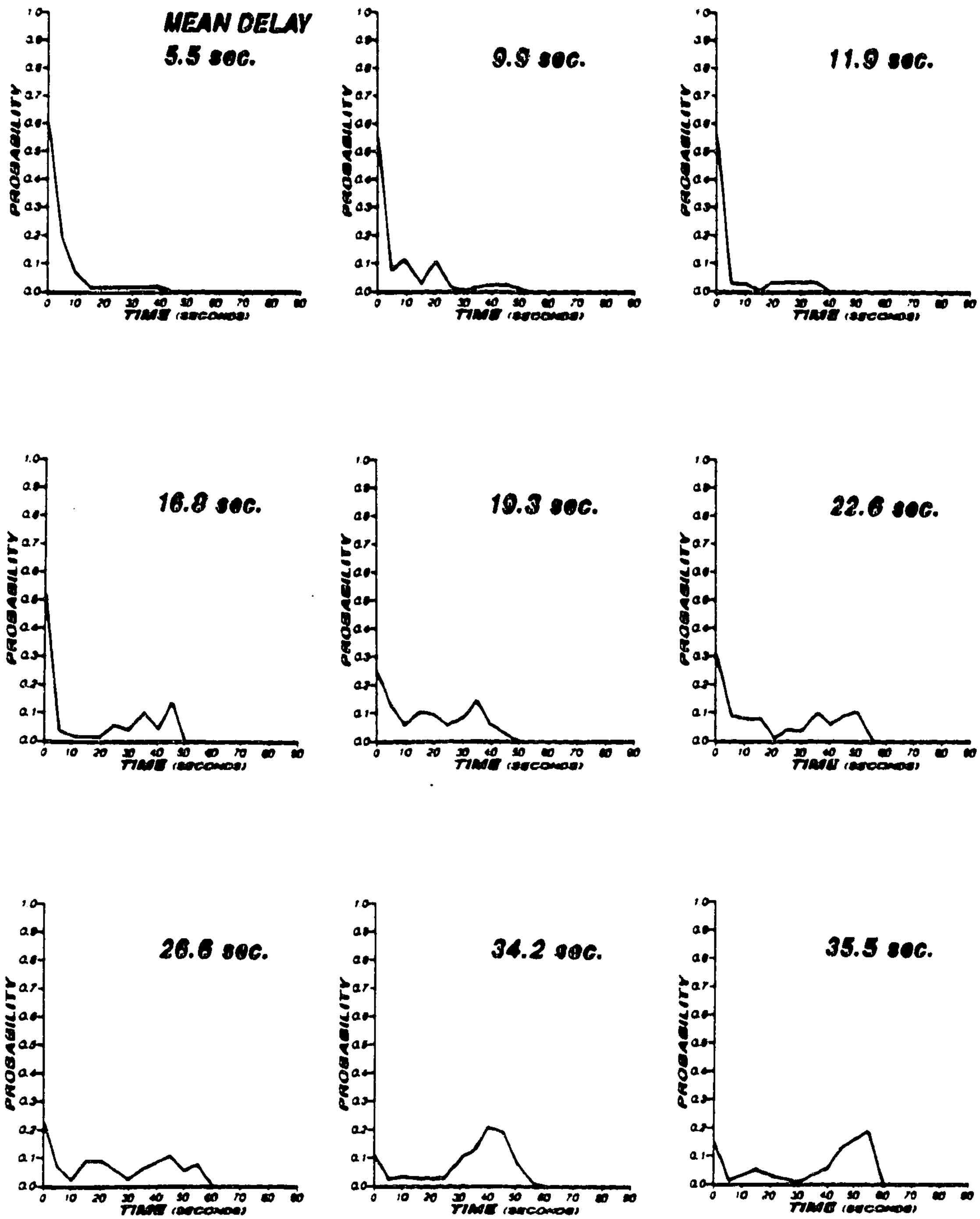

Figure 5.2: Overall Intersection Performance

B.2) SHORT DELAYS

To illustrate typical short delays conditions for the one-ways in the downtown core, the delay probability function and cyclic flow profile for Location R (103 Avenue Westbound at 106 Street) is presented in Figure 5.3.

The data illustrates an approach with nearly perfect coordination. Free flow is supported by a mean delay of 3.2 seconds, 85 per cent of the vehicles delayed less than five seconds, and an equivalent inflow and outflow cyclic flow profile. The mean delay of 3.2 seconds was the lowest value of the nineteen intersections surveyed. The cyclic flow profile indicates good coordination. The well defined platoon is centered within the green phase. Zero arrivals during the first five seconds of green clears the queues formed by onturning vehicles.

The evidence presented by the DELAY program indicates that coordination abilities of this intersection could not be improved. At present the optimal coordination environment exists. The entire platoon arrives in the green phase, there is a long green to cycle ratio, a short queue dispersal interval exists at the beginning of green, and vehicles arriving on red are only delayed slightly.

A second route reputed to have good coordination potential is Location H (111 Avenue Eastbound at 116 street). Figure 5.4 illustrates the delay probability function and cyclic flow profiles.

This intersection is of interest because the delay probability function reflects the traffic characteristics. The delay probability

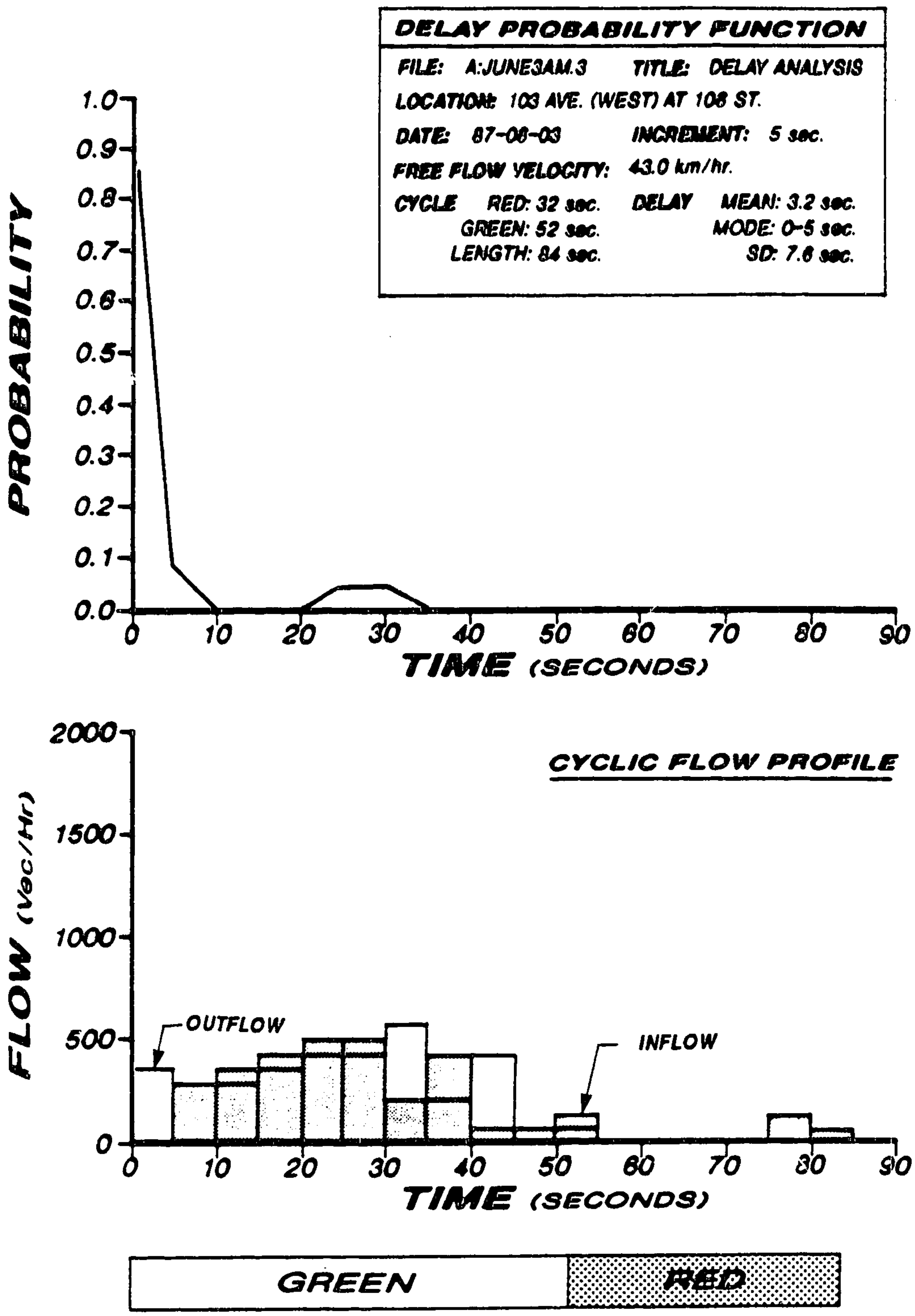

Figure 5.3: Example of Good Coordination at location R

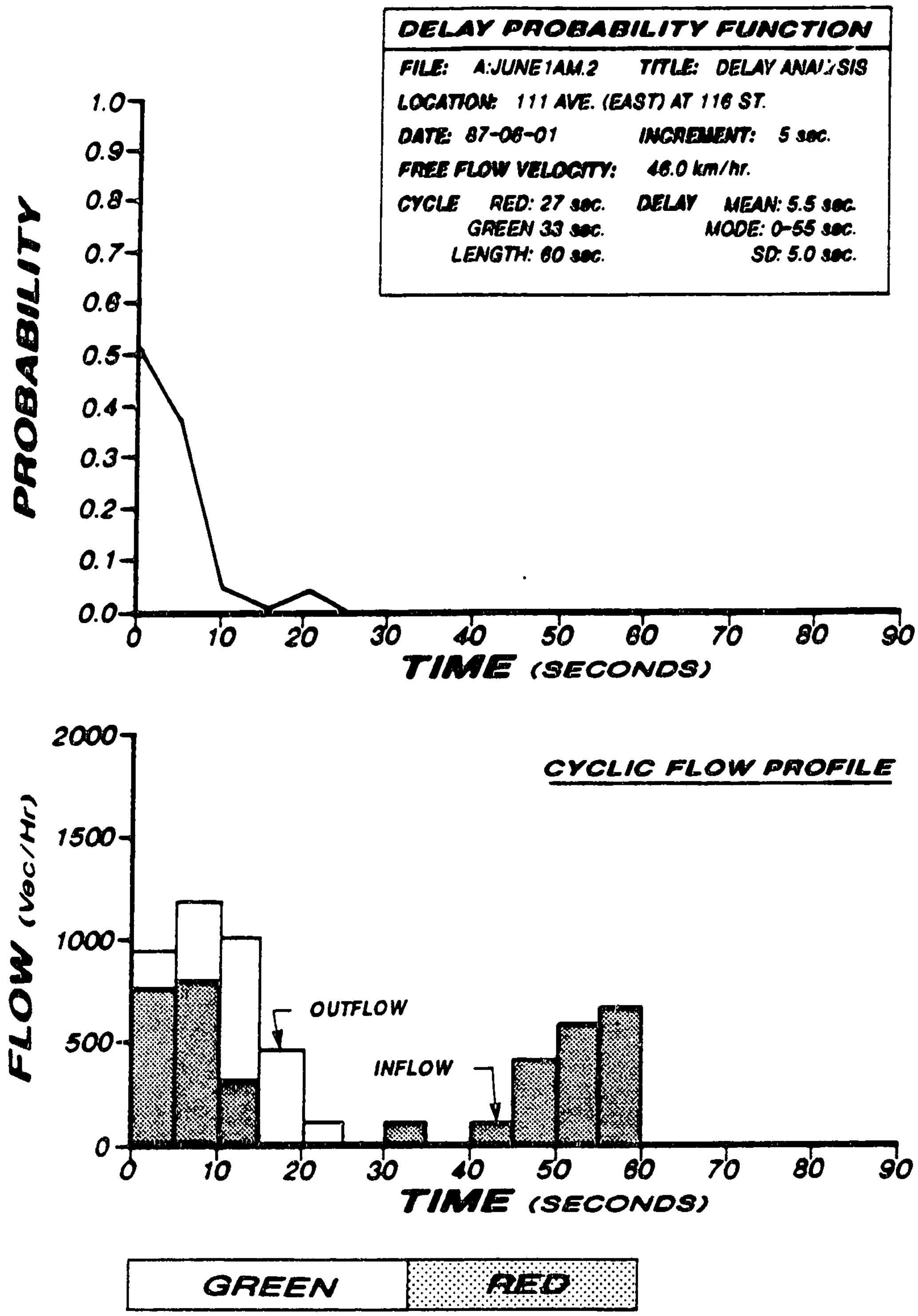

Figure 5.4: Example of Good Coordination at Location H

distribution is shifted towards a zero delay with 90 % of the vehicles delayed less than ten seconds and a mean delay of 5.5 seconds. This information alone appears to indicate that the intersection is free flowing. However, the cyclic flow profiles indicate that this is not the case. For a free flowing condition to exist, the inflow must equal the outflow. During the green phase, the outflow is always slightly greater than the inflow indicating that vehicles are impeded by their predecessors. This theory is supported by the data which shows a platoon arrival pattern from the last 15 seconds of red and the first 15 seconds of green. The probability function indicates that 52 % of vehicles delayed less than five seconds and 38 % of vehicles are delayed from five to ten seconds. In contrast, the free flowing conditions of Location R has 85 % of the vehicles delayed less than five seconds. This implies that a large portion of the vehicles are impeded by their predecessors but in all likelihood do not come to a complete stop. The approach would have small stopped delays but a significant amount of overall delay.

Despite the fact that the mean delay is short, measures could be taken to improve the coordination. Shifting the green offset to allow the entire platoon to arrive during green would further decrease delays and suggest a free flowing condition.

B.3) RANDOM ARRIVAL

In order to evaluate neutral coordination abilities, Location L (170th Street Southbound at 107th Avenue) was chosen for analysis.

This isolated location was selected to ensure a uniform arrival pattern. The inflow cyclic flow profile is illustrated in Figure 5.5.

As expected, the cyclic flow profile does not exhibit a recognizable platoon arrival pattern. This hypothesis was tested by comparing the inflows to a random Poisson (Ref) probability distribution. Table 5.1 presents the calculations. A variance to mean ratio of 1.001 indicates the inflow arrival pattern is a Poison distribution.

The delay characteristics and cyclic flow profile for Location L are illustrated in Figure 5.6. The uniform arrival pattern produces a growing queue over the red phase which dissipates after approximately 15 seconds of green. At this point the inflow becomes nearly equivalent to the outflow. The remaining 25 seconds of the green phase are free flowing and would account for a mode delay of zero to five seconds. The 25 % of vehicles delayed less than five seconds correspond closely with the 22 % of vehicles arriving during 15 to 35 seconds of the green phase. The remaining vehicles are delayed proportional to their arrival time on red, and account for the delays greater then 15 seconds. A maximum delay value of 50 seconds corresponds to the red phase length of 47 seconds plus lag time upon signal changes. The delay probability function echoes the results expected for uniform arrival pattern. i.e. a mode delay of zero caused by free flowing vehicles and the remaining delays distributed over the length of the red phase.

The uniform inflow pattern indicates that delay would not

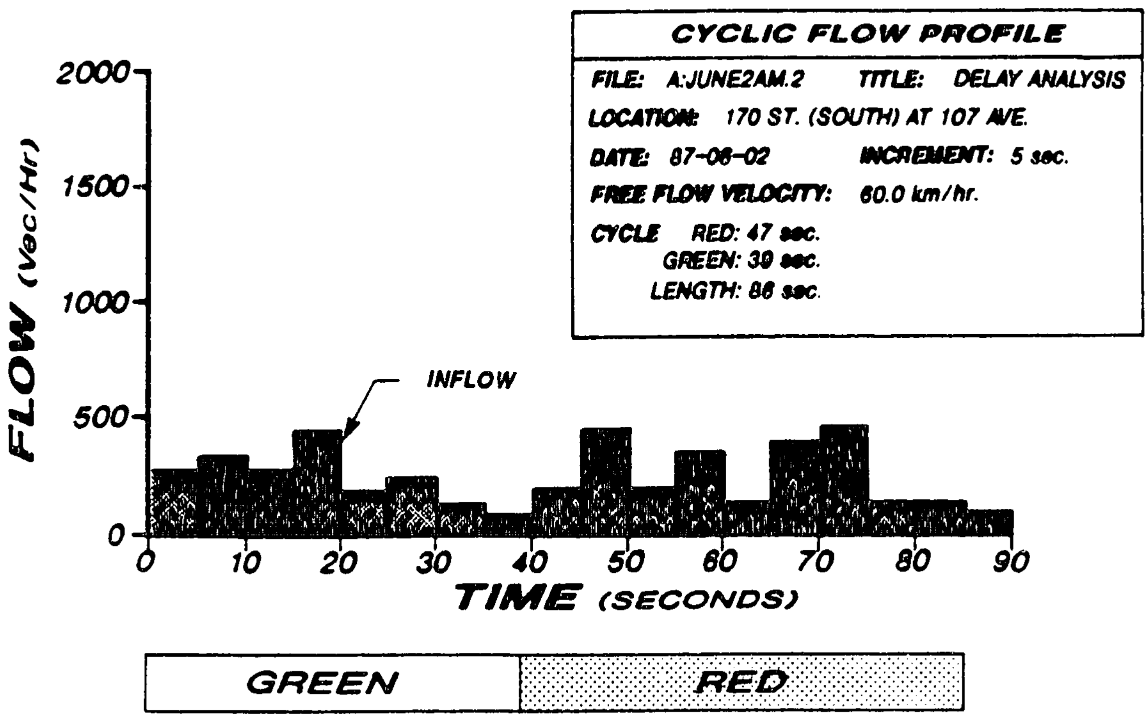

Figure 5.5: Inflow Cyclic Flow Profile at Location L

Cycle Interval (Seconds)	Arrivals	$(x - \bar{x})$	$(x - \bar{x})^2$
0 - 5	6	0.588	0.346
5 - 10	7	1.588	2.522
10 - 15	6	0.588	0.346
15 - 20	9	3.588	12.874
20 - 25	4	-1.412	1.994
25 - 30	5	-0.412	0.168
30 - 35	3	-2.412	5.818
35 - 40	2	-3.412	11.642
40 - 45	4	-1.412	1.994
45 - 50	9	3.588	12.874
50 - 55	4	-1.412	1.994
55 - 60	7	1.588	2.522
60 - 65	3	-2.412	5.818
65 - 70	8	2.588	6.698
70 - 75	9	3.588	12.874
75 - 80	3	-2.412	5.818
80 - 85	3	-2.412	5.818

$\bar{x}$ = Mean = 5.412 $\qquad \Sigma(x - \bar{x})^2 = 92.12$

$$s^2 = \frac{1}{n}\Sigma(x - \bar{x})^2 = \frac{92.12}{17} = 5.419$$

$$\frac{s^2}{m} = \frac{5.419}{5.412} = 1.001$$

Table 5.1: Poisson Distribution Test for Random Arrivals at Location L

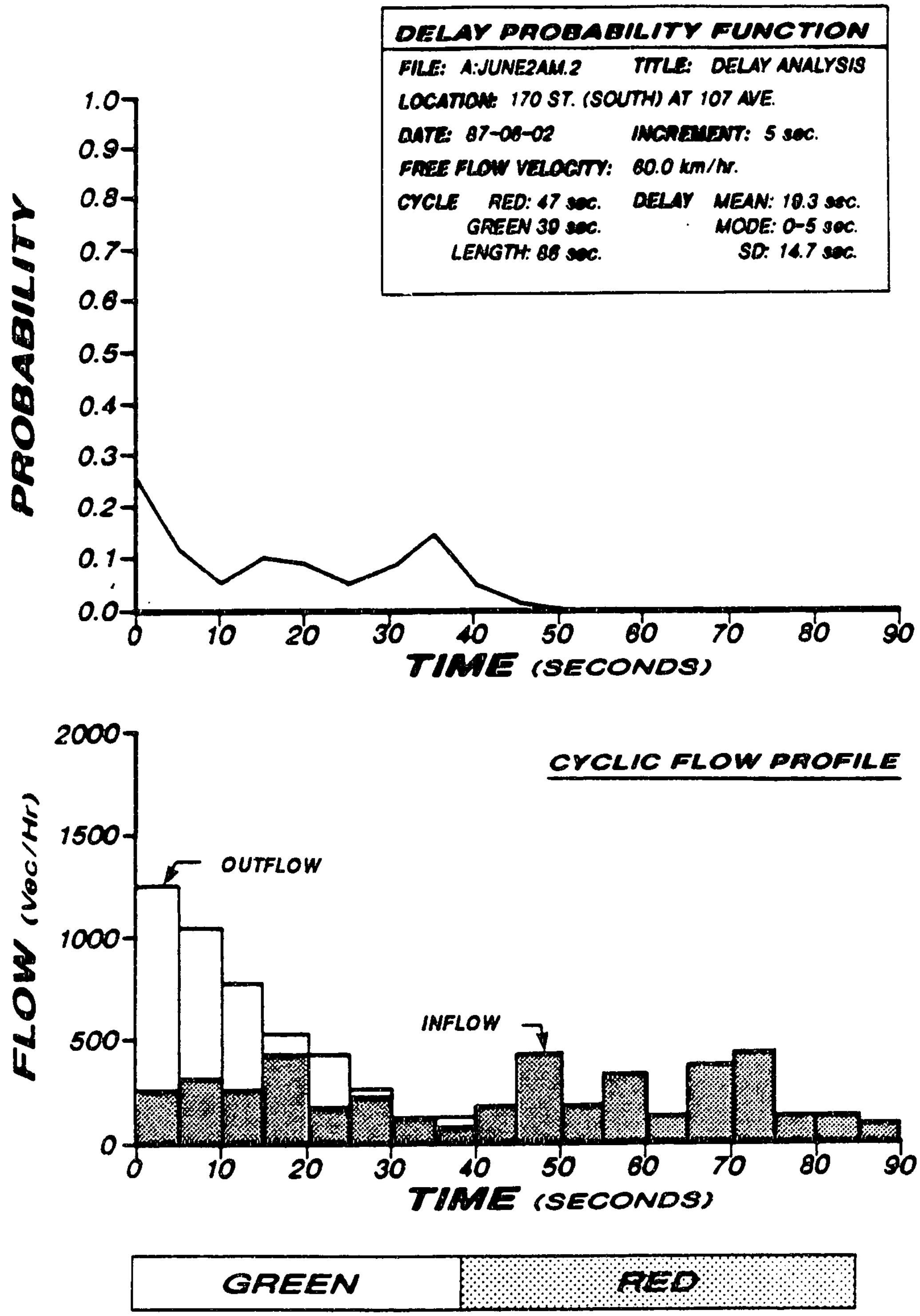

Figure 5.6: Example of Random Arrivals at Location L

change with movement of the green phase within the cycle. Traffic flow could only be improved through a combination of increased cycle time and / or increasing the green phase.

B.4) LONGER DELAYS

The area of Kingsway Avenue between 109th and 111th Streets was identified as a route with delay problems. This location suffers from high traffic volumes, skewed geometry, and consequently poor coordination. Two locations on Kingsway Avenue were chosen for analysis. Figure 5.7 illustrates the delay probability function and cyclic flow profiles for Location E (Kingsway Avenue Westbound at 109th Street).

The delay probability function is a close reflection of the prevailing traffic characteristics. The delay probability function is dominated by a peak of delays from 30 to 50 seconds. This delay duration corresponds to the platoon arrival at the first 30 seconds of a 55 second red phase. The mode delay of 40 to 45 seconds reflects the midpoint of the platoon arrival on red. The cyclic flow profile shows that the queued vehicles are dispersed over the first 15 seconds of green. The low inflow for the last 15 seconds of green does not take advantage of the free flow potential at the end of green. However, the few free flowing vehicles in this area account for the small peak (15 %) of zero delays. The low plateau of delays of 5 to 30 second duration can be accounted for by the vehicles arriving on the last 20 seconds of red and the first 15

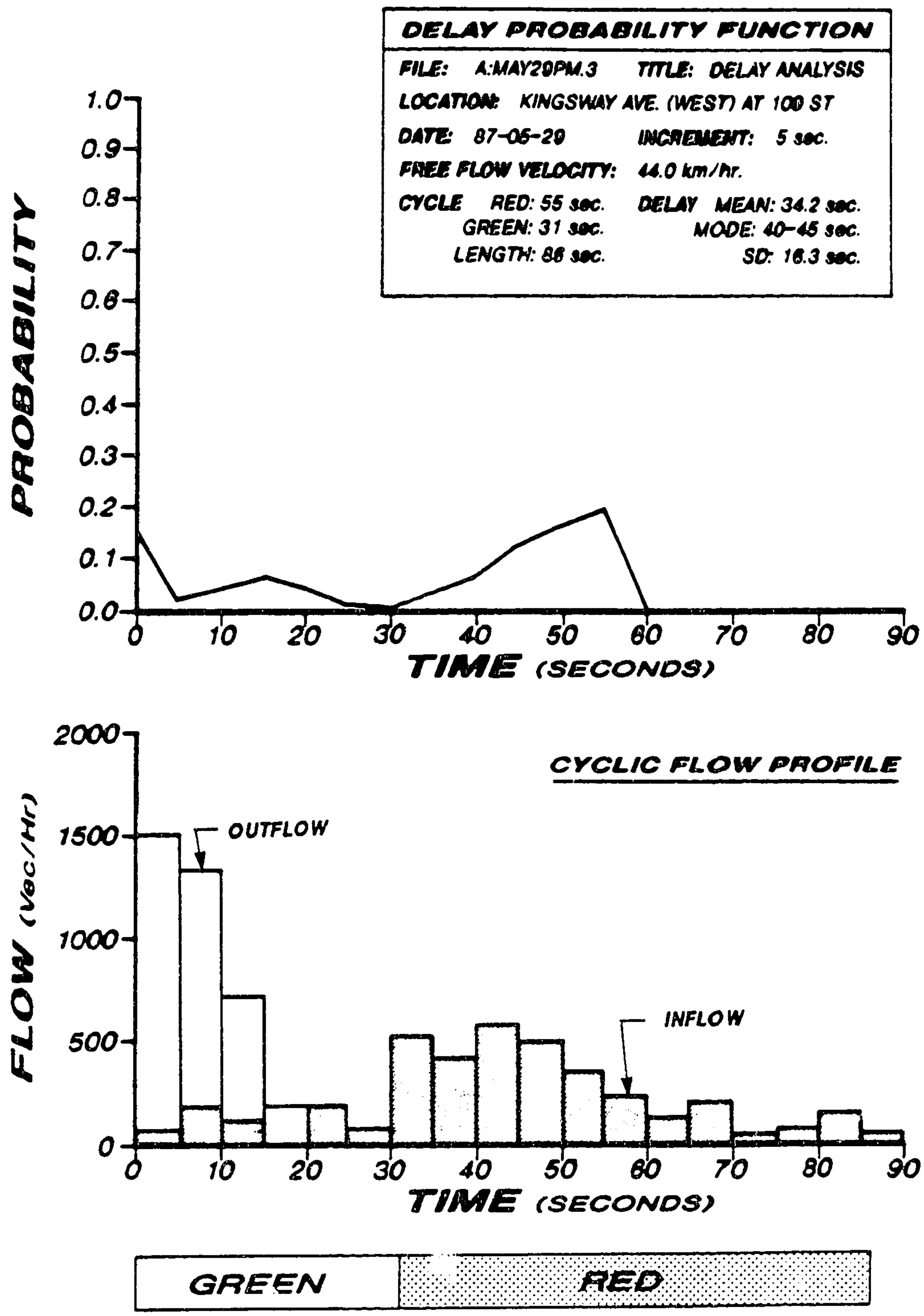

Figure 5.7: Example of Poor Coordination at Location E

seconds of green.

The data illustrates a situation in which the worst possible coordination exists; the green / cycle time ratio is low; a well defined platoon arrives at the beginning of red; non platoon arrivals are minimal; and the free flowing portion of green is not utilized. The solution to coordination problems at this approach is obvious, the green phase should be offset to accommodate a larger portion of the platoon.

A second approach of interest with longer delays is Location F (Kingsway Avenue Westbound at 111th Avenue). Figure 5.8 illustrates the delay probability function and cyclic flow profile.

The delay distribution is characterized by three peaks each caused by a different delay characteristic. The initial peak of zero delays corresponds to the free flowing conditions encountered during the last 15 seconds of green. The second smaller peak is centered around a 15 second delay and is caused by a combination of two factors. The first influence is the random arrival of vehicles during the last 30 seconds of red causing a delay plateau of zero to 30 seconds. The second factor is caused by vehicles arriving at the back of a queue, thus superimposing upon the plateau. As the queue takes 15 seconds to dissipate these vehicles have a corresponding average delay of 15 seconds. The third peak in delays corresponds to the latter portion of the platoon arriving during the first 15 seconds of red. The mode delay of 55 to 60 seconds indicates that these vehicles are delayed for the duration of red.

As with the previous example, coordination could be improved

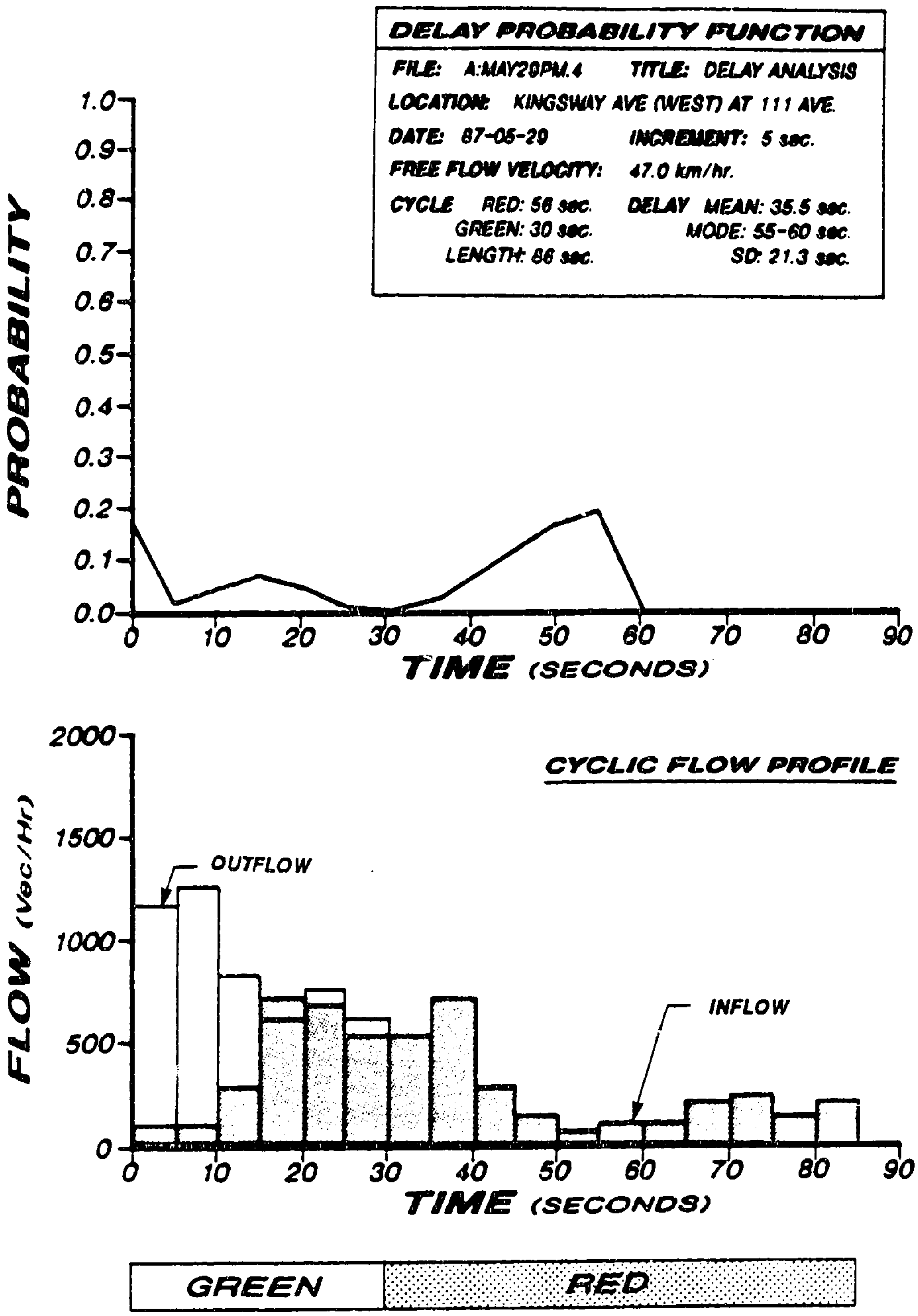

Figure 5.8: Example of Poor Coordination at Location F

by offsetting the green phase to accommodate a larger portion of the platoon.

Comparing the two poorly coordinated intersections shows that the larger mean and mode delay occur at location F which has a larger portion of its platoon arriving on green. One factor that could attribute to this phenomenon is the higher initial discharge rate at Location F. A higher initial discharge of 1500 compared to 1200 vehicles / hour would result in a faster dissipation of the queue and should reduce subsequent vehicle delays. Comparison in two delay distribution shapes indicate differences in the traffic flow characteristics.

B.5) SPECIAL FEATURES

Beneficial side effects produced by the DELAY program soon became apparent upon analysis of the data. The following paragraphs outline these features.

B.5.a) Comparison of Delay Probability Functions.

The intersections at Location J (111th Avenue Westbound at 142nd Street) and Location B (87th Avenue Westbound at 114th Street) both have an identical mean delay of 16.8 seconds. This implies similar traffic characteristics. However, inspection of the delay probability functions soon excludes this possibility. Figures 5.9 and 5.10 illustrate the delay probability functions and cyclic flow

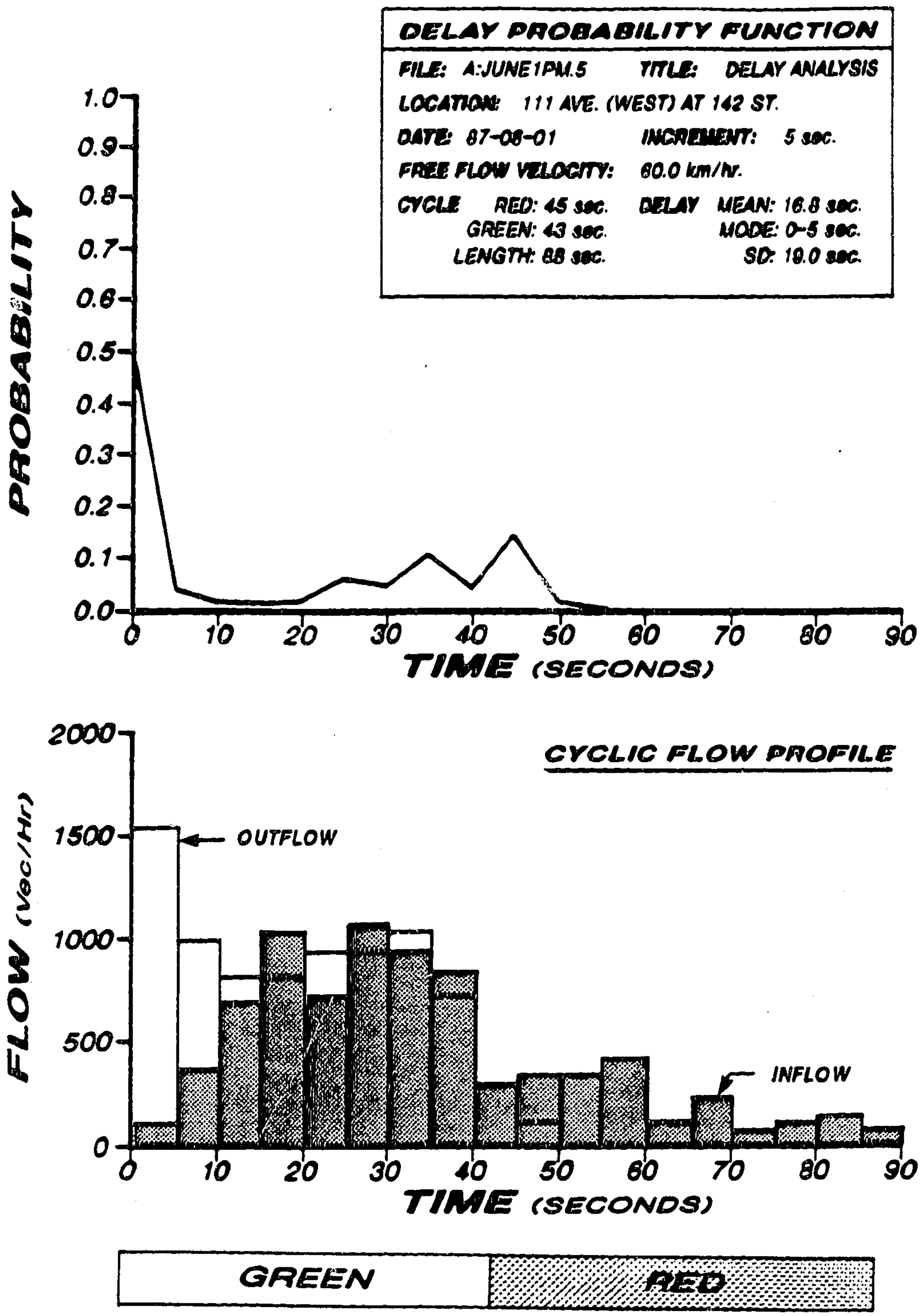

Figure 5.9: Comparison of Delay Distributions, Location J

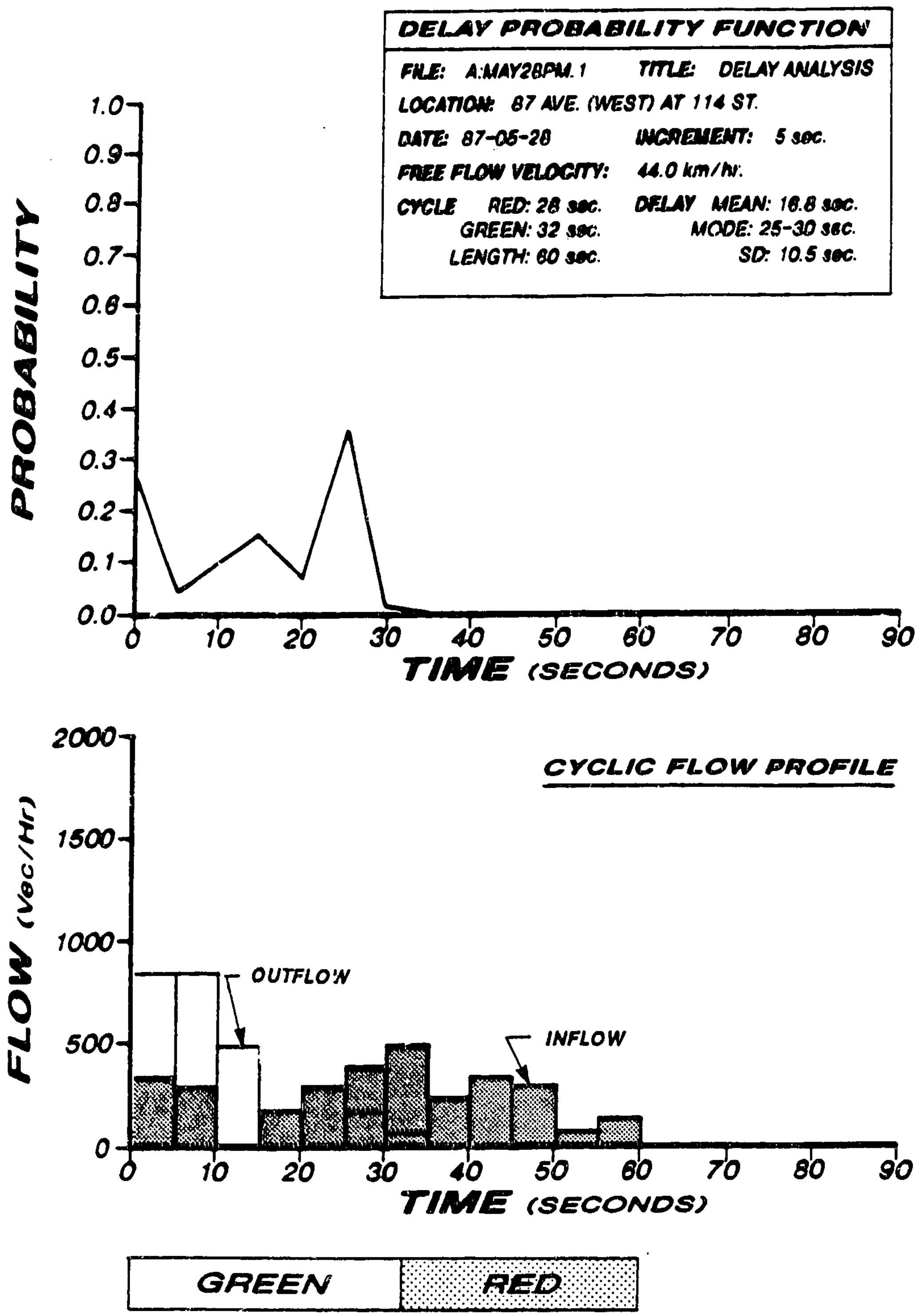

Figure 5.10: Comparison of Delay Distributions, Location B

profiles of the respective intersections.

The delay distribution for Location J shows two distinctive types of delay; free flowing vehicles and vehicles delayed on the red phase. The majority (52 %) of vehicles arrive in a free flowing platoon after approximately ten seconds of green. The second type of delay is 25 to 50 seconds in duration and accounts for approximately 38 percent of the traffic volume. These longer delays are proportional to the vehicle arrival time on red.

The signal offsets appear to be arranged so that the platoon arrival is optimal within the cycle. The first ten seconds of green dissipate queued vehicles, followed by a free flowing platoon for the remainder of green. Coordination could only be improved by increase green or cycle times.

In contrast, the delay distribution for Location B does not reflect a definite traffic pattern. The inflow cyclic flow pattern is inconsistent in that neither a platoon or a random arrival pattern are evident. The only recognizable traffic characteristic is the free flowing vehicles at he end of green. These vehicles account for the 25 percent of vehicles with zero delay. The mean delay of 16.8 seconds was likely influenced by the short cycle time and not caused by any set traffic pattern. Low traffic volumes combined with an indeterminate arrival pattern would not lend themselves well to coordination techniques. Shifting the green phase may result in minimal improvements of the delay values.

Comparison of the two intersections shows a similarity in the value of mean delay only. The different traffic conditions indicate both intersections would reject coordination improvement techniques. Location J is at optimal coordination while the Location B lacks the prerequisite traffic inflow pattern required for coordination improvements.

B.5.b) Delay Characteristics.

Location C (Kingsway Avenue Eastbound at 109th Street) provides a good example of typical delay distribution patterns and corresponding traffic characteristics. Figure 5.11 illustrates.

The delay distribution shows three types of vehicle delays. The initial peak of zero delays are produced by free flowing vehicles arriving on the unimpeded portion of the green phase. The probability of zero delays reflects the percent of free flowing vehicles and is a good general indicator of signal performance. A second type of delay is produced by vehicles arriving at the back of a moving queue. Delay durations typically range from five seconds to the time required to dissipate the queue. These vehicles arrive during the last few seconds of red or the first few seconds of green. The arrival time indicated that vehicles are not stopped but slowed down by the signal. The final type of delay is caused by vehicles stopped on the red signal. They range in duration from the time required to dissipate the queue to the duration of the red phase. Delay durations correspond directly with the arrival time within the red phase, i.e. vehicles arriving at the beginning of red experience the longest delays. The delay probability is proportional

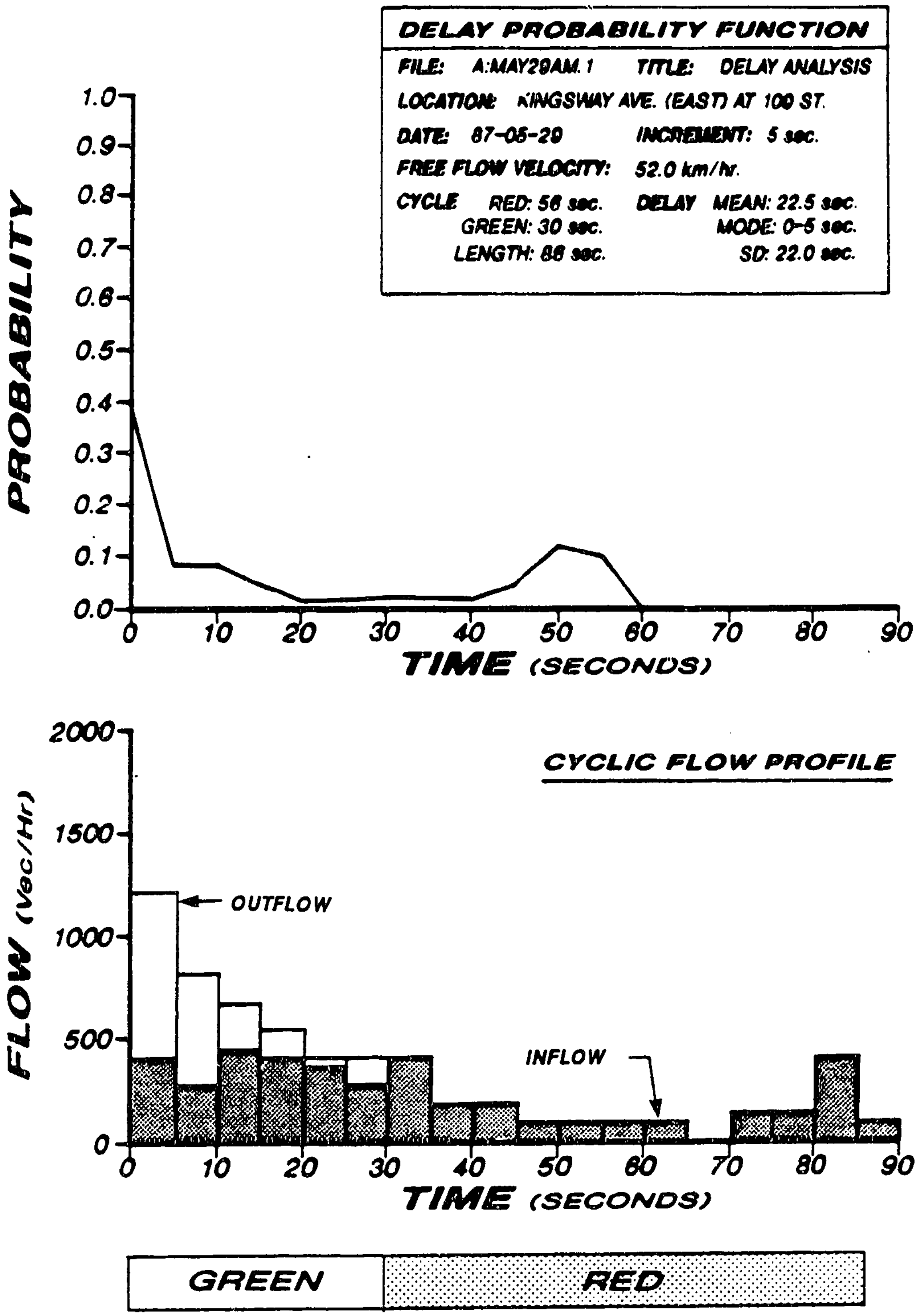

Figure 5.11: Example of Delay Characteristics at Location C

to the inflow volume as the shape of the probability function indicates. Peaks correspond to inflow surges, valleys correspond to low inflows, and plateaus correspond to uniform flow periods. Figure 5.1. illustrates two categories of vehicles delayed on red. A low probability delay plateau is caused by a small uniform inflow volume centered within the red phase. A delay peak is caused by a surge of inflow during the first portion of the red phase. The peak delay duration of 50 seconds matches the length of the red phase.

C) COMPARISON OF DELAY CALCULATIONS

The DELAY program methods were compared with current delay claculation methods. Raw data collected by the traffic analyzer was used to calculate delays based on three different methods. Sample calculations based on the Highway Capacity Guide (Ref 13), the Canadian Capacity Guide for Signalized Intersections (Ref 10), and the DELAY program calculations are available in the Appendix.

Results of the delay calculations are summarized in Table 5.2. The average delay of the three methods was determined in order to arrange the delays in ascending order. To compare the results graphically Figure 5.12 plots each delay method versus the intersection location.

From these results it appears that the Highway Capacity Manual predicts the lowest delay values followed by the Canadian Capacity Guide, and the DELAY Program. In order to quantify the differences each method was compared to the DELAY program by calculating the

	Delay in Seconds		
Location	H.C.M.	DELAY	C.C.G.
R	3.0	3.2	7.4
H	4.3	5.5	8.6
Q	4.1	6.5	10.2
I	4.2	8.2	7.6
S	5.0	5.0	12.5
M	4.8	5.5	11.9
P	4.4	11.9	8.0
G	5.7	11.3	7.5
K	6.3	9.9	11.4
A	8.3	16.8	8.1
B	8.0	15.9	10.5
O	8.2	17.0	10.8
J	7.9	16.8	14.4
L	11.4	19.3	15.1
C	8.3	22.5	20.5
N	12.0	22.6	15.8
D	13.7	26.6	18.0
F	11.4	35.5	20.8
E	12.1	34.2	20.5
Average	8.0	15.484	12.61

Table 5.2: Summary of Delay Calculations

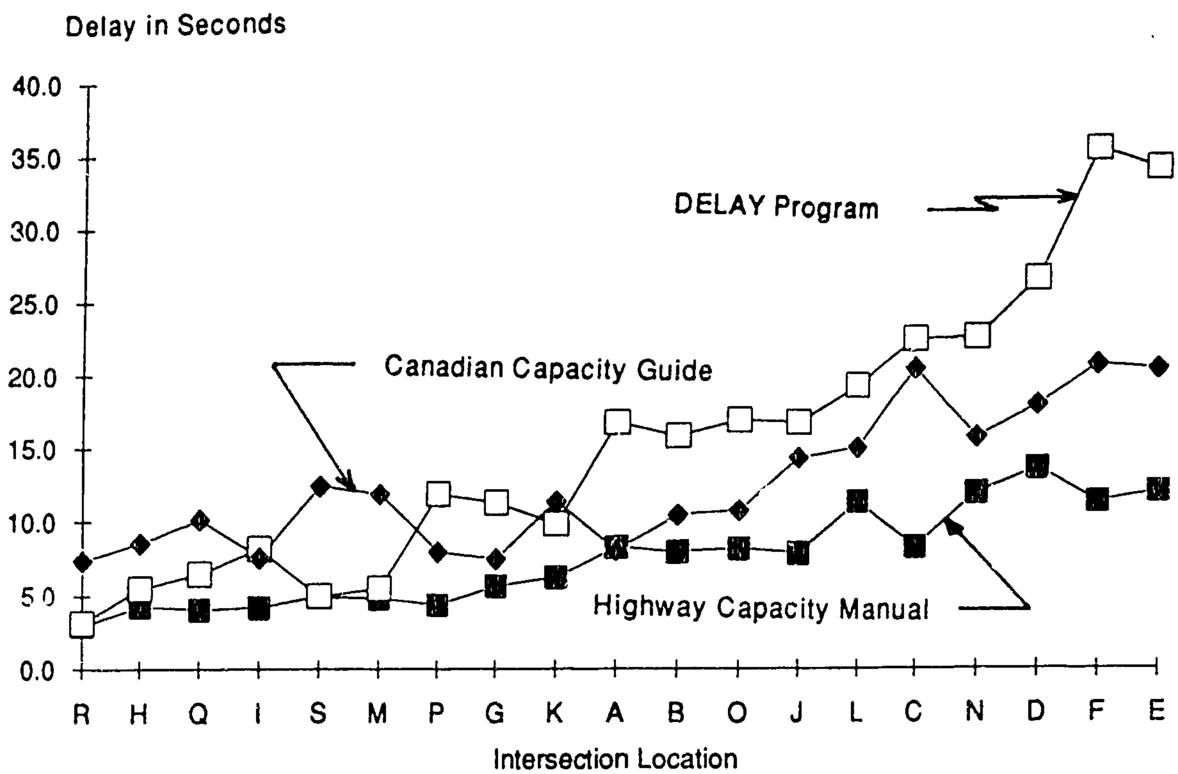

Figure 5.12: Comparison of Delay Calculations

percentage difference between delay values. The results of the delay comparison are summarized in Table 5.3 and represented graphically in Figure 5.13.

The results illustrate that the DELAY program consistently calculates a longer delay than the American Highway Capacity Manual. On average the DELAY program is 41 percent longer. By definition the American Highway Capacity Manual calculates stopped delay which should be less than overall delay calculated by the DELAY program.

In order to quantify the differences between stopped delay and total delay two references were investigated.

A future publication in the 1989 Transportation Research Board Record entitled "Accuracy of Delay Surveys at Signalized Intersections" (Ref 12) indicates that the relationship between stopped and total delay depends on the duration of red and the vehicle deceleration. The following formula (Ref 12) illustrates:

$$\frac{D}{Ds} = \frac{r^2}{(r - ta)^2}$$

Where D = Total Delay
Ds = Stopped Delay
r = Length of Red Phase
ta = Deceleration Delay

In a typical urban environment deceleration delay would be constant. Assuming a deceleration delay of 4.6 seconds and a red interval of 25 to 55 seconds the stopped delay would range from 66 to 84 percent of the total delay.

A second comparison of stopped versus total delays can be made based on the delay formulas in the Canadian Capacity Guide and the American Highway Capacity Manual. The Canadian Capacity Guide

	% Difference in Delay	
Location	H.C.M. vs DELAY	C.C.G. vs DELAY
R	-6.2	131.2
H	-21.8	56.4
Q	-36.9	56.9
I	-48.8	-7.3
S	0.0	150.0
M	-12.7	116.4
P	-63.0	-32.8
G	-49.6	-33.6
K	-36.4	15.2
A	-50.6	-51.8
B	-49.7	-40.0
O	-51.8	-36.5
J	-53.0	-14.3
L	-40.9	-21.8
C	-63.1	-8.9
N	-46.9	-30.1
D	-48.5	-32.3
F	-67.9	-41.4
E	-38.3	-40.1
Average	-41.4	7.1

Table 5.3: Summary of Delay Calculations Compared to the DELAY Program

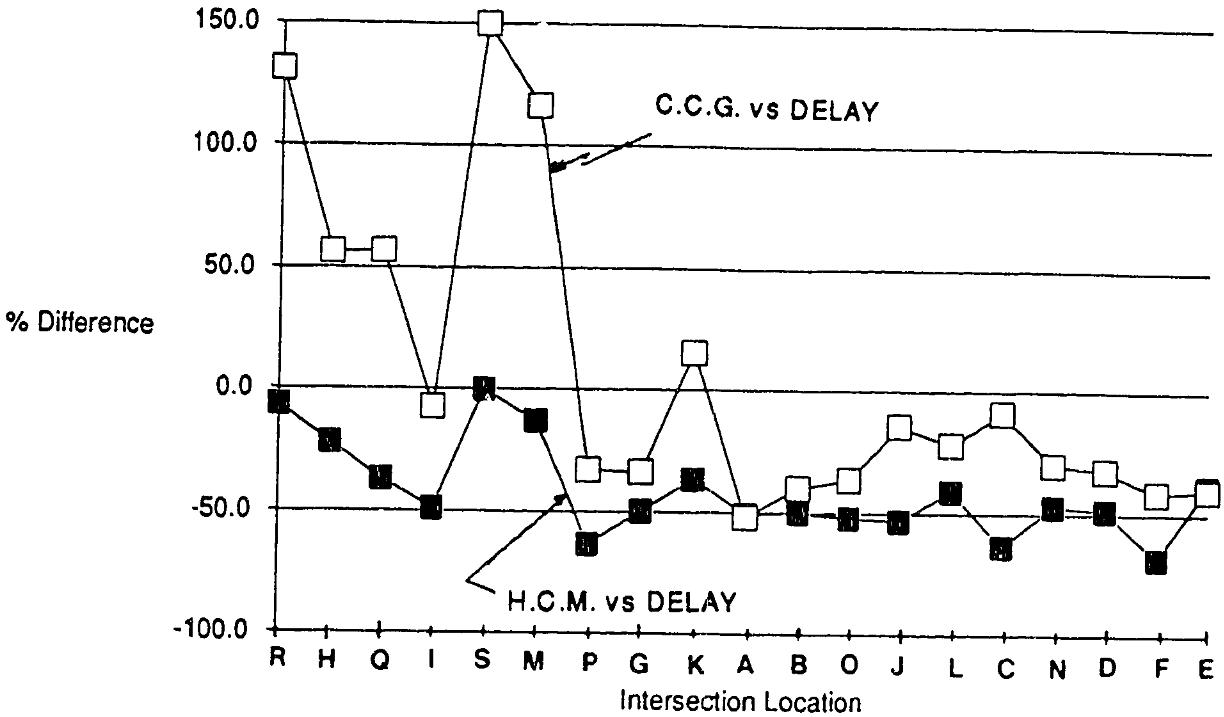

Figure 5.13: Delay Calculations Compared to the DELAY Program.
Note: 1) C.C.G. vs DELAY compares overall vs overall delay
2) H.C.M. vs DELAY compares stopped vs overall delay

calculates total uniform delay based on the following formula (Ref 10):

$$Dt = 0.50 \frac{C*(1-L)^2}{(1-L*X)}$$

The American Highway Capacity Manual measures stopped uniform delay and is expressed as follows (Ref 13):

$$Ds = 0.38 \frac{C*(1-L)^2}{(1-L*X)}$$

Where Dt = Total Uniform Delay
Ds = Stopped Uniform Delay
L = g/c
g = Effective green time (seconds)
c = Cycle time (seconds)
X = Volume / Capacity
C = Capacity

The two formulas differ only in terms of the proceeding coefficient of 0.38 versus 0.50. Inherent to the two formulas is the assumption that stopped delay is 76 percent of total delay.

Table 5.3 shows that the Highway Capacity Manual delays are approximately 59 percent less than the DELAY program. This difference could be explained by a low volume to capacity ratio for the surveyed data. The 76 and 66 to 84 percent range are based on delay measurements for a wide range of volume to capacity ratios. The analysis was performed on undersaturated conditions with low volume / capacity ratios in the order of 0.1 to 0.3. It would be expected that during saturated conditions the difference between stopped delay and overall delay would be minimal. During low volume / capacity ratios the difference between total delay and stopped delay would be greater. Since this analysis was performed in low volume / capacity ratios the difference in stopped and total delays should be greater than the values indicated by the three references. The analysis value of 59 percent appears reasonable under the circumstances.

As the Canadian Capacity Guide delay calculation models total delay the delay durations should correspond to the DELAY program. The Canadian Capacity Guide value is approximately seven percent longer than the DELAY program. Figures 5.12 and 5.13 illustrate a wide variance in Canadian Capacity Guide delays with overestimation of short delay and underestimation of longer delays. Given the large variance in both delay methodologies a seven percent difference is reasonable under the circumstances.

CHAPTER VI, CONCLUSIONS

The DELAY program provides an effective tool for evaluating the signal coordination of an individual intersection. This statement is supported by the following observations:

1) In comparison with other delay calculation methods the DELAY program calculates accurate values of total delay given the vagueness of the delay term. Comparison with stopped delay calculations are reasonable considering the inherent differences between stopped and overall delay.

2) The DELAY program is a good overall indicator of the coordination potential at an intersection. The distribution shape can be used as a starting point to analyze the traffic characteristics. Initial observations of the delay probability function indicate the percentage of free flowing vehicles, the presence of a platoon, and a random arrival pattern.

3) In depth analysis of the delay probability function provides a detailed explanation of traffic behavior. Each portion of the distribution has a suggestive shape that illustrates the arrival or dispersion of a platoon, the development or discharge rates of queues, and the delay pattern of vehicles impeded by red. Knowledge

of detailed traffic behavior provides the traffic engineer information to improve coordination.

4) The normalized delay probability function allows for comparison of signal performance at different intersections. Comparison of intersections on a coordinated route could indicate problem areas within the route. In addition the delay distribution could determine the effects of signal changes with a before / after analysis.

The DELAY program has already been utilized for comparative analysis. Applications include a route coordination analysis in St. Albert (Ref 20,21) and preliminary research into the benefits of the SCOOT on-line traffic control method in Red Deer.

5) The DELAY program is versatile. Flexibility in the interpretation of input parameters allows for a variety of applications. The DELAY program has been utilized to study pedestrian walking speeds (Ref 22). The author has also utilized the cyclic flow diagrams for a multiple lane analysis of signal warrants.

6) Knowledge gained by this research project uncovers additional questions that require exploration. Examples of possible future research projects include:

a) Expansion of the DELAY program to include multilane and possible multidirectional intersection analysis. Further expansion could allow for possible traffic actuated algorithms.

b) Exploration of the relationship between stopped delay and overall delay. The DELAY program is currently being used to investigate this relationship, however the results are not yet published.

c) Expansion of the DELAY program to include queue formation and discharge.

d) Expansion of the DELAY program to include saturated conditions and subsequent overflow delays. Although it was not within the scope of this research the DELAY program has successfully handled overflow delays in a route analysis commissioned for the City of St. Albert (Ref 20,21).

e) Further analysis of the shape of the delay distribution shape could provide insight into the complex issues of signal coordination. The delay distribution characteristics provides a subjective visual indication of the signal performance. Further research could possibly quantify the quality of signal coordination in more tangible terms.

The results of the research have shown that the main objective of the research has been met. The DELAY program provides a practical system for the evaluation of signal coordination at an individual intersection.

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APPENDIX

SAMPLE CALCULATION

HIGHWAY CAPACITY MANUAL

Location : A
Description : 87th Avenue Westbound at 114 Street
File : May28pm.1
Cycle : 60 Seconds
Green : 32 Seconds
Red : 28 Seconds
Capacity : 1550 veh/hr

Cycle	Arrivals on Red	Total Vehicles
1	2	4
3	2	2
3	2	2
4	4	6
5	2	4
6	0	1
7	1	4
8	2	3
9	1	1
10	2	4
11	4	8
12	1	2
13	2	3
14	5	6
15	1	2
Totals	31	53

Platoon Ratio

$$Rp = \frac{\dfrac{\text{Green Vehicles}}{\text{Total Vehicles}}}{\dfrac{\text{Effective Green}}{\text{Cycle Time}}}$$

$$Rp = \frac{22/53}{30/60} = 0.830$$

Table 9-2 indicates type 2 arrival type.

Start of Survey 2:14:06
End of Survey 2:28:43
Duration of Survey = 877 Sec

$$\text{Volume} = \frac{53 \text{ veh} * 3600 \text{ sec}}{877 \text{ Sec} * 1 \text{ hr}}$$

Volume = 218 veh/hr
X = V/C = 218/1550
X = 0.1406

$$\text{Delay} = \frac{0.38\ C\ (1 - g/c)^2}{(1 - (g/c)\ X)}$$

$$\text{Delay} = \frac{0.38\ (60)(1 - 30/60)^2}{1 - (30/60)(0.1406)} = 6.13 \text{ Sec}$$

From Table 9-13
PF = 1.35

Delay = 6.13 * 1.35 = 8.3 Seconds

SAMPLE CALCULATION

CANADIAN CAPACITY GUIDE

Location : A
Description : 87th Avenue Westbound at 114 Street
File : May28pm.1
Cycle : 60 Seconds
Green : 32 Seconds
Red : 28 Seconds
Capacity : 1550 veh/hr

From H.C.M calcultion Volume = 218 veh/hr.

$$\text{Delay} = \frac{0.50\ C\ (1 - g/c)^2}{(1 - (g/c)\ X)}$$

$$\text{Delay} = \frac{0.38\ (60)(1 - 30/60)^2}{1 - (30/60)(0.1406)} = 8.1\ \text{Sec}$$