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Publication of this paper sponsored by Committee on Freeway Operations.

Description of a Combined Approach for Arterial Signal Coordination Considering Bandwidth and Delays

K.G. BAASS and B. ALLARD

ABSTRACT

The coordination of traffic lights on arterial streets can be achieved by maximizing the bandwidth or by trying to minimize delays and stops encountered on the artery and on the side streets. Both of these approaches have advantages that are partly retained in a compromise solution, where a green band is selected from among several possible bands so as to cause the least delay to the driver. A first step in this direction is described by giving the outline of a program that analyzes the relation among delays, speeds, offsets, bandwidths, and cycle lengths over a wide range of speeds and cycles. This program can be used by the practitioner to obtain the speed (for a given cycle length) that maximizes the bandwidth, or to determine the cycle (for a given speed) that maximizes bandwidth. It can also be useful to find the offset, speed, or cycle length that causes a reasonable delay to the driver while retaining an acceptable green band. The program that combines bandwidth maximization and delay minimization was applied to five data sets taken from the literature. It was found that the new approach is feasible and could have economic advantages. It was further found that, for low traffic volumes and no platoon dispersion, there is a relation between bandwidth and delays; larger bands generally result in less delay than smaller ones. But as dispersion and traffic volumes increase, this relation no longer holds. It was also strongly confirmed in all cases studied that delays increase with longer cycle lengths for a given value of $K = C \cdot V$, and it was shown that there is a tendency for increasing delay with increasing cycle length for a given speed on the artery.

Traffic signal coordination on arterial streets that are not part of a network remains an important problem for the traffic engineer. Two approaches to the coordination of traffic lights are available: bandwidth maximization, and the minimization of a disutility function, which is measured in terms of delays, stops, fuel consumption, and air pollution. Both of these ways of solving the problem have advantages, and an approach that combines these two methods would be of interest. This would retain the undoubtedly important advantage of the psychological effect of the green band and, at the same time, would be more efficient in terms of delays and stops and reducing fuel consumption and time lost by the driver.

There are many variables that intervene in the solution of the problem. Delays and stops on a coordinated artery depend on signal settings, offsets and bandwidth, platoon size, dispersion, and platoon speed. Relatively little is known about the relationships between these variables. Certain intuitive notions, such as the idea that the larger the bandwidth the lower the delay encountered on the artery, are commonly perceived by the user but have not been conclusively demonstrated.

The aim of the present paper is to describe the development of an algorithm and a computer program based on an approach that combines bandwidth maximization and disutility minimization. Some of the results obtained by applying this program to five arterial data sets are given. Because the number of relations between the intervening variables is high, only the most important relations were studied. The results indicate that certain economic benefits for drivers can be achieved by applying the proposed procedure.

COMBINED PROGRAM

The program developed contains two parts. The first part determines the bandwidths and offsets over a wide range of speeds and cycles, whereas the second part evaluates the disutility function for the bands and offsets developed in the first part. This is done by simulating traffic flow through the artery. In order to allow the investigation of as many relations between the intervening variables as possible, it was decided not to use a microscopic simulation model. The more macroscopic simulation approach used by Robertson (1) is still detailed enough to represent an average platoon, and this was incorporated into the evaluation part of the program. It has been shown in many applications that this provides satisfactory results. The initial development of these two subroutines was carried out by Couture (2), who also conducted the first tests.

The objective of the combined approach is to choose an offset that provides a green band of satisfactory width (not necessarily the maximum width for a given speed) and that ensures, at the same time, less delay and fewer stops than other bands of comparable width.

Bandwidth Algorithm

The bandwidth algorithm is based on the procedure described by Baass (3). Certain basic relations exist that depend on the geometry of the problem and that are useful for the development of an efficient algorithm. It was proved by Little et al. (4) that for equal speeds and volumes in both directions, a maximal bandwidth is given when the offsets between lights are 0 or half a cycle (semi-integer coordination). Bands with unequal speeds and volumes can be derived from this optimal solution by geometric transformations. In a first phase the bandwidth-generating algorithm was thus limited to a constant speed on the artery in both directions and a constant flow of traffic on the artery. These conditions can be changed by using the adjustments described by Little et al. (4).

The geometry of Figure 1 shows that, for all combinations of V • C = K, the bands have to have the same widths. K can be interpreted as a scale constant, and it is the distance traveled at a speed v (m/sec) during the cycle time C (sec).

In order to obtain a complete understanding of the relationships between the variables, the program allows for a wide range of K (where K = V • C is a scale constant) for which bands and offsets are determined. Describing the bands and offsets from K = 800 to K = 12,000 covers a range of speeds between V = 20 and 100 km/h and cycles from 40 to 120 sec.

The algorithm is based on the interference approach described by Brooks (5), although this had to

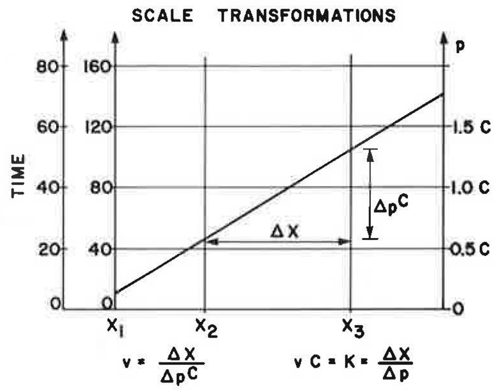

FIGURE 1 Scale transformations.

be modified to take into account two problems not considered by Brooks or Little et al. The first problem concerns the occurrence of multiple bands that are encountered frequently. The presence of multiple bands may have an important impact on delays and stops and may be altogether undesirable from the standpoint of bandwidth efficiency. The second problem is frequently encountered in the case of arteries with nearly equal distances between intersections and with the same red times at each light (as may happen in regular grids). In this case several bands of equal width (for a given speed) are obtained by different offset schemes, which generate different delays and stops. The incorporation of these two elements into the bandwidth algorithm is briefly outlined and illustrated by two simple examples. The detailed algorithm is described elsewhere.

Little et al. (4) have shown that in the case of semiinteger coordination there are 2**(n - 1) possible offset schemes to be considered for determination of a maximum band for a given speed and cycle. These offset schemes can be described, for simplicity of representation and for rapidity of calculations, by using the binary system. Consider n intersections; the offset of the first intersection is arbitrarily set to 0 and the intersections are numbered from 1 to n from left to right. If a light is in phase with the first light, its offset is 0; if not it is 1. The following offset scheme represents a sequence of binary numbers, and the decimal equivalent describes the offset scheme in a unique way:

0 1 0 1 1 1 1 0 1 0

This offset scheme is represented by the number 378. Offset scheme 9 would indicate that light n and light (n - 3) are out of phase. This simplified representation is essential for the rapid execution of the program.

The principles of the modified algorithm can best be illustrated by considering Figure 2.

The initial calculations are the same as those of Brooks as described by Gazis (6). The light with the minimum green is determined from which the maximum possible band can be identified. Its slope is defined by the speed. The red lights will interfere at the top (left) and at the bottom (right) with this maximal band, because the red lights can have two positions on the 50 percent cycle horizontals in the time-space diagram. The left and right interferences are easily calculated together with their corresponding offsets with respect to the first intersection. The left interferences can then be ordered by decreasing magnitude. The data in Table 1 describe the situation shown in Figure 2.

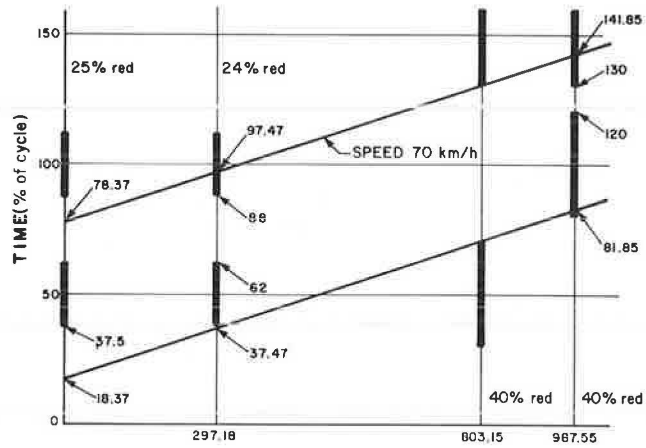

FIGURE 2 Determination of interferences; artery in Laval, Quebec; data set 2.

TABLE 1 Interferences and Offsets for Example in Figure 2

I	LIGHT (K)	LEFT(I)	RIGHT(I)	THETA(K) LEFT	RED(K) %
1	1	40.87	0.00	0	25
2	4	11.85	38.15	0	40
3	2	9.47	24.53	1	24
4	3	0.00	0.00	0	40

The enumeration of all possible bands could be done in a systematic way based on these interferences, but it is evident that this is an infeasible approach. An efficient way must be found to generate only the largest bands because, for delay evaluation purposes, there is interest in the band of maximum width and in all bands B that are wider than an acceptable minimum. This requirement can be stated as an inequality: $X \cdot B_{max} \le B \le B_{max}$, where X is a value between 0 and 1 chosen by the user. The procedure adopted for calculating these bands and the corresponding offsets is a good heuristic. It calculates 2(n - 1) bands, which ensures that at least the n largest bands for each speed are found, together with the corresponding offsets. The efficiency of the heuristic was verified in all of the examples tested in the five data sets.

The first band is calculated considering only the offsets, thus producing the left interferences and a bandwidth of BAND = MINGREEN - LEFT(1). The next (n - 1) bands are obtained by exchanging right interferences with left interferences (on the dotted diagonal in Table 1) by always using the maximal right interference for all j < i. The next (n - 2) bands are obtained by exchanging right interferences with left interferences on the solid diagonal (Table 1). Multiple bands are possibly present when the interferences are larger than the corresponding red times. The double band is given by the difference between the interference and the red time minus the largest interference of the remaining lights that have their interferences on the same side. This is easily verified in Figure 2. The data in Table 2 give the calculations required to obtain the n largest and double bands.

The algorithm always produces the maximum band and in most cases the n largest bands. This holds especially for n bands of equal width. This can be seen in Figure 3 for the special case of equal distances between intersections. The data in Table 3

TABLE 2 Calculation of the N Largest Bands

CALCULATIONS	BAND	OFFSET	NUMBER
60-40.87 40.87-25-11.85	19.13 4.02	0 1 0 0	4
60-0.0-11.85	48.15	0 0 1 1	3
60-38.15-9.47	12.37	0 0 1 0	2
60-38.15-0.0	21.85	0 1 1 0	6
60-40.87-38.15 40.87-25-9.47	0.0 6.40	0 1 0 1	5
60-11.85-24.53 24.53-24-0.0	23.62 0.53	0 1 1 1	7

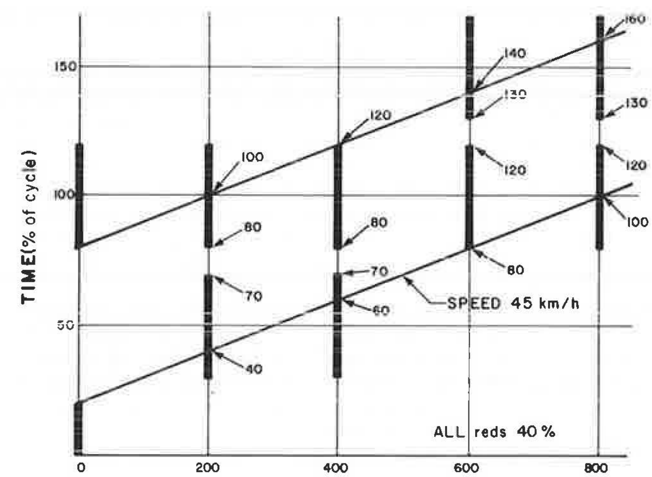

FIGURE 3 Determination of interferences for an artery with equal distances between intersections.

TABLE 3 Calculation of Bands and Offsets

I	LIGHT (K)	LEFT(I)	RIGHT(I)	THETA(K) LEFT	RED(K) %
1	3	40	10	0	40
2	5	30	20	1	40
3	2	20	30	0	40
4	4	10	40	1	40
5	1	0	0	0	40

BAND %	OFFSET	N	DELAY 850v/h	DELAY 1700v/h
20	0 0 0 1 1	3	14.9	69.4
20	0 0 1 1 1	7	17.2	72.4
20	0 0 1 1 0	6	16.7	67.1
20	0 1 1 1 0	14	17.2	72.4
20	0 1 1 0 0	12	14.9	69.4
0	0 0 0 1 0	2	24.4	77.7
0	0 1 1 1 1	15	28.1	74.6
0	0 0 1 0 0	4	24.4	77.7

give the necessary calculations. There are five maximal bands with quite different delays.

Evaluation of Delays and Stops

The evaluation of traffic performance is done by determining delays, stops, and an index of performance that is defined in the same way as in TRANSYT (1). The traffic is input at the beginning of the artery in a uniform pattern, and the platoon is followed downstream while considering entering and exiting vehicles at the intersections (uniform entries over green period from the side streets). The platoon is dispersed ($F = 1/1 + kt$) by using Robertson's formula (1). The procedures for calculating delays and stops are similar to those used in TRANSYT, in which interval size can be varied. The delays encountered on the side streets are determined by Webster's formula (7), and the stops on the side streets are estimated as in the SOAP (8) program. The timings and offsets of lights as well as platoon speeds are transferred from the first part of the program to this evaluation procedure.

The program produces graphic and corresponding printed output (see Figure 4). There are four different graphics illustrating the relations among

1. Band, speed, and delay for a given cycle length; the delay is the minimum delay calculated for all bands $X \cdot Bmax \leq B \leq Bmax$;
2. Delay and cycle for different values of $K = C \cdot V$;
3. Delay and cycle for different speeds; and
4. Bandwidth and cycle for different speeds.

These outputs can be used in practical applications or for research purposes. The execution times of the program are reasonable, considering the repeated delay evaluations for different offsets and for each speed (interval for speed evaluation 0.2 km/h for $10 < V < 125$ km/h, interval for cycle evaluation 5 sec for $40 < C < 120$ sec, interval for delay evaluation 1 sec). The example artery cited by Little (4) of 10 intersections necessitates 1.5 min of execution time on an IBM 4341 computer.

ANALYSIS OF RESULTS

To clarify some of the relationships between the different intervening variables an experiment was conducted by using the program and fixing the values of certain variables and letting only one variable change at a time. Delay, a basic indicator of performance, was studied in relation to speed, bandwidth, cycle length, and volume. This was done for five data sets, which are

1. An artery with 5 intersections at equal distances (200 m) and 40 percent of red time at each intersection;
2. An artery in Laval, Quebec, cited by Baass (3), with 4 intersections;
3. The artery used in MAGTOP (9) with 5 intersections;
4. The artery described by D.A. Bowers in the ITE manual (10, Figure 96, pp. 234), with 8 intersections; and
5. The artery that served as an example for Little (4), with 10 intersections.

There are certain traffic conditions that could be termed ideal for the application of the bandwidth approach. These correspond to its basic hypotheses. The conditions would include few vehicles on the artery, low degree of saturation, no platoon dispersion, constant platoon speed, and few vehicles entering the artery from the side streets. Given these conditions, it could be intuitively hypothesized that a larger band would cause fewer delays and stops than a smaller one. This was the first point to be investigated. The second was to verify, on a larger sample of arteries and over a wider range of cycles, the hypothesis formulated by Kahng and May (11), Mao et al. (12), and Rogness (13), which states that delay would increase on an artery when cycle length increases. This hypothesis was studied with respect to bandwidth, offsets, and to the constant K. The third point was to investigate the relation among a given speed, the cycle length, and delay; it was hypothesized that, for a given speed, a shorter cycle length is preferable with respect to delay.

Because these hypotheses are most likely to be true on a near ideal sample artery, the cases given in Table 4 were studied on the first data set.

Figure 5 shows the relationship between speed, bandwidths, and delays for an 80-sec cycle or for K = 800 to K = 10,000 for a volume of Q = 212 vehicles per hour. There is less delay as compared with neighboring values for each peak in the bandwidth curve. But clearly, comparable bands do not necessarily have comparable delays. Delays also depend on the speeds and offsets. In fact, the offset element is an important one. Each of the regions around the peaks in this graph have particular offset schemes [see Baass (3)]. They are given, for this example, in Table 5.

It can be seen that the offsets remain the same over a wide range of speeds, and that this has an influence on the delays. In this particular case there is a peak in bandwidth at the speed of 18 km/h, where the bandwidth is equal to the minimum green; the only delay encountered for the platoon is at the first light in each direction of in-bound and out-bound bands because there is no dispersion. Generally speaking there is a relation between bandwidth and delay, which is also illustrated in Figure 6. For a given value of K, wider bands do produce less delay at this level of volume. Furthermore, it is clearly seen that there is a relationship between cycle and delay (which should not come as a surprise, considering the way delays are calculated). Because K is given by the product of the cycle length and the speed (in Figure 5), and the delay decreases (in Figure 6) for a given value of K, these figures can be used to choose the best values of speeds and cycles. A practical illustration is given later in this paper. Figure 7 shows a general trend of increasing delay for a given speed as cycle lengths increase. The peak of the bandwidth in Figure 8 is reflected as a low delay in Figure 7 and, as an exception, the cycle of 80 sec gives the lowest delay for a speed of 18 km/h. From this graph it is possible to find the cycle that minimizes the delay for a given speed and that retains a band whose width is shown in Figure 8. This figure also gives the cycle length that maximizes the bandwidth for a given speed.

As volume increases to 850 vehicles per hour, the curves still behave in much the same way as at Q = 212 vehicles per hour. However, the bandwidth factor becomes less important as differences in delays disappear between curves of equal K. A further increase of volume to 1,700 vehicles per hour (still having no platoon dispersion) is illustrated in Figures 9-11. Bandwidths have no further impact on delays, except for the speed of 18 km/h, where the band corresponds to the minimum green. It would be desirable to achieve bands that correspond to the width of the minimum green, which is not necessarily

I M P R E S S I O N   D E S   D O N N E E S

NOMBRE DE CARREFOURS:	8
DUREE DU CYCLE MIN., MAXI., INT (SEC)	40 130 5
NOMBRE DE VITESSES UTILISEES:	5
VALEUR DES VITESSES:	17.7 23.5 35.6 53.5 71.3 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
NOMBRE DE CONSTANTES UTILISEES:	5
VALEUR DES CONSTANTES:	1416 1880 2848 4280 5704 0 0 0 0 0 0 0 0 0 0
INCREMENT POUR LA DISPERSION DES PELOTONS:	1.00
FACTEUR MULTIPLICATEUR DES ARRETS POUR LE CALCUL DE L'INDICE DE PERFORMANCE:	8
FACTEUR DE PONDERATION POUR LES VOLUMES:	1.00
NUMERO DE L'ENSEMBLE DE DONNEES:	BOWERS

CARREFOUR — V O L U M E S

	ARTERE						RUE SECONDAIRE					
	MONTANT	VIR.GAU	VIR.DRO	DESCEND	VIR.GAU	VIR.DRO	MONTANT	VIR.GAU	VIR.DRO	DESCEND	VIR.GAU	VIR.DRO
1	850.	0.	0.	850.	0.	0.	0.	0.	0.	0.	0.	0.
2	850.	0.	0.	850.	0.	0.	0.	0.	0.	0.	0.	0.
3	850.	0.	0.	850.	0.	0.	0.	0.	0.	0.	0.	0.
4	850.	0.	0.	850.	0.	0.	0.	0.	0.	0.	0.	0.
5	850.	0.	0.	850.	0.	0.	0.	0.	0.	0.	0.	0.
6	850.	0.	0.	850.	0.	0.	0.	0.	0.	0.	0.	0.
7	850.	0.	0.	850.	0.	0.	0.	0.	0.	0.	0.	0.
8	850.	0.	0.	850.	0.	0.	0.	0.	0.	0.	0.	0.

DEBIT DE SATURATION

	--- ARTERE ---		-- RUE SEC. --	
	MONT.	DESC.	MONT.	DESC.
1	3400.	3400.	3400.	3400.
2	3400.	3400.	3400.	3400.
3	3400.	3400.	3400.	3400.
4	3400.	3400.	3400.	3400.
5	3400.	3400.	3400.	3400.
6	3400.	3400.	3400.	3400.
7	3400.	3400.	3400.	3400.
8	3400.	3400.	3400.	3400.

LIENS	VALEUR DE LA CONST. DE ROBERTSON	
1	0.3500	0.3500
2	0.3500	0.3500
3	0.3500	0.3500
4	0.3500	0.3500
5	0.3500	0.3500
6	0.3500	0.3500
7	0.3500	0.3500

CARREFOUR	ABSCISSE	ROUGE
1	0.0 METRES	50.00 POURCENT
2	213.36 METRES	50.00 POURCENT
3	396.24 METRES	50.00 POURCENT
4	609.60 METRES	50.00 POURCENT
5	676.56 METRES	50.00 POURCENT
6	783.34 METRES	50.00 POURCENT
7	991.46 METRES	50.00 POURCENT
8	1188.72 METRES	50.00 POURCENT

VERT MINIMUM: 50.00

DUREE DU CYCLE: 40

CONST(K):	1416.00	1880.00	2848.00	4280.00	5704.00
VITESSE:	35.40	47.00	71.20	107.00	142.60
BANDE:	27.12	16.73	23.83	16.66	13.45
RETARD:	21.61	20.71	19.84	19.78	18.06

DUREE DU CYCLE: 45

CONST(K):	1416.00	1880.00	2848.00	4280.00	5704.00
VITESSE:	31.47	41.78	63.29	95.11	126.76
BANDE:	27.12	16.73	23.83	16.66	13.45
RETARD:	23.01	22.07	19.42	19.11	21.25

DUREE DU CYCLE: 50

CONST(K):	1416.00	1880.00	2848.00	4280.00	5704.00
VITESSE:	28.32	37.60	56.96	85.60	114.08
BANDE:	27.12	16.73	23.83	16.66	13.45
RETARD:	26.66	25.19	22.01	22.42	23.85

BOWERS DU ITE 8 CARREFOURS F=0.35 Q=850

VITESSE BANDE RETARD

VITESSE	B.MAX	R.MIN	**DECALAGE	BANDE	RETARD	**DECALAGE	BANDE	RETARD	**DECALAGE	BANDE	RETARD	**DECALAGE	BANDE	RETARD
31.50	10.66	39.60	100	10.7	39.6									
31.60	11.10	38.52	100	11.1	38.5									
31.70	11.54	38.52	100	11.5	38.5									
31.80	11.98	38.52	100	12.0	38.5									
31.90	12.41	38.52	100	12.4	38.5									
32.00	12.84	38.17	100	12.8	38.2									
32.10	13.27	38.17	100	13.3	38.2									
32.20	13.69	38.17	100	13.7	38.2									
32.30	14.11	38.01	100	14.1	38.0									
32.40	14.53	37.86	100	14.5	37.9									
32.50	14.95	37.86	100	15.0	37.9									
32.60	15.36	37.86	100	15.4	37.9									
32.70	15.78	37.39	100	15.8	37.4									
32.80	16.19	37.39	100	16.2	37.4									
32.90	16.59	37.39	100	16.6	37.4									
33.00	17.00	37.39	100	17.0	37.4									
33.10	17.40	37.39	100	17.4	37.4									

FIGURE 4 Partial computer output for data set 4.

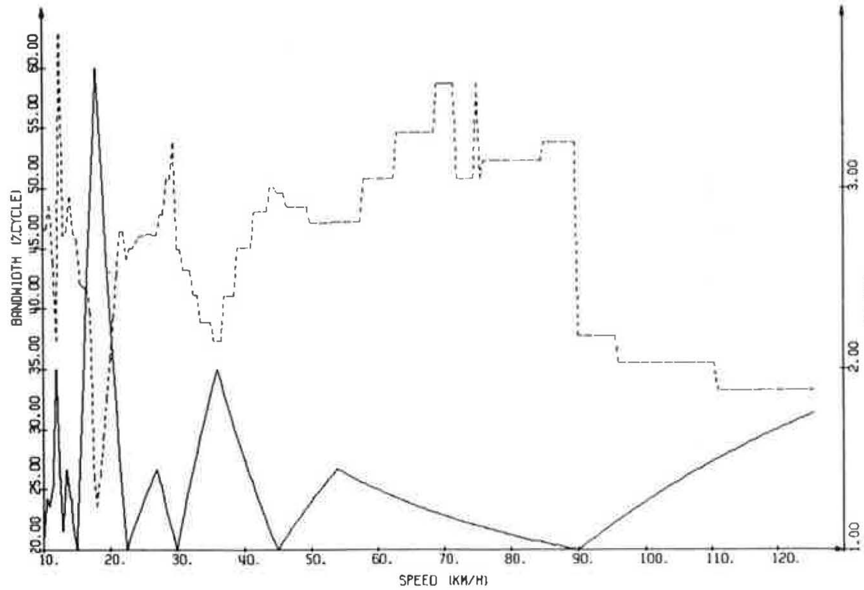

FIGURE 5 Band-speed-delay curves for data set 1 (C = 80 sec, Q = 212 vehicles/hr, k = 0.0).

TABLE 4 Traffic Conditions Studied for the Five Data Sets

VOLUME	SAT. FLOW	DEGREE X	DISPERS. k
212	3400	0.1	0.0, 0.35
450	3400	0.22	0.0, 0.35
850	3400	0.42	0.0, 0.35
1700	3400	0.83	0.0, 0.35

TABLE 5 Offset Schemes Corresponding to Figure 4

SPEED BEGIN	SPEED END	OFFSET SCHEME
15	22.5	11
22.5	30	10
30	41.1	7
41.1	45	13
45	71.6	8
71.6	90	16
90	125	1

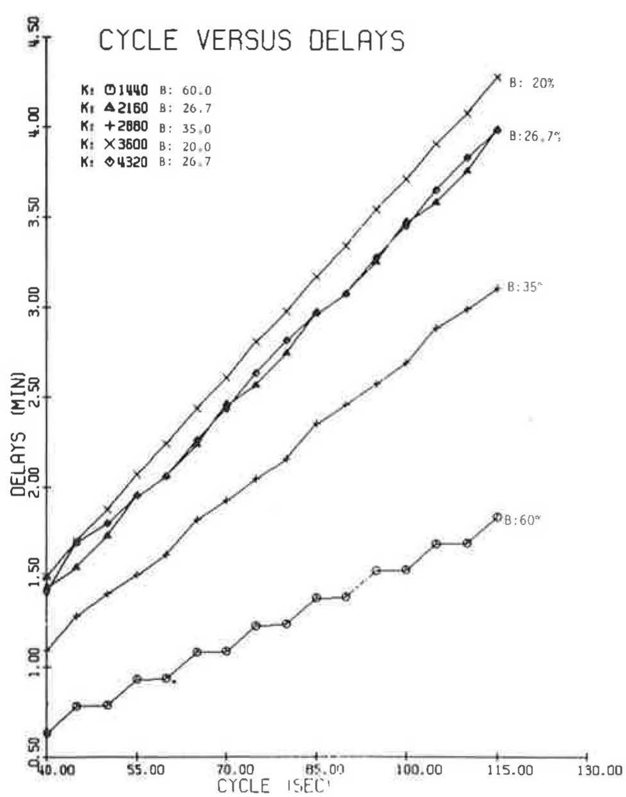

FIGURE 6 Data set 1 (Q = 212 vehicles/hr, k = 0.0).

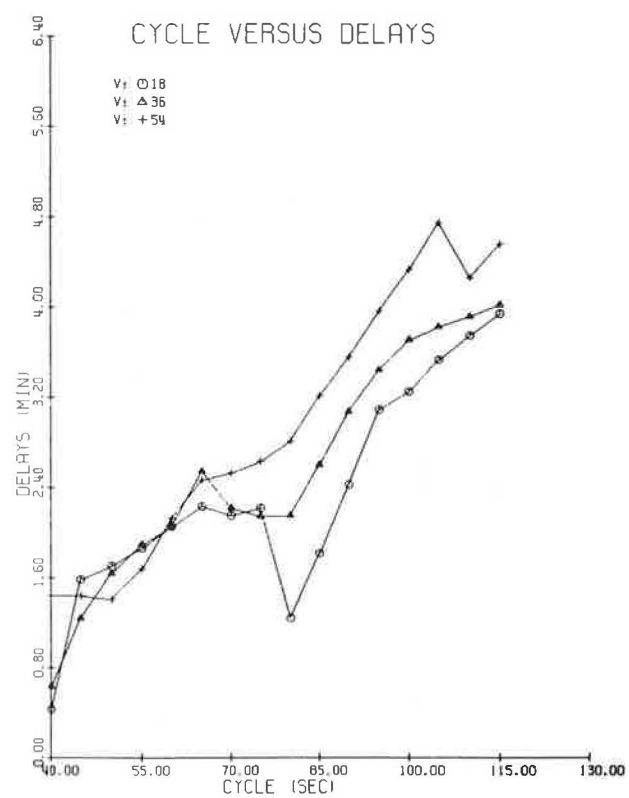

FIGURE 7 Data set 1 (Q = 212 vehicles/hr, k = 0.0).

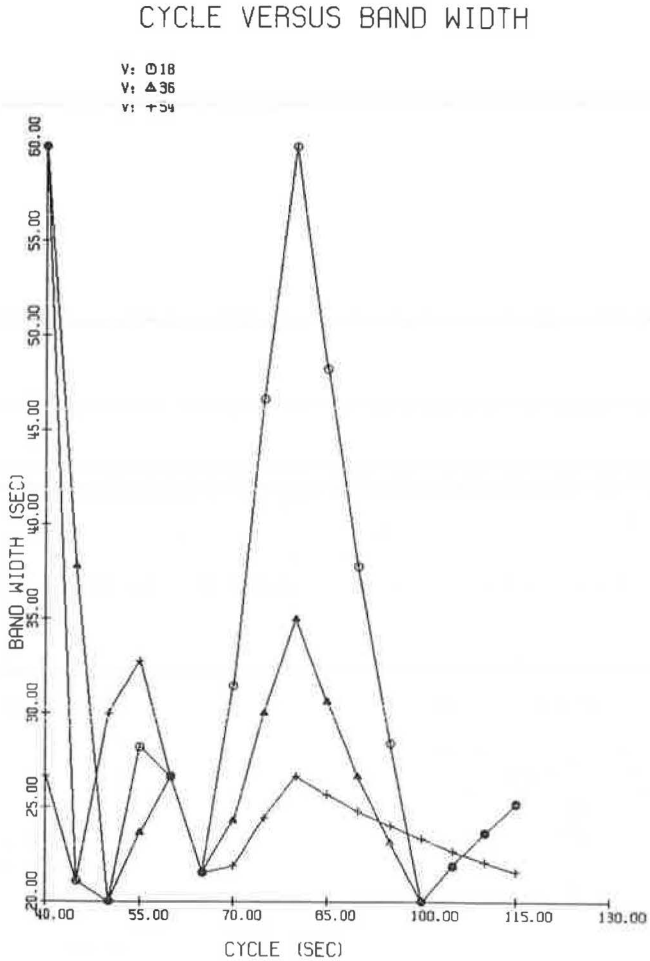

FIGURE 8 Data set 1 (Q = 212 vehicles/hr, k = 0.0).

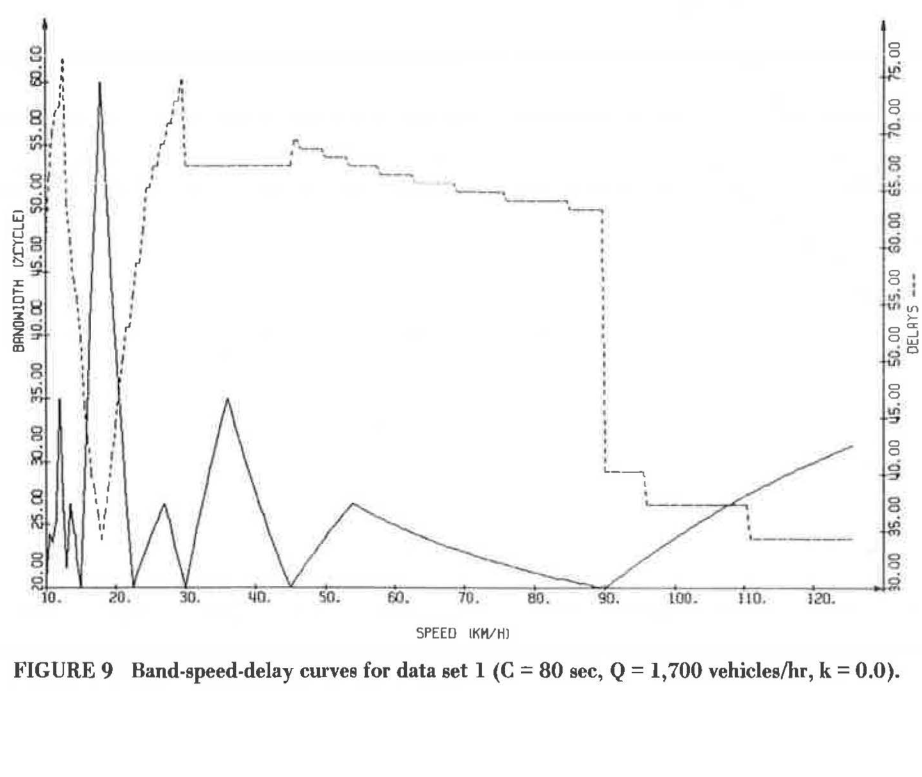

FIGURE 9 Band-speed-delay curves for data set 1 (C = 80 sec, Q = 1,700 vehicles/hr, k = 0.0).

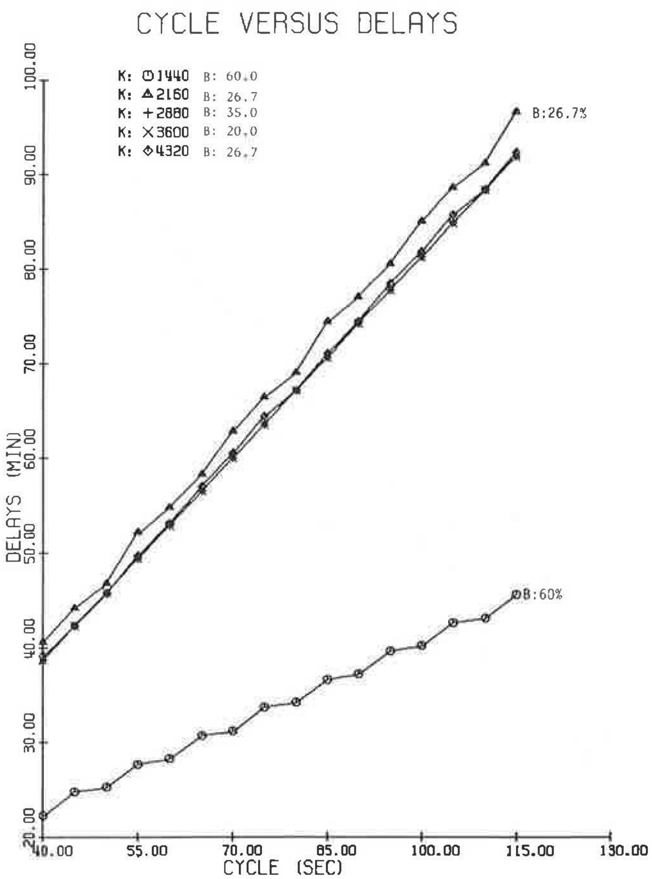

FIGURE 10 Data set 1 (Q = 1,700 vehicles/hr, k = 0.0).

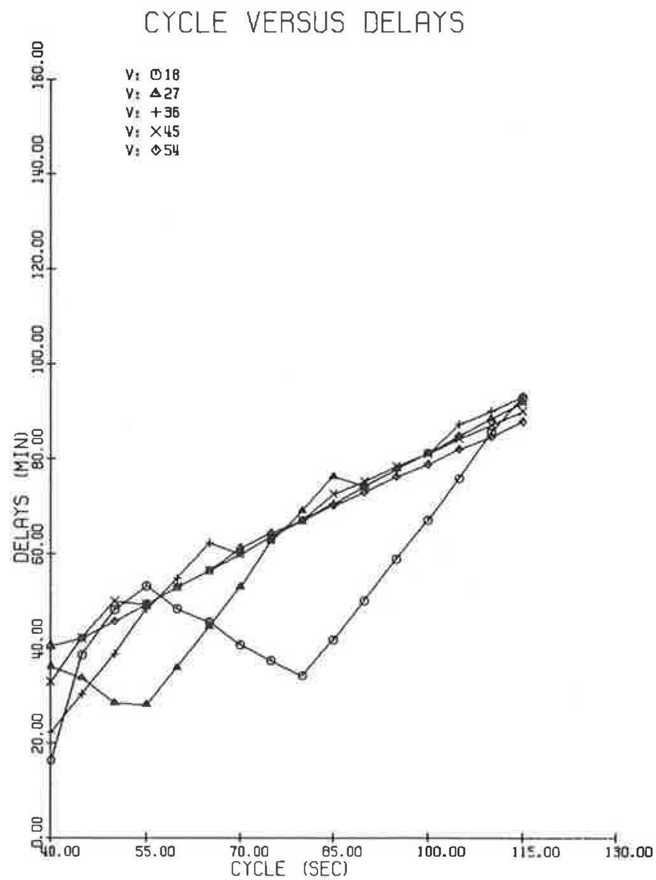

FIGURE 11 Data set 1 (Q = 1,700 vehicles/hr, k = 0.0).

possible, because there are many cases where the geometry of the artery and the red times prevent such a solution.

At low volumes with dispersion (Q = 212 vehicles per hour, k = 0.35), the relationship between bandwidth and delays is still discernible (see Figures 12-14), but as volumes increase this relation no longer holds.

The conclusion is that platoon dispersion alone is sufficient to invalidate the first hypothesis for a general case. However, the relation among cycle length, delay, and K is strongly confirmed. The tendency for delays to increase with increasing cycle lengths for a given speed is also verified in most cases.

The sample data set 2, which represents a more

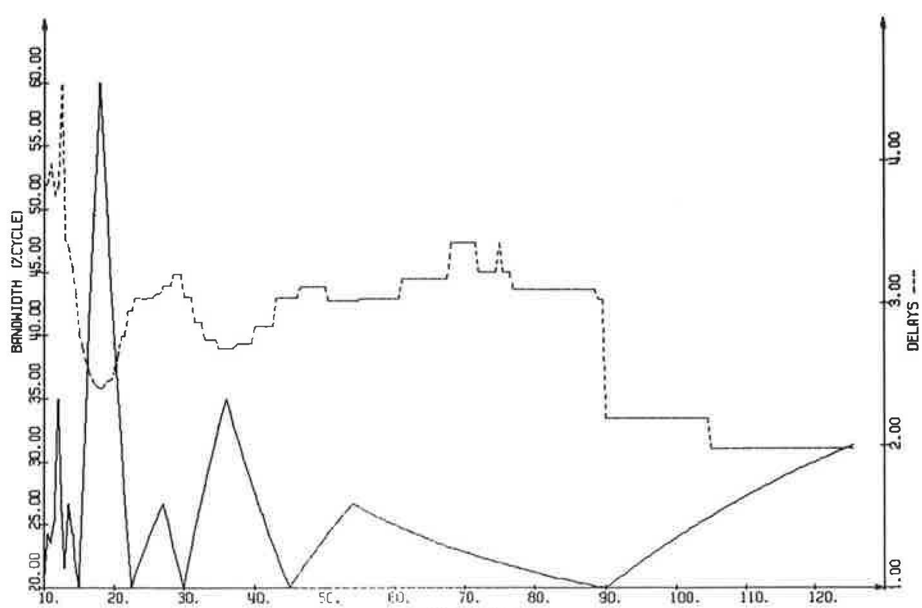

FIGURE 12 Band-speed-delay curves for data set 1 (C = 80 sec, Q = 212 vehicles/hr, k = 0.35).

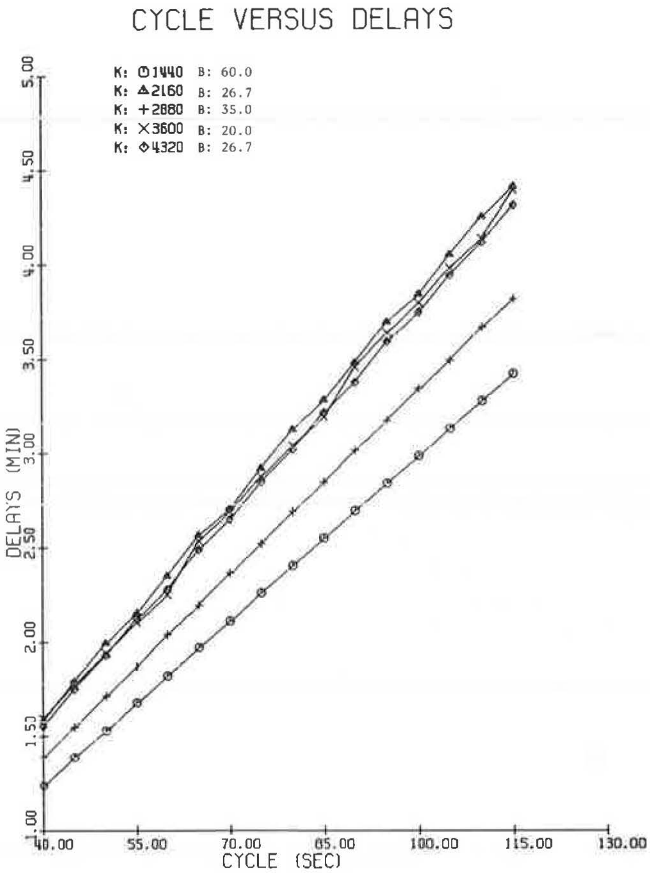

FIGURE 13 Data set 1 (Q = 212 vehicles/hr, k = 0.35).

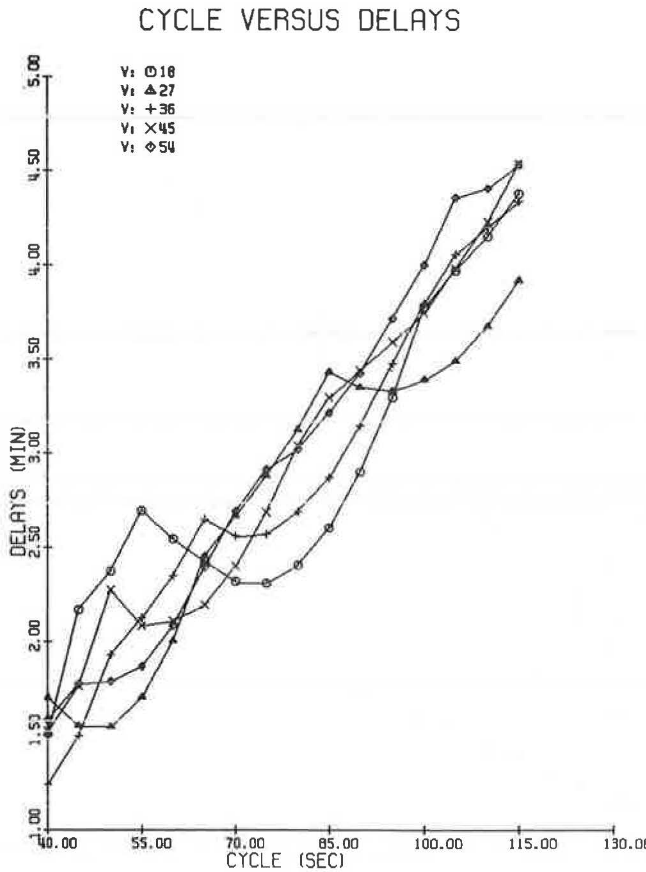

FIGURE 14 Data set 1 (Q = 212 vehicles/hr, k = 0.35).

general artery, was analyzed in the same detail. Only two results are reported here.

At low volumes (Q = 212 vehicles per hour, k = 0.0) and no dispersion, Figures 15-17 show that bandwidths have an influence on delays. The same cannot be said when dispersion is introduced at the same volume. Figures 18-20 for a volume of 850 vehicles per hour and dispersion indicate that larger bandwidths alone do not guarantee lower delays in all cases. But there are regions in Figure 18 that are more interesting than others with respect to bandwidth and delays. Choosing a certain point on the curve and implementing the corresponding offsets alone, however, does not guarantee minimum delays.

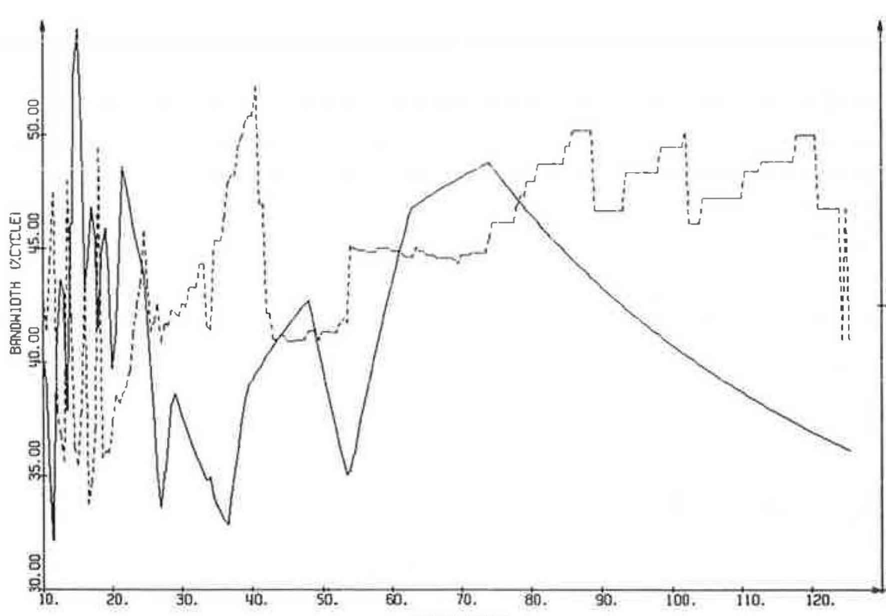

FIGURE 15 Band-speed-delay curves for data set 2 (C = 80 sec, Q = 212 vehicles/hr, k = 0.0).

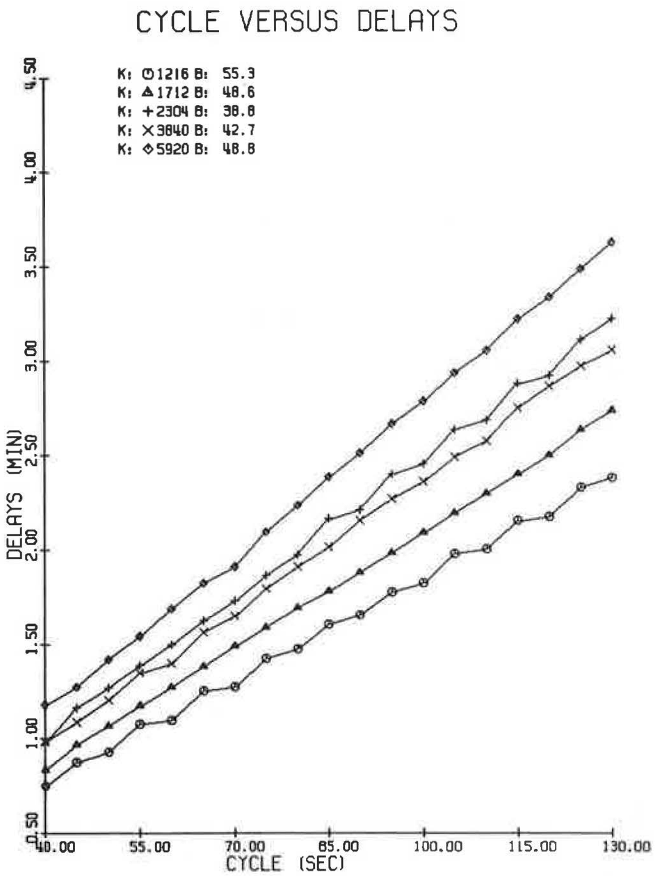

FIGURE 16 Data set 2 (Q = 212 vehicles/hr, k = 0.0).

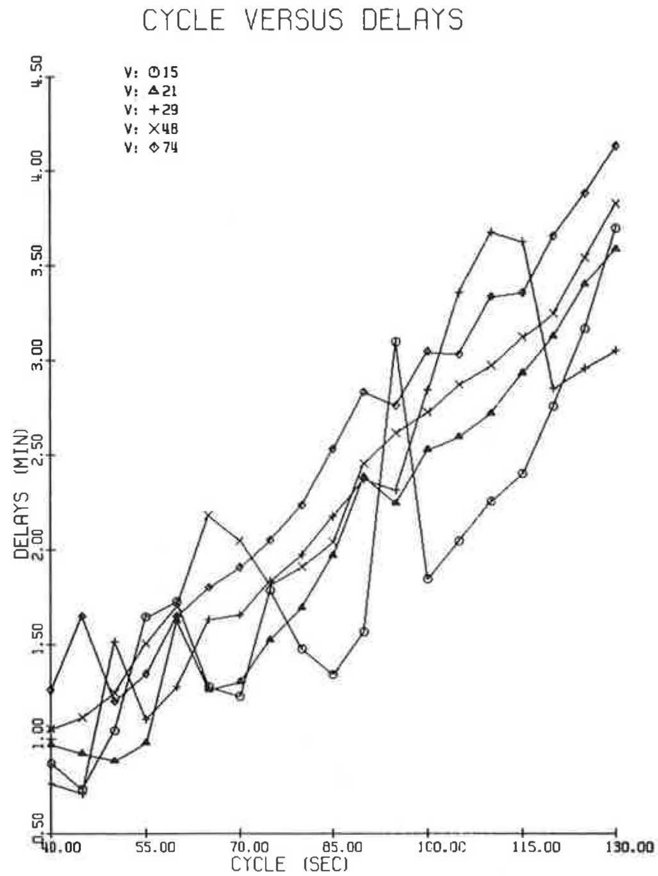

FIGURE 17 Data set 2 (Q = 212 vehicles/hr, k = 0.0).

Because certain portions of the curve have the same offset (see Table 6 for an example), different platoon speeds are possible, which have bands from 32.8 to 42.7 percent in width. But the corresponding delays may vary widely. It would be necessary to indicate to the driver, through traffic signs, the speed that minimizes delay.

Two further examples illustrate the points made. These are both arteries with 850 vehicles per hour of traffic volume and a degree of saturation of 0.40 with a dispersion of k = 0.35. The example cited in MAGTOP is illustrated in Figures 21-23, and the artery described by Little et al. (4) is illustrated in Figures 24-26. The latter example shows that the

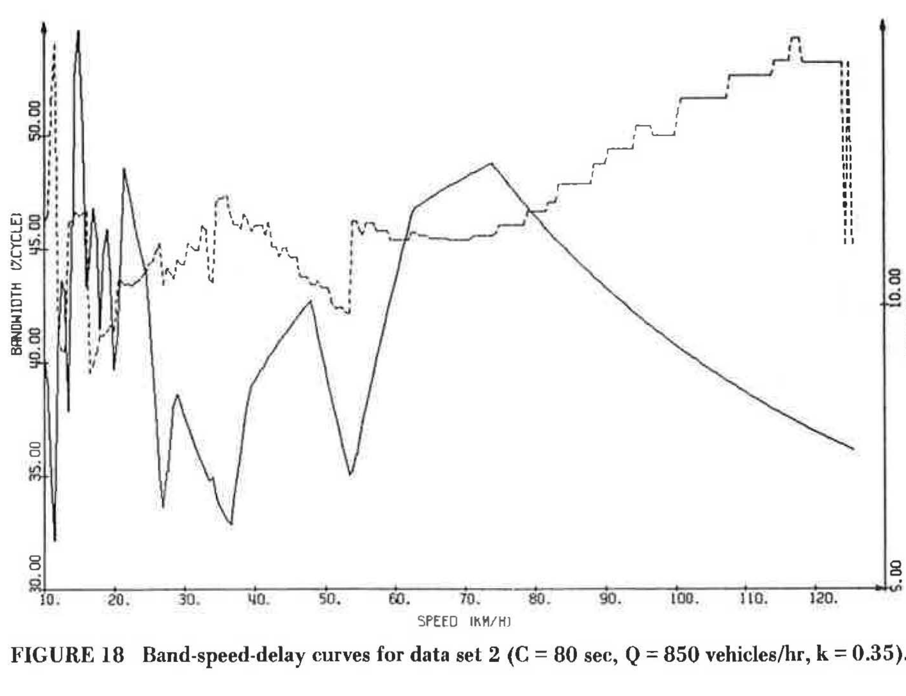

FIGURE 18 Band-speed-delay curves for data set 2 (C = 80 sec, Q = 850 vehicles/hr, k = 0.35).

TABLE 6 Domain of Offset Scheme 5

OFFSET SCHEME 5		
SPEED	BAND	DELAY
36.40	32.80	11.76
48	42.7	9.94
53.5	35.1	9.55

bandwidth is not necessarily in phase with the delays (large band, low delay), but in all cases there is a strong relationship between cycle lengths and delays.

The program can also be useful in practice to help the engineer to choose offsets, speeds, and cycle lengths. In practical applications there are three possibilities with respect to the choice of the cycle and the speeds on an artery.

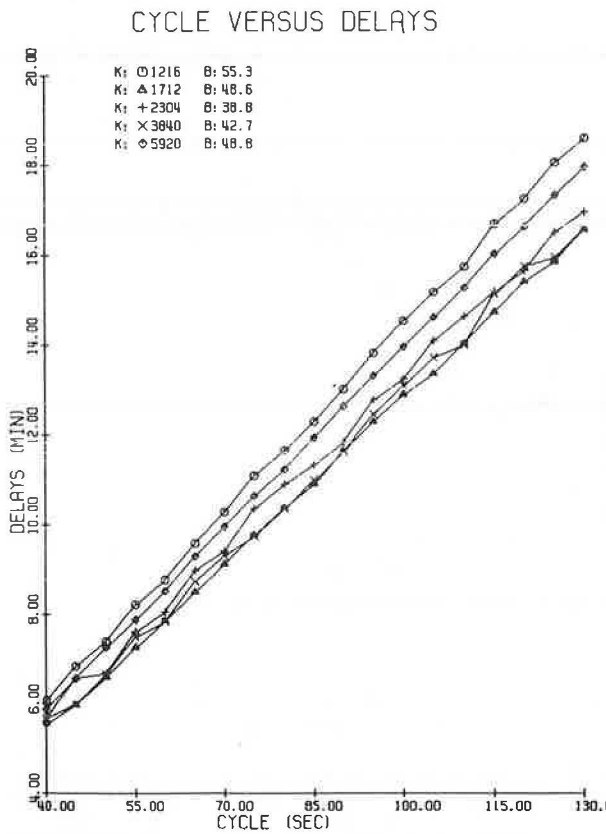

FIGURE 19 Data set 2 (Q = 850 vehicles/hr, k = 0.35).

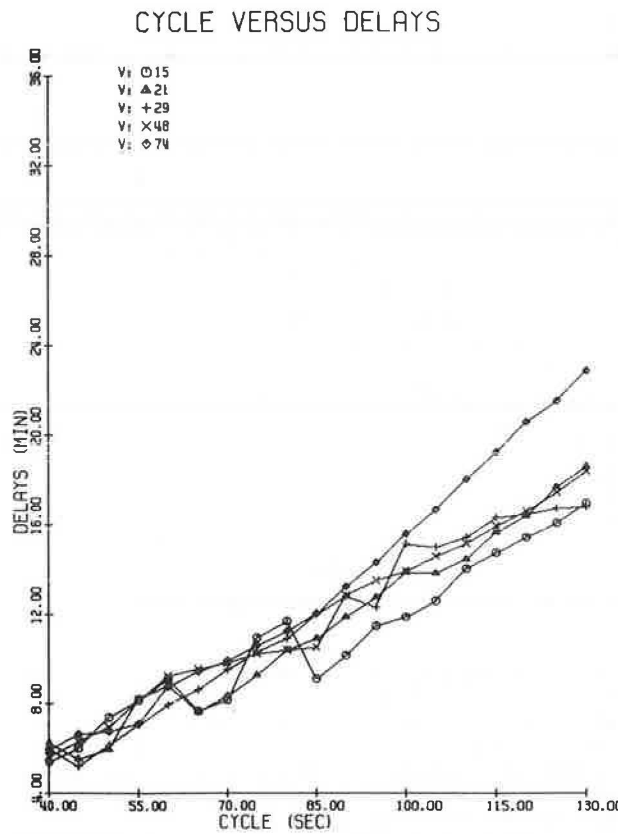

FIGURE 20 Data set 2 (Q = 850 vehicles/hr, k = 0.35).

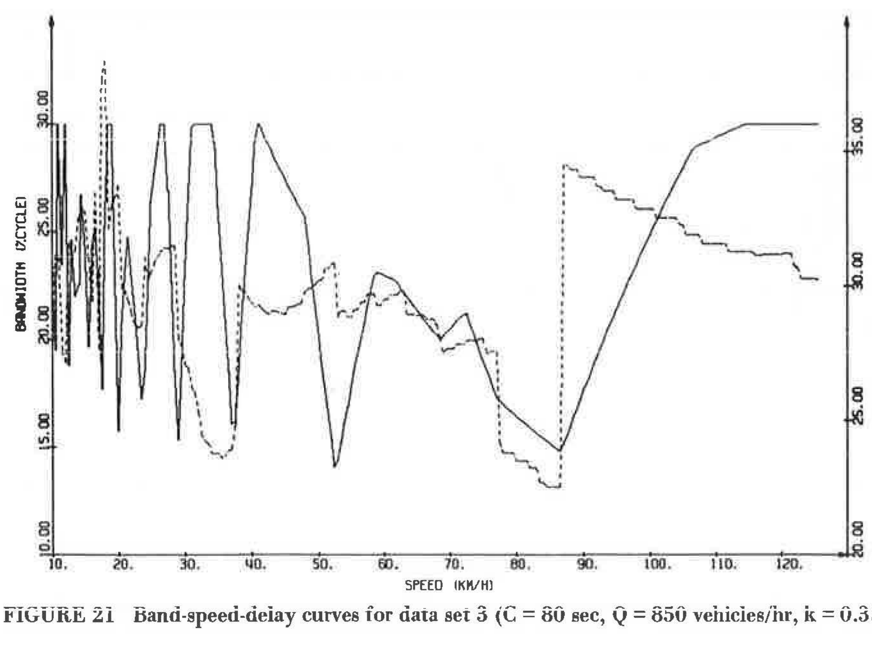

FIGURE 21 Band-speed-delay curves for data set 3 (C = 80 sec, Q = 850 vehicles/hr, k = 0.35).

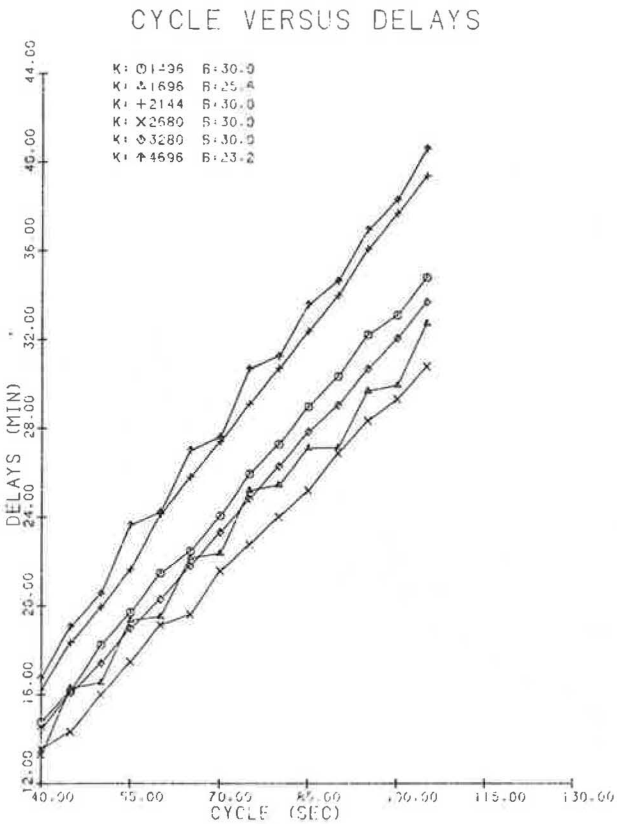

FIGURE 22 Data set 3 (Q = 850 vehicles/hr, k = 0.35).

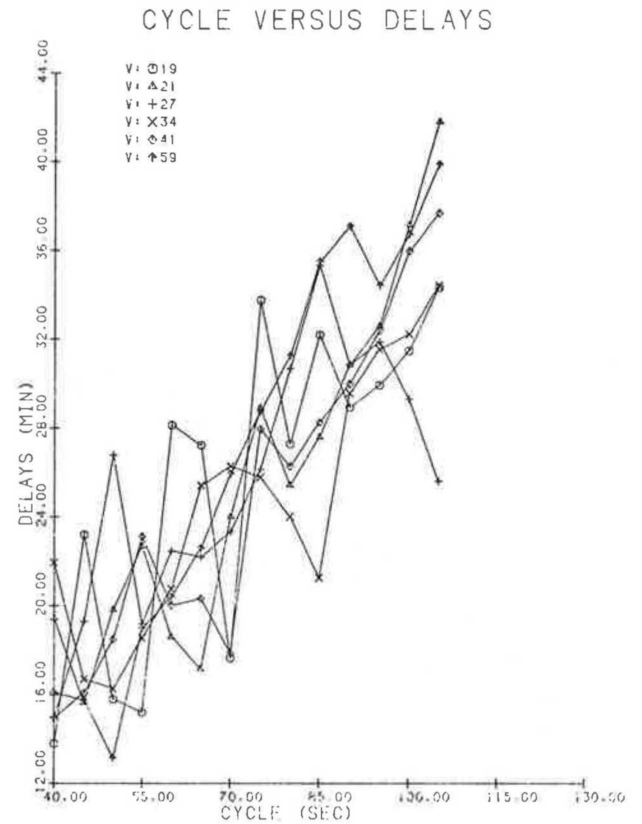

FIGURE 23 Data set 3 (Q = 850 vehicles/hr, k = 0.35).

1. The cycle length and the speed can vary between a minimum and a maximum value.
2. The cycle length is fixed, but the speed can vary between a minimum and a maximum value.
3. The cycle length can vary between a minimum and a maximum value, but the speed is fixed.

The choice of a good offset, speed, and cycle length can be done with the graphic output of the program. This is illustrated by using the example of data set 4 at Q = 850 vehicles per hour with a platoon dispersion factor of k = 0.35.

1. Let $40 < V < 55$ and $55 < C < 80$. Figure 27 shows high delays in the region of acceptable speeds at a cycle length of 80 sec, but there is an interesting band at V = 35.6 km/h with B = 23.8 and a delay of 33.44, the offset scheme being 100. Be-

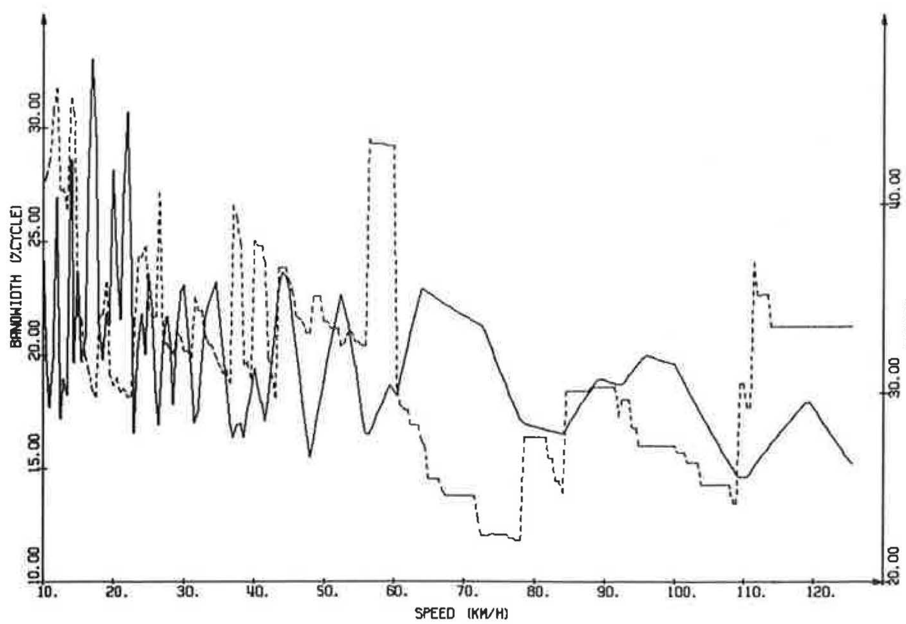

FIGURE 24 Band-speed-delay curves for data set 5 (C = 80 sec, Q = 850 vehicles/hr, k = 0.35).

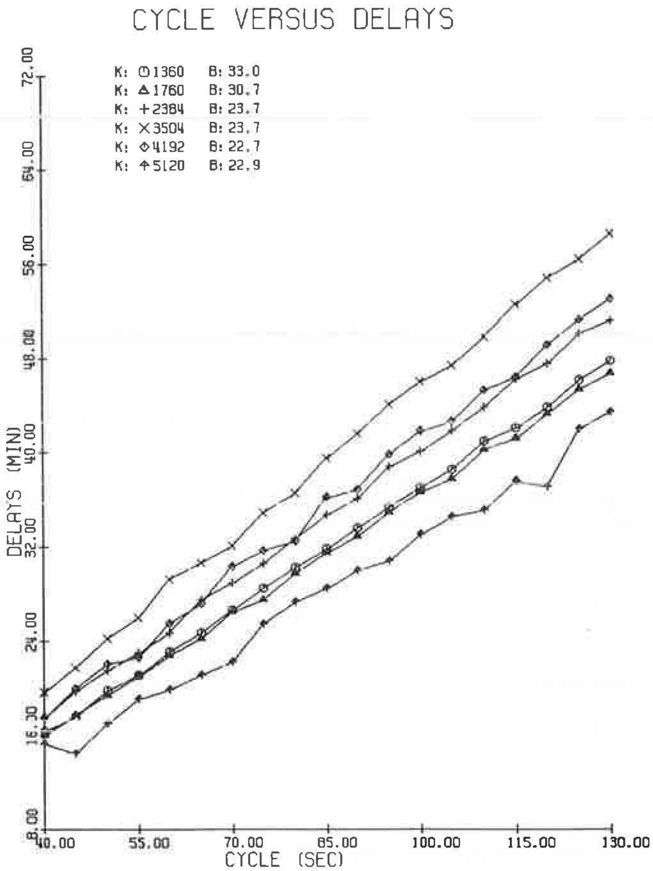

FIGURE 25 Data set 5 (Q = 850 vehicles/hr, k = 0.35).

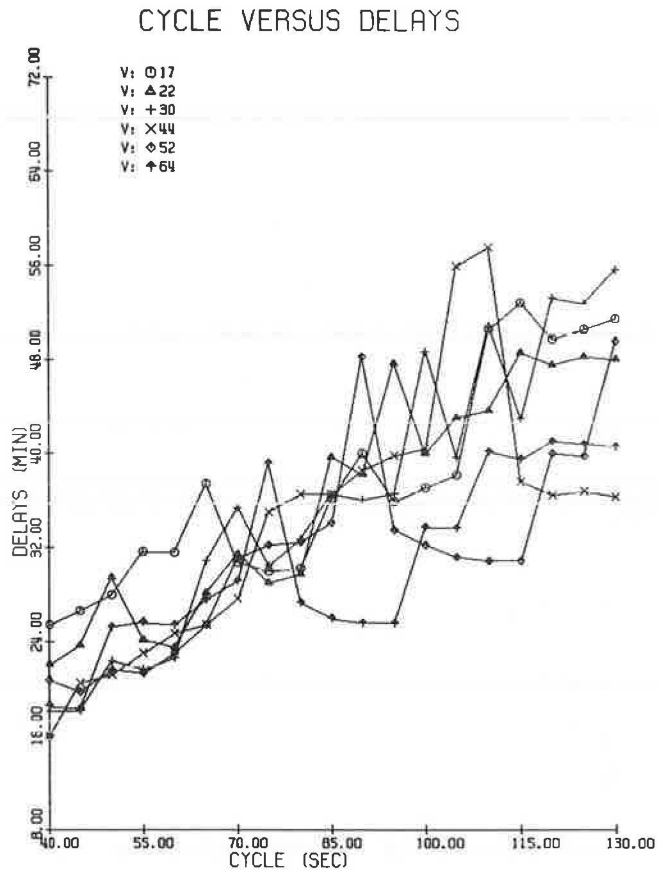

FIGURE 26 Data set 5 (Q = 850 vehicles/hr, k = 0.35).

cause the speed is too low, Figure 28 is used. This indicates that for the same value of K = V • C = 35.6 • 80 = 2,848, delays can be reduced by shortening the cycle length. The smallest allowable cycle would give the smallest delay. The solution would be C = 55 sec, speed = 51.78, delay = 32.62, and offset scheme 100.

2. Let C = 60 sec and 40 < V < 60. This corresponds to 2,400 < K < 3,600, which represents, at a cycle of 80 sec, a range of speeds of 30 < V < 45. Figure 27 would indicate the best speed of 35.6 km/h at 80-sec cycle length. The best choice would be C = 60 sec, V = 47.5 km/h, delay = 26.23, and offset scheme 100.

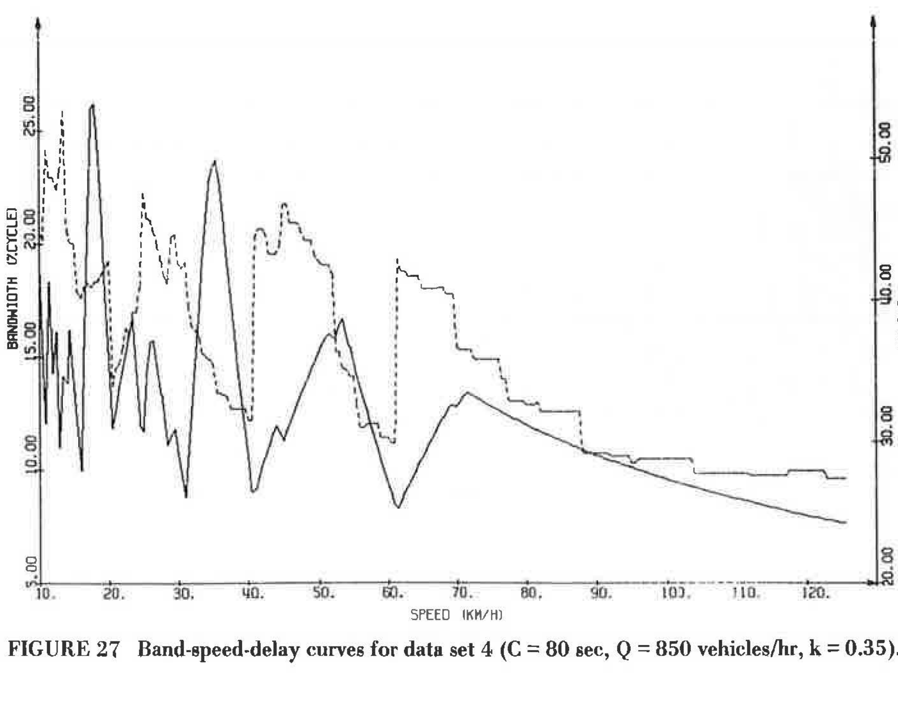

FIGURE 27 Band-speed-delay curves for data set 4 (C = 80 sec, Q = 850 vehicles/hr, k = 0.35).

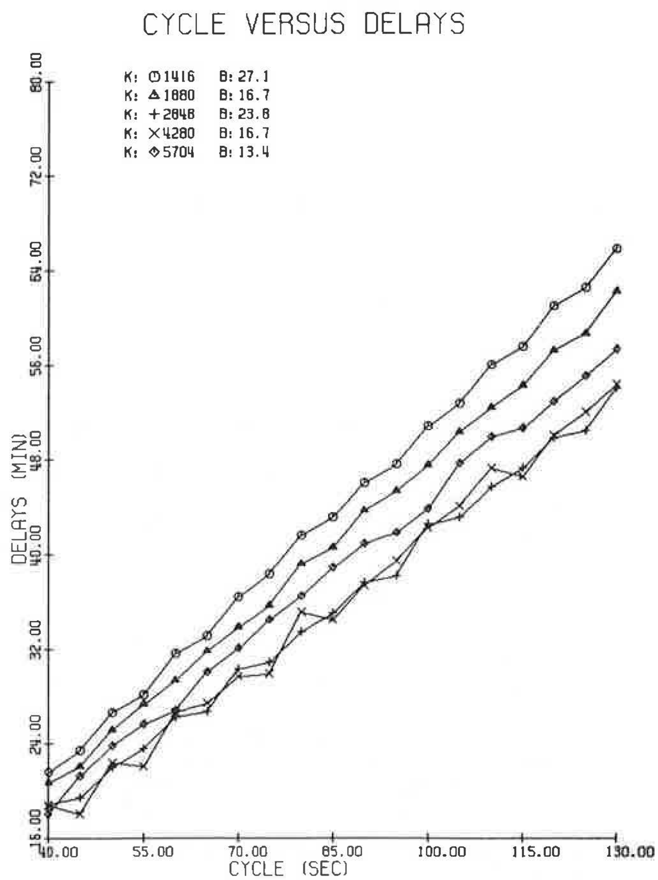

FIGURE 28 Data set 4 (Q = 850 vehicles/hr, k = 0.35).

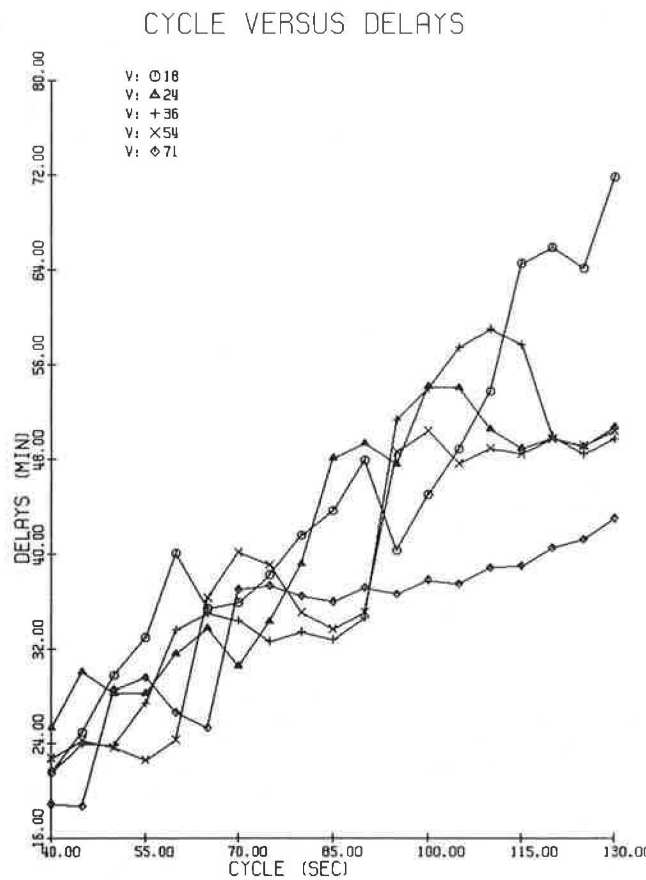

FIGURE 29 Data set 4 (Q = 850 vehicles/hr, k = 0.35).

3. Let V = 54 km/h and 80 < C < 100. Follow the curve in Figure 29 for a speed of 54 km/h. The best cycle length would be 85 sec with a band of 12.74 percent and a delay of 33.71. At a cycle of 80 sec the bandwidth would be 16.6 percent and the delays would be 35.15. The offset scheme is 31.

It would be interesting for this kind of decision to introduce an objective function that would evaluate the trade-off between a gain in delay against a loss in bandwidth.

CONCLUSIONS

Experiments with different data sets indicate that there is a clear relationship between delays and bandwidths in the case of an artery with simple geometry and no platoon dispersion. Delays are smaller as bands increase. This relation holds only for low degrees of saturation (in this case around 0.40). In more general situations of geometry and with platoon dispersion, there is no strong indication of a clear relationship between bandwidth and delay, because this depends also on speeds and offset schemes. However, the output of the program allows the identification of offsets that ensure low delays for large bands. It can be concluded from analysis of all five data sets that there is a clear relationship among K, the delay, and cycle lengths, which indicates that shorter cycle lengths cause less delay to the traffic on the artery. There is also a relation between cycle length and delay for a given speed, with the delays generally decreasing as cycle lengths are shorter.

The proposed combined method of arterial coordination analysis can be useful to the practitioner because it allows cycle lengths, speeds, and offsets to be chosen to give minimum delays while retaining a band of reasonable width. The procedure also allows the determination of the cycle length that maximizes the bandwidth for a given speed, and the speed that produces a maximum bandwidth for a given cycle length can also be found. The use of this combined approach would favor the retention of the psychological advantages of the bandwidth approach for the driver, while being, at the same time, more efficient in terms of delays. Further work will be devoted to a deeper analysis of the relationship between bandwidths and delays, and to a more detailed study of the relationships between the intervening variables and the number of stops encountered on the artery.

Discussion

Edmond C.P. Chang*

The basic issues and considerations between maximum bandwidth and minimum delay approaches to arterial signal coordination under two-phase signal operations were discussed in the paper by Baass and Allard. The procedure developed allows an engineer primarily to "determine the cycle length that maxi-

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mizes the bandwidth for a given speed and to find the speed that produces a maximum bandwidth for a given cycle length." Graphic-type comparisons were used to study the interrelationships among cycle, speed, progression bandwidth, and systemwide delay measurement. The experiment proved three basic hypotheses.

1. A larger progression band would cause fewer delays and stops than a smaller one in low saturation; that means no platoon dispersion, constant platoon speed, and fewer vehicles entering the artery from the side street.
2. In a large sample of arteries and a wide range of cycles, delay would increase on an artery when cycle length increases.
3. At a given speed, a shorter cycle length is preferable in considering delay.

Also described in the paper is the theoretical development of a computer program based on combining bandwidth maximization and disutility minimization. The results of this computer program, applied to five arterial data sets, were discussed. However, more clarification of the following topics would contribute to a better understanding of this paper.

1. It is not clear, at least at the beginning of the paper, that the application and discussion of this paper are focused on the two-phase arterial traffic signal coordination of a low-volume, low-speed, and short-distance-spaced urban grid-type network.
2. Interesting discussions in this paper introduce the possible trade-off analysis between the relationships of increase of delay and the decrease of progression bandwidth with respect to the increase of cycle length. A similar type analysis that would also be beneficial is to consider the decrease of delay versus the traffic volume difference in both travel directions in an arterial street system.
3. Many of the negative effects of platoon dispersion on delay were mentioned, but far fewer were discussed on the benefit of increased arrival traffic in a more uniform platoon and safer operation caused by maximum progression.
4. Because this paper emphasized the two-phase traffic signal, it simplified the important impact of variable phasing sequence in optimizing traffic signal operations and in reducing the total system delay.
5. A search of the optimal solution for all combinations of cycle and speed is not practical and is unnecessary if the computation algorithm starts with a satisfactory engineering solution.
6. At the beginning of the paper the disutility function of applying a TRANSYT-type macroscopic simulation model was investigated. However, it is not clear how the result, using the algorithm developed by the authors, would differ from that using the algorithm in TRANSYT under the specific coded platoon dispersion factor (PDF) and the stop penalty factor (SPF).

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Publication of this paper sponsored by Committee on Traffic Signal Systems.