TRAFFIC CONTROL AT SIGNALIZED INTERSECTIONS

by

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A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1967

Approved by:

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INTRODUCTION

Since World War I traffic mileage has increased, and the rate of increase has also accelerated since World War II. The problems of traffic considering the flow of street and highway traffic are concerned with the achievement of a more efficient system of road transportation. The traffic engineer started to provide stop signs or a signal at an intersection. In the early days all signals were on a fixed-time basis, that is, the time of a signal cycle was not varied. Later it was found a signal cycle at a single intersection could be varied according to the traffic demands. Various forms of actuated signals were developed after World War II. The variation of a signal cycle depends on the number of vehicles waiting under the red light, the length of time waited by the first vehicle under the red light, and the time spacing of the vehicles moving with the green light. Traffic control at an intersection is governed by traffic regulations and by various types of traffic devices. The price paid for such control is delay.

Control of traffic flow is empirical in nature. In order to determine the nature of the problem, one must acquire a certain understanding of the simplest possible types of traffic conditions. The phenomenon of traffic flow is associated with the directed movement of vehicles between origins and destinations in reasonable accord with the constraints imposed by the regulations of an established system. Directed movement, or flow, takes place on a street and through intersections. The traffic control problem is more complicated on a two-way street than it is on a one-way street.

Traffic control at signalized intersections on two-way streets can be achieved by proper synchronization (offset) of the signals at each intersection. The maximum synchronization of the signals reduces the delay of vehicles while travelling along the two-way street. The details of the problem will be discussed later. The problem can be solved by use of a time-space diagram.

Three different approaches may be used to reduce delay at an intersection. The third approach may be used to compute delay at an intersection. The traffic algorithm and half integer synchronization techniques to be described in this paper deals with a solution making use of a time-space diagram. The time-space diagram is described later. The simulation of the traffic delay by queueing theory is not included in the optimal solution of the given six signals problem. It is used to determine the cause of delay at an intersection to give the theoretical application of traffic delay at a signalized intersection. The basic theory underlying of all three approaches is not described in this paper. Brief summaries of the techniques are described in this paper. The first two approaches have been programmed for an IBM 1620. The simulation of traffic delay governed by queueing theory has been programmed for an IBM 1410. The flow diagrams for the first two approaches are shown in this paper. The computer program for a simulation of traffic at signalized intersections is written in Appendix C. The three approaches described in this paper are applicable for any similar problem.

THE AREA OF DELAY STUDY AND PROBLEM

The area used for delay study consists of intersections on the two major streets of N-Manhattan Avenue (N-S street in Manhattan) and Anderson Avenue (E-W street in Manhattan). The space diagram for the particular area under study is shown in Fig. 1. The cross streets on the major streets reading from north to south and then from east to west are Pioneer St., Bluemont Avenue, N-14th St., N-17th St., Denison and Sunset. Kansas State University campus lies west of Manhattan and north of Anderson Avenue. There is a parking lot on the NW corner of these intersections for students of Kansas State University. On the SE of this area lies the business center named "Aggieville Shopping Center". The student dormitories and parking lot for staff and students lie on the west side of N-Manhattan Avenue at Pioneer St. The K-State Union parking lot lies at the NE corner of 17th Street and Anderson Avenue.

The traffic delay study was made during peak hours. Readings were taken after each red interval. The number of vehicles waiting for the green light (during red interval) were noted as a length of queue. Samples from this study are given in Appendix A. The delay study shows the delay of vehicles caused by the red light on N-Manhattan Avenue at the signalized intersection at Bluemont Avenue. The period of delay study was

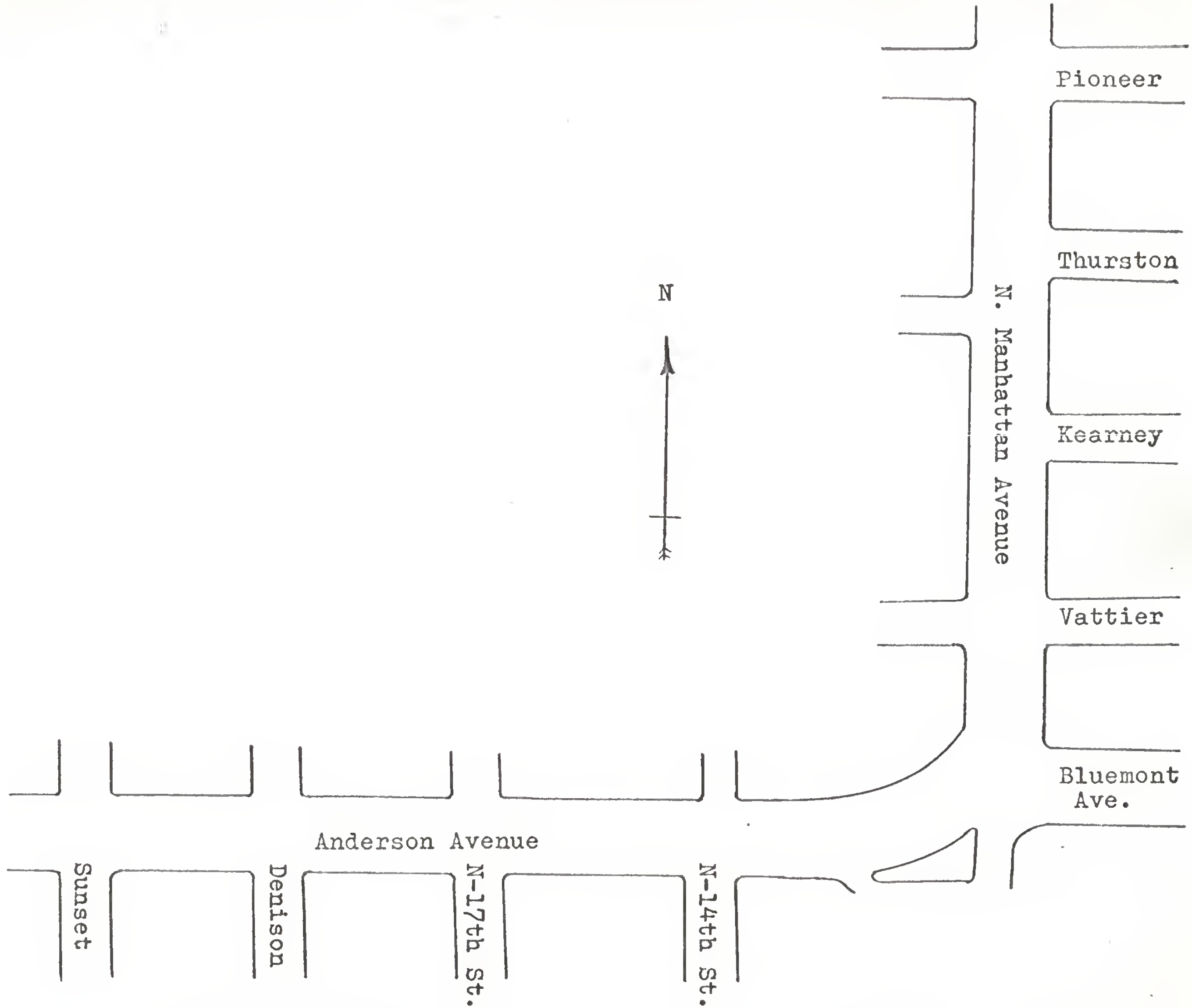

Fig. 1.--Space diagram of the intersections (not to scale).

for a half hour. Details of the delay study made at other intersections are given in Appendix B, showing the location studied, time and total delay for left, through traffic and right turn traffic. The percentage delays calculated for left, through and right turn traffic, are included in the same Appendix B.

It was found by means of the field data of delay study that the traffic on N-Manhattan Avenue and Anderson Avenue was heavy during peak hours. A considerable amount of the traffic was found to be westbound on Bluemont Avenue at 7:30 to 8:30 a.m. and at 12:30 to 1:30 p.m. There was heavy eastbound traffic on Pioneer St., northbound on Bluemont Avenue, eastbound on N-14th St. and N-17th St. during afternoon hours from 4:30 to 5:30 p.m. The N-S road between Pioneer St. and Bluemont Avenue and the W-E road between N-14th St. and Denison were found to be very busy with heavy traffic flow during particular times in a day. The whole area is affected by the heavy traffic at certain peak hours. The traffic situations vary because of the opening and closing of businesses and activities of the staff and students of Kansas State University. In general, movement of traffic flow on the given area of study was at peak load during the morning from 7:30 to 8:30 a.m., at noon from 11:30 a.m. to 1:30 p.m. and in the afternoon from 4:30 to 5:30 p.m.

An attempt was made to count the total traffic volume (vehicles/hour) while the delay situation was studied. The approximate values of observed volume (vehicles/hour) for each intersection are shown in Table 1. For long range consideration the demand volume for solving this problem are taken higher than that of the observed or pulsed volume. Table 1 shows the design capacity or volume and the demand volume for each signalized intersection. The red intervals (in seconds), green times (in seconds), amber (in seconds) and the total cycle lengths (in seconds) for each intersection were recorded during the field data study and are shown in Table 2. The same data were rechecked with the design of signals in the Traffic Engineering Office of the City of Manhattan. Their chart showed the existing signal times on major streets utilized to solve traffic problems by a different technique.

Table 1. Actual volume demand (vehicles/hour) used in the problem and design capacity (vehicles/hour).

Notation	Intersections on major street	Volume from study	Volume demand used in input data	Design capacity
A	Pioneer	250	300	410
B	Bluemont	300	350	490
C	N-14th St.	300	350	480
D	N-17th St.	300	350	490
E	Denison	250	300	400
F	Sunset	200	300	400

Table 2. Existing signal timing in the six signal problem.

Notation	Intersection on major street	Red	Yellow	Green	Cycle
A	Pioneer	14	3	33	50
B	Bluemont	40	3	17	60
C	N-14th St.	34	3	23	60
D	N-17th St.	27	3	30	60
E	Denison	27	3	30	60
F	Sunset	27	3	30	60

It is impossible to reduce the delay completely in all directions at a signalized intersection. A solution can be found for minimum delay. An attempt was made to reduce the delay completely for the traffic flow on major streets. This procedure meant that vehicles must be allowed to proceed along the major street at a suitable speed in both directions without stopping or slowing down because of red light interference. This is a particularly difficult problem. An attempt was made to find the desired solution to the problem by two different techniques. For two-way traffic considering the delay along N-Manhattan Avenue and Anderson Avenue, an attempt was made to find the optimal solution of the problem.

Table 3. Distances between two signalized intersections in the six signal problem.

Intersection	Distance in feet
A-B	2393
B-C	635
C-D	1348
D-E	635
E-F	953

TIME-SPACE DIAGRAM AND DEFINITIONS

To set the timing of the signals for satisfactory traffic flow for fixed-time control requires a manual analysis of the traffic situation. Such designs are time consuming and do not always lead to the best possible solution. The problem can be approached theoretically by proper setting of all traffic signals along the artery (street). The correct timing for each signal in order to arrive at the best overall solution can be achieved by designing a time-space diagram.

A time-space diagram for the six signal problem is drawn in Fig. 2. The vertical scale for the horizontal broken lines A, B, C, D, E, and F represents the signalized intersections at true-scale distances from each other. Pioneer St. (intersection A in Fig. 2) is considered as an origin. The rest of the intersections are labeled according to the North-South and East-West directions. The horizontal scale represents the time in seconds. The horizontal dark lines at each intersection

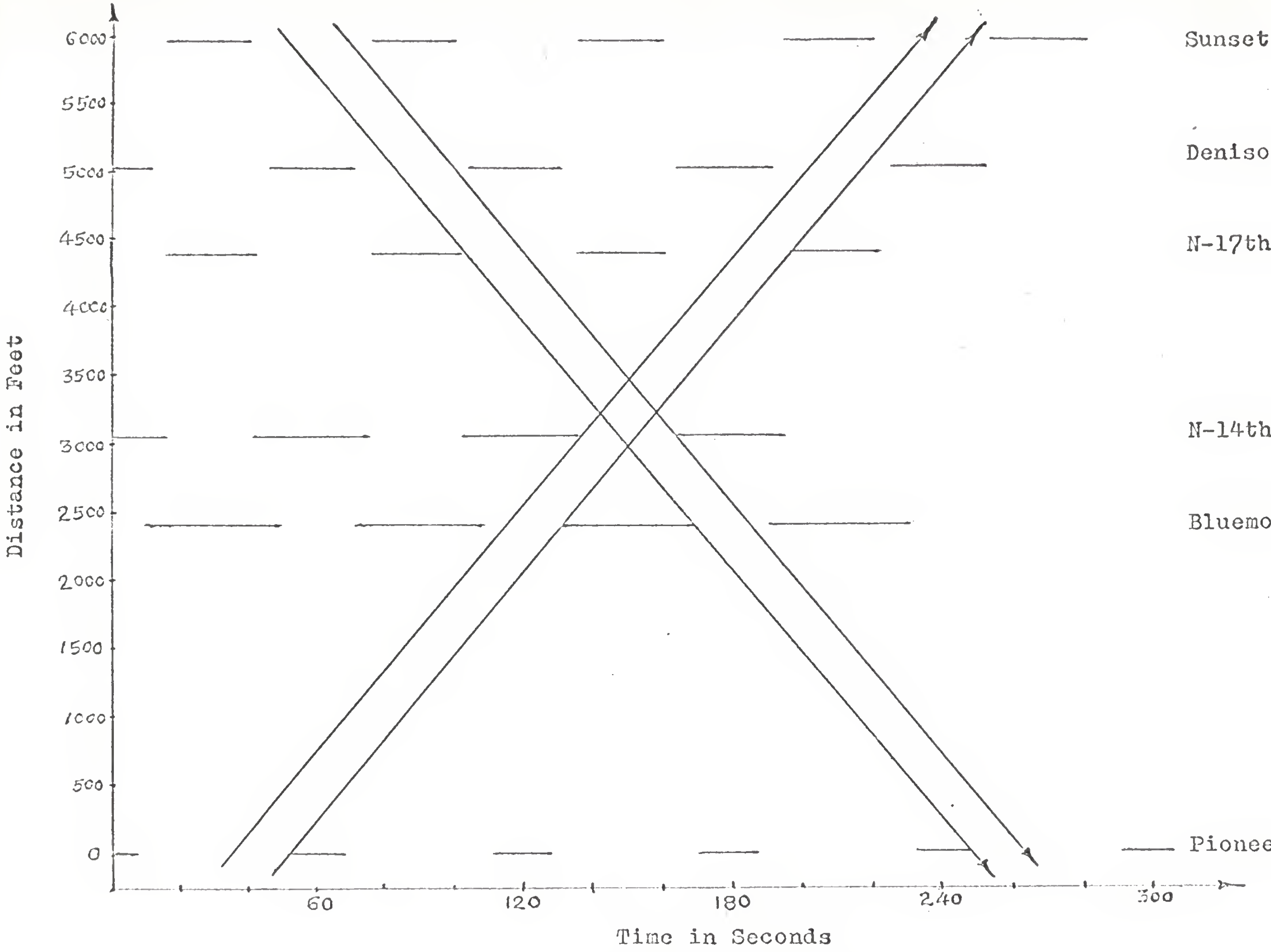

Fig. 2.--Time-space diagram of the problem with possible volume, 480 veh/hr.

represent the red-signal interval time in both directions while the blanks between reds at each intersection are the green (plus amber) interval times, called green split (in seconds). The two pairs of parallel diagonal lines represent the through-band-width in opposite directions. The through-bandwidth along the street will be defined as the elapsed time in seconds between the passing of the first and the last possible vehicle in a group of vehicles moving in accordance with the designed speed of a progressive signal system. Each direction may have its own through-bandwidth (in seconds). The offset necessary between two progressive traffic signals in a system is defined as the number of seconds or per cent of the time cycle that the green indication appears at a given traffic control signal after a certain time instant which is used as a time reference base. The slope of the two pairs of parallel lines represents the speed a vehicle must maintain in order to be part of a group (platoon) of vehicles moving along the major street without signal interference.

The direction of traffic flow from intersection, A (Pioneer St.) to F (Sunset) is called outbound while the direction of traffic flow from intersection, F (Sunset) to A (Pioneer St.), i.e., traffic flow in opposite direction is called inbound for a two-way street. The diagonal line that forms the front edge (earlier in time) of a through-band and one that forms the rear edge (later in time) in the time-space diagram have been marked f and r respectively. The horizontal scale can be expressed in time cycles for the time-space diagram instead of time in seconds.

In the design of a time-space diagram, the input information is limited to the distances between the intersections in the problem and the green ratios for these signals. The distances between the intersections for the problem are shown in Table 3. The detail concerning the designing of a time-space diagram is discussed under the different approaches to the problem.

SPEED-VOLUME CURVE

Generally, a highest-speed and lowest-cycle combination is selected within allowable limits for both speeds and cycle times. A further restriction can be imposed by considering the speed-volume relationships. The speed-volume curve is shown in Fig. 3. As the traffic volume increases, the range in average speed decreases. The traffic volume decreases with increasing speeds. This relationship holds true for normal free flow. At a point of maximum volume at a reduced speed, the flow becomes unstable and finally turns to the forced flow. The speed and volume decrease simultaneously in the forced flow region. Forced flow occurs on the highway and the normal flow occurs on small highways and in street traffic flow. In this discussion, the flow of vehicles is assumed to be that of a normal flow adjusting to the given relations. The various values of speed are used in this paper within allowable limit

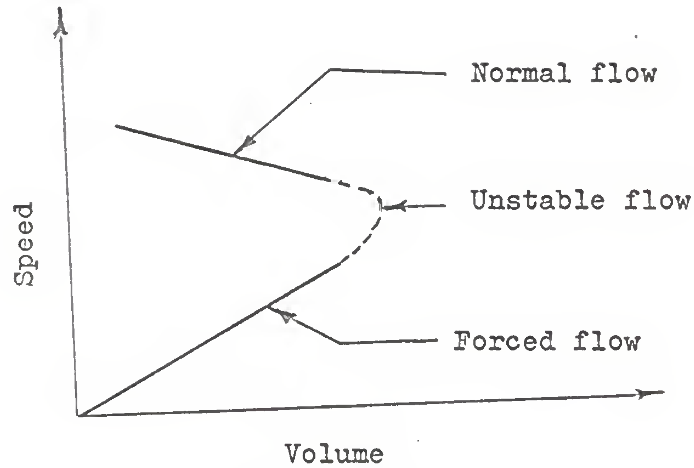

Fig. 3.--Speed-volume curve.

for the given demand volume. The speed-volume curve may differ considerably in values represented, depending on road conditions (e.g., lane width, paving, grade) and weather conditions (e.g., slipperiness, visibility). The volumes are obtained from traffic counts. The actual volume can be considered as a pulsed volume but not as a free flow volume.

OBJECTIVES AND LIMITATIONS OF PROBLEM

The quality of the design may depend on the criterion of optimality or measure of effectiveness chosen. The main objectives in designing the time-space diagram for the solution of the problem may be defined as follows: (1) minimize the length of queue, i.e., reduce the red phase interference in the through-band, (2) maximize through-bandwidths, (3) maximize some criteria of flow capacity, and (4) select a maximum speed and minimum cycle combination that meet flow demands.

The author has tried to select the highest speed and lowest cycle time within the allowable ranges of speed and cycle time. An attempt has been made to make use of higher speeds within the legal speed limits from 20 m.p.h. to 30 m.p.h. The shorter cycle such as 60 seconds or 50 seconds are also used in the problem. Shorter cycles reduce the average waiting time for vehicles stopped at a red signal. In fact, the shorter cycles reduce the feasible volume (vehicles/hour) because of acceleration and deceleration losses at signalized intersections. An effort has been made to determine the best combination of speed and cycle in order to meet the flow demands for a variable under given restrictions.

APPROACH BY TRAFFIC ALGORITHM

Algorithms for traffic-signal control can be employed to design the time-space diagram for the solution of the given six signal problem. The dependent variables of the algorithm are the traffic flow variables, volume and speed. The independent variables of the system are the traffic signal variables, cycle, split and offset. The intersection with the lowest green ratio from the set of intersections is selected as a base. All other intersections may be considered independently in relation to this base. There are other disturbances upon which the system depends such as arrival rates, road conditions, weather conditions, special priorities (emergency and police vehicle, etc.). The effect of these disturbances in this problem is neglected.

The weighted least square fit model is used for the purpose of selecting the best combination of the highest speed and lowest cycle within allowable limits for both speeds and cycle times. This combination of cycle time and speed means that the speed is influenced by 1/2 x cycle time x mean speed = K* which yields a better solution than any other such combination. The system constant K* is also called "Best space periodicity constant". The weighted least square fit model by a weighting coefficient a_i is determined by

$$A = \frac{4}{V^2} \sum_{i=1}^{N} (D_i - K\, m_i)^2 \cdot a_i^2 \quad \text{-------- (1)}$$

where N = number of signals in the problem.

V = speed of vehicles in either direction.

D_i = distance between intersection i and the base.

K = space periodicity constant = $1/2 \cdot c \cdot v$

$m_i = (1 \pm g_i) \cdot n_i$ = the modified integer,

$0 < g_i < 0.5$

n_i = An integer

(The sign (+ or -) depends on the occurrence of a lead-trial or trial-lead fit.)

$a_i = \max_L [F_{iL}]$

where F_{iL} is later defined as a function of required volume and green ratio for intersection i in direction L. If we differentiate the model function A of equation (1) with respect to K and setting $\delta A/\delta K$ equal to zero for minimum criterion of function A, we get the optimal space periodicity

$$\text{Constant} = K^* = \frac{\sum_{i=1}^{N} a_i^2 \sum_{i=1}^{N} a_i^2 D_i m_i - \sum_{i=1}^{N} a_i^2 D_i \sum_{i=1}^{N} a_i^2 m_i}{\sum_{i=1}^{N} a_i^2 \sum_{i=1}^{N} a_i^2 m_i^2 - (\sum_{i=1}^{N} a_i^2 m_i)^2} \quad \text{--- (2)}$$

The free flow volume for an intersection can be calculated by inserting the actual or pulse volume (observed from the field count data) and the green ratio of the traffic-signal at that intersection. The relationship for computing free flow volume can be obtained by

$$\frac{\text{Actual (Pulse) Volume}}{\text{Free (Capacity) Volume}} \times F = \text{Green Ratio}$$

where Green Ratio = $\frac{\text{Green Time}}{\text{Cycle Length}}$

and F = A safety or inefficiency factor. It is always greater than one. The safety factor, F is used to compensate for acceleration and deceleration losses caused by signalization and also for possible inaccuracy of the assumed speed-volume curve.

The minimum through-bandwidth required to allow a demand at a given speed can be determined by

$$B_{min \cdot L} = \frac{\text{Actual Demand}}{\text{Free Flow Volume}} \times C \times F$$

where C = cycle time in seconds.

The safety factor, F used in expressing both relations is modified by the cycle time, C as $F = 1 + E \cdot \frac{100}{C}$ where the values of safety factor, E varies from 0.00 to 0.50.

After finding the best combination of cycle and speed within allowable limits for the demand volume, signal offsets are selected accordingly for each signalized intersection for a maximum feasible through-band design. Assuming weighting factor α_i and $1-\alpha_i$ for direction 1 and 2, respectively, where $0 < \alpha_i < 1$, the offset for intersection i is given by

$$\phi_i = t_{i1}\,\alpha_i + (C - t_{i2})(1 - \alpha_i) - 1/2(G_i - G_b).$$

This formula of the offset is used for the lead-trial interference configuration. The condition for lead-trial can be recorded if $C/2 \leq T_i < C$, where T_i is turn-around time from the intersection i to the base. And the offset for a trial-lead ($0 \leq T_i \leq C/2$) configuration is given by

$$\emptyset_i = t_{i1} \cdot \alpha_i + (C - t_{i2})(1 - \alpha_i) - 1/2(G_i - G_b) + C \cdot \alpha_i$$

where $t_{i1} = \frac{D_i}{V_i}$ = Time required to travel up to intersection i from the base in direction 1.

$t_{i2} = \frac{D_i}{V_2}$ = Time required to travel up to intersection i from the base in direction 2.

C = Cycle time in seconds.

G_b = Green interval of base. (Minimum green interval from the set of signals.)

G_i = Green interval of intersection i.

A program for the IBM 1620 was made in order to compute the best values of the space periodicity constant K* using the equation (2) for the optimal constant. The various values of weighting factor and the modified integer were selected in the program for the space periodicity constant. Unfortunately, the values of optimal space periodicity constant obtained for the six signal problem were not satisfactory to determine which one can be utilized to obtain the best combination of speed and cycle time within allowable limits. The program concerning values of the input and output are not shown in this paper.

The main line computer program was written in FORGO for the IBM 1620 to compute the free flow volume, the best design of offset, the through-bandwidth and the selected speed and cycle time combination, i.e., the space periodicity constant.

The flow diagram for the main line program is shown in Fig. 4. The inefficiency factor, F is varied by different values of factor, E $(0 \leq E < 0.5)$ and cycle time. This factor affects the free flow volume and through-bandwidths. The weighting factor, α_i was varied from 0.1 to 0.9 for the computation of offset of the signalized intersections with respect to the base traffic signal. In the six signal problem, the intersection at Bluemont Avenue was selected as the base. The variation in the weighting factor affects the value of the offset required for the signals when designing a time-space diagram. The output from the program which was necessary to make the time-space diagram was dependent on varying the constants over their range hence, different values of free flow volume, offset, through-bandwidths and the space periodicity constant are obtained. No attempt was made to draw the time-space diagram from the output of the solution to the problem by this algorithm because of many output results.

APPROACH BY HALF INTEGER SYNCHRONIZATION

The stopping or slowing down of a vehicle due to red interference while passing through a street by maintaining the preassigned speed can be reduced by proper synchronization of the traffic signals along the street. The half integer synchronization technique can be applied with better results than traffic algorithm as it contains fewer variables in the basic approach to the solution of the problem. This method also gives

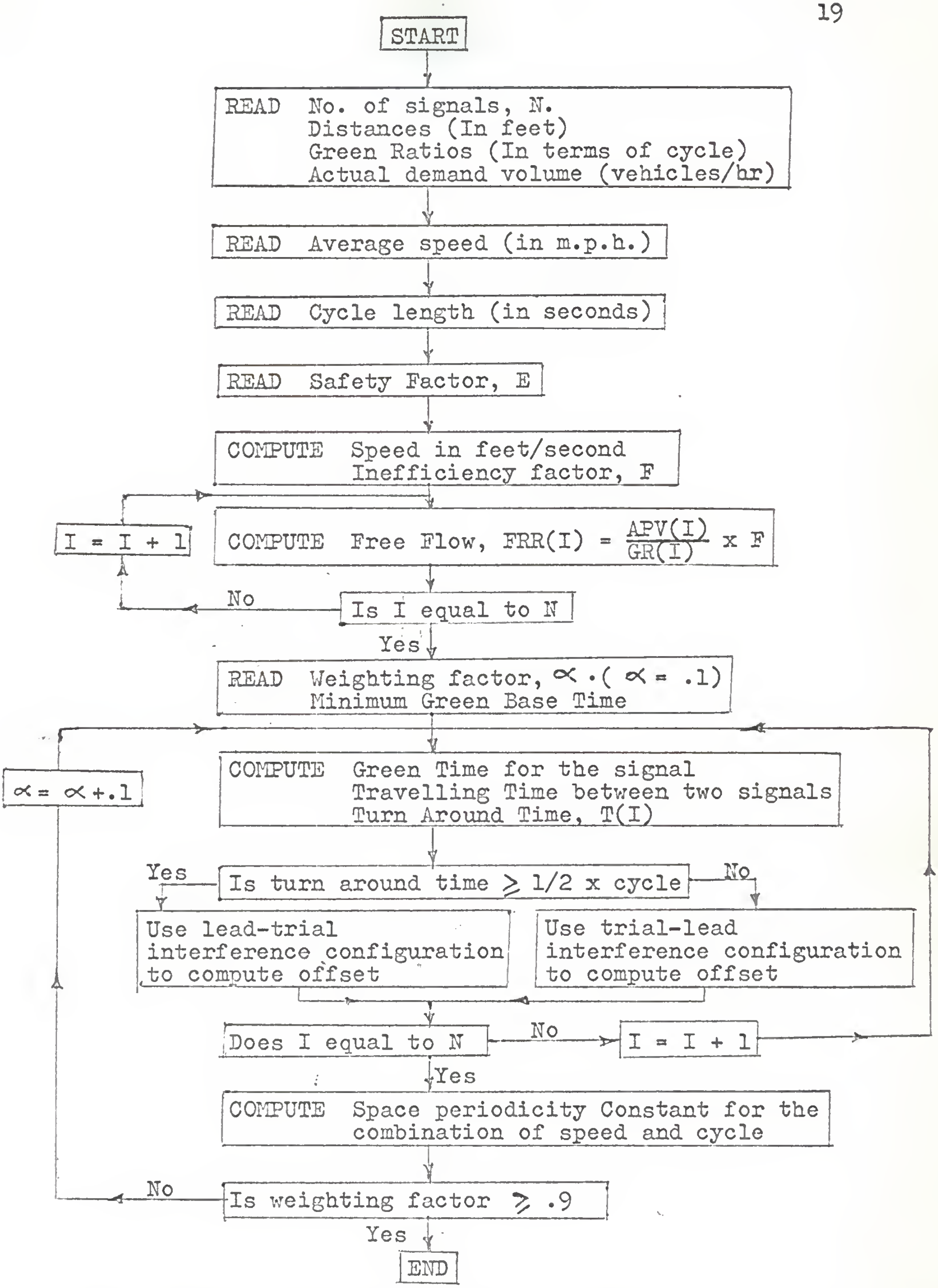

Fig. 4.--Flow diagram of Traffic Algorithm.

a better solution when green times differ from signal to signal. It can be possible to vary the speed in either direction between any two adjacent signals.

A solution of same six signal problem was attempted by use of Half Integer Synchronization. This method (4) has been proved to be the best optimal technique for the solution of the given problem. The basic theory is not described in this paper. It has been shown why it is called half integer synchronization (8). The problem is solved for equal bandwidths. This method is also applicable to unequal bandwidth if the platoon size is known. A computer program using this approach has been written in FORGO for solution on the IBM 1620. This program can be applied to any similar type of problem using very few changes in the input data format of the program. The limitation in the use of this technique is that the cycle times for all signals in the problem must be the same, i.e., the cycle length must be the same one for all signals.

The summary of the technique which is important in the use of this program is described in this paper. The procedure given here is applicable to any size of the problem.

The number of the signals in order of distances along the street is i = 1, 2, - - - n. In the six traffic signal problem, Pioneer St. is considered as the first signal in the program and number i increases according to the signals of N-S and E-W. The direction of increasing is called outbound. The known data from the study which is utilized here are as follows:

the signal cycle length, C in seconds; the red times, r_1, r_2, - - - r_n in fractions of a cycle; the signal positions, x_1, x_2 - - - x_n in feet (known from city map); the outbound speeds between signals, v_1, v_2, - - - v_{n-1} in feet/second; and the inbound speeds between signals $\bar{v}_1$, $\bar{v}_2$, - - - $\bar{v}_{n-1}$ in feet/second (known by legal allowable speed limits along the street).

The computation proceeds in the following steps:

1. Calculate the mean travelling time in fraction of cycle for each signal from the base,

   Y_1, Y_2, - - - Y_n from

   $$Y_i = 0$$

   $$Y_i = Y_{i-1} - (1/2)(r_i - r_{i-1}) + (x_i - x_{i-1})(1/2c)\left[\frac{1}{v_{i-1}} + \frac{1}{\bar{v}_{i-1}}\right]$$

2. Calculate the difference of travelling time between two signals (in fraction of cycle) for inbound and outbound,

   z_1, z_2, - - - z_n from

   $$z_1 = 0$$

   $$z_i = z_{i-1} + (x_i - x_{i-1})(1/2c) \times \left[\frac{1}{v_{i-1}} - \frac{1}{\bar{v}_{i-1}}\right]$$

3. Calculate the maximum equal bandwidth for each signal,

$$B = \underset{i}{\text{Max}}\cdot\underset{j}{\text{Min}}\cdot\underset{\delta = 0,\ 1/2}{\text{Max.}} \left[U_{ij}(\delta) - r_j \right]$$

where $U_{ij}(\delta) = 1 - \text{man}(Y_j - Y_i - \delta)$.

where $0 \angle \text{man}(z) \angle 1$. It is always true.

(e.g., man (-.2) = 1 - man (.2) = 0.8,

man (5.2) = 0.2 and man (.3) = 0.3)

4. A synchronization, O_{c1}, - - - O_{cn}, for maximal equal bandwidths is calculated by selecting i = c to be a maximizing i and δ_{c1}, - - - δ_{cn} be the corresponding maximization of δ's value (substituting either 0 or 1/2). Then,

$$\theta_{cj} = \text{man}\left[Z_j - Z_c + \delta_{cj}\right]$$

The bandwidth in each direction is Max $[0, B]$ where θ_{ij} is defined as the offset or relative phase of the signals S_i and S_j, measured as the time from the center of a red of S_i to the next center of red of S_j (in terms of cycle), $0 < \theta_{ij} < 1$.

Figure 5 outlines the procedure followed by the computer program using the half integer synchronization technique. The description of input data required for the program is given in Table 4. Table 4 describes the card type, description of data items and numbers of cards essential per computation. The different values of input data are chosen for the optimal solution of the problem. The four different samples of input data which were selected are given in Table 5. The output from

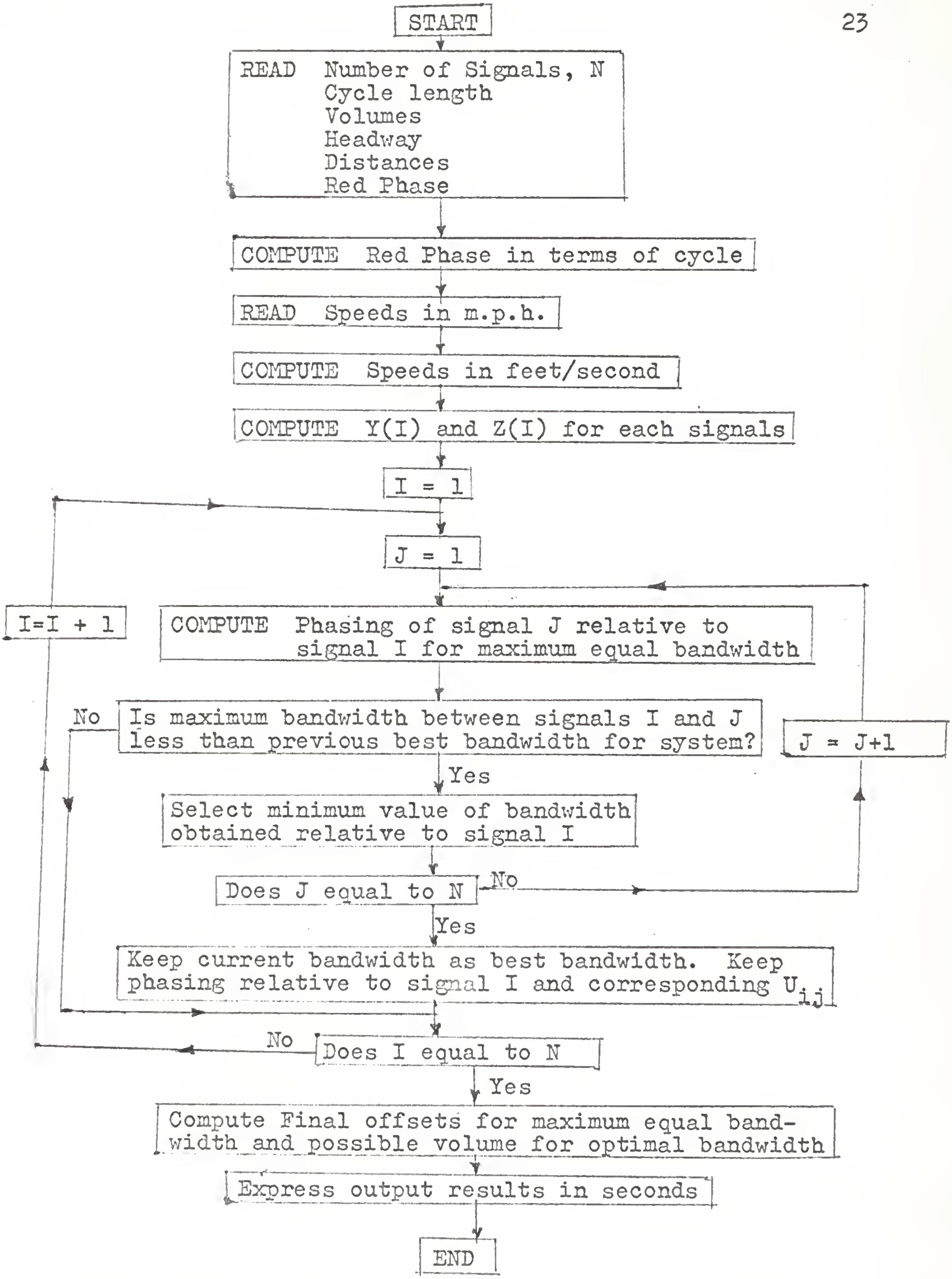

Fig. 5.--Flow diagram of half integer synchronization.

the sample input data is given in Table 7. The different figures obtained in output are explained completely in Table 6, defining the detail of card type, description of data item and the result obtained per computation.

Table 4. Input data to program (half integer synchronization).

Entry	Description of data item	Units
Card-type 1		
1	Number of signals	Integer
2	Cycle length	Seconds
3	Inbound volume	Veh/hr.
4	Outbound volume	Veh/hr.
5	Vehicle headway	Seconds
	One card per computation	
Card-type 2		
1	Distance of signal from origin	Feet
2	Red Phase of signals	Seconds
	Number of cards = number of signals	
Card-type 3		
1	Inbound block speed	
2	Outbound block speed	
	Number of cards = number of signals	

Table 5. Selected input in half integer program.
(As illustrated in Table 4)

1.	6	60.0	350.0	350.0	2.0
	0.0	15.0			
	2393.0	40.0			
	3028.0	34.0			
	4376.0	27.0			
	5011.0	27.0			
	5964.0	27.0			
	20.0	20.0			
	20.0	20.0			
	20.0	20.0			
	20.0	20.0			
	20.0	20.0			
2.	6	60.0	350.0	350.0	2.0
	0.0	20.0			
	2393.0	30.0			
	3028.0	25.0			
	4376.0	27.0			
	5011.0	25.0			
	5964.0	27.0			
	25.0	25.0			
	25.0	25.0			
	25.0	25.0			
	25.0	25.0			
	25.0	25.0			
3.	6	60.0	350.0	350.0	2.0
	0.0	25.0			
	2393.0	35.0			
	3028.0	32.0			
	4376.0	27.0			
	5011.0	27.0			
	5964.0	27.0			
	25.0	25.0			
	25.0	25.0			
	25.0	25.0			
	25.0	25.0			
	25.0	25.0			
4.	6	60.0	350.0	350.0	2.0
	0.0	15.0			
	2393.0	40.0			
	3028.0	34.0			
	4376.0	27.0			
	5011.0	27.0			
	5964.0	27.0			
	30.0	30.0			
	30.0	30.0			
	30.0	30.0			
	30.0	30.0			
	30.0	30.0			

Table 6. Output data from half integer synchronization program.

Entry	Description of data item	Units
Card-type 1		
1	Number of signals	Integer
2	Cycle length	Seconds
3	Vehicle headway	Seconds
	One card per computation	
Card-type 2		
1	Inbound bandwidth	Seconds
2	Outbound bandwidth	Seconds
3	Number of restricting (critical) signal	Integer
	One card per computation	
Card-type 3		
1	Distance of signal from origin	Feet
2	Red Phase of signals	Seconds
3	Right Hand Side of red phase from origin where the origin is taken as the center of red for the critical signal	Seconds
4	Offset relative to restricting signal	In terms of cycle length
	Number of cards = number of signals	
Card-type 4		
1	Front edge of outbound band	In terms of cycle length
2	Rear edge of inbound band	
3	Total system travel time inbound	In terms of cycle length
4	Total system travel time outbound	
	One card per computation	

Table 7. Selected output results from half integer program.

1.	6	60.0	2.0	
	12.68	12.68	6	
	0.0	15.0	27.5	0.5
	2393.0	40.0	50.0	0.5
	3028.0	34.0	17.0	0.0
	4376.0	27.0	13.5	0.0
	5011.0	27.0	13.5	0.0
	5964.0	27.0	13.5	0.0
	.83636	4.1636	3.3886	3.3886
2.	6	60.0	2.0	
	13.3	13.3	4	
	0.0	20.0	10.	0.0
	2393.0	30.0	15.	0.0
	3028.0	25.0	12.5	0.0
	4376.0	27.0	13.5	0.0
	5011.0	25.0	12.5	0.0
	5964.0	27.0	43.5	0.5
	0.2359	2.764	2.7109	2.7109
3.	6	60.0	2.0	
	13.3	13.3	4	
	0.0	25.6	12.5	0.0
	2393.0	35.0	17.5	0.0
	3028.0	32.0	16.0	0.0
	4376.0	27.0	13.5	0.0
	5011.0	27.0	13.5	0.0
	5964.0	27.0	43.5	0.5
	0.2359	2.764	2.7109	2.7109
4.	6	60.0	2.0	
	21.568	21.568	2	
	0.0	15.0	7.5	0.0
	2393.0	40.0	20.0	0.0
	3028.0	34.0	17.0	0.0
	4376.0	27.0	43.5	0.5
	5011.0	27.0	13.5	0.0
	5964.0	27.0	13.5	0.0
	0.42689	2.5731	2.259	2.259

The same six traffic signal problem has been tried by hand calculation using the half integer synchronization technique. The solution took about one hour. The signals are at 0, 2393, 3028, 4376, 5011 and 5964 feet corresponding red times are 0.4, 0.6, 0.6, 0.45, 0.45, 0.45 cycle. c = 60 seconds = cycle length, v = speed = 21 m.p.h. in both directions. Figure 2 shows the time-space diagram for maximum bandwidths; B = 16 seconds. The method here gives a bandwidth of 16 seconds using the phases (listed in order of increasing signal distance), 0, 1/2, 0, 1/2, 0, 1/2. The possible volume for the obtained maximum bandwidth is 480 vehicles/hour.

The procedure for plotting the time-space diagram for the output using the half integer synchronization program is described here.

The time in seconds (or cycle) can be chosen as horizontal axis while the position of all traffic signals along a street can be marked on a vertical axis with respect to origin. The first intersection, A is taken as an origin for distance axis (vertical axis). Thus the position of signals A, B, C, D, E, and F can be marked with true scale on a distance axis. The restricted (critical) signal can be learned from the output results. The various figures of output results are explained in Table 6 by words. The center of the red interval (rc) of critical signal S_c is always taken as the origin for the time axis. The center of red of S_c is taken as a reference point for other signals. The cycle timing for the critical signal can be drawn by knowing the red interval, green interval and common cycle length. The left side of the outbound band is at rc/2, the right side at rc/2 + B (where B is the maximum equal bandwidths). The inbound band has its left side at 1 - rc/2 - B and its right side at 1 - (rc/2). The edges of the outbound band at S_j (next signal) are found by adding t_{cj} (travelling time from signal S_c to S_j in outbound) to the edges at S_c. For inbound direction add $\bar{t}_{cj}$. The time t_{cj} and $\bar{t}_{cj}$ will be equal if the speed in both directions is the same. The right hand side of red phase from origin where the origin is taken as the center of red for the critical signal, is known from the output data. The right hand side of red phase of rest of traffic signals can be marked on the time-space diagram. The complete timing of cycles for each signal can be drawn by knowing the cycle length and the red interval of the signal. The red time interval is represented by a dark line and green (plus amber) by blank. The offset relative to the restricting signal gives an idea about the phase of the signal with respect to a critical signal whether it is in phase or out of phase. Thus, all the horizontal broken lines for each signal can be drawn. The front edge of the outbound band (in seconds) is marked at the first intersection, A which is known from output results. The equal maximum bandwidths is known. The rear edge of outbound band (in seconds) can therefore be marked by adding the maximum bandwidth, B in the front edge of the outbound band at the first intersection.

The rear edge of the inbound band (in seconds) which is known from output results, can be marked at the first intersection, A. The front edge of the inbound band can be found by subtracting the maximum bandwidth, B from the rear edge of inbound band. The total system travel time for outbound and inbound gives the rear and front edges of outbound and inbound respectively at the last intersection. In the case of the inbound band, the total system travel time is subtracted from the quantity at the first intersection. Thus the complete two pairs of diagonal lines can be drawn. The illustrating example of plotting a time-space diagram is described as follows.

The time-space diagram shown in Fig. 6 can be drawn by using the output No. 2, from the sample output results (shown in Table 7). The vertical scale is represented by one inch being equal to 1000 feet on vertical axis. The positions of signal A, B, C, D, E, and F are marked on the vertical scale at 0, 2393, 3028, 4376, 5011, 5964 feet respectively from the first intersection, A which is taken as the origin for the vertical axis. The horizontal scale is represented by one inch equal to 40 seconds on the horizontal axis. The restricting signal is number 4 or D. If there is a real interference at any signal on the through-band, the signal is called the restricting signal. The offset for this signal is always zero, i.e., in phase. The center of the red interval is taken as the origin for the horizontal axis. The horizontal line of 13.5 seconds (right hand side of red phase for restricting signal)

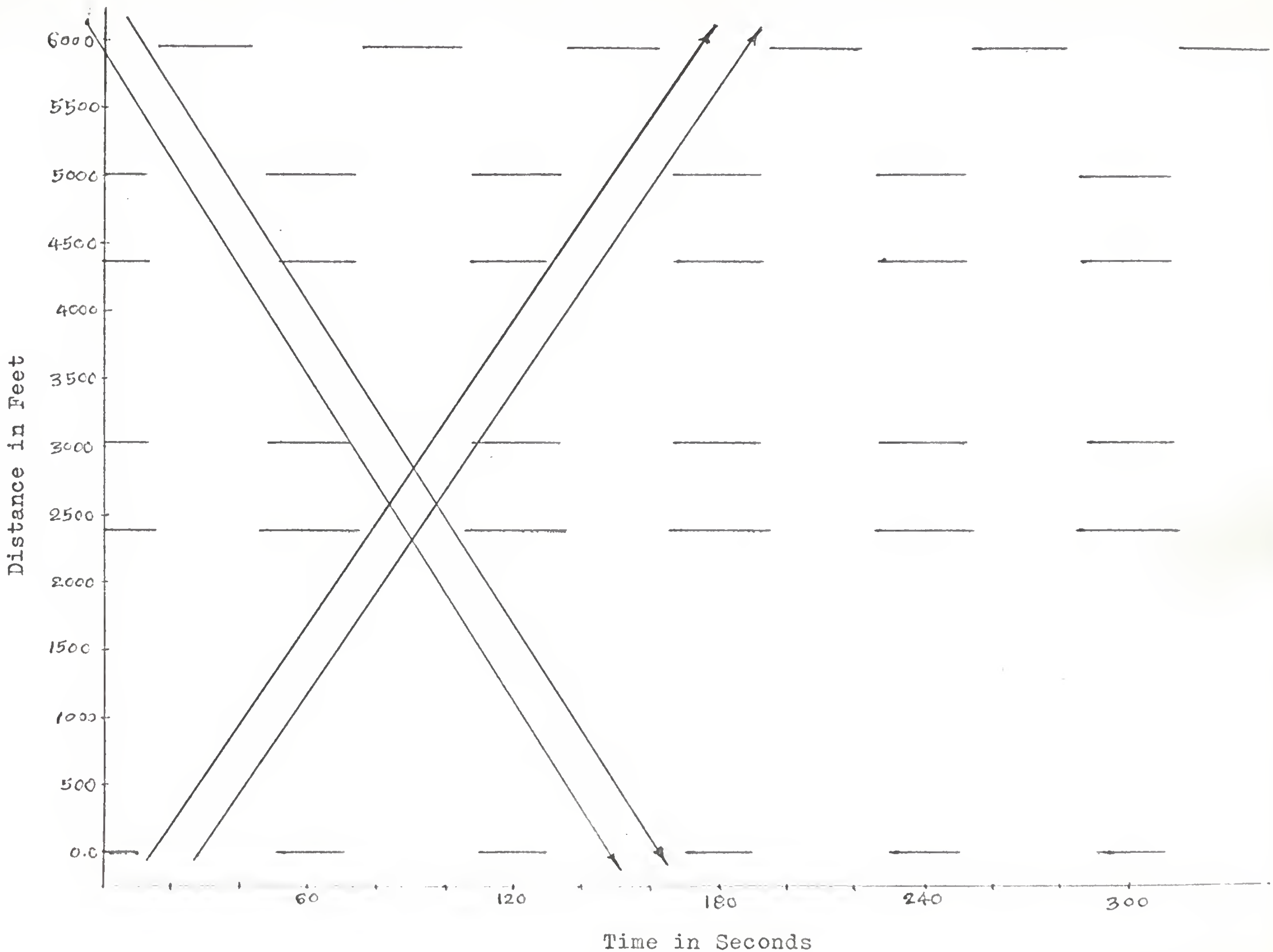

Fig. 6.--Time-space diagram with equal bandwidths, 13.3 sec. and volume, 399 veh/hr.

is drawn at intersection, D. The green time is represented by blank of 33 seconds, the full line of 27 seconds red time is drawn on the restricting signal, D. Thus the process of repeating cycle times on the intersection is drawn for four or five cycles. Similarly, the right hand side of red phase for other signals A, B, C, E, and F is marked at 10.0, 15.0, 12.5, 12.5, and 43.5 seconds respectively from origin. The repeating cycle timings are drawn by horizontal broken lines for all signals by knowing the red times and the common cycle length. The front edge of the outbound band is marked at 14.5 seconds (.2359 x 60 sec.) from its origin on first intersection, A. The rear edge of the outbound band is marked at 27.8 seconds by adding maximum bandwidths. The rear edge of the inbound band is marked at 166 seconds (2.764 x 60 sec.) from origin on first intersection, A. The front edge of the inbound band is marked at 152.7 seconds by subtracting the maximum bandwidths. The front and rear edges of the outbound band on the last intersection, F are marked at 177.1 and 190.4 seconds respectively from the origin. The speed is 25 m.p.h. in both directions. Thus the four points on the first and last intersection for front and rear edges of the outbound band are joined by two diagonal parallel lines because of same speed in either direction. If the speed varies along the street from signal to signal the edges of outbound (inbound) for each signal must be calculated separately by knowing the distances between adjacent signals and speed. The front and rear edges of inbound band on the last intersection are marked at 3.0 and 16.3 seconds from the origin. The four points on first and last intersections for the inbound band are joined by two parallel diagonal lines. The possible volume for the maximum equal bandwidths, 13.3 seconds was 399 vehicles/hour in both directions. Similarly, other diagrams from output results No. 1, 3, and 4 from Table 9 are shown in Figs. 7, 8, and 9 respectively.

The solution of the problem was not satisfactory from the output results 1, 3, and 4. It can be seen by designing the time-space diagram for the output results which is shown in Figs. 7, 8, and 9. The time-space diagram shown in Fig. 7 was not optimal for the required solution of the problem because of the complete red interference of signal number 2 in the maximum equal through-bandwidths. The last two time-space diagrams shown in Figs. 8 and 9 were not satisfactory because of red interference in through-bandwidths by this technique.

However, this technique comes very close to the optimal solution of the problem. It is easy to approach such a problem by using this technique. It is simple to design the time-space diagram from the output results by using this technique.

The time to solve a problem involving six signals takes about one minute on an IBM 1620 computer. This program is limited to problems with 50 signals on an IBM 1620 computer.

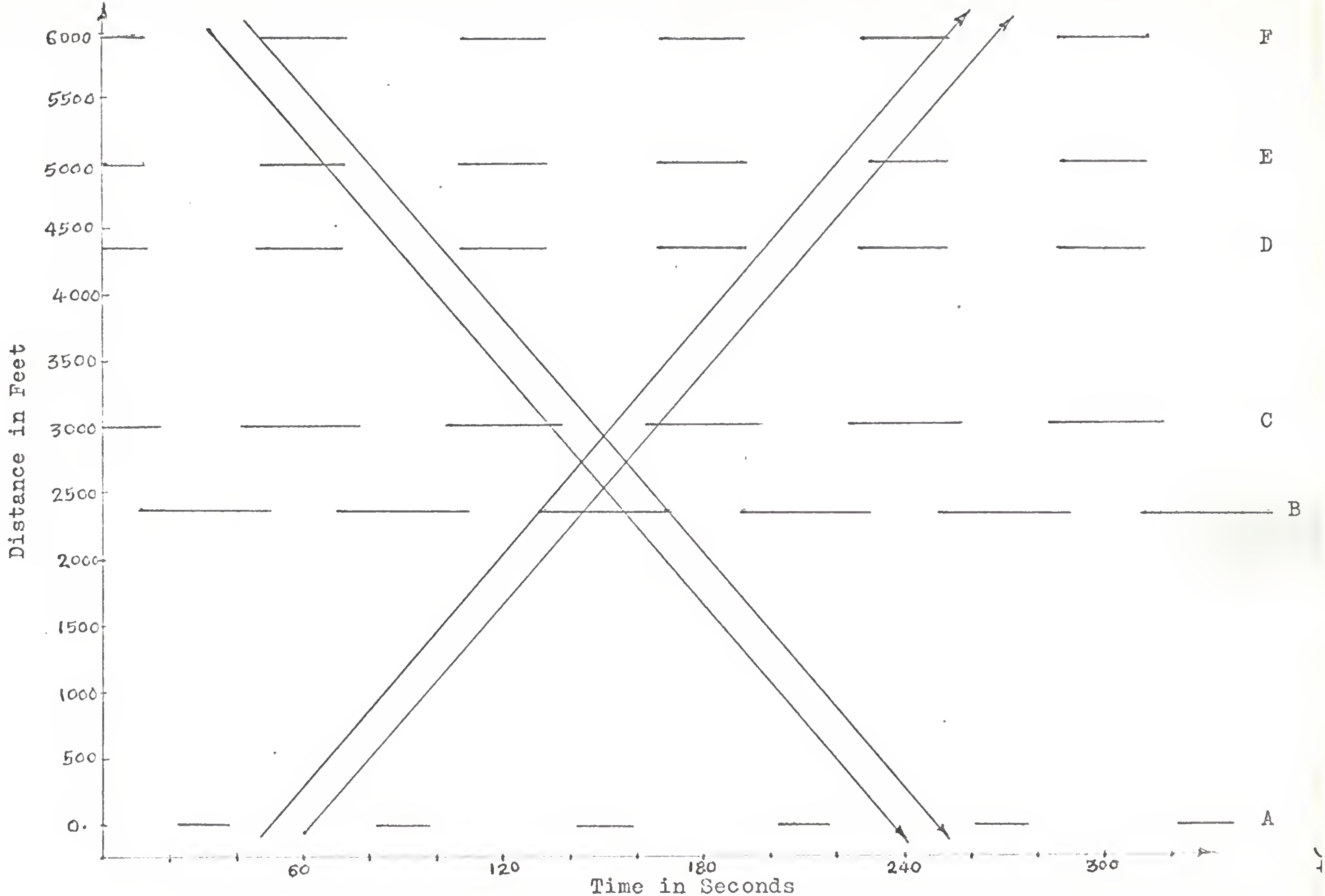

Fig. 7.--Time-space diagram for equal bandwidths, 12 sec. and through-band volume, 380 veh/hr.

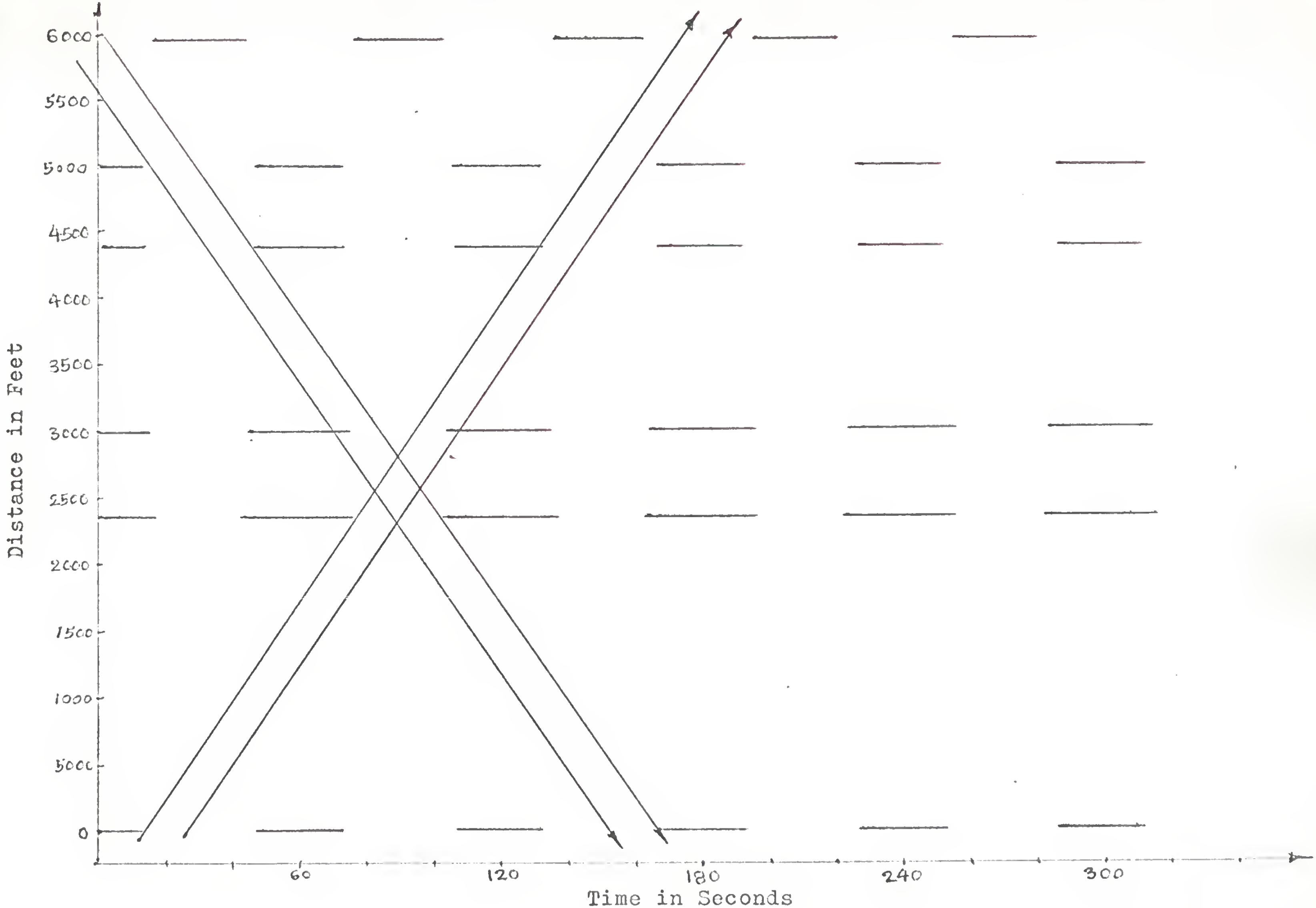

Fig. 8.--Time-space diagram for equal bandwidths, 13.3 sec. and volume, 399 veh/hr.

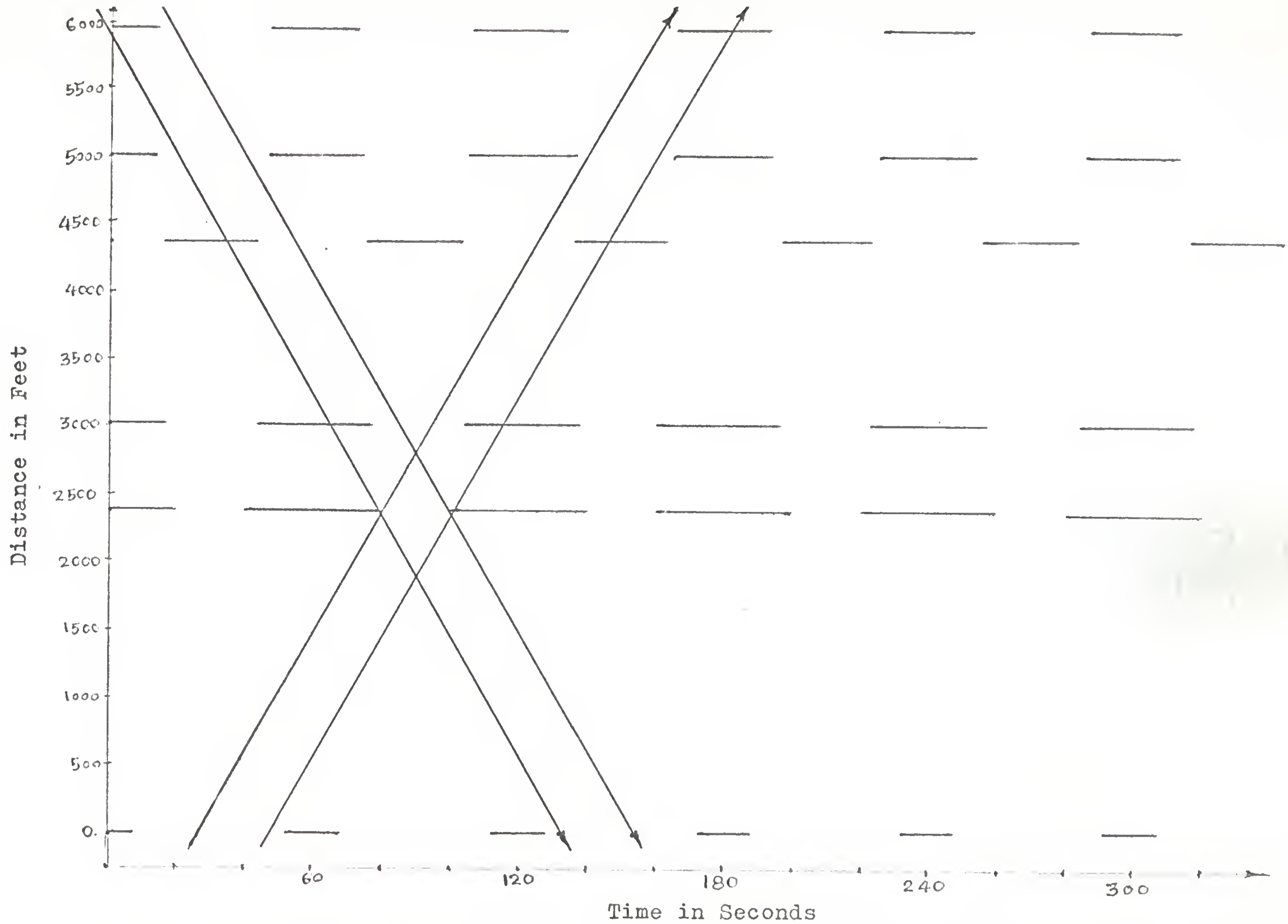

Fig. 9.--Time-space diagram for equal bandwidths, 21.5 sec. and volume 648 veh/hr.

SIMULATION OF TRAFFIC DELAY AT SIGNALIZED INTERSECTION BY QUEUEING THEORY

At an intersecting road or street, cross street traffic has to stop while the main street traffic proceeds. The delay of traffic (under red light) depends upon many variables. The most important are approach volumes and turning movements. The intersection model for the simulation of traffic delay in the six signal problem is an intersection of two, two-lane or three-lane, two-way streets.

In the six signal problem, the two-way street is N-Manhattan Avenue and Anderson Avenue while the intersecting streets (cross street) are Pioneer St., Bluemont Avenue, N-14th St., N-17th St., Denison and Sunset. So the major street is two-way N-Manhattan Avenue and Anderson Avenue.

The model includes the approaches to these intersections for a length sufficient so that vehicles enter the system before being influenced by any condition existing at the intersection. Hence, it is assumed that there is no disturbance on traffic flow while arriving at the intersection. In brief, the simulation of traffic delay is accomplished as follows. Each time a major-street vehicle arrives at the intersection the model is analyzed. If the major-street vehicle can be released and has not been delayed, the traffic on both cross-street approaches is brought up to this time (vehicles delayed) and the major-street vehicles are released. If the major-street vehicle has been delayed or is stopped, only cross-street right-turning vehicles are permitted to proceed while all others are further stopped. While a major-street vehicle is stopped waiting to make a left turn, no through or left-turning cross-street vehicle can enter the intersection. The opposing lane is permitted to continue until a gap arrives which is accepted by the stopped vehicle. The simulation process is repetitive, generating new traffic as necessary, until the "run" is completed.

The vehicles arriving at the intersection are generated randomly by the simulation model assuming the time between arrivals follow an exponential distribution. The time between arrivals is simulated by the model using the pre-selected hourly actual volume. The model for exponential time between arrivals is given by

$$T = - \frac{1}{\text{Actual hourly volume}} \times \ln(F)$$

where F is randomly generated from a random number generator in fraction ($F < 1$). The time, T is the time between arrival for one vehicle at an intersection. The brief description of the procedure used in this model for the computer program is as follows.

The total arrival of vehicles is simulated randomly by the model during the red signal time. The total delay (number of vehicles in queue) is simulated for 30 cycles with the same situation of traffic. The total delay depends on the time between arrivals (exponentially distributed) during the red signal period. The total vehicles that can travel with the green light are also simulated in the program using this model.

In the first phase of signal, the green light is assumed on major street. The total vehicles which can proceed with the green light are simulated using the model. The vehicles in the cross street queue waiting for the green light are also simulated. Then the green time required for the cross-street traffic is calculated proportionately using the green time interval and total number of vehicles moving during the green interval. The cumulative average delay is computed to compare with observed and the delay by simulation.

In the next phase of the signal cycle, i.e., from green to red on the major street, the total delay is simulated on the major street by using the same model. The total delay is repeated for 30 cycles assuming the same situation of traffic flow. Total time required for the vehicles which were delayed in the previous phase of signal, i.e., under red interval on cross-street is chosen from traffic engineering standards (2). The time required to bring the queue of vehicles up to speed which were delayed on the cross-street while waiting at the red light is assumed to be 4 seconds. The time required to clear the intersection for each vehicle after achieving motion in queue is assumed to be 2 seconds. It is possible to clear more vehicles than the total queue (in vehicles) with green light. Again the extra vehicles are generated randomly that can pass through during the green time.

For this case, the proportional green time required on the major street is computed by green time on cross-street and total vehicles that can pass with the green interval. The cumulative average delay is computed to compare with observed and delay by simulation. A restriction on the random subroutine is made to reduce the large fluctuation of times between arrival.

A computer program for the IBM 1410 was written for the above procedure and is shown in Appendix C. Thus, the procedure described above was used in the simulation of traffic delay for the six signal (fixed time base) problem. The variables used in the program are described in Appendix D. The input data with description of the items necessary in this program are shown in Table 8. The traffic delays for six signals were simulated by this program. The sample output for the intersection at Bluemont Avenue is shown in Table 9 considering the delay at the major street, i.e., at N-Manhattan Avenue. The theoretical delay for 30 cycles with same traffic analysis is compared with the actual observed delay and cumulative delay. It is shown in Fig. 10. It was observed that delay in the actual delay study was more than delay by simulation. The actual delay was studied during peak hours, therefore, it was not the constant all day. The delay by simulation was the average delay of traffic during a day. The program for simulation of the six signal problem takes about 15 minutes on the IBM 1410. The other output results were not shown here. The simulation technique was applied to traffic delay by using queueing theory.

Table 8. Selected input in simulation program.

Sig. No.	Cycle length in sec.	Green ratio on major street	Green ratio on cross street	Flow capacity at major street in vehicles/hour	Flow capacity at cross street in vehicles/hour
A	50.0	.64	.22	300.00	300.00
B	60.0	.30	.30	350.0	300.00
C	60.0	.40	.33	400.00	300.00
D	60.0	.50	.40	350.0	350.0
E	60.0	.50	.40	300.0	300.0
F	60.0	.50	.50	300.0	300.0

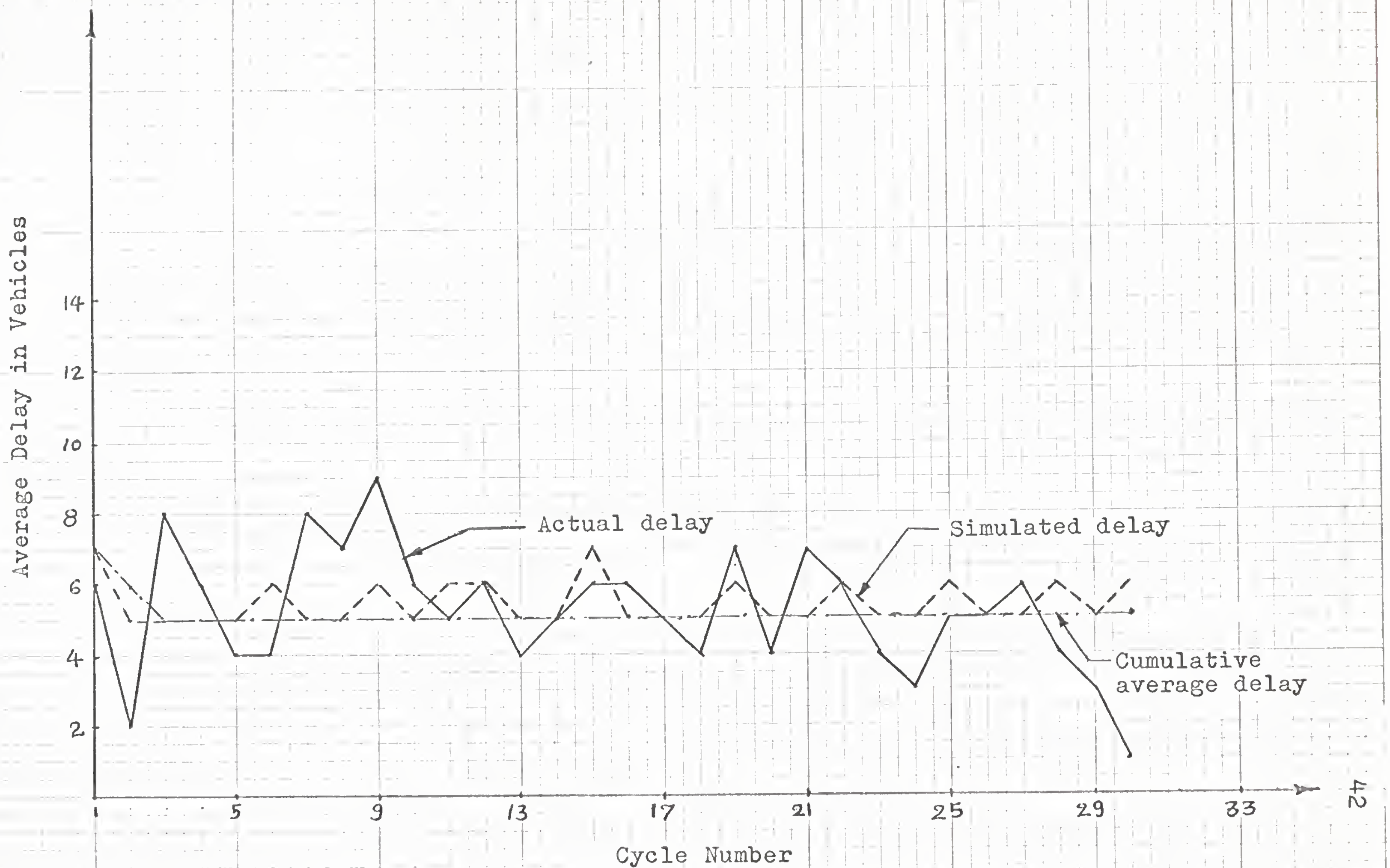

Fig. 10.--Comparisons of delay in vehicles per cycle for average delay by simulation and actual delay at Bluemont Avenue.

Table 9. Output results from simulation program.

Cycle No.	Total arrival in vehicles	Green time required for total arrival in secs.	Length of queue in vehicles	Total delay in secs.	Aver. time between arrival in secs.	Aver. arrival rate in vehicles/sec.	Relative green time required for queue in secs.	Cum. aver. total delay in vehicles
1	6	21.49	7	22.72	3.24	.30	21.0	7
2	5	19.95	5	22.77	4.55	.21	18.0	6
3	5	18.40	5	21.29	4.25	.23	18.0	5
4	6	20.51	5	24.93	4.98	.20	15.0	5
5	6	24.39	5	21.05	4.21	.23	15.0	5
6	5	18.06	6	23.3	3.88	.25	21.6	5
7	5	18.09	5	22.13	4.42	.22	18.0	5
8	5	20.19	5	26.64	5.32	.18	18.0	5
9	6	21.64	6	21.61	3.60	.27	18.0	5
10	7	21.88	5	24.17	4.83	.20	12.8	5
11	5	18.61	6	22.87	3.81	.26	21.6	5
12	6	25.72	6	26.91	4.48	.22	18.0	5
13	7	23.45	5	22.47	4.49	.22	12.8	5
14	6	19.86	5	22.20	4.44	.22	15.0	5
15	6	21.70	7	23.86	3.40	.29	21.0	5
16	6	20.28	5	24.63	4.92	.20	15.0	5
17	5	19.81	5	23.48	4.69	.21	18.0	5
18	7	24.19	5	21.03	4.20	.23	12.8	5
19	6	20.95	6	21.53	3.58	.27	18.0	5
20	6	19.55	5	22.39	4.47	.22	15.0	5
21	6	19.10	5	22.05	4.41	.22	15.0	5
22	6	24.93	6	21.65	3.60	.27	18.0	5
23	7	22.45	5	22.90	4.58	.21	12.8	5
24	6	18.81	5	23.78	4.75	.21	15.0	5
25	5	18.44	6	21.41	3.56	.28	21.6	5
26	7	18.69	5	21.83	4.36	.22	12.8	5
27	6	22.29	5	22.29	4.45	.22	15.0	5
28	6	19.61	6	23.47	3.91	.25	18.0	5
29	6	21.04	5	23.13	4.62	.21	15.0	5
30	5	18.51	6	24.29	4.04	.24	21.6	5

CONCLUSION

It should again be pointed out that control of only the six signals described in the report were considered in this paper. The different approaches can be generalized for any similar type of problem. The input information and size of problem must be changed before proceeding with the program. The discussion of methods and flow diagrams are meant for general usage of the technique.

It was found practically from the delay study that the same improvements are needed in the proper offset of all the six signals. The attempt was made to reduce the complete delay on the selected traffic flow. The two techniques were applied to the best solution of the problem by designing the time-space diagram. The optimum solution of the synchronization of the six signals is found by half integer synchronization technique.

The traffic algorithm technique failed here for the optimal solution of the problem because of carrying more constant variables which affect the output results for the design of the time-space diagram.

The half integer synchronization technique was observed to be a quite satisfactory and basic approach to the solution of the problem. Fewer significant variables were found in this technique. This technique was used for five different sets of input data in the problem. The two outputs were quite satisfactory to the solution of problem. In one case, the maximum bandwidths were found to be 16 seconds. The possible volume for the maximum bandwidth was 480 vehicles/hour. The speed for the outbound and inbound band was 21 m.p.h. This is the speed that vehicles travelling along the major street must maintain. The timing of the six signals must be changed and synchronized to obtain the offset determined by this technique. The speed was particularly low in this solution.

The simulation of traffic delay was programmed for an IBM 1410. The simulation model used in the traffic delay was the exponential time between arrivals (queueing theory). Thus, the program was made to compute the theoretical delay and cumulative delay for traffic at the intersection. The theoretical delay was less than the actual delay studied. The actual delay study was made during the peak traffic hours of the day.

The author has suggested retiming and synchronizing the six signals according to the optimal solution obtained. It is the best solution for low speed and long range plan when the traffic flow will increase from the present volume of 300 vehicles/hour, since the solution given here will handle 480 vehicles/hour.

ACKNOWLEDGMENTS

In compiling the necessary data for this paper, the cooperation of Manhattan City Engineer's Office, and Civil Engineering Department of Kansas State University in furnishing all available information is gratefully acknowledged. In particular, appreciation and thanks is expressed to Professor and Director of IBM 1620 computing center at Kansas State University, Professor J. J. Smaltz for his constructive suggestions, guidance, close cooperation, painstaking efforts in reviewing the report, kind advice and encouragement during the entire study period.

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APPENDICES

APPENDIX A

Sample Field Count Data of Delay Study

Location of study:* N-Manhattan Avenue and Bluemont Avenue

Time and date of study: October 13, 1966 between 4:45-5:15 p.m.

Cycle number	Length of queue (in vehicles) under red light		
	Left turn	Through	Right turn
1	1	2	6
2	2	1	2
3	4	4	8
4	4	2	6
5	2	3	4
6	9	2	4
7	7	3	8
8	6	2	7
9	7	2	9
10	6	2	6
11	8	2	5
12	8	1	6
13	9	3	4
14	10	3	5
15	7	1	6
16	5	2	6
17	6	1	5
18	7	2	4
19	6	3	7
20	7	2	4
21	5	2	7
22	4	1	6
23	4	2	4
24	5	1	3
25	3	2	5
26	4	3	5
27	4	2	6
28	5	3	4
29	3	1	3
30	2	1	1
Totals	160	61	156

*Delay study taken per cycle for the traffic coming from N-Manhattan Avenue (North-South bound) at Bluemont Avenue.

APPENDIX B

Total Delay Study Chart

Location	Time and date	Total delay			Percentage delay		
		Left	Through	Right	Left	Through	Right
Bluemont Ave. at N-Manhattan Ave.	October 10, 1966 between 4:30-5:30 p.m.	18	126	226	0.0487	0.34	0.6113
(Traffic from East to West bound at N-Manhattan Ave.)	October 11, 1966 between 11:30 a.m.- 1:30 p.m.	15	152	230	0.0378	0.38	0.5822
	October 12, 1966 between 7:30-8:30 a.m.	6	100	216	0.0184	0.307	0.6746
Anderson Avenue at N-14th St. (Traffic from East to West bound at N-14th St.)	October 12, 1966 between 4:30-5:30 p.m.	51	81	2	0.381	0.605	0.014
	October 13, 1966 between 7:30-8:30 a.m.	20	76	4	0.20	0.76	0.04
	October 13, 1966 between 11:30 a.m.- 1:30 p.m.	52	114	3	0.308	0.675	0.017
N-Manhattan Ave. at Bluemont Ave. from North to South bound at Bluemont Ave.	October 13, 1966 between 4:45-5:15 p.m.	149	61	152	0.412	0.1685	0.4195
	October 14, 1966 between 4:30-5:30 p.m.	113	40	130	0.40	0.1415	0.4585
Anderson Ave. at N-17th St. (Traffic from East to West bound)	October 14, 1966 between 8:00-8:30 a.m.	7	53	40	0.07	0.53	0.40
	October 15, 1966 between 7:35-8:35 a.m.	13	88	93	0.067	0.4537	0.4793

APPENDIX C

MAIN LINE PROGRAM OF SIMULATION OF TRAFFIC BY QUEUEING THEORY

```
 MON$$      JOB
 MON$$      COMT 15 MINUTES,15 PAGES
 MON$$      ASGN MJB,12
 MON$$      ASGN MGO,16
 MON$$      MODE GO,TEST
 MON$$      EXEQ FORTRAN,,,,,,,NAME
11 FORMAT(4X,F4.2,3X,F3.1,3X,F5.1,4X,F5.1)
55 FORMAT(4X,F4.2)
22 FORMAT(1H ,I2,3X,I2,2X,F5.2,2X,I2,1X,F5.2,2X,F5.2,3X,F5.2,1X,F5.1)
33 FORMAT(1H ,3HINT,1X,3HTOT,2X,5HGREEN,1X,3HQUE,1X,5HTOTAL,1X,8HAVG
  1TIME,1X,3HAVG,3X,5HGREEN)
44 FORMAT(1H ,3HNO.,1X,4HARRI,2X,4HTIME,1X,3HLEN,1X,5HDELAY,1X,8HBET
  1ARRI,1X,5HARRIV,1X,8HTIME REQ)
66 FORMAT(1H ,I3)
   IT=0
15 WRITE(3,33)
   WRITE(3,44)
   ICA=0
   IMQA=0
   LOOP=0
   READ(1,11)GRM,C,VOLMS,VOLCS
   READ(1,55)GRC
   GIM=GRM*C
13 LOOP=LOOP+1
54 IC=0
   IM=0
   TMS=0.0
   TCS=0.0
 5 TLMS=VOLMS/3600.
   CALLRANDOM(Z)
   R=Z
   TM=(-1./TLMS)*ALOG(R)
   IM=IM+1
   TMS=TMS+TM
   IF(TMS-GIM)5,6,6
 6 TLCS=VOLCS/3600.
   CALLRANDOM(Z)
   R=Z
   TC=(-1./TLCS)*ALOG(R)
   TCS=TCS+TC
   IC=IC+1
   IF(TCS-(GIM+3.))6,8,8
 8 AIC=IC
   AIM=IM
   ATBAC=TCS/AIC
   AAQCS=AIC/TCS
   RGIB=AIC*GIM/AIM
   IC=AIC
```

APPENDIX C (CONTINUED)

```
   IM=AIM
   IF(IM-15)52,54,54
52 IF(IC-10)29,54,54
29 WRITE(3,22)LOOP,IM,TMS,IC,TCS,ATBAC,AAQCS,RGIB
   ICA=ICA+IC
   ICAV=ICA/LOOP
   WRITE(3,66)ICAV
31 GIC=GRC*C
   ICS=0
12 ICS=ICS+1
   TTHG=ICS*2+4
   IF(ICS-IC)23,24,24
23 IF(TTHG-GIC)9,10,10
 9 GO TO 12
24 TCSG=TTHG
   ICG=IC
25 TLCS=VOLCS/3600.
   CALLRANDOM(Z)
   R=Z
   TCG=(-1./TLCS)*ALOG(R)
   TCSG=TCSG+TCG
   ICG=ICG+1
   IF(TCSG-GIC)25,26,26
26 ICS=ICG
   TTHG=TCSG
10 IMQ=0
   TMSQ=0.0
27 TLMS=VOLMS/3600.
   CALLRANDOM(Z)
   R=Z
   TMQ=(-1./TLMS)*ALOG(R)
   IMQ=IMQ+1
   TMSQ=TMSQ+TMQ
   IF(TMSQ-(GIC+3.))27,28,28
28 AIMQ=IMQ
   AICS=ICS
   ATBAM=TMSQ/AIMQ
   AAQMS=AIMQ/TMSQ
   RGIBM=AIMQ*GIC/AICS
   IMQ=AIMQ
   ICS=AICS
   IF(ICS-12)51,31,31
51 IF(IMQ-15)30,31,31
30 WRITE(3,22)LOOP,ICS,TTHG,IMQ,TMSQ,ATBAM,AAQMS,RGIBM
   IMQA=IMQA+IMQ
   IMQAV=IMQA/LOOP
   WRITE(3,66)IMQAV
   IF(LOOP-30)13,14,14
14 IT=IT+1
   IF(IT-6)15,16,16
```

APPENDIX C (CONTINUED)

```
 16 STOP
    END
   MON$$      EXEQ FORTRAN
    SUBROUTINERANDOM(Z)
 18 A=IRANDM(45713)
    Z=A/100000.
    IF(Z-0.8)100,100,18
100 IF(Z-0.5)18,19,19
 19 RETURN
    END
 1AMON$$      EXEQ AUTOCODER,,,NOPCH
 2A           HEADR*****RANDOM NUMBER GENERATOR SUBROUTINE*****
 3A           TITLEIRANDM
 4A           SBR  X13
 5A           MLNA 4+X13,*+6
 6A           MLNB 0,RECEIVE=3
 7A           C    RECEIVE,STORE=3
 8A           BE   CALC
 9A           MLNA RECEIVE,STORE
10A           MLNA -0000001-,RNUM=21-11
11A           MLNA STORE,RNUM-18
12ACALC       M    -1977326743-,RNUM
13A           MLCWARNUM-5,299
14A           SW   295
15A           MLNB RNUM,RNUM-11
16A           B    5+X13
17A           LTORG*
18A           DCW  -)-
19A           END
   MON$$      EXEQ LINKLOAD
              CALL NAME
   MON$$      EXEQ NAME,MJB
   .64   60.0   300.0    300.0
   .22
   .30   60.0   350.0    300.0
   .30
   .40   60.0   400.0    300.
   .33
   .50   60.0   350.0    350.0
   .40
   .50   60.0   300.0    300.0
   .40
   .50   50.0   300.0    300.0
   .50
   MON$$      JOB  ACT$$  PATEL M.N.         I. E.      0092C40409
```

APPENDIX D

Symbols used in Simulation Program

Notation	Description	Units
GRM(GRC)	Green ratio of signal at major (cross) street	Fraction of cycle
GIM(GIC)	Green interval of signal at major (cross) street	Seconds
VOLMS(VOLCS)	Actual volume on major (cross) street	Veh/hr.
IM(ICS)	Number of vehicles proceeding with green light on major (cross) street	Integer
IMQ(IC)	Number of vehicles waiting during red interval on major (cross) street	Integer
TC, TM, TMQ, TCG	Time between arrival	Seconds
ATBAM(ATBAC)	Average time between arrival on major (cross) street	Seconds
AAQMS(AAQCS)	Average arrival rate per second on major (cross) street	Fraction of cycle
RGIBM(RGIB)	Relative green interval required on major (cross) street	Seconds
IMQAV(ICAV)	Cumulative average delay (in vehicles) at major (cross) street	Integer
TTHG	Time required for vehicles delayed due to red light to cross the intersection	Seconds

TRAFFIC CONTROL AT SIGNALIZED INTERSECTIONS

by

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AN ABSTRACT OF A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1967

The purpose of this report was to study the traffic delay and find out the proper synchronization of the signal cycle at each signalized intersection in such a way that the vehicles must be allowed to proceed along the major streets at suitable speed in both directions without stopping or slowing down due to red light interference. An attempt was made to minimize red-phase interference (delay of vehicles) in the through-band and to maximize through-bandwidths and the flow capacity. The optimal solution of the problem can be defined by designing a time-space diagram.

The traffic algorithm developed by L. A. Yardeni and the half integer synchronization technique developed by Little, Martin and Morgan were applied in order to arrive at the optimal solution of the six traffic signals under study. These two techniques were programmed for processing on an IBM 1620 digital computer. The traffic algorithm technique failed to find the optimal solution of the six signal problem because of the many variations which affect the results for designing a time-space diagram.

The approach to the problem by half integer synchronization was found to be optimal. In the optimal solution of the problem, the maximum equal bandwidths were 16 seconds in both directions with a possible volume of 480 vehicles per hour at a speed of 21 miles per hour. The flow capacity was found to be higher at low speeds when compared with the flow capacity at higher speeds.

The simulation of a traffic delay study for fixed-time signals was applied to six signals. The model was developed by the author using an exponential distribution of time between arrival (queueing theory). The theoretical delay on the major street was compared with the actual delay. The computer program for the simulation of this traffic delay by queueing theory was written in this paper for solution on an IBM 1410.