

MAXBAND-86: Program for Optimizing Left-Turn Phase Sequence in Multiarterial Closed Networks

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Four variables are available to the traffic engineer that can be used to optimize the flow of traffic in signalized urban networks. Three of these—green phase time, offset, and cycle length—are well known, and a number of computer programs are available to determine them. A fourth variable, left-turn phase sequence, is less well known and can be computed only for arterial networks by existing software. Recognizing that the left-turn phase sequence might be an important variable in multiarterial closed networks, the Federal Highway Administration (FHWA) contracted with Texas Transportation Institute (TTI) to extend the MAXBAND program, which was restricted to single arterials and triangular networks, to such general networks. The extensions made to the MAXBAND program resulted in MAXBAND 86; these extensions are described in this paper. The application of MAXBAND 86 to a study of the effect of the left-turn phase sequence in 10 multiarterial closed networks is described also. The study included comparison of MAXBAND-produced timing plans with and without phase sequence optimization and an analysis of the effects of using phase sequence patterns given by MAXBAND in the TRANSYT program. The results indicate that optimization of the phase sequence can often provide a substantial benefit in terms of reduced delay and stops.

Traffic engineers have long recognized that traffic signals located within the downtown network should be coordinated to provide orderly movement of vehicular traffic. The need for network signal timing is to keep the traffic moving by the timely display of green signals to the platoons traveling through the arterial signal networks.

In determining optimal signal timing plans for signalized networks, the traffic engineer needs to incorporate the following decision variables:

1. Offset,
2. Green phase time,
3. Cycle length, and
4. Left-turn phase sequence.

A number of computer programs have been developed to assist the traffic engineer in obtaining signal timing plans for urban traffic arterials and networks. None of these programs incorporate all four decision variables. Delay-based programs such as TRANSYT (1) and SIGOP II (2) select offsets, green times, and cycle lengths, whereas bandwidth programs such as MAXBAND (3) select offsets, cycle lengths, and left-turn phase sequences. The modification of these programs to include all four of the above-mentioned decision variables is either impossible or computationally infeasible. Cohen and Mekemson explored the possibility of using MAXBAND and TRANSYT-7F sequentially (4). In this approach, MAXBAND is used to provide an initial timing plan, including an optimized phase sequence for TRANSYT, which then proceeds to adjust the offsets and green times to minimize a weighted combination of delay and stops. The results of this approach indicate that optimizing the left-turn phase sequence can result in delay and stop reductions on multiphase arterial signal systems.

The original MAXBAND program was capable of optimizing signal timing plans only for arterials and those networks that are composed of three arterials forming a single triangular loop. Thus, the approach of using maximum-bandwidth and minimum-delay strategies sequentially cannot be readily extended to general grid traffic networks.

APPROACH: MAXBAND 86

In order to provide the capability of optimizing the left-turn phase sequence in general multiarterial closed networks, the Federal Highway Administration (FHWA) decided to generalize the limited MAXBAND network capability to such networks. This work was performed by the Texas Transportation Institute under contract to FHWA. In addition, several other modifications were added to the model to improve its user-friendliness. These include a new signal timing summary table and an algorithm to automatically generate the network closure constraints for multiarterial closed networks. The MAXBAND 86 program and a study in which the effect of

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optimizing the left-turn phase sequence in networks was examined for the first time are described in this paper.

SYSTEM OVERVIEW

MAXBAND 86 consists of a main program and four major submodules, namely, INPUT, MATGEN, MPCODE, and OUTPUT. The main program acts to control the execution of each of these submodules. It communicates with the submodules by means of an argument list of CALL statements. The function of each submodule is explained in the following paragraph.

The INPUT module controls the reading of data, does error checking, and performs calculations, which include using weights given by the user to obtain bandwidth ratios and objective function coefficients. The MATGEN module formulates the problem as a mixed-integer linear program and writes the formulation on a file. At this point, module MPCODE reads the file written by module MATGEN and begins the optimization process. At the termination of MPCODE, control is transferred to the OUTPUT module, which writes the solution report.

The overall structure of the original MAXBAND program remained unchanged during its evolution to MAXBAND 86. However, the MPCODE module is the only one that was not substantially revised. Changes in each of the modules range in degree and character. These changes include expansion of variable dimensions, addition of new variables, addition of new subroutines, and modification of subroutines to handle problems of a more general nature. A major addition was subroutine LGEN and its supporting subroutines. Their purpose is to identify the independent set of loops and to store information regarding loop geometry in a form used by the MATGEN module to write the network closure constraints.

The design of the MAXBAND data input structure for network problems was such that the user ended by providing some duplicate information. Further, the program did not check whether these duplicate data were consistent or not. This problem could have been eliminated by modifying the structure of input data records. However, because the objective of this research was to retain the existing input data formats so that already coded problems could be run without major changes, this was not done. Instead, several subroutines were added to the module that reads data. The purpose of these subroutines is twofold: first, to provide the capability for extensive error checking of duplicate or inconsistent data, and second, to give the user an option by which the duplicate data can be eliminated.

DESIGN ASSUMPTIONS

In order to provide traffic signal timing methodology for general networks, there was a need to define the scope of

networks that could be optimized by MAXBAND 86. The following design assumptions were used to specify cases to be considered by the program.

1. The network must be completely connected; that is, there can be no disjoint arterials or subnetworks. (Note that these latter cases may be treated by solving each of the independent subsystems and then combining the results.)
2. No more than two arterials may compose an intersection; that is, there are no five-way or six-way intersections. (The green-split calculations do not currently permit this more complex analysis.) Here an arterial consists of any one-way or two-way linear road segment with two or more signals, and a network is made up of one or more such arterials.
3. The network may have a maximum of 36 independent loops, with no more than six arterials forming the boundaries of a loop.

The prior version of MAXBAND allowed the user to optionally analyze a portion of an arterial for which data were read. This feature is retained for arterial problems. However, the user cannot do this for a network problem, because in this case there exists the possibility of creating a disconnected network.

MAXBAND 86 NETWORK FORMULATION

The network problem formulation draws on work by Little and Kelson (5-7) and is presented in the MAXBAND 86 research reports (8-10). The problem formulation consists of the following major components:

1. The objective function, a weighted combination of one-way bands mathematically expressed as

$$\text{maximize } \sum_{i=1}^n c_i b_i + c_i \bar{b}_i$$

where n is the number of arterials in the network, c_i (\bar{c}_i) is the outbound (inbound) direction objective function weight for the i th arterial, and b_i (\bar{b}_i) is the outbound (inbound) band for the i th arterial.

2. Independent formulations of each arterial in the network.
3. Optional constraints to control the relative importance of arterials to each other.
4. A set of network closure constraints, which consists of a constraint for each independent closed loop in the network. The purpose of these constraints is to combine the individual arterial formulations by ensuring that the sum of the offsets in a loop is equal to an integral multiplier of the cycle length. A major contribution of this research was the derivation of an algorithm to determine the set of independent loops in the network, described in the next section.

MAXBAND'S LOOP-GENERATION ALGORITHM

The network progression problem requires the identification of the network connectivity in order to provide network closure constraints for optimization. Identification of the independent loops allows the MAXBAND 86 program to simplify the network topology and use the information to write the loop-closure constraints for optimization. For example, there are $(l - n + 1)$ fundamental loops in a network, where n is the number of nodes and l is the number of links in that network. The loop identification algorithm allows the program to develop the simplest $(l - n + 1)$ equations defining the complete network topology. Several algorithms have been developed to find this fundamental set of loops (11-13). A modified version of Paton's algorithm (11) is used in MAXBAND 86 because it is computationally efficient and requires less storage space in the computer than other algorithms. The differences between the original and the modified algorithms are as follows:

1. As opposed to Paton's original algorithm, the modified algorithm uses the node with the most links incident to it as the root of the spanning tree. This results in a simpler loop set in most cases.
2. The construction of the tree and cotree is completed before tracing of the loops is begun.
3. The links in the cotree are examined and if possible the loops are further reduced to simpler ones.

The reason for placing more emphasis on finding simpler loops is that their coefficients in the formulation matrix will occupy less space.

As shown in Figure 1, the modified Paton algorithm requires a node adjacency matrix as part of the input data

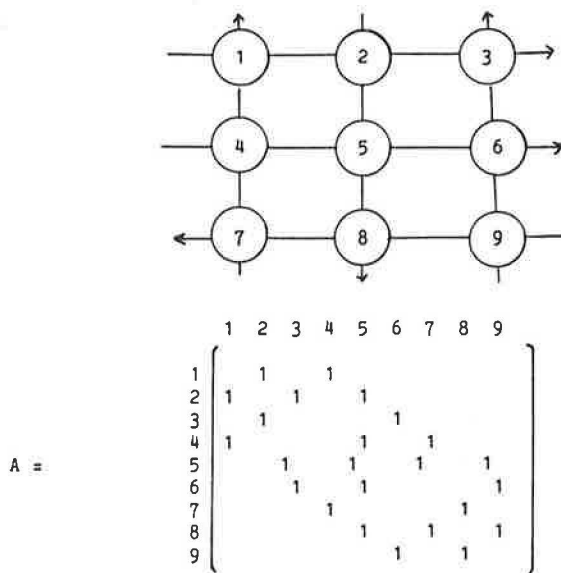


FIGURE 1 Application of modified Paton algorithm. (Note: orientation of arteries has no effect on the adjacency matrix.)

file. MAXBAND 86 creates this matrix from the unique node identification numbers that the user must supply. These identification numbers can be any alphanumeric string up to five characters long. Starting from 1, MAXBAND assigns a sequence number to each node identification number. It also identifies arterials intersecting at a particular node and their corresponding signal numbers. All the network information is stored in a logical table for easy reference.

CAUTIONARY NOTE

The MAXBAND 86 program retains the Mixed Integer Linear Program (MILP) package MPCODE that was used in the previous versions of the program. This package solves the MILP problem, which forms the basis of MAXBAND. This can lead to severe computational problems for larger closed networks, because the resulting optimization problem will become very complex.

For example, MAXBAND 86 may be given problems that, when formulated, can result in a linear integer programming problem that has more than 1,000 constraints and variables and close to 350 discrete variables for a signal network of 50 signalized intersections. Because it was not anticipated that the existing MPCODE optimization module could handle optimization problems of this size, smaller array dimensions were set in the MPCODE. Under the existing configuration, the problems that the MPCODE can theoretically handle now may have up to 700 variables, 990 constraints, and 200 discrete variables. The research team recognized that the largest deficiency of MAXBAND 86 is the efficiency of the optimization module, and it is unclear whether the existing optimization technique as implemented in the current MAXBAND 86 can find a global optimum solution to the problem of a large signal network.

APPLICATION: LEFT-TURN PHASE SEQUENCE IN NETWORKS

As has previously been mentioned, the motivating factor for performing this work was to provide the capability for optimizing the left-turn phase sequence in any network with multiphase signals. Thus, when the program became available, a set of experiments was performed on 10 real-world networks for which data were available. Descriptions of these networks are given in Table 1. In most cases, the existing signal design was not available. The available data consisted of input streams for the TRANSYT-7F program, which included experimental signal-phasing designs that did not necessarily have any relationship to the phasing designs at the actual sites. However, all other traffic and geometric data reflected actual site conditions. Therefore, in the signal phasing for this set of experiments, all approaches that had a left-turn lane or turning pocket were assigned an exclusive left-turn phase regardless of whether such a phase was warranted. However, very short mini-

TABLE 1 NETWORK DESCRIPTIONS

| Network | Signal | | | | | Location |
|---------------|--------------------------|------------------|---------------|----------------|--|------------|
| | Signalized Intersections | Left Turn Phases | Cycle Lengths | Spacing (Feet) | | |
| Daytona Beach | 12 | 20 | 120 | 600-777 | | Florida |
| Odgen | 13 | 12 | 80 | 381-776 | | Utah |
| Owosso | 16 | 23 | 80 | 358-3600 | | Michigan |
| Walnut Creek | 13 | 21 | 100 | 200-1720 | | California |
| Ann Arbor | 14 | 17 | 100 | 321-820 | | Michigan |
| Memphis | 17 | 12 | 100 | 393-799 | | Tennessee |
| Bay City | 16 | 20 | 100 | 478-3979 | | Michigan |
| Houston | 13 | 13 | 100 | 450-2700 | | Texas |
| Los Angeles | 15 | 15 | 100 | 746-2471 | | California |
| San Ramon | 17 | 19 | 120 | 510-4900 | | California |

mum greens (8 sec) were assigned to the left-turn phases, so any effect due to unwarranted phases was small. No other changes were made to the input data. In particular, no left-turn volumes were increased, because it was determined that such modifications would result in findings that would be biased in favor of phase-sequence optimization. This is because increasing left-turn volumes would result in longer left-turn phases, which would result in larger increases in bandwidth produced by optimizing the phase sequence.

Two sets of experiments were performed:

1. In the first set, the MAXBAND 86 program was executed to provide timing plans for all 10 networks both with and without phase-sequence optimization (no leading lefts had phase-sequence optimization). The NETSIM program was then used to simulate the network performance using both sets of MAXBAND 86 timing plans.

2. In the second set, the MAXBAND 86 timing plans from the first set of experiments were used as starting solutions for the TRANSYT-7F program, which then produced minimum delay/stop solutions. The NETSIM program was then used to simulate the network performance using both sets of TRANSYT-7F timing plans.

GENERAL REMARKS

Before discussion of the results, the following comments should be made:

1. The NETSIM model is a stochastic microscopic model that uses a sequence of randomly generated numbers to assign values to random variables such as speed, queue discharge headway, start-up delay, and left-turn gap ac-

ceptance. For this reason, estimates of measures of effectiveness (MOEs) such as delay and stops will have a certain amount of variability depending on the particular sequence of random numbers used. Past experience with the model on undersaturated networks of comparable size to the ones used in this work has shown that this variability is about 3½ percent. This means that when different timing plans are compared for the same network, a difference of 4 percent is probably statistically significant. A review of the 15- and 30-min cumulative statistics for the 10 networks studied indicated that the network statistics were indeed stable, which implies that the networks were undersaturated.

2. The cycle lengths were held fixed and are representative of cycle lengths used for typical multiphase operation.

3. The external links were not included in the Experiment 1 NETSIM runs because MAXBAND calculates a fixed deterministic green time for each movement (not phase), and all the benefits derived from improved progression accrue to the internal links. Thus delay on the external links will be independent of the phase-sequence patterns chosen. However, in the case of TRANSYT, it is not possible to hold the green time fixed for movements on external links without holding all green times fixed. Therefore, the external links were included for the Experiment 2 TRANSYT and NETSIM runs, so TRANSYT and MAXBAND timing plans are not comparable.

4. Four signal cycles were used as the "fill time" for each NETSIM run. One 30-min simulation run was made. Thus, as mentioned in the first item in this list, differences of less than 4 percent are not significant.

5. All signals were simulated as fixed time (as is usually the case for closed networks), and all left-turn movements from an exclusive lane were fully protected.

TABLE 2 MAXBAND BEFORE-AND-AFTER RESULTS

| Arterial | Total ¹ | Total | % | NETSIM ² | NETSIM | % | NETSIM ³ | NETSIM | % |
|--------------|--------------------|------------------|-----|---------------------|-------------|-----|---------------------|-------------|-----|
| | Band-Width Before | Band-Width After | | Delay Before | Delay After | | Stops Before | Stops After | |
| Daytona | 1.57 | 2.48 | +58 | 84.4 | 56.7 | -34 | 1.70 | 1.30 | -23 |
| Odgen | 2.56 | 3.08 | +20 | 46.2 | 39.9 | -14 | 1.73 | 1.51 | -13 |
| Owosso | 3.99 | 4.20 | + 5 | 55.0 | 53.2 | - 3 | 1.44 | 1.40 | - 3 |
| Walnut Creek | 2.09 | 2.77 | +32 | 70.1 | 61.2 | -13 | 1.72 | 1.55 | -10 |
| Ann Arbor | 3.29 | 3.70 | +12 | 44.2 | 35.0 | -21 | 1.22 | 1.07 | -12 |
| Memphis | 2.98 | 3.36 | +12 | 35.2 | 30.9 | -12 | 1.15 | 0.90 | -22 |
| Bay City | 2.88 | 3.57 | +23 | 82.2 | 74.0 | -10 | 1.75 | 1.63 | -12 |
| Houston | 2.44 | 2.82 | +15 | 78.7 | 70.1 | -11 | 1.80 | 1.58 | -12 |
| Los Angeles | 3.03 | 3.61 | +19 | 66.4 | 60.6 | - 9 | 1.45 | 1.33 | - 8 |
| San Ramon | 1.88 | 2.43 | +29 | 115.0 | 108.2 | - 6 | 2.12 | 2.08 | - 2 |

1. Fraction of Cycle, Sum of All Bands

2. Seconds/Vehicle

3. Stops/Vehicle

RESULTS

The results of Experiment 1 (Table 2) show that in most of the networks substantial reductions in delay, stops, or both were achieved as a result of optimizing the phase sequence.

The results of Experiment 2 (Table 3) show that, in many cases, the improvements due to phase-sequence optimization appear smaller. In part, this is because the results have been "watered down" by the presence of the external links, which increase the total delay both before and after Experiment 2 (without the Experiment 1 activities).

DISCUSSION

It should be pointed out that the experiments performed here were limited to the examination of whether phase-sequence optimization using a bandwidth-based program such as MAXBAND 86 had potential for producing signal-timing plans that would, if implemented, result in lower values for delay and stops. Both MAXBAND 86 and TRANSYT-7F were used in a straightforward fashion, with no attempt to perform a deeper analysis of the problem. The results indicate that, given the limited purposes of these experiments, left-turn phase-sequence optimization has at least the potential to provide more effective signal-timing plans in networks with multiphase signal operations.

Conduct of these experiments uncovered a number of issues that were beyond the scope of this study but that could have had an important effect on the results.

1. One issue was bandwidth weighting in MAXBAND. In these experiments, equal directional bandwidth on individual arterials was used. Previous studies have shown that directional weighting, especially where there are unequal through greens, can significantly affect delay and stops (14).

2. Another issue was multiple solutions in MAXBAND. Although MAXBAND produces a global optimum, the experience with the 10 networks used here indicates that usually a number of solutions are found that have the same bandwidth to four or five decimal places. Thus, there is no practical difference among these solutions in terms of total bandwidth, but some may, for various reasons, give better performance in terms of delay and stops. It should be noted that this problem has previously been pointed out by Baass (15,16) with respect to single arterials. However, the network problem differs from the single-arterial problem as follows:

a. For single arterials, the multiple solutions indicated by Baass are due to different combinations of cycle length and speed.

b. For multiarterial networks, the multiple solutions occur for constant cycle length and speed and are due to the different possible ways in which the total bandwidth available in the network is divided among the arterials that make up the network.

TABLE 3 TRANSYT BEFORE-AND-AFTER RESULTS

| Network | TRANSYT | | | NETSIM | | | NETSIM | | |
|--------------|-----------|----------|----------|--------------|-------------|----------|--------------|-------------|----------|
| | PI Before | PI After | % Change | Delay Before | Delay After | % Change | Stops Before | Stops After | % Change |
| Daytona | 186. | 165. | -11 | 96.5 | 79.3 | -18 | 1.99 | 1.79 | -10 |
| Odgen | 81.5 | 75.7 | - 7 | 56.4 | 50.0 | -11 | 2.08 | 1.89 | - 9 |
| Owosso | 130. | 126. | - 3 | 56.5 | 57.6 | + 2 | 1.59 | 1.57 | - 1 |
| Walnut Creek | 216. | 202. | - 6 | 92.8 | 76.3 | -18 | 2.52 | 2.05 | -19 |
| Ann Arbor | 86.4 | 85.7 | - 1 | 54.5 | 55.4 | + 2 | 1.61 | 1.58 | - 2 |
| Memphis | 83.2 | 83.8 | 0 | 52.4 | 50.2 | - 4 | 1.61 | 1.42 | -12 |
| Bay City | 184. | 183. | - 3 | 91.9 | 91.6 | 0 | 2.05 | 2.03 | - 2 |
| Houston | 234. | 235. | 0 | 96.0 | 89.0 | - 7 | 2.13 | 2.17 | + 2 |
| Los Angeles | 210. | 201. | - 4 | 83.5 | 82.8 | - 1 | 1.82 | 1.79 | - 3 |
| San Ramon | 155. | 147. | - 5 | 120.9 | 117.6 | - 3 | 2.36 | 2.35 | 0 |

The multiple-solutions problem will probably have a greater impact when phase sequence is optimized, if only because of the increased number of integer variables and hence possible solutions due to the optimization.

Preliminary indications are that the major causes of differences in delay and stops between solutions having the same bandwidth are as follows:

1. For a given solution, the position of the bands on some of the arterials relative to the start or end of the green time may cause parts of platoons to be stopped at certain intersections on those arterials.

2. The result of solutions for a network is usually that most of the arterials achieve virtually the entire amount of bandwidth that they would have received if optimized separately. A few (usually one or two) receive substantially less than the bandwidth they would have received if optimized separately. This compromise is due to requirements of the network closure constraints. For this reason, many of the near-optimal solutions differ only in terms of which arterials are degraded. Thus, if in one solution a minor arterial is degraded while in another solution a major arterial is degraded, one would expect the former solution to perform better in terms of delay and stops than the latter.

CONCLUSION

From the results of this study, it can be concluded that optimizing the left-turn phase sequence in multiarterial closed networks has potential for improving the performance of signal-timing plans, but that further research, such as that described in the Results section, is required.

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