MULTIBAND—A Variable-Bandwidth Arterial Progression Scheme

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A new approach to arterial progression optimization was developed that incorporates a systematic traffic-dependent criterion. The method generates variable bandwidth progression schemes in which each directional road section is assigned an individually weighted band. The computer program for this method is named "MULTIBAND." Similar to MAXBAND, MULTIBAND uses mixed-integer linear programming for the optimization. The approach offers the traffic engineer a much wider range of design options than do existing arterial progression methods. In particular, the program provides a capability to adapt the progression scheme to the specific traffic flow pattern on each link of the arterial. Simulation results indicate that this method can produce considerable gains in performance when compared with traditional progression methods.

Arterial progression methods are widely used in the United States, as well as in other countries (*1,2*). The conceptual basis for the progression design is that traffic signals tend to group vehicles into platoons with more uniform headways than would otherwise occur. The platooning effect is accentuated on the major streets that have signalized intersections at frequent intervals. In these circumstances, to encourage platooning seems desirable so that continuous movement (or progression) of vehicle platoons through successive traffic lights can be maintained. In this case, the signal timings are designed to maximize the width of continuous green bands in both directions along the artery at the expected speed of travel. In general, such signal systems operate best when the main-street flow is predominantly through traffic and when the number of vehicles turning onto the main street is small.

Advances in optimization techniques and computational capabilities have steadily increased the sophistication of arterial progression methods. Two of the most advanced and versatile of these methods today are PASSER-II (*3*) and MAXBAND (*4*). The latter method uses a powerful optimization technique (mixed-integer linear programming) and is an extension of earlier work by Little (*5*). It can find the optimal solution for the problem and calculate cycle time, offsets, progression speeds, and order of left-turn phases to maximize the weighted combination of the bandwidths in the two directions along the artery. It was also extended for application to multi-arterial closed networks (*6*).

The FHWA has been promoting in recent years the systematic optimization of traffic signal timings in urban areas (*7*). As part of this effort, TRANSYT-7F, a delay-based signal network optimization method, was adopted for use in North America (*8*). Yet many traffic agencies find it necessary to impose on the TRANSYT solution some arterial progression scheme for the main streets (*9*). The objective is to obtain a smoother flow of traffic on the principal arteries than is achieved by TRANSYT settings alone. This process has led to the development of hybrid versions in which the TRANSYT program is constrained by a bandwidth solution for the arterial street (*10,11*). Other methods for combining the advantages of bandwidth-based models with delay-minimizing models were proposed by Wallace and Courage (*12*) and by Hisai (*13*). Tsay and Lin (*14*) described an inverted-funnel progression scheme for the same purpose. Other authors (*15–17*) have also shown that substantial benefits are to be gained by concurrent use of delay-based methods (such as TRANSYT–7F and SIGOP-III) and bandwidth-based methods (such as MAXBAND and PASSER-II). Such benefits accrue primarily because of the phase-sequence decision capabilities of the progression methods. A different approach is described that combines the advantages of the progression methods with traffic flow optimization criteria into a simultaneous optimization model.

BACKGROUND

A basic limitation of existing bandwidth-based programs is that their progression design criterion does not depend on the actual traffic flows on the arterial links and, therefore, is insensitive to variations in such flows. The total bandwidth that is obtained for the arterial can be allocated in any desired ratio among the two directions of travel. A common practice is to apportion it according to the directional volume ratio (k). Possible choices for this parameter include the ratio between the highest link volumes in each direction, or the ratio between the average (or total) link volumes in each direction. Neither of these choices can guarantee the best (or even a good) progression for delays and stops in different traffic flow patterns.

Because of turn-in and turn-out traffic, volumes along each direction of the arterial are not generally constant. Consequently, the idea of a uniform platoon moving through all the signals in one direction, which forms the conceptual basis for the bandwidth approach, does not always hold. Moreover, the ratio of volumes on opposing road sections between each pair of adjacent signals is also varying. That a single parameter (k) for the entire arterial can adequately reflect this diversity is, therefore, inconceivable. The situation is readily illustrated by an example taken from Hawthorne Boulevard in Los Angeles

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NO. OF STOPS	MULTIPLE STOP PROBABILITY ISOLATED WESTBOUND	ISOLATED EASTBOUND	COORDINATED WESTBOUND	COORDINATED EASTBOUND
0	0.43	0.37	0.70	0.74
1	0.42	0.43	0.22	0.22
2	0.15	0.18	0.08	0.04
MORE THAN 2	0.00	0.02	0.00	0.00
RMS OF STOPS	1.02	1.33	0.54	0.38

MAXIMUM CROSS STREET: WAITING TIME(SEC)	WAITING TIME DISTRIBUTION (%) ISOLATED	COORDINATED
0 - 20	75	46
20 - 40	15	17
40 - 60	8	15
60 - 80	2	14
80 - 100	0	8
AVERAGE CROSS STREET: WAITING TIME (RMS IN SECONDS)	16	43
PERFORMANCE INDEX	2374	968

FIGURE 4 Observed disutilities in the case study.

This case study compares the efficiency between coordination and free control using the current signal-timing plans that were developed for off-peak conditions. The result would probably be different if the timing plans were designed specifically for late-night operation. Though signal-timing plan optimization is an important issue, it was considered to be beyond the scope of this study.

CONCLUSIONS

Late-night, low-volume arterial signal control involves a trade-off between the motorists on the artery and those on the cross street. The conventional measures of effectiveness such as stops, delay, and fuel consumption are not appropriate for evaluating this trade-off because they do not reach significant levels. The measures proposed provide a better assessment of motorist disutility under these conditions.

The methodology described facilitates the choice between coordination and free operation on arterial roadways controlled by semiactuated signals when traffic is light. The choice is made on the basis of a disutility function that is a combination of the number of stops on the artery and the average cross-street waiting time. The disutilities are obtained from simulation. The methodology has been implemented as the DELVACS program. A case study using DELVACS was performed under the Gainesville, Florida, closed-loop signal system to demonstrate the usefulness of this method. The results indicated that this method provides a promising tool for late-night arterial signal control. But fine tuning, on the basis of local traffic conditions, especially pedestrian volumes, would be required when applying this method.

The methodology focuses on system efficiency for arterial stops and cross-street waiting times, but other factors, such as local preference, should also be considered in the determination between coordination and free operation on an arterial roadway.

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(*18*). The ratio of total traffic volumes in the two directions along the arterial is 2/1. Table 1 presents NETSIM simulation results for different bandwidth ratios. The bandwidth ratios that produce the lowest delay (6/1 or even 10/1) bear no relationship to the actual traffic volume ratio. A recent study proposed to determine the directional bandwidth ratio using a crude estimate of link delays (*19*). Although some improvements were obtained, this approach still produces only a single adjustment parameter for the entire arterial. Existing bandwidth maximization programs are lacking a suitable traffic-dependent optimization criterion and, therefore, cannot guarantee an optimum result for varying traffic flow patterns.

A new optimization approach is described that is designed to remedy the known deficiencies. This approach places the arterial bandwidth optimization concept on a more solid foundation by incorporating into the calculation procedure a systematic traffic-dependent criterion. The volume on each link of the artery, together with other traffic parameters such as capacity and speed, will have an effect on the optimization outcome through suitably chosen link-specific weighting factors, as contrasted with a single weight for all links in existing programs. Thus, the objective of providing volume-weighted progression while reducing delay (or travel time) and stops can be achieved. The computer program that performs this objective is named "MULTIBAND." The MULTIBAND method was originally developed by Gartner et al. (*20*).

DESCRIPTION OF METHOD

The MULTIBAND method was developed as an extension of the MAXBAND method. Both methods use a mixed-integer linear programming code for optimization. To explain the MULTIBAND method, the basic, symmetric, uniform-width bandwidth maximization problem is defined and expanded by incorporating a wider range of decision variables.

The generalized time-space diagram is shown in Figure 1. Consider an arterial with n signals; let S_i denote the signal at Node (Intersection) i, where $i = 1, \ldots, n$. For convenience, all time variables are measured in units of the cycle time. The following variables are defined:

b ($\bar{b}$) = outbound (inbound) bandwidth;
r_i ($\bar{r}_i$) = outbound (inbound) red time at S_i;
w_i ($\bar{w}_i$) = interference variables, time from right (left) side of red at S_i to left (right) edge of outbound (inbound) green band;
$t(h,i)$ [$\bar{t}(h,i)$] = travel time from S_i to S_h outbound [S_h to S_i inbound];
$\phi(h,i)$ [$\bar{\phi}(h,i)$] = internode offsets, time from center of an outbound [inbound] red at S_h to the center of a particular outbound [inbound] red at S_i;
Δ_i = intranode offset, time from center of $\bar{r}_i$ to nearest center of r_i; positive if center of r_i is to right of center of $\bar{r}_i$; and
τ_i ($\bar{\tau}_i$) = queue clearance time, an advance of the outbound (inbound) bandwidth at S_i to clear up turning-in traffic before arrival of main-street platoon.

The directional interference constraints ensure that the progression bands use only the available green time and do not infringe on any of the red times. From Figure 1, at each signal,

$$w_i + b \leq 1 - r_i$$
$$\bar{w}_i + \bar{b} \leq 1 - \bar{r}_i \tag{1}$$

The loop integer constraint results from the fact that the signals of the arterial are synchronized, that is, they operate on a common cycle time. Starting at the center of the outbound red at S_h and proceeding along a loop consisting of the points

center of outbound red at S_i,
center of inbound red at S_i,
center of inbound red at S_h, and
center of outbound red at S_h,

the terminal point is removed an integral number of cycle times from the point of departure. Summing algebraically the appropriate internode and intranode offsets along the loop,

$$\phi(h,i) + \bar{\phi}(h,i) + \Delta_h - \Delta_i = m(h,i) \tag{2}$$

where $m(h,i)$ is the corresponding loop integer variable. This equation can be expressed in terms of the time variables defined earlier. In an arterial with n signals, there are $n - 1$ such

TABLE 1 NETSIM SIMULATION RESULTS FOR HAWTHORNE BOULEVARD

E/W Volume Ratio	E/W Band Ratios	Delay (Sec/Veh)	Deviation from Optimal (%)
	1/1	80.73	26.9
2/1	2/1	71.44	12.3
	3/1	68.09	7.0
	4/1	67.07	5.4
	5/1	66.39	4.4
	6/1	63.61 (minimum)	0.0
	7/1	64.11	0.8
	8/1	64.06	0.7
	10/1	63.85	0.4

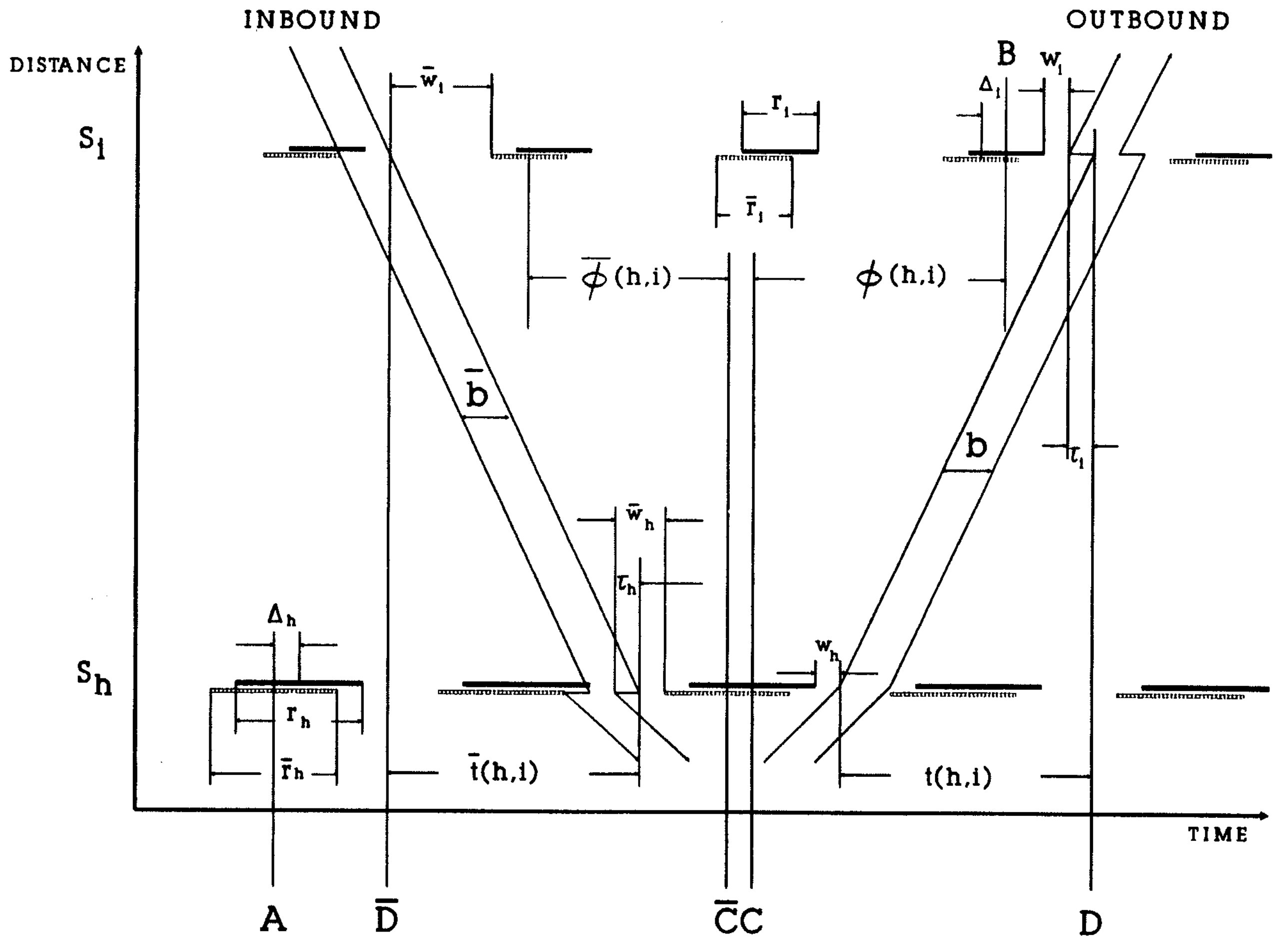

FIGURE 1 Time-space diagram for MAXBAND model.

constraints. A symmetric progression, $b = \bar{b}$, results in the following bandwidth maximization problem (BMP).

BMP-1

Given cycle time (splits), travel times (or speeds), and queue clearances, find bandwidth $b = \bar{b}$, offsets, and interferences to maximize $b = \bar{b}$, subject to interference and loop integer constraints. From the outputs of BMP-1, the final time-space diagram can be generated.

This basic maximization problem can be extended to make it a more versatile design tool for the traffic engineer. The first extension concerns the directional weighting of the two bands. In many cases, the traffic engineer may wish to favor one direction of traffic over the other, for example, the inbound direction during the morning peak period and the outbound direction during the afternoon peak period. A balanced progression may be desirable during off-peak periods. Let k be the target ratio of inbound to outbound bandwidth (taken as the ratio of total inbound to total outbound volumes along the arterial). The objective function and the ratio constraint can be set up as

Max$(b + k\bar{b})$, subject to

$\bar{b} \geq kb$ if $k < 1$ (outbound direction favored),

$\bar{b} \leq kb$ if $k > 1$ (inbound direction favored), and

$\bar{b} = b$ if $k = 1$ (balanced progression).

The first two inequalities can be replaced by a single inequality called the "bandwidth ratio constraint."

$$(1 - k)\bar{b} \geq (1 - k)kb \tag{3}$$

The inequality sign is used to avoid restricting the larger band to a specific ratio once the smaller band has reached its maximum potential.

The second extension is to let both the common signal cycle time C (sec) and the link-specific progression speed v_i ($\bar{v}_i$) (ft/sec) be optimizable variables (Link i represents the road section between S_i and S_{i+1}). This procedure introduces considerable flexibility in the calculation of the best arterial progression. Each of these variables is constrained by upper and lower limits. In addition, changes in speed from one link to the next can also be limited. Let the limits be as follows:

C_1, C_2 = lower and upper limits on cycle length seconds,

(e_i, f_i) $(\bar{e}_i, \bar{f}_i)$ = lower and upper limits on outbound (inbound) speed (ft/sec), and

(g_i, h_i) $(\bar{g}_i, \bar{h}_i)$ = lower and upper limits on change in outbound (inbound) speed (ft/sec).

For the outbound direction,

$$C_i \leq C \leq C_2 \tag{4}$$

$$e_i \leq v_i \leq f_i \tag{5}$$

$$g_i \leq v_{i+1} - v_i \leq h_i \tag{6}$$

Corresponding expressions are obtained for the inbound direction.

Another important decision capability that is offered by the mixed-integer linear programming technique is in determining the order of the left-turn phase (if one is present) with respect to the through green at any signal. This procedure is performed by means of 0–1 decision variables. A left-turn green can be chosen to lead or lag, whichever gives the most total bandwidth. The traffic engineer can specify which combination of leads or lags in each direction is permitted. Figure 2 shows the four possible patterns of left-turn green phases. Only some or none of these patterns may be allowed at any particular intersection. The variables for the phase-sequence decision are included in the loop-integer constraints.

Incorporating all these extensions into BMP–1 yields a more versatile bandwidth maximization problem, as follows.

BMP–2

Given splits, queue clearances, target ratio of bandwidths, and limits on cycle time, link speeds, and changes in speeds, find cycle time, offsets, interferences, bandwidths $(b, \bar{b})$, link progression speeds, and left-turn phase patterns to maximize $b + k\bar{b}$, subject to cycle time constraint, bandwidth ratio constraint, interference constraints, loop integer constraints, and speed and speed-change constraints.

In order to calculate the offsets, green splits must be available, or, alternatively, the user can provide traffic volume and capacity information for each intersection and the program will calculate the splits. BMP–2 is the current version of the MAXBAND program. Next, the changes introduced in MAXBAND to obtain the MULTIBAND model are described.

In MULTIBAND, a different band is assigned to each directional road section of the arterial. The bandwidth can be individually weighted with respect to its contribution to

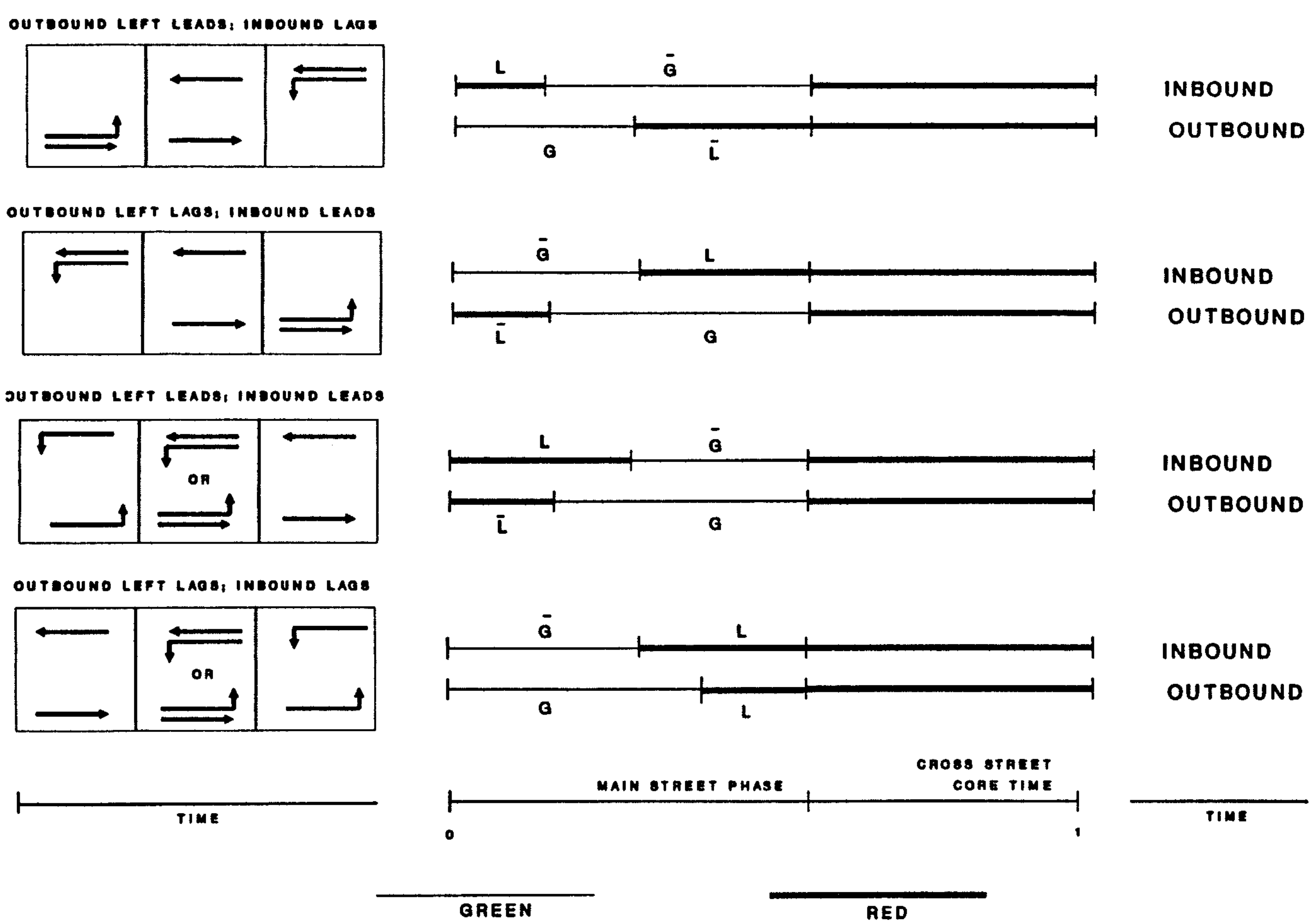

FIGURE 2 Four possible patterns of left-turn phases.

the overall objective function. (Note: The bands are continuous; only the width can vary.) Thus, a method is obtained that is sensitive to varying traffic conditions and the progression scheme can be flexibly applied to the different possible traffic flow patterns. The user can still choose uniform bandwidth progressions if desired, but this is now only one of many user options.

Referring to the geometry shown in Figure 3, the following variables are defined:

b_i ($\overline{b}_i$) = outbound (inbound) bandwidth between signals S_i and S_{i+1}; there is now a specific band for each directional road section or link.

w_i ($\overline{w}_i$) = time from right (left) side of red at S_i to centerline of outbound (inbound) green band; the time reference point at each signal is moved from the edges to the centerline of the band.

The following constraints apply in the outbound directions at signal S_i:

$$w_i + b_i/2 \leq 1 - r_i$$

$$w_i - b_i/2 \geq 0 \tag{7}$$

The pair of constraints can be combined as follows:

$$b_i/2 \leq w_i \leq (1 - r_i) - b_i/2 \tag{8}$$

The same relationship must be observed at signal S_{i+1}, because band b_i must be constrained at both ends:

$$b_i/2 \leq w_{i+1} \leq (1 - r_{i+1}) - b_i/2 \tag{9}$$

Corresponding relationships exist in the inbound direction (marked by a bar on all variables). These are the directional interference constraints. By redefining the time reference points to the centerline of the bands (or, the progression line), rather than the edges, the loop integer constraints given by Equation 2 remain unchanged and so do the travel time and speed-change constraints.

The bandwidth ratio constraint (Inequality 3) is now also changed to reflect the multiband situation. For each pair of parallel links,

$$(1 - k_i)\overline{b}_i \geq (1 - k_i)k_i b_i \tag{10}$$

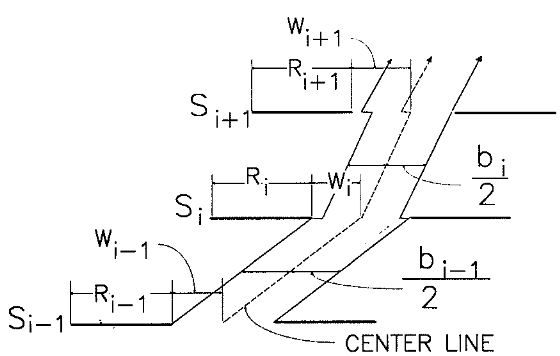

FIGURE 3 Geometry explaining the variables.

where k_i = target ratio of inbound to outbound bandwidth on Section i (taken as the ratio of the corresponding volumes in each direction). There are now $n - 1$ such constraints.

The most important departure compared to existing progression methods occurs in the definition of the objective function. Because in MULTIBAND the bands are link specific, they can be weighted disaggregately to achieve desirable traffic objectives for each link. The new objective function has the following form:

$$\text{maximize } B = \frac{1}{n - 1} \sum_{i=1}^{n-1} (a_i b_i + \overline{a}_i \overline{b}_i) \tag{11}$$

where a_i ($\overline{a}_i$) are the link-specific weights in the two directions. There are a multitude of options available for choosing the weighting coefficients. The following weighting options were chosen:

$$a_i = \left(\frac{V_i}{S_i}\right)^p \qquad \overline{a}_i = \left(\frac{\overline{V}_i}{\overline{S}_i}\right)^p$$

where

V_i ($\overline{V}_i$) = directional volume on Section i, outbound (inbound); either the total volume or the through volume can be used. The latter is called the "platoon volume."

S_i ($\overline{S}_i$) = saturation flow on Section i, outbound (inbound); this is the capacity volume in vehicles per hour of green (vphg).

p = exponential power; the following values were used: $p = 0$ (unit coefficients), $p = 1$ (i.e., volume/capacity ratio), $p = 2$ [i.e., (volume/capacity ratio)^2], $p = 4$ [i.e., (volume/capacity ratio)^4].

Other weighting options can easily be specified. This procedure provides considerable flexibility to the user. The result is the multiband, multiweight maximization program BMP−3.

BMP−3

Given splits; queue clearances; target ratios of bandwidths for each section; and limits on cycle time, link speeds, changes in speeds, and allowed left-turn phase patterns; find cycle time, offsets, interferences; link-specific bandwidths (b_i, $\overline{b}_i$); link progression speeds; and left-turn phase patterns; to

$$\text{maximize } B = \frac{1}{n - 1} \sum_{i=1}^{n-1} (a_i b_i + \overline{a}_i \overline{b}_i)$$

subject to cycle time constraint, bandwidth ratio constraints, interference constraints, loop integer constraints, and speed and speed-change constraints.

The increased decision capabilities of MULTIBAND require a corresponding increase in the size of the optimization problem. Typically, for a 10-signal arterial, there will be 66 variables and 160 constraints in MULTIBAND compared to 50 variables and 100 constraints in MAXBAND. This represents increases of 32 and 60 percent, respectively.

EVALUATION

The MULTIBAND computer program was created by modifying the existing MAXBAND program (*21*). The core of MAXBAND is MPCODE, a mathematical programming package that uses a branch-and-bound technique to solve the mixed-integer linear programs (*22*). The matrix generator module in MAXBAND, which prepares the input file for MPCODE from the traffic data, was revised to generate the new multiband, multiweight objective function as well as the new link-specific bandwidth variables, interference variables, bandwidth ratio constraints, and interference constraints. MPCODE was altered to handle the larger number of expected variables and constraints necessary to solve the MULTIBAND model. The output module in MAXBAND, which also calculates the cycle time, offsets, and phase sequences from the MPCODE results, was modified to provide time-space plots with variable bandwidths, as shown later.

In order to assess the performance of the multiband approach, it was compared with the performance of MAXBAND on a data set representing Canal Street in New Orleans. A diagram of the Canal Street network as prepared for NETSIM simulation appears in Figure 4. Canal Street itself is represented by the vertical arrows. The side streets are represented by horizontal arrows. On each section of street a list of three numbers, such as (0, 432, 120) is given, indicating that in each

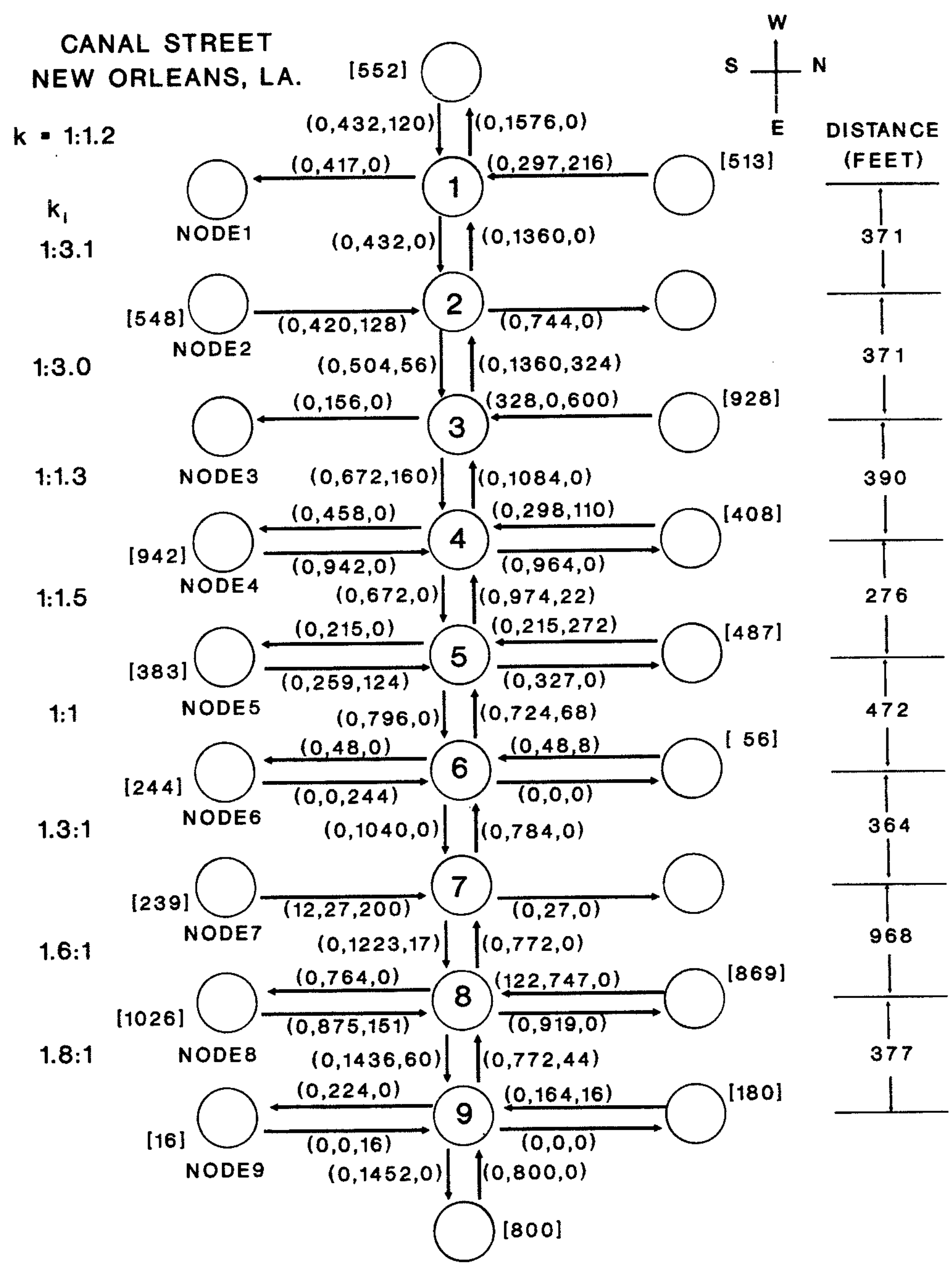

FIGURE 4 Canal Street network prepared for NETSIM simulation.

hour approximately 552 cars travel on that section of street and that when they get to the intersection, 0 percent turn left, 78 percent go straight, and 22 percent turn right. There is a wide variation in sectional volume ratio values (k_i) from 1:3.1 to 1.8:1; however, the ratio of the total volumes in each direction is 1:1.2. In this particular data set, there are no left turns allowed from Canal Street, although cars from some of the side streets do turn left onto Canal Street.

MULTIBAND was run on the Canal Street data set using seven different weighting schemes, as presented in Tables 2 and 3. MAXBAND was also run using its two possible weighting schemes $k = 1$ and k = total volume ratio (TVR). Both programs incorporate a centering routine that centers the progression bands within the available green space if there is leeway to do so. The simulations indicate that centering usually improves network performance. A selection of time-space plots is shown in Figures 5–10. Different MULTIBAND options result in different progression configurations, which in turn are quite different from those generated by MAXBAND. Each signal-setting scheme was simulated using NETSIM, considering the arterial alone as well as the arterial with the side streets. The results were also used to calculate a weighted combination of the average delay and the average number of stops, which is a performance index used by TRANSYT.

The simulation results are presented in Tables 2 and 3. The following notation is used for the weighting coefficients:

TVR = total volume ratio (for the entire arterial).

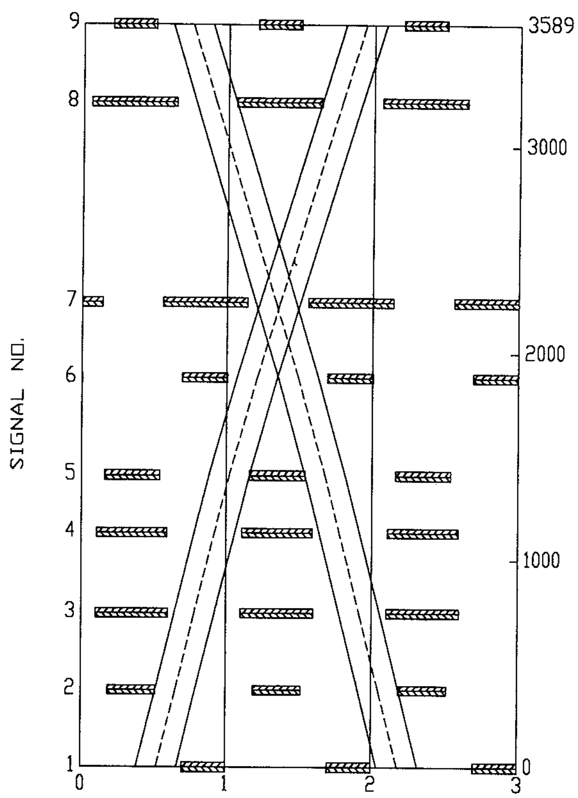

FIGURE 5 MAXBAND time-space diagram for Canal Street symmetric progression for k = 1.0 and cycle time = 70 sec.

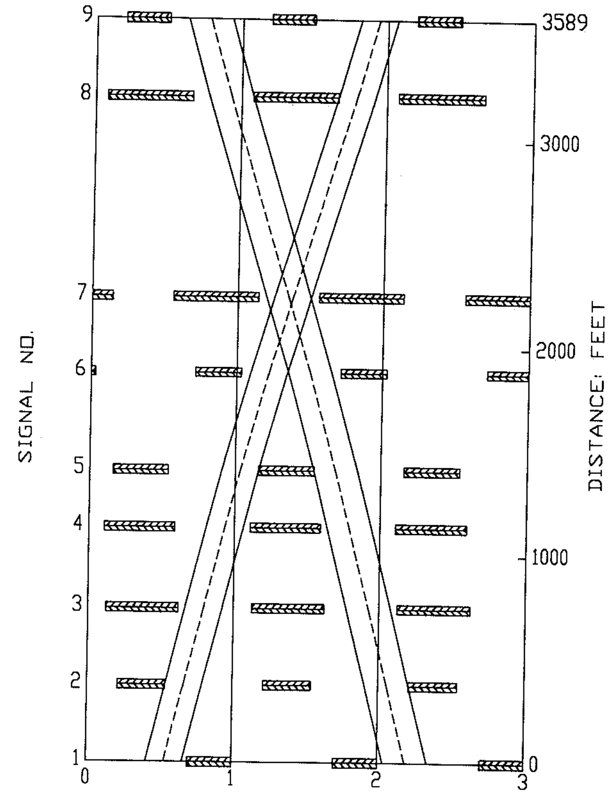

FIGURE 6 MAXBAND time-space diagram for Canal Street for band weight = total volume ratio, k = 1:1.2, and cycle time = 60 sec.

TVR = total volume ratio (for the entire arterial),
TVC = (total volume)/(total capacity) for each directional section, and
PVC = (platoon volume)/(platoon capacity) for each directional section.

The results indicate a clear advantage of the MULTIBAND settings over the MAXBAND settings in all cases. Additional evaluations were conducted for other arterial data sets, which also included multiphase sequences, with comparable results. Two samples of MULTIBAND progression schemes for Main Street in Waltham, Massachusetts, are shown in Figures 11 and 12. This arterial has several multiphase signals.

MULTIBAND produced improvements in all performance characteristics (delay, stops, speed, miles per gallon, and a weighted combination of delay and stops) compared to MAXBAND, no matter which weighting option was chosen, and whether or not data on side-street cars were included when calculating the performance characteristics. Depending on which characteristic is considered as being of primary importance, different weighting options produce the best results. However, the differences between various MULTIBAND options or between different MAXBAND options are in general much less than the difference between a MULTIBAND option and a MAXBAND option.

Without side-street cars being taken into consideration, the MULTIBAND option with the lowest average delay (24.11 sec) is $(TVC)^4$. The MAXBAND option with the lowest average delay (28.84 sec) is TVR. Thus, MULTIBAND obtains

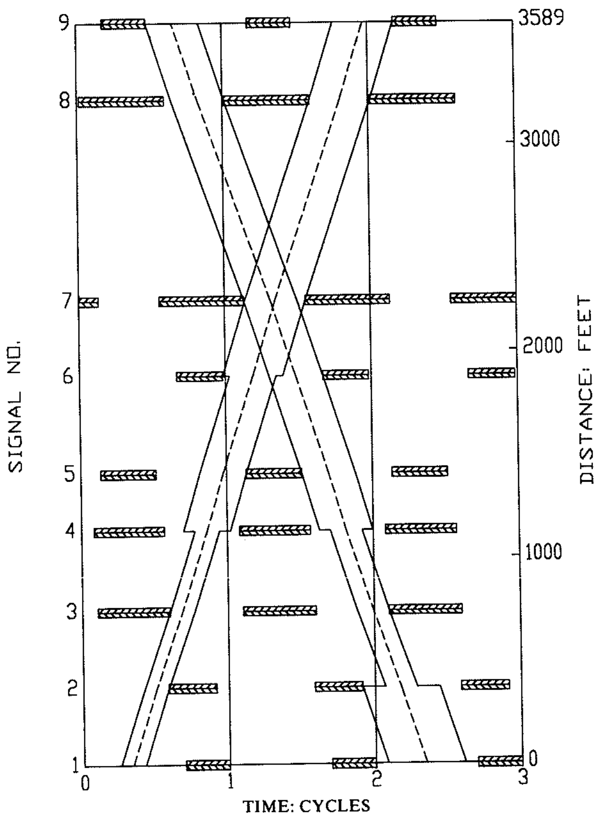

FIGURE 7 MULTIBAND time-space diagram for Canal Street for band weights = total volume/capacity ratio and cycle time = 60 sec.

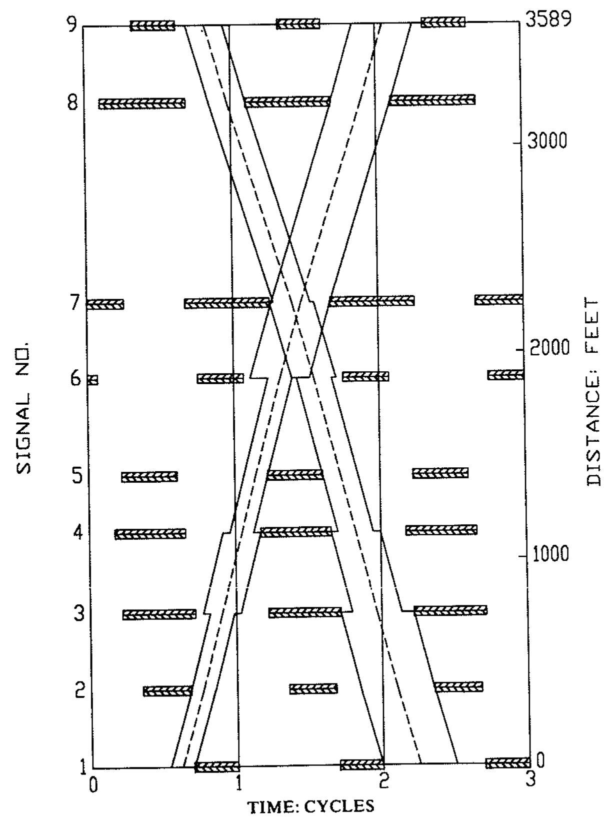

FIGURE 9 MULTIBAND time-space diagram for Canal Street for band weights = (total volume/capacity ratio)^4 and cycle time = 68 sec.

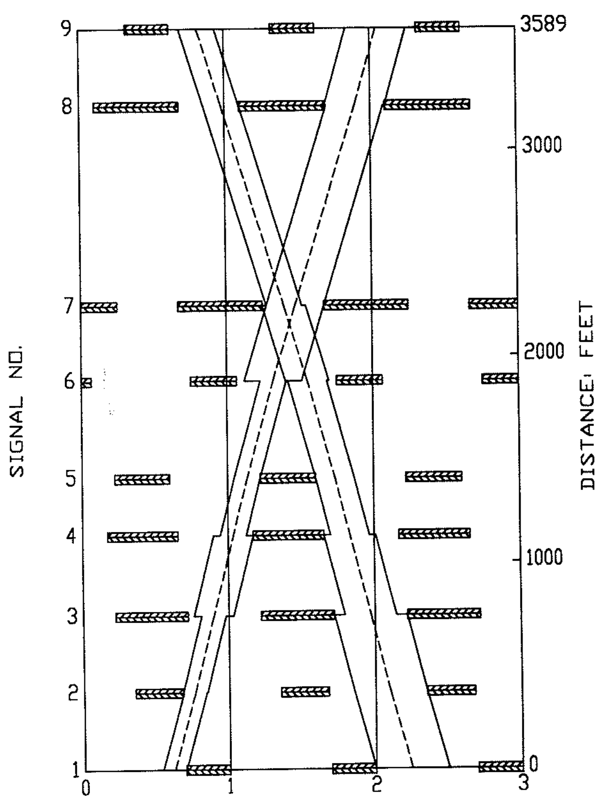

FIGURE 8 MULTIBAND time-space diagram for Canal Street for band weights = (total volume/capacity ratio)^2 and cycle time = 70 sec.

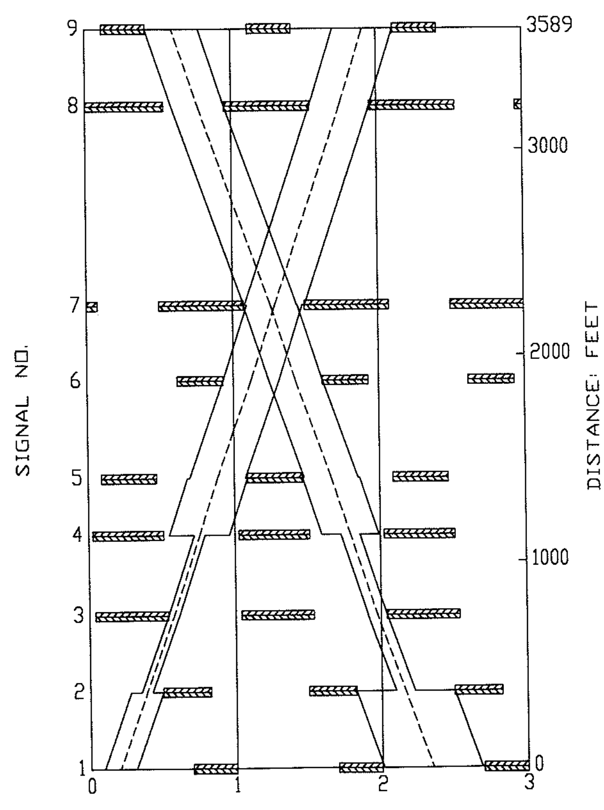

FIGURE 10 MULTIBAND time-space diagram for Canal Street for band weights = (platoon volume/capacity ratio)^4 and cycle time = 60 sec.

TABLE 2 SIMULATION RESULTS FOR CANAL STREET (WITHOUT SIDE STREETS)*

Method	Weighting Coefficient	Average Delay	Average# of Stops	Average Speed	Average M.P.G.	Delay + 20 (Stops)
MAXBAND	1	29.69	1.35	15.98	10.70	56.65
MAXBAND	TVR	28.84	1.35	16.11	10.78	55.84
MULTIBAND	1	25.62	1.13	16.82	11.20	48.30
MULTIBAND	TVC	25.20	1.07	16.96	11.28	46.68
MULTIBAND	PVC	25.08	1.02	16.99	11.30	45.40
MULTIBAND	$(TVC)^2$	25.35	1.20	16.80	11.15	49.31
MULTIBAND	$(TVC)^4$	24.11	1.14	17.08	11.30	46.87
MULTIBAND	$(PVC)^4$	25.25	1.01	16.95	11.29	45.53

*Each entry is the average from five simulation runs of the same traffic light settings with different seed numbers. Settings for $(PVC)^2$ were the same as those for $(PVC)^4$.

TABLE 3 SIMULATION RESULTS FOR CANAL STREET (WITH SIDE STREETS)*

Method	Weighting Coefficient	Average Delay	Average# of Stops	Average Speed	Average M.P.G.	Delay + 20 (Stops)
MAXBAND	1	26.74	1.15	15.60	9.89	49.74
MAXBAND	TVR	25.78	1.14	15.79	10.01	48.58
MULTIBAND	1	23.09	1.02	16.43	10.35	43.49
MULTIBAND	TVC	22.85	1.01	16.47	10.41	43.05
MULTIBAND	PVC	22.86	0.98	16.41	10.42	42.46
MULTIBAND	$(TVC)^2$	25.23	1.09	15.89	10.12	47.03
MULTIBAND	$(TVC)^4$	23.54	1.04	16.33	10.31	44.34
MULTIBAND	$(PVC)^4$	23.08	0.97	16.40	10.41	42.48

*Each entry is from a single simulation run.

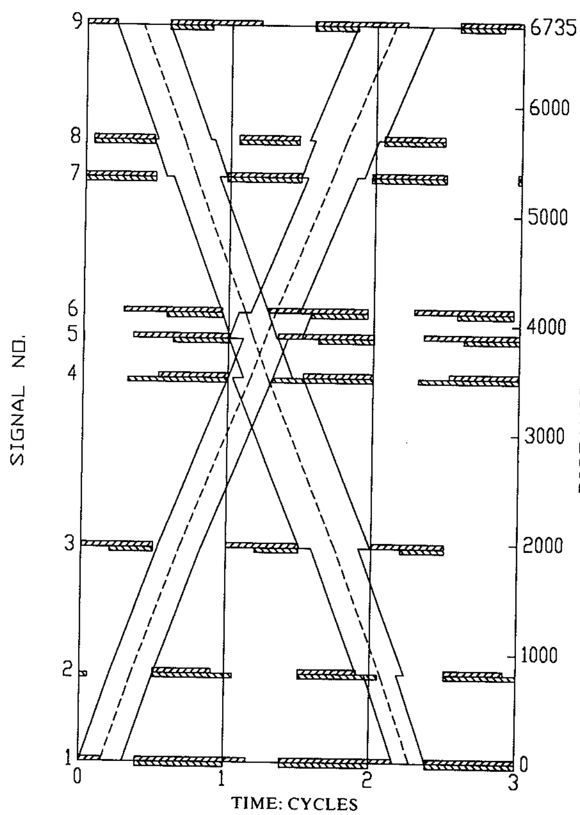

FIGURE 11 MULTIBAND time-space diagram for Main Street for band weights = total volume/capacity ratio and cycle time = 97 sec.

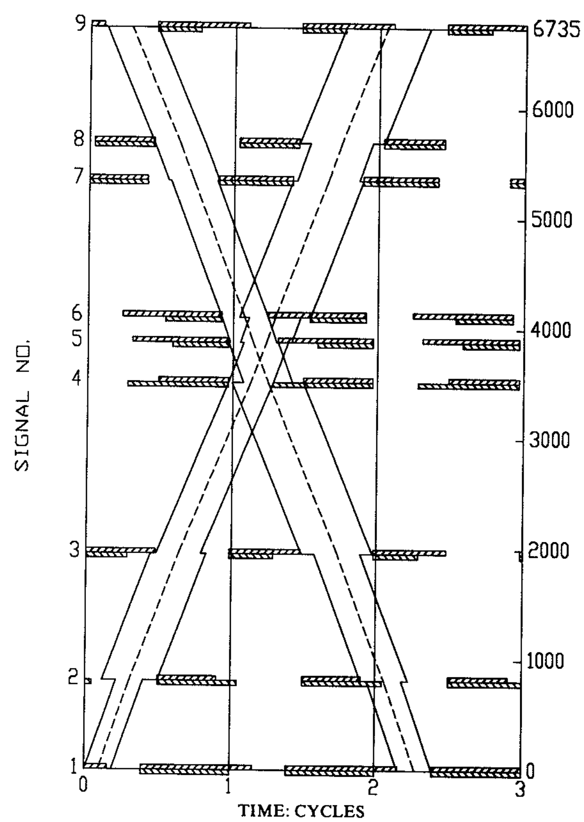

FIGURE 12 MULTIBAND time-space diagram for Main Street for band weights = (platoon volume/capacity ratio)^4 and cycle time = 95 sec.

an improvement of approximately 16 percent in average delay. If instead the average number of stops is considered, the best MULTIBAND options are PVC and $(PVC)^4$, with 1.01 stops per vehicle, whereas both MAXBAND options produce 1.35 stops per vehicle. Here, MULTIBAND obtains an improvement of approximately 25 percent.

With side streets included, the MULTIBAND option with the lowest average delay (22.85 sec) is TVC. The MAXBAND option with lowest delay (25.78 sec) is TVR. MULTIBAND obtains an improvement of about 11 percent. If stops are considered, the best MULTIBAND option is $(PVC)^4$ with 0.97 stop and the best MAXBAND is again TVR with 1.14 stops. The improvement with MULTIBAND is approximately 15 percent.

Figures 13–16 show graphically the average delay, average speed, average number of stops, and the combined performance index of the different optimization runs, with side streets not included. Also shown are the 95 percent confidence intervals. If the NETSIM simulation were run many times using different random seeds, 95 percent of the time the results would fall within these intervals. The confidence intervals were calculated using the method of Gafarian and Halati (*23*) for the statistical analysis of output ratios in traffic simulation. They clearly show the superior performance of MULTIBAND compared to MAXBAND. Comparable results are obtained when side streets are included in the NETSIM averages.

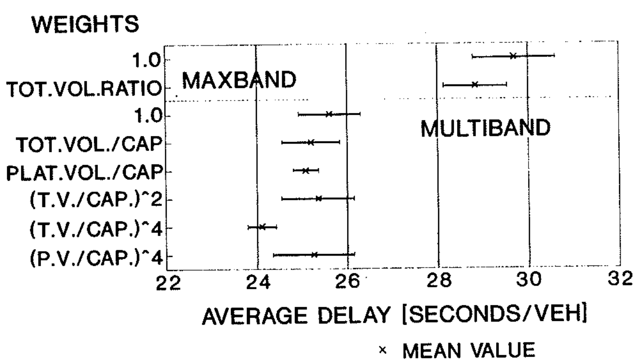

FIGURE 13 Canal Street—average delay comparison.

CONCLUSIONS

A new approach to arterial traffic signal optimization is based on a multiband, multiweight method. This approach offers to

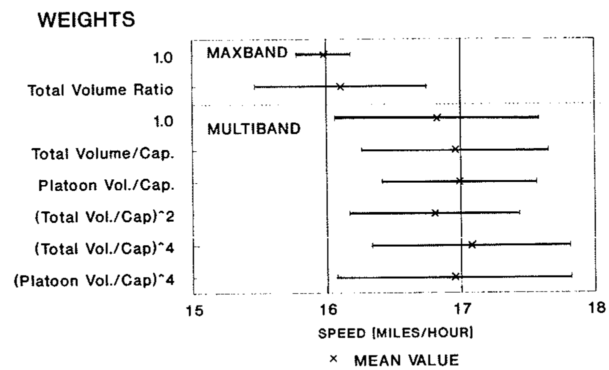

FIGURE 14 Canal Street—average speed comparison.

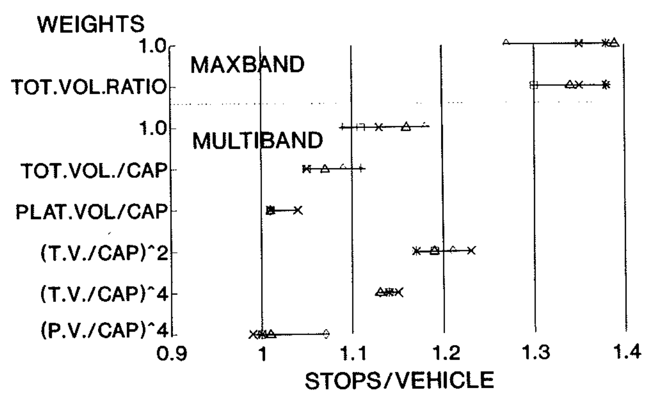

FIGURE 15 Canal Street—number of stops comparison.

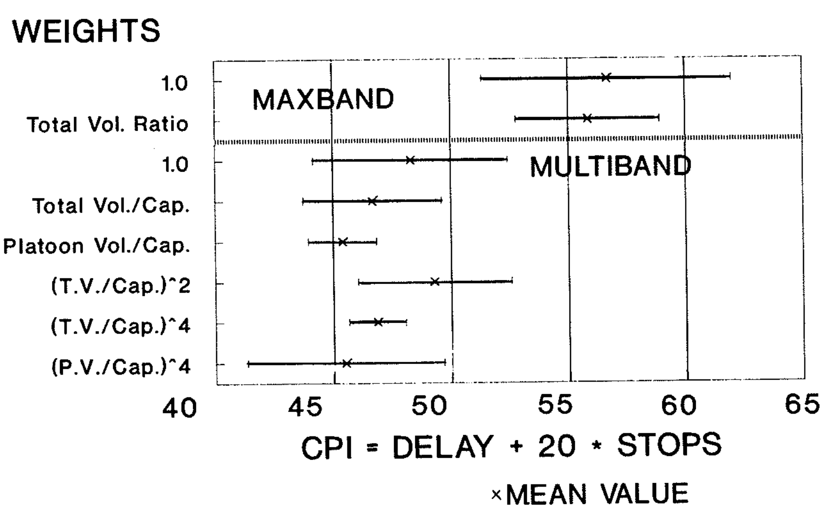

FIGURE 16 Canal Street—combined performance index (CPI).

the traffic engineer a much wider range of design flexibilities than do existing arterial progression methods. It provides a capability to adapt the progression scheme to the specific traffic flow patterns that exist on each link of the arterial. Such capability is not presently available in any other progression scheme. By using advanced mathematical programming techniques, an optimal solution can be determined that calculates cycle time, offsets, progression speeds, and phase sequences to maximize a combination of the individually weighted bandwidths in each directional section of the artery. Through progressions with variable bandwidths are maintained along both directions of the artery. Choosing appropriate weighting coefficients and target ratio values, the users can generate alternative progression schemes to fit a multitude of traffic objectives that they may wish to explore. Evaluation results, using NETSIM simulation, show that significant improvements in delays, stops, travel speeds, and fuel consumption are possible with this scheme.

The new approach lends itself to extension in a number of directions. Included among these are asymmetrical bands, tailoring progressions to prevailing origin-destination flows, and signal network optimization. Further research in these areas is in progress.

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