A Practical Computer Program for Designing Traffic-Signal-System Timing Plans

ROBERT L. BLEYL, Research Associate, Yale University, Bureau of Highway Traffic

This paper discusses the elements, techniques, and characteristics of a practical computer program developed for designing progressive traffic-signal-system timing plans. The elements discussed include directional travel distance variations, directional and sectional speed differences, band widths, offsets, cycle lengths, progressive speeds, and splits.

The computer program, written in FORTRAN IV programming language, converts all speed and distance units to travel time units. The timing plan resulting in the greatest efficiencies is then determined from a time-travel time diagram. The program favors the directional band widths in proportion to the desired relative band widths and prints a series of tables which indicate, from the ranges specified for the numerous variable elements, the optimum timing plan.

•IN recent years, various computer programs for designing progressive traffic-signal-system timing plans have been produced. A review of several available programs revealed a lack of certain desirable features which limit their value as practical programs. Accordingly, the development of a practical computer program for solving signal progression problems was undertaken. The program described in this paper is the outgrowth of that project.

A brief discussion of variables to be considered in determining an "optimum" timing plan is included first in this paper as an aid in understanding the problems associated with progressive traffic-flow plans. Since the techniques employed to handle the variables in the program differ from the conventional approach, they are discussed in detail. The computer program developed is described in the concluding section.

SIGNAL SYSTEM VARIABLES

It has generally been assumed that a traffic-signal system was constant throughout. Although this assumption facilitates the construction of a time-space diagram, it is unrealistic.

Virtually no signal system is homogeneous and consistent throughout. In addition to curves and grades, there are changes in roadway widths, adjacent land uses, and traffic conditions. These factors influence the movement of traffic and should be considered when attempting to time a system for progressive movement.

Signal Spacing

One axis of the traditional time-space diagram has always represented the centerline distance between signal installations. In progressive timing plans there are two signal-to-signal distances of more importance than the centerline distance between the signals. They are the stop line-to-stop line travel distances for each direction of travel. These two directional travel distances will differ when there are horizontal curves in the

---

Paper sponsored by Committee on Traffic Control Devices.

alignment, or when signalized cross streets are skewed, offset, or of differing widths. In some cases the differences in the directional travel distances are insignificant, but in others the differences are great enough to require offset adjustments in order to provide maximum efficiency. In any case, a practical program should provide for this contingency.

Travel Speeds

Many elements of the traffic-signal system influence the speeds at which vehicles travel. Included among these are the roadway widths and other cross-sectional elements, the use of the abutting property, and the desires, patterns, and volumes of traffic. Whenever these elements vary within a system, it seems logical to expect that the traffic speeds might also vary.

The old practice of timing a traffic-signal system for a single, constant speed throughout its entire length is far from reality. Traffic speed patterns may vary not only from one section of a system to another, but also by direction of travel at any point within the system. This natural variability in the speed patterns also should be considered in the design of progressive signal-system-timing plans.

PROGRESSIVE TIMING VARIABLES

There are five elements of the time-space diagram which may be variables: band width or efficiency, offsets, cycle length, progressive speeds, and splits or intervals.

Band Width

The primary objective in timing a progressive signal system is to determine the combination of signal-timing elements which will result in the largest band width for a given cycle length. The ratio of band width to cycle length is referred to as the "efficiency" of the system. In order for the "optimum" or best solution (the greatest efficiency) to be found, all four of the other signal-timing elements must be allowed to vary. The best solution is reached only when the optimum cycle length has been found, the appropriate splits used, the optimum progressive speeds determined, and the optimum offsets obtained. For practical application, the variability of all these elements must be held within acceptable ranges.

Offsets

The heart of the signal progression problem is the determination of the offsets which will yield the maximum efficiency for both directions of flow simultaneously under a given set of conditions. It can be shown that in order for the maximum band width in both directions to be reached simultaneously, the offset of the center of the green interval at every signal must be either 0 percent or 50 percent. This condition then specifies that there are only $2^{(N-1)}$ possible combinations of offsets, where N is the number of signals in the system.

There are several adequate algorithms, or techniques, for determining which of the $2^{(N-1)}$ possible solutions is the best solution without testing every possible combination (1, 2, 3). The algorithm used in the computer program described is essentially the same as that described by Brooks (1). From a base signal, which is the signal having the shortest green interval, the two progressive bands for this interval width are created. The interferences to these bands resulting from both the 0 percent and 50 percent offset conditions are determined for each signal. The total interference to the bands is then selected in such a way that it is a minimum; hence, the band width is a maximum.

Cycle Length

For all signals in a system to be timed for progressive movement, they must have the same basic cycle length or be harmonic to the basic cycle length (double, half, etc.). The harmonic case is rarely justified and generally causes more interference than benefit to progressive traffic movement. Its use may be employed in special situations; but for this program it will not be further considered.

With all signals in a system having the same cycle length, the efficiency of the system will vary as that common cycle length is varied. At some point within the range of acceptable cycle lengths (usually between 40 and 120 sec), the efficiency will reach a peak. The cycle length at the peak efficiency may not necessarily be a multiple of 5 sec. For example, it may be determined that a cycle length of 58.9 sec is the optimum for a given set of conditions. However, inasmuch as the progressive speeds and the cycle length are inversely proportional, and since a cycle length which is a multiple of 5 sec is generally required from a practical standpoint, a slight adjustment in the progressive speeds will result in a usable cycle length at the peak efficiency.

Progressive Speeds

In time-space diagrams designed in the past, the progressive speed has frequently been considered as a by-product of the design. Any progressive speed that happened to result from a given timing plan was accepted as long as it was not extreme. Traffic flow was expected to adjust to that progressive speed, whether it was higher or lower than normal traffic speeds. However, studies by Desrosiers and Leighty (4) have shown that drivers will not adjust their speeds to coincide with some arbitrary progressive speed. Therefore, if the progressive timing is to be beneficial and serve its intended purpose, it is necessary for the system to have progressive speeds which coincide with the normal movement of traffic.

As previously indicated, many elements of the traffic-signal system influence the speeds at which vehicles travel. Field studies should be made for each section of the system to determine those progressive speeds that will be most beneficial to traffic flow. These speeds are often considered to be the directional average running speeds for the section. The desired progressive speeds must be specified in advance, and only slight variations from these speeds should be permitted in the design if the timing plan is to be effective.

Split

The split is the ratio of time devoted to each phase at a signalized location. This phase split is commonly determined on the basis of the roadway characteristics and traffic volumes for each approach. This determination, however, is subject to certain overriding conditions. A minimum amount of time generally must be provided for any phase. Where pedestrians are present, a minimum amount of time must be provided to allow the pedestrians to cross the street. Also, in determining the length of the green interval, which is the portion of the phase available to accommodate the progressive bands, a fixed amount of time for the clearance period must be deducted from the phase split allotment. Accordingly, there is a different green interval for each cycle length, and any procedure to find the optimum cycle must of necessity use the appropriate green interval for that cycle.

APPROACH

The techniques used in this computer program for determining traffic-signal-system timing plans differ from those used in the conventional time-space diagram. The conventional approach is based on a plot of time along one axis of the diagram (more commonly the X-axis) and of distance along the other. Speeds are represented by the slope of a line on the diagram; thus, a line parallel to the time axis represents a speed of zero. Figure 1 shows a conventional time-space diagram and identifies the various elements.

The approach used by the author in determining traffic-signal-system timing plans converts all speed and distance units to travel time units. The diagram is then constructed in terms of time along both axes; the distance axis being replaced by an average-travel-time axis. This modification of the conventional time-space diagram is made to account for the variable elements and to simplify the calculations.

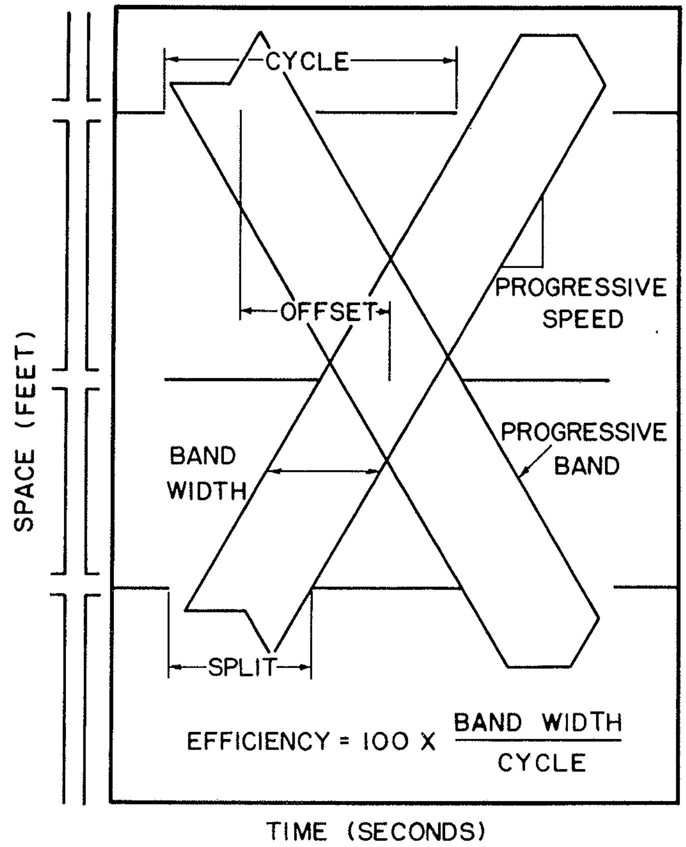

Figure 1. Conventional time-space diagram.

To construct the modified diagram, the travel distances between stop lines must be known for each direction of flow at successive signalized locations. The desired progressive speed in each direction for each section of the system also must be specified.

For example, a section of roadway having different directional travel distances and different desired progressive speeds is shown in Figure 2. The desired progressive speeds between signals at A and C are constant, but they are different between the other pairs of signals. Similarly, the directional travel distances between signals at D and E are constant, but they are different throughout the balance of the system. For simplicity in the example, the splits at all signals provide 50 percent green time to the system.

The time to travel between successive signals is calculated for each direction by dividing the travel distance for that direction by the desired progressive speed. The two directional travel times are then averaged to determine the average travel time for the section. This average travel time is used in determining the spacing of signals along the average-travel-time axis.

Inasmuch as travel times are employed in solving the problem instead of actual distances and desired progressive speeds, it may be easier to identify the system in terms of desired directional travel times than it is to calculate these from measured distances and desired speeds. The computer program permits this optional approach to be used.

In the example, the travel times in seconds for each section can be calculated by the formula:

$$\text{Travel time} = \frac{\text{feet}}{\text{mph} \times 1.47}$$

TABLE 1

TRAVEL TIMES BETWEEN SIGNALS
(Seconds)

Row	Item	Section		
		AC	CD	DE
1	Westbound	29.0	19.0	29.6
2	Eastbound	27.0	19.0	20.4
3	Average	28.0	19.0	25.0
4	Difference	1.0	0.0	4.6
5	Offset shift (%)	2.0	0.0	9.2

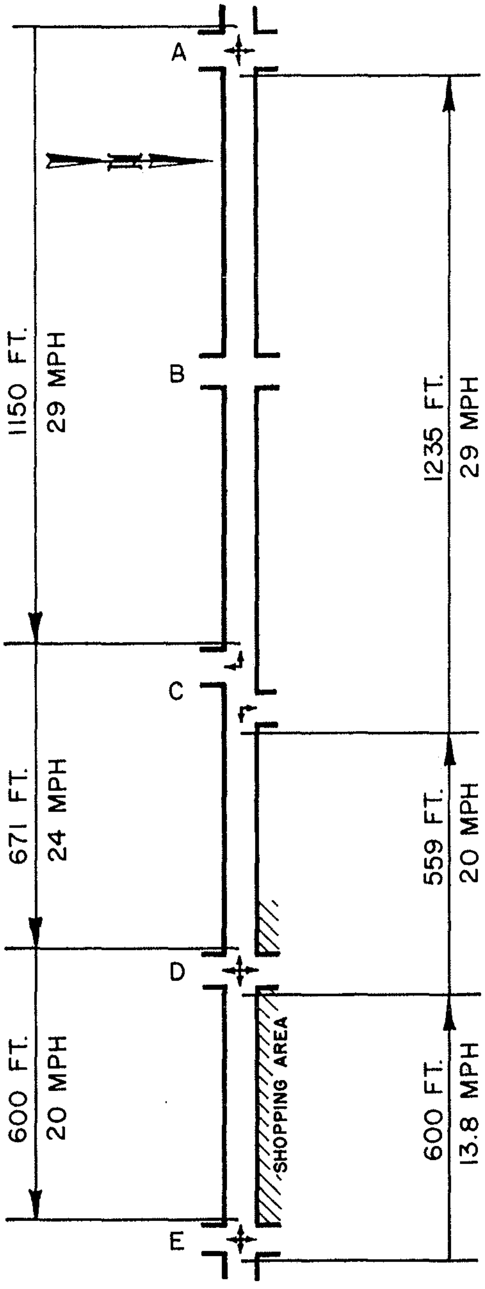

Figure 2. Roadway section for example.

The resulting travel times for each direction are shown in rows 1 and 2 of Table 1. The average travel time for each section is then determined (row 3 of Table 1).

The average travel-time spacing of all signals in the system is plotted along the space axis of the time-space diagram. The time-travel time diagram can then be solved manually by the usual trial-and-error, graphical, or mathematical techniques, or by a computer using appropriate algorithms to find the optimum or satisfactory linear progressive bands for both directions.

Besides the change of axis, the primary difference between the modified time-space diagram and the conventional time-space diagram is the indicator of speed. The speed of the progressive band in the conventional diagram is measured by the slope of the band. In the modified diagram, the speed is indicated by the difference in slope of the progressive band from a 45-deg angle. (If different scales are used for the two axes, speed is indicated by the difference in slope of the progressive band from the slope having a 1:1 ratio.) A progressive band having a slope of 45 deg will have a series of progressive speeds exactly equal to the desired progressive speeds; therefore, a solution with a slope in this region should be sought. At slopes flatter than 45 deg, the series of progressive speeds will be lower by the ratio of the travel time to cycle time (the slope of the progressive band).

One possible solution for the example problem (which, incidentally, is the optimum solution) is shown in Figure 3. For this solution, a 50-sec cycle has been selected which yields a band width of 20.2 sec and has an efficiency of 40.4 percent. The offset pattern for this solution is 0 percent-50 percent-0 percent-50 percent for signals A, C, D, and E, respectively.

The slope of the progressive band is slightly less than 45 deg and has a travel-time-to-cycle-time ratio of 0.94. Each of the desired progressive speeds is multiplied by this ratio to determine the actual progressive speeds at the 50-sec cycle (Table 2).

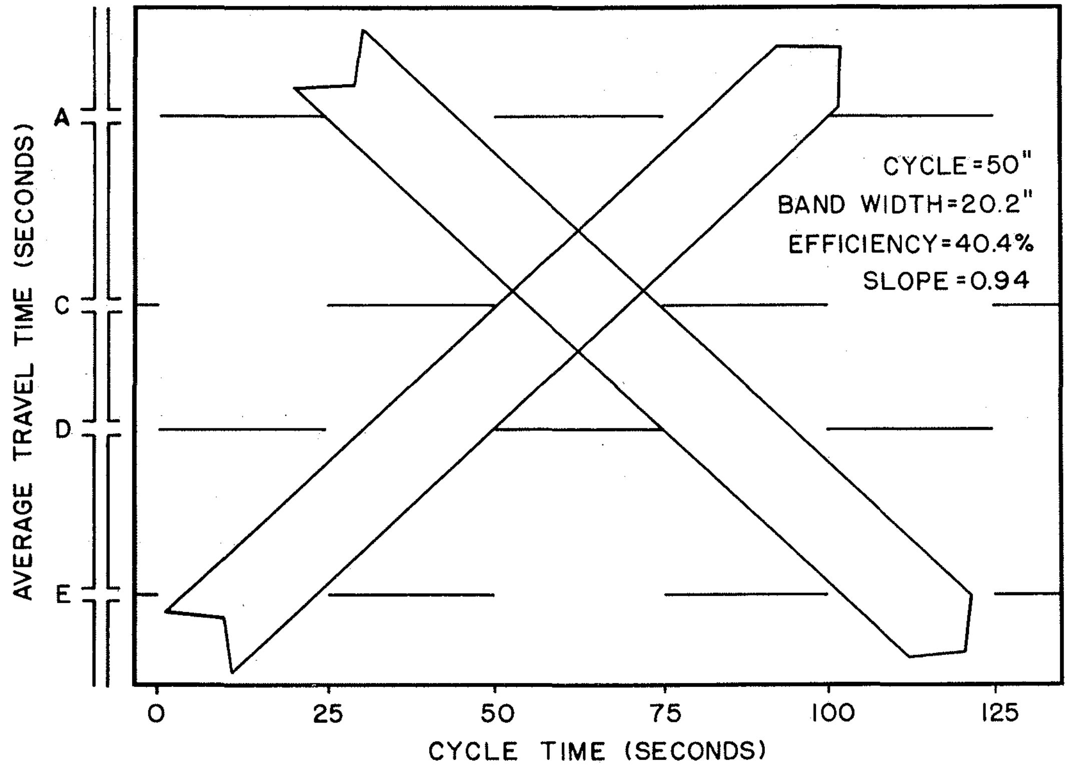

Figure 3. Solution of modified time-space diagram.

TABLE 2

DESIRED AND OBTAINED PROGRESSIVE SPEEDS
(miles per hour)

Item	Section		
	AC	CD	DE
Westbound desired	29.0	20.0	13.8
Westbound obtained	27.3	18.8	13.0
Eastbound desired	29.0	24.0	20.0
Eastbound obtained	27.3	22.6	18.8

TABLE 3

OFFSET ADJUSTMENT FOR DIRECTIONAL DIFFERENCES

Row	Item	Signals			
		A	C	D	E
1	Basic offsets from diagram	0	50	0	50
2	Section AC adjustment = 2%	0	48	98	48
3	Section CD adjustment = 0%	0	48	98	48
4	Section DE adjustment = 9%	0	48	98	39

If travel times are measured instead of speeds and distances, they must be divided by this factor (0.94) to determine the travel times between signals for the progressive bands.

After the linear progressive bands in both directions have been found and the offsets for all signals determined, one final offset adjustment is necessary to account for the directional differences: the offset of all signals on one side of each section having different directional travel times must be shifted an amount equal to the difference between the travel time for the section and the directional average travel time for the section.

For the given example, this difference is included in row 4 of Table 1. By using the selected cycle length of 50 sec, the differences for each section can be converted to cycle percentages. These percentages, which are the required offset shift in seconds, are calculated by the formula:

$$\text{Offset shift} = 100 \times \frac{\text{difference}}{\text{cycle length}}$$

For the example, the results of this calculation are included in row 5 of Table 1.

The offset adjustment is accomplished by shifting the offsets of all signals on one side of the section an amount equal to the required shift contained in row 5 of Table 1. The shift is a decrease in offset for the direction having the shorter travel time.

For the example, the basic offset and all intermediate steps in the adjustment are given in Table 3. Row 1 contains the basic offset condition obtained from the time-space diagram. Each offset at this point should be either 0 percent or 50 percent for balanced progression. After all adjustments have been made, the offsets which yield equal band widths in both directions are contained in the last row of Table 3.

Further adjustments in the offsets may be made to favor one direction of flow over the opposing direction. If desired, the conventional time-space diagram can be constructed for each direction as shown in Figure 4.

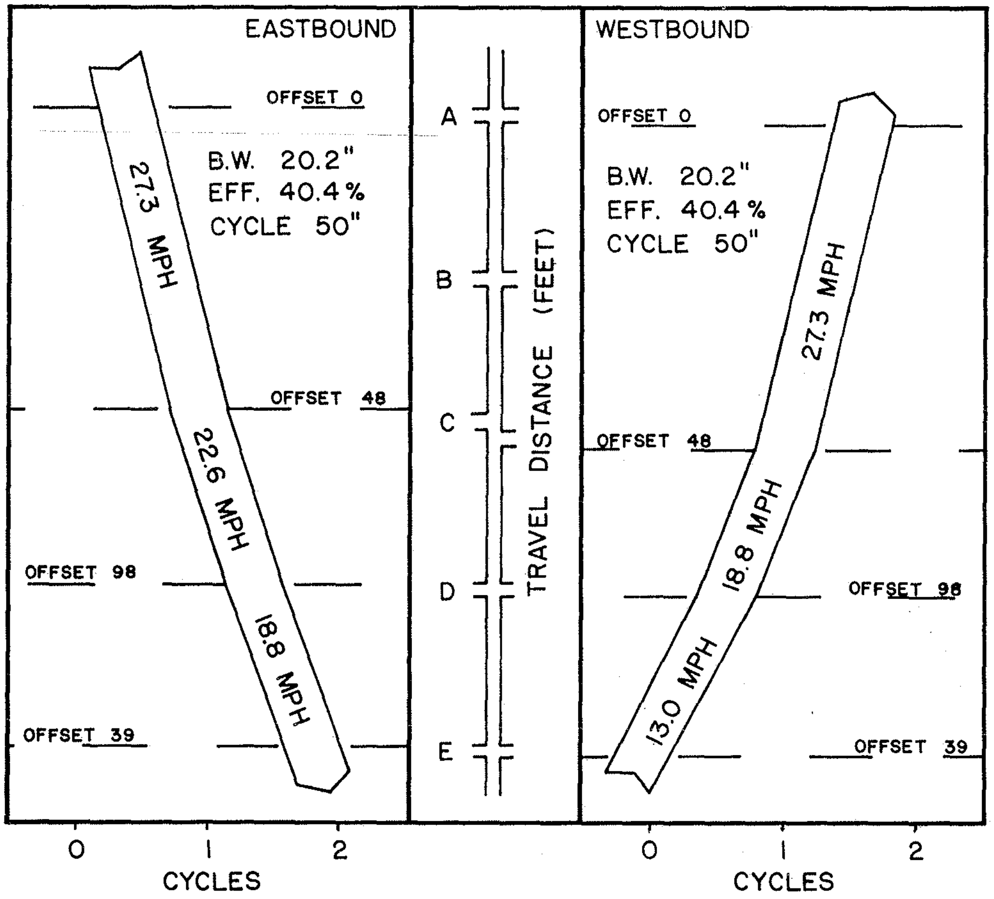

Figure 4. Conventional time-space diagram solutions.

COMPUTER PROGRAM

The computer program determines the timing plan which will produce the greatest efficiencies for a traffic signal system. The program is designed to handle all the variable elements, including signal spacing, travel speeds, cycle lengths, progressive speeds, splits, and offsets. The program was also designed so that the offsets can be adjusted to favor the band width in one direction over that of the opposing direction in proportion to the relative widths desired.

The program has been written in FORTRAN IV computer programming language. An attempt has been made to make the programming compatible with 360 FORTRAN specifications, level I, thus enabling the program to be run on almost any digital computer. The program has been extensively tested, but it has not been exposed to all possible combinations of conditions.

The running time for a problem varies with the cycle length range and the number of signals. For a typical 10-signal system and a 20-sec cycle length range, the execution time on an IBM 7040/7094 DCS is 3 sec. Input to the program is from data processing cards; output from the program is a series of printed tables.

Organization Identification Card

The name of the organization using the program is included on the printouts. This identification is coded on a single card which is placed as the first data card preceding all other data input cards. Up to 32 characters may be used for each of two lines of identification. The rightmost position of each line must be located in columns 40 and 80, respectively, of the organization identification card. An example of this card is shown with the illustration of the other input cards in Figure 5.

Input Cards

The input cards consist of 12 general control cards and a series of sets of 2, 3, or 4 signal cards. These various cards contain the basic information needed to define the system and its variability. Although the program is designed to accommodate variable conditions, it also handles constant conditions.

The general control cards are numbered from 1 through 12 and the signal cards are lettered A through E. Figure 5 shows a listing of input cards for a typical problem.

The first 40 columns of each input card are used to identify the information contained on the card. With two minor exceptions, the information contained in these 40 columns is ignored by the program. The identification information for each of the cards is in Figure 5. The last character of the identification is located in column 38 of all general control cards and signal cards.

General Control Cards—Card 1 contains the name of the system and is used to identify the problem when several runs are being made at one time and also to identify the output. Up to 40 characters may be used for the system name, which must begin in column 41.

Card 2 contains the subtitle of the run and is used primarily to identify the time of day and other conditions of the run. The subtitle, which may contain up to 40 characters, will also be included on all output. It must begin in column 41.

Card 3 identifies the number of signals in the system. The program requires at least 2 signals, and as many as 100 may be included. The units position of the number of signals must be located in column 45.

Card 4 indicates the minimum and maximum cycle lengths to be considered acceptable. If only one specific cycle length is acceptable, it should be coded as both the minimum and maximum. The units positions of the minimum and maximum cycle lengths are to be located in columns 45 and 55, respectively.

Card 5 contains the suggested maximum speed tolerance from the desired progressive speeds specified on other cards. If this item is coded 0, no tolerance will be allowed, and only cycle lengths which are multiples of 5 sec will be considered. In this case, the minimum and maximum cycle lengths coded on card 4 must also be multiples of 5 sec. If coded other than 0, the program will find, within the limits specified, the optimum cycle from all possible cycles. The units position is column 45.

```
1        10        20        30        40        50        60        70        80
I--------I---------I--CARD---I---------I---------I-COLUMNS-I---------I---------I


EXAMPLE OF ORGANIZATION IDENTIFICATION CARD
======= == ============ ============== ====
                         YALE UNIVERSITY               BUREAU OF HIGHWAY TRAFFIC


EXAMPLE OF INPUT CARDS FOR ONE RUN
======= == ===== ===== === === ===
1                       NAME OF SYSTEM  HIGHLAND DRIVE (US-55) SIGNAL SYSTEM
2                            SUB-TITLE  EVENING PRE-PEAK TRAFFIC PATTERN
3          NUMBER OF SIGNALS IN SYSTEM       6
4            MIN AND MAX CYCLES (SECS)      40        70
5       SUGGESTED MAX SPEED TOL. (MPH)       3
6    SYSTEM OFFSET TRANSPOSITION (PCT)       0
7                      COLUMN HEADINGS  DIR. 1      DIR. 2  NAME/PED-X   SPLIT/CI
8             DIRECTION IDENTIFICATION  OUTBOUND   INBOUND
9            BAND WIDTH PROPORTIONMENT      55        45
A    LOCATION NAME + PHASE SPLIT (PCT)                      ROCK VIEW       52
B   PED X-ING + CLEARANCE TIMES (SECS)                           17          4
C               TRAVEL DISTANCE (FEET)     385
D      PROGRESSIVE SPEED DESIRED (MPH)      30
A    LOCATION NAME + PHASE SPLIT (PCT)                      BAKER           59
B   PED X-ING + CLEARANCE TIMES (SECS)                           15          4
C               TRAVEL DISTANCE (FEET)     767       848
D      PROGRESSIVE SPEED DESIRED (MPH)      30        31
A    LOCATION NAME + PHASE SPLIT (PCT)                      LANCASTER      47.5
B   PED X-ING + CLEARANCE TIMES (SECS)                           17.5       3.5
C               TRAVEL DISTANCE (FEET)   1514.8    1422.9
D      PROGRESSIVE SPEED DESIRED (MPH)     33.5      35.5
A    LOCATION NAME + PHASE SPLIT (PCT)                      EVERETT         54
B   PED X-ING + CLEARANCE TIMES (SECS)                           17          3
C               TRAVEL DISTANCE (FEET)     494       534
D      PROGRESSIVE SPEED DESIRED (MPH)      34        36
A    LOCATION NAME + PHASE SPLIT (PCT)                      YORK            60
B   PED X-ING + CLEARANCE TIMES (SECS)                           16          3
C               TRAVEL DISTANCE (FEET)    1049
D      PROGRESSIVE SPEED DESIRED (MPH)      37        39
A    LOCATION NAME + PHASE SPLIT (PCT)                      LAKE            64
B   PED X-ING + CLEARANCE TIMES (SECS)                           17          3
10  PROCESSING INSTRUCTION TO COMPUTER     RUN
11       PUNCHED OUTPUT REQUESTED ALSO     YES
12              ADDITIONAL RUNS FOLLOW      NO


EXAMPLES OF CARD E (OPTIONAL TO CARDS C AND D)
======== == ==== = ======== == ===== = === =
E   TRAVEL TIME BETWEEN SIGNALS (SECS)      24
E   TRAVEL TIME BETWEEN SIGNALS (SECS)      18        19.5
```

Figure 5. Examples of input data cards.

Card 6 is used to transpose, by a constant amount, the offsets of all signals in the timing plan. This feature facilitates the establishment of the proper offset relationship for signals common to more than one signal system. The offset transposition on this card would be coded 0 in the initial runs and coded with the desired offset transposition in a subsequent run, if desired. The units position of the offset shift (in percent) must be in column 45.

Card 7 is included in the input deck for convenience sake only and does not change from run to run. It aids in reviewing a listing of the input cards, but contributes nothing to the program. It may not be omitted, however.

Card 8 identifies the two general directions in which traffic moves along the system. This identification would normally be the words INBOUND, OUTBOUND, or any of the

8 compass points followed by the suffix BOUND, such as N-BOUND. Up to eight characters may be used for identifying each direction. The directions must begin in columns 41 and 51, respectively.

Card 9 signifies the desired proportionment of the band widths by direction. This proportionment may be presented as a percentage (such as 50 50), or as a ratio (such as 2 1); if it is desired to have band widths proportional to directional traffic volumes, these volumes may be used to specify the proportionment. In favoring the band width in one direction over that of the opposite direction, the program will accomplish one of three things: (a) if the proportion is realistically attainable, it will be obtained; (b) if the band width in the preferred direction reaches its maximum possible width before the desired proportion is reached, no further adjustment will be made and the maximum band width condition will be indicated by asterisks on the printout; and (c) if the band width in the unfavored direction becomes small enough to no longer be meaningful (for this program, 5 sec or less), the maximum attainable band width in the favored direction will be selected. The units positions for the proportionment factors of the two directions indicated on Card 8 must be in columns 45 and 55, respectively.

Card 10 contains the processing instruction SCAN, to scan the cycle range in order to find the peaks in the efficiency curve (which peaks may be further investigated in subsequent runs), or RUN, to process the full program using the cycle length found in the scanning process to have the highest efficiency. With either of these instructions, the last letter of the message must be placed in column 45.

Card 11 is used to produce an intermediate deck of output cards containing the parameters of the optimum timing plan. This intermediate deck provides the results of the timing plan in a form which could be used by a supplemental program designed to plot, draw, or print the time-space diagram of the solution. The message YES or NO is punched with the last letter of the message in column 45. A YES message produces the intermediate output only if the option RUN on card 10 was selected.

Card 12 contains a message to inform the computer whether or not additional runs follow. If input cards for another run follow, a YES is punched with the last letter of the message in column 45. If NO is punched, the program will terminate after completing the current run.

The general control cards numbered 1 through 9 precede, in numerical order, the signal cards A through E in the input deck. General control cards 10 through 12 follow the signal cards.

Signal Cards—Card A contains the name of the signal location and the percent phase split to be devoted to the system being timed, regardless of minimum green time requirements for the cross street or for pedestrians to cross the system. The name may occupy up to 12 characters and must begin in column 61. The units position for the percent phase split is located in column 77.

Card B contains the minimum total time that must be provided during each cycle for the cross street or to allow pedestrians to cross the system. The units position is located in column 67. Also contained on this card is the required clearance interval (in seconds) for the traffic on the system. The units position (or the decimal point, if a decimal value is used) is located in column 77.

Card C contains the directional travel distances (in feet) from the signal described on the preceding Card A to the signal described on the following Card A. The units positions must be located in columns 45 and 55, respectively, for the directions specified on Card 8. In case the travel distances in both directions are identical, the second field may remain blank and the computer will make the entry.

Card D contains the desired directional progressive speeds (in miles per hour) from the signal described on the preceding Card A to the signal described on the following Card A. The units positions must be located in columns 45 and 55. In case the progressive speeds in both directions are identical, the second field may be left blank and the computer will make the other entry.

Card E contains the desired directional travel times (in seconds) from the signal described on the preceding Card A to the signal described on the following Card A. This card is complementary to Cards C and D. If Card E is included, Cards C and D must be omitted. If Cards C and D are included, Card E must be omitted. The program distinguishes this card by the letter E in column 1. The units positions of the travel times must be located in columns 45 and 55 on Card E. In case the desired travel times are identical in both directions, the second field may be left blank and the computer will make the second entry.

A series of either three or four cards, ABE or ABCD, will be followed by another series of either three or four cards for each signal in the system. The last series will contain only two cards, AB. The entire set of signal cards designated by the alphabetic characters is located in the input deck between general control Cards 9 and 10. The order in which the signal card sets are placed in the deck must correspond with the direction designated on Card 8 under the heading DIR. 1.

If decimal distances, speeds, travel times, splits, cycle lengths, offsets, or intervals are used, these items may be coded on the various general control cards and signal cards by locating the decimal point in the specified units position and following it by one or two decimal places. The only exception is the number of signals on Card 3, which must be a whole number and may not have a decimal point punched.

Printed Output

The program is designed to prepare three tables on an on-line printer. If necessary, the program can be easily modified to punch the output or write it on tape for subsequent printing.

The first table (Fig. 6) is included in the output primarily as a reference convenience. It is a listing of the parameters and controls transmitted to the program from the input card deck which rapidly reveals mispunched or miscoded information. The

```
                                INPUT INFORMATION

1                        NAME OF SYSTEM  HIGHLAND DRIVE (US-55) SIGNAL SYSTEM
2                             SUB-TITLE  EVENING PRE-PEAK TRAFFIC PATTERN
3           NUMBER OF SIGNALS IN SYSTEM      6
4             MIN AND MAX CYCLES (SECS)    40.00     70.00
5        SUGGESTED MAX SPEED TOL. (MPH)     3.00
6     SYSTEM OFFSET TRANSPOSITION (PCT)     0.00
7                       COLUMN HEADINGS  DIR. 1    DIR. 2    NAME/PED-X  SPLIT/CI
8              DIRECTION IDENTIFICATION  OUTBOUND  INBOUND
9             BAND WIDTH PROPORTIONMENT    55.00     45.00
A     LOCATION NAME + PHASE SPLIT (PCT)                      ROCK VIEW      52.00
B    PED X-ING + CLEARANCE TIMES (SECS)                          17.00       4.00
C                TRAVEL DISTANCE (FEET)   385.00    385.00
D       PROGRESSIVE SPEED DESIRED (MPH)    30.00     30.00
A     LOCATION NAME + PHASE SPLIT (PCT)                      BAKER          59.00
B    PED X-ING + CLEARANCE TIMES (SECS)                          15.00       4.00
C                TRAVEL DISTANCE (FEET)   767.00    848.00
D       PROGRESSIVE SPEED DESIRED (MPH)    30.00     31.00
A     LOCATION NAME + PHASE SPLIT (PCT)                      LANCASTER      47.50
B    PED X-ING + CLEARANCE TIMES (SECS)                          17.50       3.50
C                TRAVEL DISTANCE (FEET)  1514.80   1422.90
D       PROGRESSIVE SPEED DESIRED (MPH)    33.50     35.50
A     LOCATION NAME + PHASE SPLIT (PCT)                      EVERETT        54.00
B    PED X-ING + CLEARANCE TIMES (SECS)                          17.00       3.00
C                TRAVEL DISTANCE (FEET)   494.00    534.00
D       PROGRESSIVE SPEED DESIRED (MPH)    34.00     36.00
A     LOCATION NAME + PHASE SPLIT (PCT)                      YORK           60.00
B    PED X-ING + CLEARANCE TIMES (SECS)                          16.00       3.00
C                TRAVEL DISTANCE (FEET)  1049.00   1049.00
D       PROGRESSIVE SPEED DESIRED (MPH)    37.00     39.00
A     LOCATION NAME + PHASE SPLIT (PCT)                      LAKE           64.00
B    PED X-ING + CLEARANCE TIMES (SECS)                          17.00       3.00
10   PROCESSING INSTRUCTION TO COMPUTER    RUN
11        PUNCHED OUTPUT REQUESTED ALSO    YES
12               ADDITIONAL RUNS FOLLOW    NO
```

Figure 6. First table printed by computer.

table includes the system identification and control information, minimum and maximum cycle lengths, suggested maximum speed tolerance, number of signals, band width proportionment factors, directional distances and speeds or travel times between each pair of signals, and the name, phase split, pedestrian crossing time and clearance period for each signal.

```
         CYCLE SCAN FOR BEST FIT

         HIGHLAND DRIVE (US-55) SIGNAL SYSTEM
         EVENING PRE-PEAK TRAFFIC PATTERN

EFF = 14.606 AT  37. SECS                 15
EFF = 18.722 AT  38. SECS                     19
EFF = 16.979 AT  39. SECS                   17
EFF = 15.324 AT  40. SECS                 15
EFF = 12.892 AT  41. SECS               13
EFF = 11.641 AT  42. SECS              12
EFF = 14.928 AT  43. SECS                 15
EFF = 16.420 AT  44. SECS                  16
EFF = 15.544 AT  45. SECS                  16
EFF = 14.706 AT  46. SECS                 15
EFF = 15.458 AT  47. SECS                 15
EFF = 16.511 AT  48. SECS                   17
EFF = 17.439 AT  49. SECS                   17
EFF = 17.238 AT  50. SECS                   17
EFF = 19.959 AT  51. SECS                      20
EFF = 22.328 AT  52. SECS                        22
EFF = 23.864 AT  53. SECS                          24
EFF = 25.344 AT  54. SECS                           25
EFF = 26.769 AT  55. SECS                             27
EFF = 28.144 AT  56. SECS                              28
EFF = 28.323 AT  57. SECS                              28
EFF = 27.890 AT  58. SECS                              28
EFF = 27.473 AT  59. SECS                             27
EFF = 27.069 AT  60. SECS                             27
EFF = 26.679 AT  61. SECS                             27
EFF = 26.301 AT  62. SECS                            26
EFF = 25.739 AT  63. SECS                            26
EFF = 24.658 AT  64. SECS                           25
EFF = 22.986 AT  65. SECS                         23
EFF = 21.296 AT  66. SECS                       21
EFF = 19.658 AT  67. SECS                      20
EFF = 18.067 AT  68. SECS                    18
EFF = 16.523 AT  69. SECS                   17
EFF = 15.022 AT  70. SECS                 15
EFF = 14.148 AT  71. SECS                14
EFF = 14.771 AT  72. SECS                 15
EFF = 15.377 AT  73. SECS                 15
EFF = 15.447 AT  74. SECS                 15
EFF = 14.661 AT  75. SECS                 15

         BEST FIND IS
            CYCLE OF  57.  EFFICIENCY =  28.323

         ITERATION IMPROVEMENTS
                      56.500             28.545
                      56.500             28.545
                      56.375             28.601
                      56.375             28.601
                      56.344             28.605
                      56.359             28.608
                      56.359             28.608
                      56.359             28.608
                      56.359             28.608
                      56.359             28.608
```

Figure 7. Second table printed by computer.

The second table (Fig. 7) contains the results of an incremental cycle scan between the minimum and maximum cycle lengths to find the maximum efficiency obtainable at each increment. A plot of the maximum efficiency obtainable at each cycle length is included in this printout. The cycle length having the highest efficiency is identified, and improvements in the efficiency by an iterative process are also included. This tabulation is useful in making further investigations at other cycles where the efficiency reaches lesser peaks. These additional investigations are made by running the program again with the minimum and maximum cycles changed to encompass only the cycle span associated with the lesser peak in the efficiency.

If the instruction RUN is contained on Card 10, the program continues using the cycle having the highest efficiency and prints the third table (Fig. 8). This tabulation indicates the timing elements that yield the greatest efficiency under the specified conditions. Each signal is identified by its name. The offsets and the system's green and clearance intervals (in percent) are listed adjacent to the name. The offsets are given

```
                     TRAFFIC SIGNAL SYSTEM TIMING PLANS

HIGHLAND DRIVE (US-55) SIGNAL SYSTEM                         YALE UNIVERSITY
EVENING PRE-PEAK TRAFFIC PATTERN                   BUREAU OF HIGHWAY TRAFFIC

PLAN  56.4 ( 55- 45)    CYCLE LENGTH (SECONDS)      56.4  55.0  50.0  60.0

    ****************    OUTBOUND DIRECTION
    *              *        BAND WIDTH (SECONDS)   17.7  17.3  15.7  18.9
    *  LISTING IS  *        EFFICIENCY (PER CENT)  31.5  31.5  31.5  31.5
    *  IN OUTBOUND *
    *  DIRECTION   *    INBOUND DIRECTION
    *              *        BAND WIDTH (SECONDS)   14.5  14.2  12.9  15.4
    ****************        EFFICIENCY (PER CENT)  25.7  25.7  25.7  25.7

SIGNAL        OFFSETS-PER CENT  INTERVAL  SIGNAL  OPT.  BEST  --OTHERS--
LOCATION      BEG.  MID.  END.  G-PCT.-Y  SPCNG.  PROGRESSIVE SPEEDS-MPH
============  ================  ========  ======  =====================

ROCK VIEW     27.5  50.0  72.5  44.9 7.1

      P.BAND  31.8        63.3  OUTBOUND   385.0  30.0  30.7  33.8  28.2
      P.BAND  42.4        68.2  INBOUND    385.0  30.0  30.7  33.8  28.2

BAKER         26.9  52.9  78.8  51.9 7.1

      P.BAND  47.3        78.8  OUTBOUND   767.0  30.0  30.7  33.8  28.2
      P.BAND  26.9        52.7  INBOUND    848.0  31.0  31.8  34.9  29.1

LANCASTER     78.3  98.9  19.6  41.3 6.2

      P.BAND  78.3         9.7  OUTBOUND  1514.8  33.5  34.3  37.8  31.5
      P.BAND  93.8        19.6  INBOUND   1422.9  35.5  36.4  40.0  33.3

EVERETT       27.7  52.0  76.4  48.7 5.3

      P.BAND  33.0        64.4  OUTBOUND   494.0  34.0  34.8  38.3  31.9
      P.BAND  45.3        71.1  INBOUND    534.0  36.0  36.9  40.6  33.8

YORK          27.3  54.7  82.0  54.7 5.3

      P.BAND  50.6        82.0  OUTBOUND  1049.0  37.0  37.9  41.7  34.8
      P.BAND  27.4        53.1  INBOUND   1049.0  39.0  40.0  44.0  36.6

LAKE          73.4   2.7  32.1  58.7 5.3

      P.BAND  84.9        16.3  OUTBOUND
      P.BAND  94.8        20.6  INBOUND
```

Figure 8. Third table printed by computer.

to the beginning, middle, and end of the green interval, since different offsets are usually required for pretimed systems than for actuated systems. The provision of all three offsets also facilitates the drafting of a time-space diagram, if desired.

The fourth column from the right (Fig. 8) (labeled OPT.) indicates the cycle length, band widths, efficiencies, and directional progressive speeds for the optimum solution. Since the optimum cycle cannot normally be installed in most equipment unless it is an exact multiple of 5 sec, the next column to the right (BEST) indicates the changes resulting from a change in the cycle length to the nearest multiple of 5 sec. The last two columns show the changes resulting from the cycle lengths 5 sec above and below the BEST cycle length. In creating these last three columns, no changes in the splits, intervals, or offsets have been made. They represent a direct expansion or contraction of the cycle length, as would be effective by solely a change in the cycle gear. More specific split, interval, band width, and offset information can be obtained by running the problem again using the progressive speeds and cycle length contained in any one of these last three columns. From a practical viewpoint, however, another run would not materially change the timing values in Figure 8.

In cases where the spacing between signals is given in the input as desired travel times instead of travel distances and desired progressive speeds, the progressive speeds (Fig. 8) are in terms of seconds instead of miles per hour. The signal spacing (in the column to the left of the progressive speeds) is listed in terms of seconds instead of feet.

The offsets to the beginning and ending edges of the progressive bands as they pass the signal listed above them are given in the left part of Figure 8 on the same lines as the progressive speeds. This information is helpful in making further adjustments for leading and lagging green intervals, split phases, and other modifications, and in manually drafting the time-space diagram. If the progressive band utilizes the full green interval at any signal, an asterisk will precede the progressive band offsets on this printout.

Other information includes the plan number, which is the same as the optimum cycle, together with the requested band width proportions located in parentheses. The proportions are expressed in percentages. The system title, subtitle, and the name of the organization using the program are also included.

If the program processing option on input Card 10, SCAN, is used, as may be desirable in the first run for a system using large minimum and maximum cycle lengths, only the first two tables (Figs. 6 and 7) will be prepared by the computer.

Punched Output

If the message YES is punched in Card 11 and the option RUN was selected on Card 10, the program will punch a deck of data processing cards containing all the parameters necessary for a supplemental computer program to plot, draw, or print a time-space diagram of the optimum solution. This intermediate deck consists of two identification cards and one additional card for each signalized location in the system.

The first identification card contains the title and subtitle, as contained on Cards 1 and 2 of the input deck. The second card contains the directional identification contained on input Card 8, the optimum cycle length, the two directional band widths, and the two directional efficiencies, in that order.

Each of the remaining cards contains the following information for each signal: the name of the signal location; the offsets to the beginning, middle, and end of the green interval; the phase split, the offsets to the beginning and ending edges of the progressive band in direction 1; the average distance to the next signal; the progressive speed to the next signal; the offsets to the beginning and ending edges of the progressive band in direction 2; the progressive speed from the next signal; and the code 1 or 2 to signify that distance and velocity are in units of feet and miles per hour or in units of seconds and seconds, respectively. The last card is identified by zero distance and velocities.

ACKNOWLEDGMENT

The author wishes to acknowledge a grant received from the National Science Foundation which offset computer expenses during the development of this program.

REFERENCES

1. Brooks, W. Douglas. Vehicular Traffic Control, Designing Arterial Progressions. IBM, 27 pp.
2. Little, John D. C., Martin, Brian V., and Morgan, John T. Synchronizing Traffic Signals for Maximal Bandwidth. Highway Research Record 118, pp. 21-47, 1966.
3. Yardeni, L. A. Vehicular Traffic Control, A Time-Space Design Model. Proc., Institute of Traffic Engineers, pp. 59-74, 1964.
4. Desrosiers, Richard D., and Leighty, Clyde H. Traffic Flow Responses to Unannounced Increases in Progression Speeds of Signal Systems. Public Roads, Vol. 34:1, pp. 1-4, 13-15, April 1966.
5. Klar, Herbert J. Traffic Signalization. Chapter 11 in Traffic Engineering Handbook, Institute of Traffic Engineers, pp. 382-458, 1965.