Directional Weighting for Maximal Bandwidth Arterial Signal Optimization Programs

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ABSTRACT

The concept of maximizing two-way progression to compute signal-timing plans for signalized arterials has been used for 60 years. One of the unknown questions that exists is how the available two-way band should be apportioned between the two directions of traffic flow. Until now, the two directions have been weighted in proportion to the ratio of the average volume in each direction. However, preliminary studies have indicated that it would be better to apportion the two-way progression bandwidths than to use the volume-ratio criterion alone. Described is a bandwidth weighting algorithm that is based on delay. A simple delay model developed for the PASSER II program was used to estimate delay. Through extensive testing, using the NETSIM model on nine real-world arterial data sets, it was found that three different expressions for the bandwidth ratio should be used; which expression was to be used depended on whether the directional volume ratio was less than 0.45, between 0.45 and 0.55, or more than 0.55. All three expressions involve the ratio of delay in the two directions. A blind test was performed by using six scenarios based on two real-world arterials that were not included in the nine test arterials used for preliminary testing. Based on comparisons using the NETSIM model, the result of this blind test indicated that the weighting algorithm developed in this research generally performed better than both the arbitrary equal-weighting and the MAXBAND average volume-ratio criteria, which have been used up to now.

The concept of maximizing progression bandwidth as the criterion for calculating optimal offsets in arterial signal systems has been used for approximately 60 years. At first, graphic manual methods were used. With the introduction of the digital computer, the bandwidth optimization problem was computerized, and a number of programs were developed (1,2). Two of them, MAXBAND and PASSER II, also optimize the left-turn phase sequence (3,4). Both programs can weight the bands to provide a wider progression band in one of the two directions. Neither of them, however, provides any guidelines for adjusting the weighting factor other than to suggest setting it equal to the ratio of the average volumes in the two directions.

Recent feasibility studies conducted by the FHWA, U.S. Department of Transportation, have indicated that proportioning the total two-way bandwidth in the ratio of volume distribution does not provide the lowest systemwide delay. The FHWA feasibility study also indicated that the fundamental causal factors and general relationships existing between bandwidth ratio and delay could not be accurately predicted, based on current technology in arterial traffic signal-timing optimization.

STUDY OBJECTIVES

In this study, the factors for determining the best directional weighting for arterial bandwidth optimization were reviewed, performance of the factors that influence the directional weighting factors were compared, and an algorithm for future development was recommended.

Specifically, three objectives of the study were to

1. Determine the factors influencing the directional weighting factor;
2. Develop a single-pass algorithm to estimate the optimal band split before the original maximum-bandwidth calculations by either MAXBAND or PASSER II and provide proper directional bandwidth weighting in the bandwidth optimization; and
3. Apply and test the algorithm developed against the equal-directional weighting and the ratio of the sum of directional volume methods; independent testing of the algorithm was conducted by the FHWA for performance evaluation.

STUDY SCOPE

The following were performed during the study: a literature review, analytical analysis, algorithm development, algorithm demonstration, and computer runs of bandwidth optimization programs to determine the effectiveness of directional bandwidth weighting. Pretimed, common cycle, and coordinated traffic signals with multiphase control for arterial streets were emphasized during the research.

LITERATURE REVIEW

Traffic demand and traffic congestion along arterial corridors require effective traffic management to

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improve traffic flow. Computer programs for optimizing signal timing along arterial street systems came during the early 1960s with the coordinated offsets for maximum throughput (1-8).

During the 1964-to-1966 period, Little first developed the maximum progression bandwidth calculations along an arterial street (by computing offsets) for given cycle times, distances, and travel speeds (4,7). In 1966, Brook developed an algorithm that improved Little's program by developing a progression scheme that maximizes the total of the two-direction through bands over the cycle length for a set of offsets, cycle lengths, and link speeds (6). In 1967, Bleyl extended Brook's algorithm by selecting the offsets that minimize the total interference to the progression band (1). Messer developed the PASSER II program by expanding Bleyl's development. In 1975, Little further extended the maximum bandwidth optimization by formulating the signal synchronization problem as a mixed-integer linear program (7,9-12). Despite different methods currently available, which are based on delay, many traffic engineers still prefer maximum bandwidth settings because of the easily understood, time-space diagrams and the apparent favoring of progressive movement along major arterial street systems (11-13). In addition, the results of several studies [for example, Wagner (1969), Wallace (1979), Rogness (1981), Cohen (1983), and Chang (1984)] demonstrated that the bandwidth method does yield consistently good results on arterial signal systems (11-13).

Bandwidth Weighting Problem

Several computer programs that maximize bandwidth have been developed, including SIGART, SIGPROG, NO-STOP-1, PASSER II, and MAXBAND (2,4,7,9,14). Both PASSER II and MAXBAND allow the users to adjust the directional bandwidth split. They do not supply the best directional split, other than to suggest the use of the ratio of total through-traffic volume in each direction. However, it is not clear whether the simple proportionality of bandwidth ratio to volume ratio gives the signal settings with the lowest delay. Furthermore, factors such as capacity, green time, and available bandwidth in each direction are ignored. To demonstrate the directional bandwidth weighting problem, two examples provided by FHWA indicated that

1. The use of directional volume ratio to split the progression bandwidth may not give the solution with the lowest delay. For example, on Hawthorne Boulevard, the bandwidth was optimized using MAXBAND for east-west traffic having a volume ratio of 2 to 1. The resulting signal offsets were input into the NETSIM model. From the results tabulated (Table 1), it may be seen that use of the volume-ratio criterion would suggest a bandwidth ratio of 2 to 1, which would give 11 to 12 percent more delay than the ratios of 6 to 1 or greater.

2. The amount of bandwidth available in each direction on an arterial is limited by the duration of the shortest green interval in each direction. Thus, it could happen that it would be appropriate to favor the direction that has more green time available to progressive movements, regardless of the volumes. To demonstrate this directional bandwidth weighting concept, assume a two-directional arterial with one direction arbitrarily defined as the outbound or A direction and the other as the inbound or B direction. For example, assume a situation in which the shortest through-green time in the inbound direction is larger than the shortest through-green time in the outbound direction. If equal weighting is given for both directions, bandwidth available in each direction is limited to the shortest green time in the outbound direction. On the other hand, giving more weight to the inbound direction may result in a situation in which the inbound band equals the shortest inbound green time with the outband band being equal to the shortest outbound green time because both MAXBAND and PASSER-II optimize the weighted sums of the inbound and outbound bandwidth.

3. In the preceding example, if the inbound bandwidth becomes equal to the shortest inbound green time, any additional bandwidth available is given to the arterial outbound direction. For example, it can happen that the user uses a 4-to-1 ratio of inbound/outbound bandwidth, but the actual final ratio is less than 4 to 1 because of the inbound band filling the shortest inbound green. This effect is shown in Figures 1 and 2. The symbols "GREENIN" and "GREENOUT" represent the inbound and outbound green times. In Figure 1, inbound/outbound weighting was equal to 1; in Figure 2, inbound/outbound weighting was equal to

TABLE 1 Hawthorne Boulevard NETSIM Test Results

East-West Volume Ratio	East-West Band Ratios	Delay (sec/vehicle)	Optimal Deviation (%)
	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

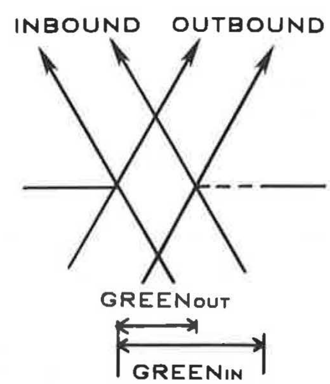

FIGURE 1 Equal bandwidth weighting.

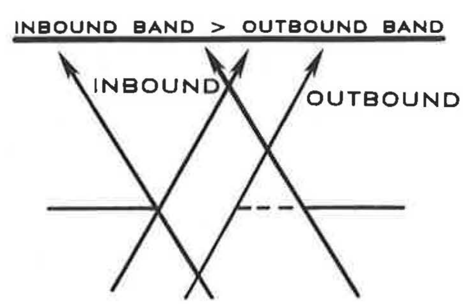

FIGURE 2 Inbound bandwidth weighting greater than outbound bandwidth weighting.

2. Figures 1 and 2 represent a special case in which the shortest green times occurred at the same intersection. However, they may occur at any intersection. This point can be further demonstrated by using the example of Foothill Drive, which is an eight-intersection arterial with left-turn lanes and left-turn phases at all intersections. The shortest inbound through-green time was 43 percent of the cycle, and the shortest outbound through-green time was 27 percent of the cycle. Optimization of offsets and left-turn phase sequence with equal directional weighting gave a bandwidth of 27 percent of the cycle in both directions; using an inbound/outbound band ratio of 3 to 1 gave an inbound bandwidth of 43 percent and an outbound bandwidth of 27 percent. The effect of Foothill Drive on delay is shown in Table 2.

TABLE 2 Foothill Drive NETSIM Test Results

In/Out Volume Ratio	Target In/Out Band Ratio	In Band (%)	Out Band (%)	Total Band (%)	Delay (sec/ vehicle)
1.75/1	1/1	27	27	54	95.33
1.75/1	3/1	43	27	70	91.44

4. It is possible that the settings of shortest green time may have nothing to do with the volume ratios. For example, the volume ratio used for the Foothill Drive scenario was inbound/outbound = 1.75 to 1. One intersection may have an unusual requirement for a longer left-turn phase in the light-volume direction. This can further complicate the problem because of the arbitrary nature of and interactions between setting minimum green time and optimizing arterial bandwidth.

Traffic Signal Optimization and Simulation Programs

Computer techniques for off-line, fixed-time signal-timing plan optimization have received widespread interest. Two primary approaches for coordinating traffic signals along arterial streets are (a) the bandwidth-maximization procedure and (b) minimization of a disutility function such as delay, stops, fuel consumption, and air pollution. The former includes PASSER II and MAXBAND; the latter includes TRANSYT-7F as an example. Research by Huddert (1969), Wallace (1979), Rogness (1981), Cohen (1981), and Chang (1984) indicates the possibility of arriving at a compromise between the method of maximizing bandwidth and minimizing delay (using a stop penalty) in computing traffic signal progression (7,11-13,15,16).

PASSER II

PASSER (Progression Analysis and Signal System Evaluation Routine) is an acronym for a series of practical computer programs developed by the Texas Transportation Institute (TTI), Texas A&M University System. The PASSER II computer model was first developed by Messer and others and modified to an off-line computer program by Messer et al. (3,6,14). It was developed primarily for high-type arterial streets with modern eight-phase protected left-turn lanes and phases. The PASSER II maximum bandwidth solution has been well accepted and implemented throughout the United States. The theory, model structure, methodology, and logic in the PASSER II computer program have been evaluated and documented.

A recently concluded Highway Planning and Research study entitled "Reduced-Delay Optimization and Other Enhancements of PASSER II-80" was conducted by Chang at TTI to develop, compare, and evaluate the effectiveness of the enhanced PASSER II-84 program for an arterial street system by considering both the maximum bandwidth procedure and minimum delay signal-timing optimization algorithm (12,15,16).

MAXBAND

The original bandwidth formulations introduced by Little for setting traffic signals to achieve maximal bandwidth were developed into a portable, off-line, Fortran 77 computer program called MAXBAND. The program produces cycle time, offsets, speeds, and left-turn phase sequences to maximize bandwidth by applying Land and Powell's MPCODE branch-and-bound optimization algorithm (3,4,7,13).

In addition to arterials, the program can also handle a three-arterial triangular loop with arbitrary weighting of each arterial bandwidth. MAXBAND is currently being expanded by TTI to optimize small network problems.

TRANSYT

The TRANSYT computer program developed by Robertson (1969) can determine a set of phase splits and offsets that minimize a performance index given by a linear combination of stops and delays (11-13). The optimization procedure used by TRANSYT is a sequential flow analysis with a gradient search technique to minimize delay from subsequent simulation runs (13,15,16).

Regardless of the inability to analyze alternative phase sequences, TRANSYT has been widely accepted and is the common optimization computer program for analyzing arterial networks. The platoon dispersion model of TRANSYT has proven to be a good descriptor and predictor of platoon behavior. The optimized signal-timing plans determined by it have been found to give consistently better results than other existing optimization programs (11-13,15,16).

NETSIM

All of the signal-timing optimization programs incorporate evaluations for selecting an optimum solution, but most of them are limited to approximate measures of effectiveness (MOEs). The NETSIM simulation program developed by FHWA has been applied to relatively sophisticated network traffic signal control strategies and validated against field data; it has provided successful quantifiable comparisons in most applications (11-13,15,16).

Because of the complexity of performing field experiments, the NETSIM program was selected. The following assumptions common to arterial signal timing were made:

1. Volumes for each movement are constant over study period.
2. Platoon structure retains a coherent length.
3. Link speeds are uniform and known.
4. Queues are deterministic and of known length.

DIRECTIONAL WEIGHTING PROGRESSION

The directional weighting progression can be stated as a constrained offset optimization problem. This offset optimization was made by developing a single-pass method to estimate the optimal directional progression bandwidth split before the original-progression calculation of either MAXBAND or PASSER II. This single-pass method will be executed to provide directional weighting factors for later progression calculations. This calculation before progression requires green split, traffic volume, and intersection spacings.

The main factors that can influence the single-pass directional weighting problem for MAXBAND and PASSER II may include

- Physical layout of signal system
- Traffic volume and travel speed
- Signal timing factors

Maximum progression solutions are based on green times and intersection spacings. The purpose of directional bandwidth weighting is to determine how much offset or extra green time should be added or deleted from the progression bandwidth in either the A or B direction. This problem differs from the slack green adjustment problem in which the location of the two-way band was adjusted to reduce overall delay without changing the amount of bandwidths in either direction. The slack green time is defined as the green time available for through movements but not used in the progression bandwidth solution. The offsets obtained by using the current slack green allocation algorithm in MAXBAND were used without modifications in the later examination.

Therefore, the directional bandwidth weighting problem can be reformulated into a constrained offset optimization problem, summarized as follows:

- Objective function:
  - Maximize progression
  - Minimize system delay
- Given:
  - Cycle, green time, travel time
- Constraint:
  - Total bandwidth
  - Desirable progression speed
  - Minimum green

The algorithm was a noniterative, one-shot precalculated method to predict the tradeoffs of adjusting directional bandwidth or the resultant offset changes. To minimize delay and stops, factors in addition to directional volume splits and minimum green times for progression movements are considered in this algorithm. The internally sensitive relationships of the estimated progression system delay and tradeoff of incremental delay changes as a function of bandwidth weighting factors are analyzed in the algorithm. These performance measures are derived from saturation flow ratio (relationship of volume and saturation flow rate) and travel time (relationship of distance and travel speed). In summary, the major study objective is to develop relationships between the progression bandwidths in the A and B directions as a function of saturation ratio and travel time. These relationships include the following:

1. Saturation ratio = (volume/capacity) * (cycle/green)
   a. Volume levels,
   b. Critical movement combinations, and
   c. Minimum green time combination.
2. Travel time = distance/travel speed
   a. Distances between intersections
   b. Existence of protected left-turn lane, and
   c. Desirable travel speed.

The other question concerned the effect of minimum greens, which was mentioned earlier. It was found that the MAXBAND and PASSER programs are formulated as follows: maximize the weighted sum of the A and B directional bands (the objective function) subject to a constraint on the ratio of the A and B bands. This formulation has the following consequence. For example, if the shortest green of the A direction is smaller than the shortest green of the B direction and the band of the A direction equals the shortest green of the A direction, this constraint may prevent the objective function from obtaining its optimum value. The answer is, in this case, to relax the constraint, which can be done most easily by giving (in this case) more weight to the B direction.

The factors that are important are determined in the best directional bandwidth weighting algorithm. Those factors were identified for determining the best directional bandwidth weighting. The factors include

- Intersection-specific demand volumes,
- Intersection-specific saturation flows,
- Green-time restrictions,
- Left-turn phase requirements,
- Saturation flow ratio, and
- Travel time between intersections.

An experimental plan for testing the effect of the directional factors by using NETSIM and MAXBAND was designed. The factors were selected for their relative sensitivity to the link weighting performance function, as defined earlier.

TESTING OF FACTORS

A detailed experimental plan was developed for testing the important factors in computing the best directional bandwidth weighting by using the MAXBAND and NETSIM programs.

The MAXBAND program was used to develop the timing parameters with directional weighting ratios varying between 1/10 and 10/1. It was also used to enumerate the timing parameters for all the possible directional weightings given by any reduced-delay algorithms. MAXBAND's capability of varying the directional bandwidth with two directional weighting factors was particularly useful in this investigation.

NETSIM was used to evaluate the relative importance of the respective factors that influence directional weighting. As indicated in Figure 3, MAXBAND was first executed to provide a MAXBAND-optimized solution for different directional weighting factors. Finally, NETSIM runs were made to vary the

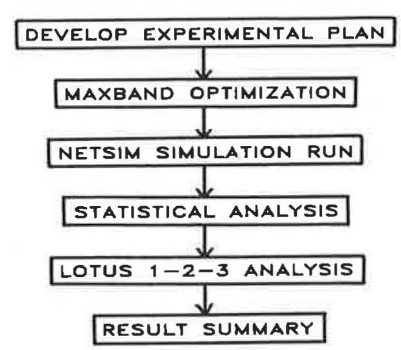

FIGURE 3 Experimental simulation plan.

TABLE 3 Summary of Experimental Simulation Study

Case	Street	No.	Cycle	Progression Band (sec) Out	In	Efficiency	Attainability	Progression Speed (mph) Out	In	Total System (sec/vehicle) Delay	Stops	Arterial System (sec/vehicle) Delay	Stops
1	M Street	8	80	28.7	28.7	0.36	0.83	30	28	59.45	1.86	11.2	0.37
2	University Drive	10	80	10.7	10.7	0.13	0.52	29	30	43.44	1.58	28.7	0.27
3	33rd Street	11	75	7.1	7.1	0.10	0.37	35	35	80.52	1.66	190.7	0.55
4	Broadway Avenue	11	60	21.4	21.4	0.36	0.69	37	37	39.93	1.48	41.6	0.31
5	Nicholasville Road	12	80	18.5	18.5	0.23	0.54	33	34	82.30	2.32	18.1	0.56
6	Frederica Street	12	80	23.1	23.1	0.29	0.59	40	41	77.01	2.48	84.5	0.45
7	South Halsted Street	12	65	16.3	16.3	0.25	1.00	29	30	88.91	1.52	129.2	0.47
8	Fannin Boulevard	15	80	24.1	9.8	0.21	0.61	36	34	66.67	2.38	92.0	0.38
9	Wisconsin Avenue	17	70	22.4	22.4	0.32	0.72	31	33	77.38	2.75	60.2	0.45

Note: Combined MAXBAND and NETSIM runs with variable speed (base case).

relative offsets of the different MAXBAND-optimized solution, thus evaluating the system performance to the solution alternatives.

Nine arterial networks, which were previously coded for MAXBAND and NETSIM, were selected to test the factors identified. Concentrated efforts were made to check that all of the possible data requirements were satisfied by the test arterials selected. Summarized in Table 3 are the basic characteristics of the nine test arterials. Because MAXBAND can provide variable link speed, both the variable speed and fixed speed options were used to provide flexibility in generating the maximum bandwidth solution. The interlink and intralink speeds were constrained to be within 10 percent of the original link design speed for the given cycle length and phase sequence.

The NETSIM analysis was simulated for a half-hour study period. The optimized MAXBAND offsets were generated from the inbound-versus-outbound bandwidth weighting factors varying from 1 versus 10 to 10 versus 1 at increments of 1. Thus, a total of 19 cases were made for each test arterial to represent the variations of bandwidth weighting factors. Two replicated runs with the same MAXBAND timing plan were made to reduce the statistical variability that may be produced in the NETSIM microscopic simulation environment. In other words, MOEs, delay, and so forth were averaged over both replications for each test case.

Experimental Simulation Plan

Simulation and statistical analyses were conducted to determine which factors are best suited for the evaluation of the directional bandwidth weighting problem. Major activities in this study task were to (a) modify the test case data and (b) test the factors affecting directional weighting. At first, the data coding was transformed to the combined link-node coding scheme for MAXBAND and NETSIM runs. Efforts were made such that adequate and compatible data inputs were available with the computer models used. After the data were modified, pilot simulation runs were made to establish a base for later comparisons. Then the modified NETSIM data sets were used to determine the effects of the various factors identified. The Statistical Analysis System (SAS) (17) was used to provide the basic descriptive statistics for the following questions:

1. What are the factors that have significant influence on the directional weighting factor?
2. How sensitive are the factors that influence the directional weighting factor?
3. What are the basic factors that are required for a single-pass preprocessor algorithm for determining the directional bandwidth split that will lower systemwide total delay?

The data collected in the simulation were then evaluated by the SAS to determine the relative importance of the factors to be put into the algorithm. Also examined by the SAS was whether the enhanced directional weighting factors could provide better combinations of reduced-delay offsets and directional bandwidth. Because the initial green split, phase sequence, and offsets between intersections were given, the evaluation focused on MAXBAND offset optimization capability using different directional bandwidth weighting ratios. The major independent variables considered were the weighting ratios, the relative offsets between the consecutive intersections, and the resultant arterial delay.

The NETSIM evaluation can provide microscopic link-to-link statistical simulation and analysis, but the output is difficult to compare except on a total systemwide basis. To study in detail the effects of various directional weighting factors on the NETSIM system performance from the nine test cases, the arterial portions of the MOEs were also separated from the side streets. Because the MOEs on the side streets are unaffected by the offsets, this detailed analysis reduced the variability of the study results. A detailed SAS analysis was summarized from the NETSIM evaluation and then downloaded and displayed through the popularly used LOTUS 1-2-3 microcomputer program. This process is shown in the flowchart in Figure 4.

Test Results

Evaluations of delay and stops were performed for all nine test cases for both the whole system and separated arterial travel directions. These evaluations were analyzed by average NETSIM system delay and stops, average NETSIM arterial delay and stops, and average NETSIM arterial inbound-versus-outbound directional delay ratio versus directional bandwidth weighting ratios.

The typical NETSIM simulation results of the average volume ratio, delay, and stops MOEs are shown in Figures 5 and 6 by the test arterial of Broadway in Lexington, Kentucky (Case No. 4). These two figures show the NETSIM average system delay and stops (y-axis) versus the different directional weighting values (x-axis) for the inbound, outbound, and average outbound and inbound travel directions. Table 4 gives the different directional weighting ratios used in the analysis.

The results of this testing-of-factors analysis indicate the following:

1. Directional weighting can substantially affect the arterial system delay and stops, according to the analysis using NETSIM simulation.
2. The variable speed options in MAXBAND are

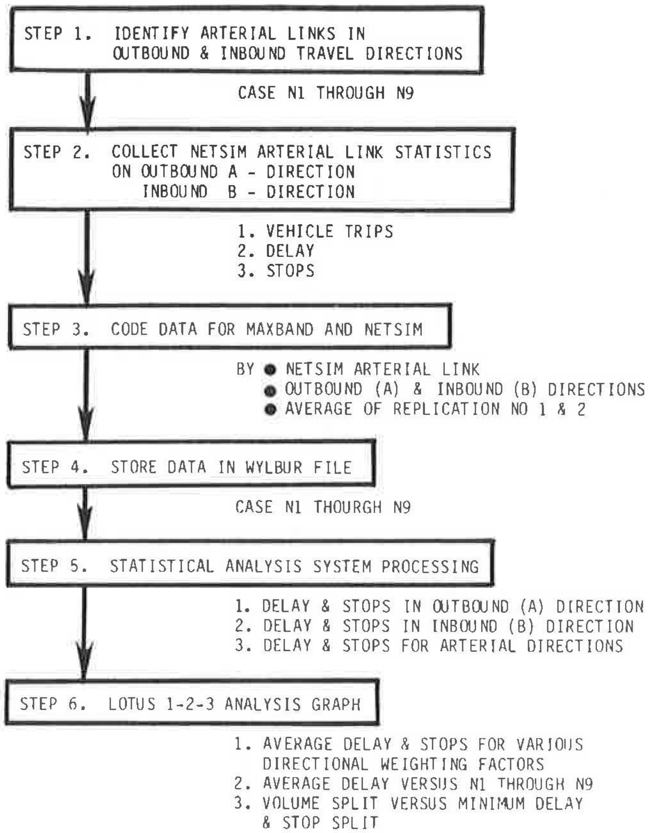

FIGURE 4 Detailed arterial analysis plan.

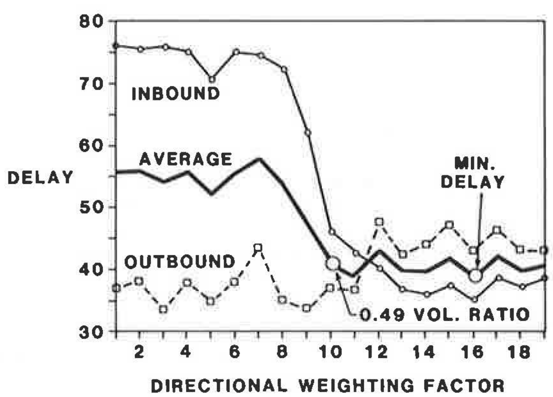

FIGURE 5 NETSIM average arterial delay study.

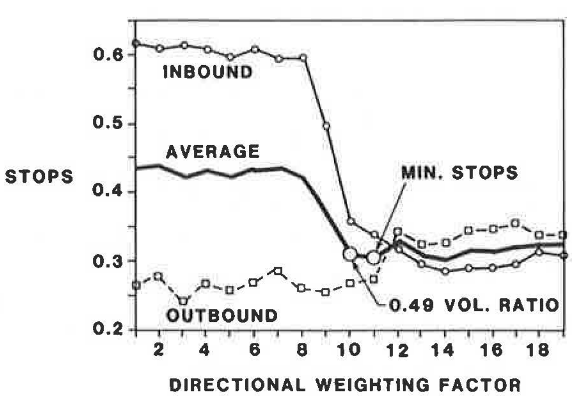

FIGURE 6 NETSIM average arterial stops study.

TABLE 4 Relationships Among MAXBAND Inbound and Outbound Weighting, Inbound-Versus-Outbound Ratio, and Normalized Directional Bandwidth Ratio

No.	Inbound Weight	Outbound Weight	Ratio of In-Out	Normalized Ratio [in/(in + out)]	
1	1	10	1/10	0.091	(weight heavy in outbound direction)
2	1	9	1/9	0.10	
3	1	8	1/8	0.111	
4	1	7	1/7	0.125	
5	1	6	1/6	0.143	
6	1	5	1/5	0.167	
7	1	4	1/4	0.20	
8	1	3	1/3	0.25	
9	1	2	1/2	0.333	
10	1	1	1/1	0.50	(equal weight)
11	2	1	2/1	0.667	(weight heavy in inbound direction)
12	3	1	3/1	0.75	
13	4	1	4/1	0.80	
14	5	1	5/1	0.833	
15	6	1	6/1	0.857	
16	7	1	7/1	0.875	
17	8	1	8/1	0.889	
18	9	1	9/1	0.90	
19	10	1	10/1	0.909	

powerful in producing various directional weighted bandwidths for given allowable through-green times and minimum green times.

3. The directional volume ratio alone cannot provide an accurate estimation of the minimum NETSIM delay directional weighting ratio. This is particularly true when

a. Inbound and outbound arterial volumes are nearly equal,
b. Link-volume ratios between intersections are inconsistent, and
c. Amounts of available through-green times are different due to the constraints of intersection-specific green splits.

In the example in Figure 5, the directional volume ratio [INBOUND/(INBOUND + OUTBOUND)] is 0.49, which indicates the lower volume level in the inbound direction. However, the NETSIM evaluation both in the system and arterial directions indicated that a higher inbound weighting could provide less delay and fewer stops. This suggested that a separate indicator, such as the directional delay ratio, should be used in estimating the likely lower-delay directional bandwidth ratio.

4. The possible reductions in delay and stops may range between 1 and 10 percent for various directional weighting ratios used according to the nine test cases studied. The absolute magnitude of improvements, that is, the reductions of delay and stops, may sometimes have less practical value because of the small amount of average delay reductions. Evidently, cases also exist that are insensitive to the arterial progression bandwidth ratio.

ALGORITHM DEVELOPMENT

A single-pass algorithm was developed to determine the best bandwidth weighting. It is compatible with the existing input data required in the current MAXBAND and PASSER II programs. Basically, the directional bandwidth weighting algorithm developed by TTI is a simplified aggregated platoon projection model that is similar to the platoon dispersion model used in the TRANSYT-7F program. This simplified model predicts the aggregated platoon travel behavior on a link-to-link basis for the given volume levels, saturation flow rates, MAXBAND-calculated green splits, and estimated travel times between intersections.

The system inputs of the directional bandwidth weighting algorithm include the following (18,19):

- Intersection-specific demand volumes
- Intersection-specific saturation flows
- Green-time restrictions
- Left-turn phase
- Travel time between intersections, computed from speeds

The system outputs include the following:

- Directional INBOUND/(INBOUND + OUTBOUND) volume ratio
- Directional INBOUND/(INBOUND + OUTBOUND) delay ratio
- Directional inbound-versus-outbound bandwidth weighting ratio or the target bandwidth ratio for use in the MAXBAND optimization runs

Theoretical Background

An interconnected signal system can result in nonuniform flow rates during cycles. If progression between signals is good, most of the traffic will arrive at the downstream intersection during the green phase of the signal. This phenomenon results in an average arrival rate during the green phase of the cycle that is greater than the average arrival rate during the red phase. On the other hand, poor progression could result in a greater arrival rate during the red phase than during the green phase. To estimate the arterial signal system performance under interconnected operations, the tentative NCHRP delay equation was modified and used in this study (6,15,16,20). The primary interest is to consider both the interactions between percent of the approach's through volume arriving on the through green and the percent of available through-green time during the whole cycle length.

The percent of an approach's through traffic coming from the through-traffic movement of an adjacent upstream intersection and arriving during the through green at the downstream intersection depends on several factors. Three principal factors considered are

1. The percent of the total through traffic in the progression platoon,
2. The size of the platoon and the rate of platoon dispersion, and
3. The quality of arterial progression between the intersections.

The optimal arterial progression time-space diagram can be used to determine the quality of progression between the intersections. A good progression system would result in better usage of the green time than would a bad progression system. The through green available for progression was used to predict the estimated arterial directional delay due to the combined effects of given MAXBAND green splits and link travel times. It was also applied with the percent through traffic and platoon dispersion factor to estimate the minimum-delay directional bandwidth weighting ratio.

This simplified platoon projection model was applied in the PASSER II model to estimate arterial delays for evaluating arterial signal system operations. The previous detailed NETSIM analysis made by Chang (1984) indicated a consistent trend between the NETSIM simulated delay and the delay predicted by this simplified platoon model (16). The NETSIM analysis in this study also indicated that a reduced-delay directional weighting algorithm could be developed from this algorithm.

Program Structure

Figure 7 shows the overall structure of this single-pass directional bandwidth weighting algorithm. The system consists of five major modules: an input module, a platoon projection module for outbound and inbound travel directions, a cumulative delay and stops estimation module, a directional delay and stops calculation module, and a directional bandwidth weighting estimation module.

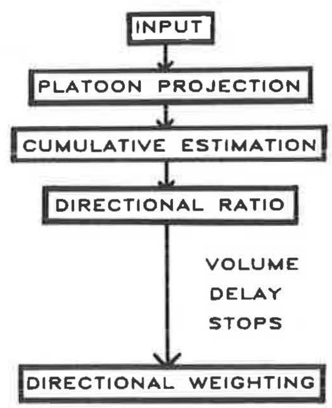

FIGURE 7 Program structure of the directional bandwidth weighting algorithm.

Input Module

The input module reads the input data from the data stored in the MAXBAND array or from a temporary card image file on FORTRAN file 5. The only conversion required from the ordinary MAXBAND input deck is to assume that the same upstream arterial volume levels and saturation flow rates exist for the downstream intersection, if a SPECIFY card was used rather than VOLUME and CAPACITY cards. This additional input provides consistent information for (a) estimating the saturation flow ratio and (b) calculating the aggregated directional delay and stops for the given inbound-versus-outbound directional bandwidth weighting ratio.

Platoon Projection Module

Essentially, the platoon projection module predicts the link-to-link progression platoons for the given volume, saturation flow rate, green time, and travel time between intersections. First, the module calculates the green time needed to clear the standing queue and transforms these values into an equivalent progression platoon size for estimating the progression through bandwidth leaving that particular intersection. Then a platoon dispersion factor is calculated based on results of a previous TTI field study to predict the downstream platoon size (6).

The single-pass method was used before the MAXBAND optimization process. A ratio of the estimated travel time and cycle length was used in place of the offset for time-based signal coordination. Two separate sets of analyses are made to estimate the platoon projection adjustment factor for the through-arterial movements at each traffic signal with respect to both outbound and inbound arterial travel directions.

Cumulative Delay and Stops Estimation Module

This module calculates and accumulates the estimated delay and stops information by using a modified tentative NCHRP delay equation. An enhanced Akcelik stops estimation equation (20) similar to those used in the PASSER II-84 model was applied. This analysis is performed on an intersection-by-intersection basis. The cumulative delay and stops information is stored separately for outbound and inbound travel directions.

Directional Volume, Delay, and Stops Calculation Module

After accumulating the volume, delay, and stops information for the arterial through movements at every intersection, this module calculates the [INBOUND ÷ (INBOUND + OUTBOUND)] volume, delay, and stops ratios for the arterial inbound and outbound travel directions.

Directional Bandwidth Weighting Estimation Module

The last module of the directional bandwidth weighting algorithm applies the normalized directional bandwidth ratio, as shown in Table 4. This ratio transfers the [INBOUND/(INBOUND + OUTBOUND)] ratio into the MAXBAND-type inbound-versus-outbound bandwidth weighting ratio or the target bandwidth ratio (K). Because the algorithm was developed mainly based on the NETSIM analysis of the nine test cases at integer weighting, the same discrete weighting analysis was made for additional verification.

Examination of the characteristics of the nine test cases indicated that for three ranges of values of the average volume ratio, three distinct expressions should exist for the bandwidth ratio as a function of the directional delay ratio. These three ranges were

1. $0.0 \leq$ volume ratio < 0.45
2. $0.45 \leq$ volume ratio ≤ 0.55
3. $0.55 <$ volume ratio ≤ 1.0

The resulting value for the bandwidth ratio [INBOUND/(INBOUND + OUTBOUND)] is then converted into the ratio INBOUND/OUTBOUND, which is then rounded to a fractional integer ratio between 1/10 and 10/1 for direct use in the MAXBAND program. Figure 8 shows a description of this process in pseudocode.

ALGORITHM DEMONSTRATION

At the completion of the algorithm, the FHWA supplied a total of six scenarios for an independent evaluation of the directional bandwidth weighting algorithm. These test scenarios consist of three traffic patterns for each of two networks not selected for

```
{ SELECT INBOUND VERSUS OUTBOUND WEIGHTING RATIO FOR MAXBAND OPTIMIZATION RUN }
{ DIR.VOL.RATIO = (INBOUND / (INBOUND + OUTBOUND) )  VOLUME RATIO }
{ DIR.DLY.RATIO = (INBOUND / (INBOUND + OUTBOUND) )  DELAY  RATIO }

  IF DIR.VOL.RATIO > 0.55 THEN              { IF INBOUND VOLUME IS HEAVY }
   BEGIN
    INBOUND=ROUND(0.35+SQRT(DIR.DLY.RATIO)/(1-SQRT(DIR.DLY.RATIO)));
    OUTBOUND=1;
   END
   ELSE
   BEGIN
    INBOUND=1;
    IF DIR.VOL.RATIO < 0.45 THEN            { IF OUTBOUND VOLUME IS HEAVY }
     BEGIN
      OUTBOUND=ROUND(0.35+(1-SQRT(DIR.DLY.RATIO))/SQRT(DIR.DLY.RATIO));
     END
    ELSE
     IF DIR.DLY.RATIO > 0.50 THEN           { IF VOLUME IS ABOUT EQUAL }
      BEGIN
       INBOUND=ROUND(0.35+SQRT(DIR.DLY.RATIO)/(1-SQRT(DIR.DLY.RATIO)));
       OUTBOUND=1;
      END
     ELSE
      BEGIN
        INBOUND=1;
        OUTBOUND=ROUND(0.35+(1-SQRT(DIR.DLY.RATIO))/SQRT(DIR.DLY.RATIO));
      END
    END;

    { OUTPUT INBOUND AND OUTBOUND BANDWIDTH WEIGHTING FACTORS }

    WRITELN(OUTFIL, 'INBOUND BANDWIDTH WEIGHT = ',INBOUND,
                    'OUTBOUND BANDWIDTH WEIGHT = ',OUTBOUND);
```

FIGURE 8 Identification of the structure of the directional bandwidth weighting algorithm.

testing. The algorithm developed was used to determine the best bandwidth weighting factor for each test scenario. The FHWA then used the NETSIM model to compare the bandwidth weighting ratio, computed from the algorithm developed, with both the equal weighting ratio and MAXBAND volume weighting ratio.

Test Cases

The two test cases were the high-type arterial Hawthorne Boulevard and the low-type arterial North Michigan Avenue. Both arterials have 13 intersections and variable spacings. The six test scenarios included the existing traffic pattern and two modified traffic patterns. All scenarios were undersaturated. The FHWA provided TTI with the MAXBAND data listings and the MAXBAND outputs with fixed cycle length and the MAXBAND-computed green splits. This base case was made with equal directional weighting in MAXBAND. The FHWA then performed the subsequent NETSIM evaluations by using the output calculated from the MAXBAND volume weighting and the directional weighting factors supplied by TTI.

These test cases were performed with four replications and 30-min study periods in each case. The results of the NETSIM delay, stops, and combined delay and stops NETSIM performance index (PI) were compared statistically by the FHWA. The NETSIM PI used is the same weighted sum of delay and stops as is used in TRANSYT. A weighting of 4 for stops was used. A subsequent analysis was made to examine the differences in using equal weighting, MAXBAND volume weighting, and the TTI calculated weighting. The SAS analysis of variance (ANOVA) was used with the DUNCAN and Student-Newman-Keuls options to evaluate the statistical differences (17).

Test Results

Table 5 shows the average PI during the four replications for each case and each bandwidth weighting method, that is, the equal bandwidth weighting (E or EQ), MAXBAND volume weighting (M or MX), and the TTI-calculated directional bandwidth weighting method (T or TTI). The SAS evaluation results of this algorithm demonstration for the six test cases are given in Table 6. Results of this study indicated the following:

1. Directional weighting can effectively improve the arterial street performance as indicated by the NETSIM-simulated delay, the stops, and the combined delay and stops (PI) evaluations.
2. The directional weighting algorithm developed by TTI provided better weighting than did equal weighting, and most of the time did better than the MAXBAND volume weighting methods.

TABLE 5 Summary of NETSIM Evaluation of Six Test Cases

		NETSIM Performance Index		
Test Arterial	No.	EQ(E)	MAX(M)	TTI(T)
Hawthorne Boulevard	H1	253.9	252.6	239.6
	H2	249.6	245.1	244.7
	H3	272.4	268.5	271.8
North Michigan Avenue	M1	180.4	163.0	160.9
	M2	152.1	153.3	146.2
	M3	166.0	161.1	159.8

Note: The number in each cell identifies the NETSIM performance index calculated by combining the NETSIM-simulated delay and stops (PI = delay + 4 * stops).

TABLE 6 NETSIM Evaluation of Six Test Cases

Test Arterial	No.	Delay	Stops	NETSIM Performance Index
Hawthorne Boulevard	H1	E,M,T	E,M,T	E.M,T
	H2	E,M.T	E,M.T	E,M.T
	H3	E,T,M	E,T.M	E,T.M
North Michigan Avenue	M1	E,M.T	E,M,T	E,M.T
	M2	M,E,T	E.M,T	M.E,T
	M3	E,M.T	E.M,T	E,M.T

Note: Results are from SAS ANOVA test using the Duncan option at the 5 percent significance level. The number in each cell identifies the grouping calculated by the SAS ANOVA Duncan test, with the comma separating each group level with significant statistical difference. Groups separated by a period were not significantly different. The ranking of the mean values is arranged from the highest value to the lowest value, reading from left to right. For example, "E,M,T" means that equal weighting and MAXBAND weighting were not significantly different but both were significantly different from TTI weighting. Both the Duncan and Student-Newman-Keuls tests were performed with the same results for all six test cases.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this study, the following conclusions can be drawn:

1. Directional weighting can effectively improve the arterial street performance as indicated by the NETSIM simulated delay, the stops, and the combined measure of delay and stops (PI).
2. The directional weighting algorithm developed by TTI provided better weighting than did equal weighting. It also indicated that it often performed better than the MAXBAND volume weighting methods.
3. Because of the inherent NETSIM simulation variations and the complexity of different variables involved, the difference between various directional weighting methods indicated that practical improvements existed quantitatively but sometimes not statistically.
4. As suggested by the algorithm, weight heavily the progression bandwidth for the high-volume direction if the directional volume difference is higher than 20 percent. If the difference of directional volume is within 20 percent, the ratio suggested by the estimated delay ratio from the algorithm should be used.

It is recommended that

1. The algorithm should be programmed and implemented into MAXBAND or PASSER II programs between the initial green-split module and the progression optimization module.
2. Future modification of the progression project module should be made to include the upstream side-street left-turn traffic impacts into the progression effects on downstream intersections.

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