Optimization of Left-Turn Phase Sequence on Signalized Arterials

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ABSTRACT

The traffic engineer has four variables available that can be adjusted to provide signal timing plans for signalized urban-suburban arterials. These are green phase time, offset, cycle length, and left-turn phase sequence. Up until recently, the last of these variables has received very little attention. In recent years, two signal optimization computer programs, MAXBAND (1) and PASSER-II (2), have been developed. Through use of these programs, the impact of changing left-turn phase sequence so as to maximize the amount of green bandwidth on a two-way signalized arterial with left-turn phases at some or all of the intersections can be explicitly considered. However, there has also been a tendency to utilize signal optimization programs that use vehicular delay as a measure of performance rather than bandwidth. Unfortunately, the delay-based programs, TRANSYT-7F (3), SIGOP-III (4), and SSTOP (5), cannot optimally select left-turn phase sequence. Thus, the objective of this study was to examine whether using a bandwidth-based program for the selection of left-turn phase sequence subsequently followed by delay-based programs to determine the final offsets generates signal timing plans with lower delay than either class of programs individually. Data from seven arterials of widely varying characteristics were available for this study. It was found that optimizing phase sequence can substantially improve the performance of MAXBAND, both in terms of increased bandwidth and decreased delay and stops. The use of phase sequence patterns optimized by MAXBAND in TRANSYT-7F has the potential for further improving signal timing plans produced by the latter program. However, use of phase sequence patterns optimized by MAXBAND in SIGOP-III apparently has the potential for producing signal timing plans with reduced performance.

The traffic engineer has four variables available that can be adjusted to improve the effectiveness of signal timing plans for signalized arterials. Three of them, green phase time, offset, and cycle length, are very familiar and can be calculated, more or less, by using various programs (1-5). The fourth variable, however, left-turn phase sequence, is less familiar as a signal timing variable; hence a detailed description of its application is in order. Take an arterial intersection with left-turn lanes or bays and left-turn phases on both arterial approaches. There are thus four possible combinations of the two left turns and two through phases (such as National Electric Manufacturers Association phases 1 and 5, and 2 and 6) (Figure 1). They are

1. Both left-turn lanes leading both through lanes (lead-lead);
2. Both left-turn lanes lagging both through lanes (lag-lag);
3. Inbound left-turn lane leading concurrently with inbound through lane; outbound left-turn lane lagging concurrently with outbound through lane (lead-lag); and
4. Outbound left-turn lane leading concurrently with outbound through lane; inbound left-turn lane lagging concurrently with inbound through lane (lag-lead).

The only extensive work that has been done on the effects of left-turn phase sequence has been performed by Texas. In particular, the FACTS (6) system was developed there. The FACTS system is a real-time arterial signal-control system that can implement signal turning plans, which are developed off-line by using the PASSER-II program in response to inputs from a surveillance system. In developing the plans, all four variables are used for optimization. In particular, each plan may have a different left-turn phase sequence and individual plans can be implemented on a cycle-by-cycle basis. The FACTS system has been installed and evaluated on the NASA-1 arterial south of Houston. Preliminary results appear promising (6).

SIGNAL TIMING PROGRAM CATEGORIES

Signal timing plans for signalized arterials in urban or suburban areas are developed by computing a set of values for each of the variables described previously. A number of computer programs are available that will optimize some of the variables. These programs can be divided into two general classes:

Class 1

Delay-based programs: These programs are characterized by a macroscopic traffic model that uses traffic flow, geometric, and signal timing inputs to estimate total delay and total stops. A gradient search optimization procedure is then used that adjusts signal parameters so as to minimize a weighted sum of stops and delay as estimated by the traffic model. Examples of such programs include TRANSYT-7F

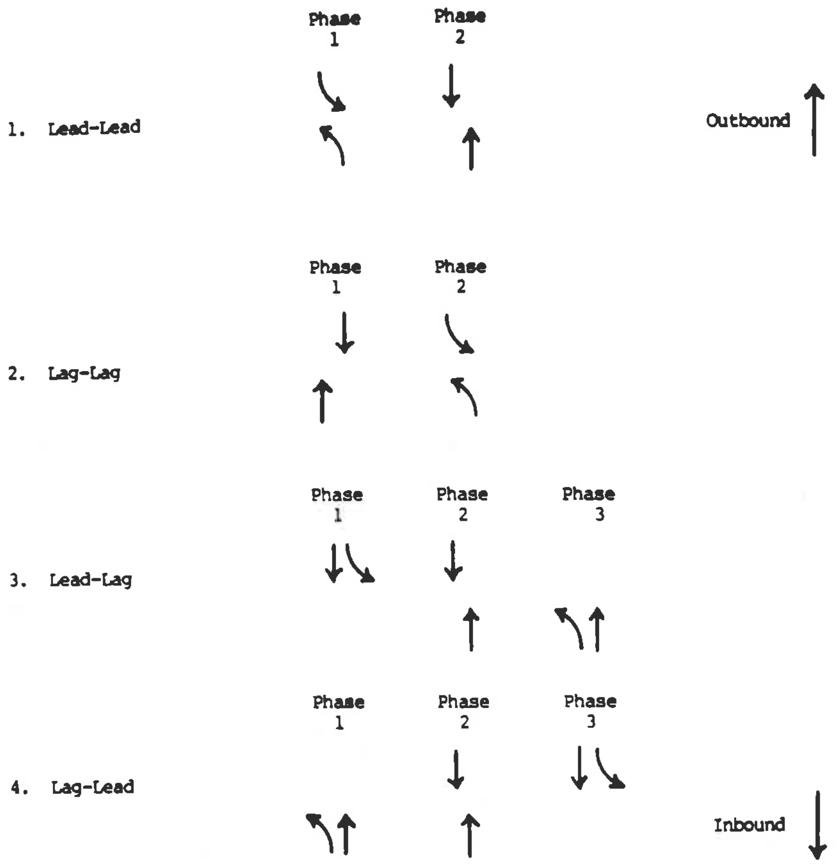

FIGURE 1 Allowable left-turn-through phase sequence combinations.

(3), SIGOP-III (4), and SSTOP (5). It should be noted that the weighed sum or delay and stops is called the Performance Index (PI) in TRANSYT-7F and Disutility (DIS) in SIGOP-III.

Class 2

Surrogate-based programs: These programs use a surrogate for the delay and stops performance measures that is much simpler to calculate, together with a more rigorous optimization procedure such as Mixed Integer Linear Programming (MILP). An example of such programs is MAXBAND (6), which uses bandwidth as the surrogate.

PROGRAM LIMITATIONS

One of the major limitations in using any of these programs is that none of them optimize all four variables. The delay-based programs optimize green phase time, offset, and cycle length; and the bandwidth programs optimize offset, cycle length, and phase sequence. The bandwidth programs sometimes have the ability to perform an initial green time allocation for each phase based on user-specified volumes and saturation flow rates. However, these computed green phase times generally remain fixed throughout the optimization procedure. PASSER-II, which has a three-step optimization process, recalculates green splits after the second step on the basis of a modified Webster's delay equation that attempts to account for platoon arrivals. One could, of course, do the same thing with MAXBAND by recomputing the splits after an optimization is complete and reoptimizing with the new splits. The logical approach to a universal program would be to extend the capability of one of them. However, adding phase sequence to the delay-based programs would involve combining a nonlinear gradient search technique with a combinatorial problem that appears computationally infeasible. This is because there are 4^n possible phase sequence combinations at n intersections with full left-turn phasing. For instance, Rogness (7) looked at the phase sequence optimization using a four-intersection arterial. This required a total of 256 (4^4) TRANSYT-7F runs to be made. On the other hand, MAXBAND's single measure of performance bandwidth provides no means for measuring and thus minimizing delay by adjusting green phase times. Green phase times are actually necessary constraints on the bandwidth optimization procedure because the maximum bandwidth occurs at zero green phase time for the cross street, which is unacceptable.

Another approach that has been suggested is to take one of the programs from each category and use them consecutively. Cohen (8) ran a number of scenarios by using data sets from two 8-intersection arterials, on the MAXBAND and TRANSYT-7F programs. He used the MAXBAND-computed green phase times together with optimized offsets and phase sequences as the starting solution for TRANSYT-7F. The latter program was then used to compute final offset and green phase times. By using the NETSIM model as the evaluation mechanism, it was shown that the resultant signal timing plans performed better than signal timing plans generated by either program alone for these two arterial networks.

In this work, findings that were based on a rather limited sample were greatly extended (7,8). The study focused on answering two questions: (a) What benefits relative to both increased bandwidths and reduced delay might be expected from optimizing the left-turn phase sequence? and (b) What is the response of delay-based programs when presented with an optimized left-turn phase sequence pattern determined by a maximum bandwidth program?

EXPERIMENTAL DESIGN

The experiments were restricted to the FHWA-supported programs TRANSYT-7F, SIGOP-III, and MAXBAND, using data sets from seven arterials, which are briefly described in Table 1. These data sets include a wide variety of geometric and traffic situations and therefore provide a good test for the effects of phase sequence optimization on arterials. The following comments apply to the conduct of the experiments:

1. The existing fixed-cycle length for each arterial was held fixed throughout all experiments. In addition, the values of green phase time computed in step a were also held fixed throughout subsequent steps b-f. This was done to isolate the effects of left-turn phase sequence optimization from the effects of green phase time and cycle-length optimization. If the cycle length and green phase times were allowed to vary, it would be impossible to determine whether phase sequence optimization alone is beneficial because of the confounding effects of the other variables.
2. A value of 4 was used as the stop weighting factor (seconds per stop) for both TRANSYT-7F's performance index (PI) and SIGOP-III's disutility (DIS). Because NETSIM was to be used as the evaluation mechanism for each of the three programs' generated signal timing plan, a NETSIM PI was constructed by using the same stop weighting factor, thus allowing a common measure across all programs.
3. The measures of effectiveness (MOEs) given for NETSIM and the values for PI given for TRANSYT-7F include both the arterial and side streets. The values for DIS given for SIGOP-III include only the arterial because there is no mechanism for including the entry link side street delays and stops in SIGOP-III. The green phase times in SIGOP-III are determined by the program that involves the use of the following mechanism: (a) The side street green phase times are initially adjusted so that the side street Volume 1 Capacity (V/C) ratio is equal to 85 percent or so that minimum green time is satisfied, whichever is larger; and (b) During optimization of DIS, more green time may be given to the side street if DIS is not thereby increased (i.e., if the SIGOP-III traffic model indicates there is unused green time on the main arterial phase.)
4. All calibration data (such as speeds, headways, etc.) required by the three optimization programs were obtained from the appropriate values used in NETSIM. NETSIM, in turn, was calibrated for each of the arterials by the user from whom we obtained the input decks. In most cases, however, the calibrations were limited to speeds and queue discharge headways.

The experiments were conducted according to the following steps for each arterial.

1. The MAXBAND program was run assuming that all left-turn phases were leading (i.e., the top diagram in Figure 1), which is standard practice in most jurisdictions at the present time. MAXBAND computes green phase times by using a modified Webster's approach and user-supplied volumes and capacities (actually saturation flow rates) that adjust for minimum green times if necessary. Green phase times are held fixed in succeeding steps to isolate the effects of left-turn phase sequence optimization as explained previously. (See Table 2 for before-and-after phase sequence optimization results.) The capacities were adjusted so as to agree with values obtained from NETSIM. This was done by noting intersection movements in the NETSIM run that were oversaturated and then adjusting downward the capacities for those movements used in MAXBAND. This results in the assignment of more green time to that movement by MAXBAND. This iterative procedure between MAXBAND and NETSIM was continued until there were no longer any oversaturated movements. MAXBAND then computes the offset pattern that produces the largest two-way bandwidth (inbound-outbound bandwidth ratio equal to 1). One of MAXBAND's user input options is the specification of a targeted inbound-outbound bandwidth ratio that could result in a higher level of performance. This option was not utilized for the previously stated purpose of isolating the effects of left-turn phase sequence optimization.
2. With green phase times fixed, TRANSYT-7F was exercised by using the default (zero offset) timing plan as the initial starting solution and capacities used in MAXBAND. TRANSYT-7F computed an offset pattern that produces the optimum PI. The default starting solution was used rather than the MAXBAND offset pattern solution to isolate the effect of left-turn phase sequence optimization from improved starting solutions. TRANSYT-7F's capability of improving the PI by adjusting all of the green phase times by using a gradient search technique was also not utilized in order to isolate the effects of left-turn phase sequence optimization.
3. With green times held fixed and by using the same mean queue discharge headway as was used in NETSIM, SIGOP-III was exercised to compute an offset pattern that minimizes DIS.
4. The three timing plans were then tested by using the NETSIM model as the evaluation tool. All simulation runs were for 30 min of simulation time. Further discussion on simulation procedures is presented in the following section.
5. MAXBAND was then run a second time to compute the offset and optimal left-turn phase sequence pattern, which produces the largest two-way bandwidth.

TABLE 1 Arterial Descriptions

Arterial	Signalized Intersections	Lanes	Optimized Left-Turn Phases	Progression Speed	Cycle Length	Signal Spacing (ft)	Location
Hawthorne Boulevard	13	8	12	45	90	560-2,600	Los Angeles, Calif.
University Boulevard	10	4	9	30	80	480-1,440	Provo, Utah
Nicholasville Road	12	4	10	35	80	520-2,160	Lexington, Ky.
North 33rd Street	9	4/6	7	35	75	353-1,605	Salt Lake City, Utah
Frederica Road	12	4	12	45	80	582-2,310	Owensboro, Ky.
Fannin Boulevard	15	6	12	35	80	300-1,900	Houston, Tex.
San Felipe Road	12	4	8	35	80	250-1,400	Houston, Tex.

TABLE 2 Before-After Phase Sequence Results for MAXBAND

	MAXBAND			NETSIM								
	Bandwidth (% of cycle, two-way band)			Delay (sec/vehicle)			Stops (stops/vehicle)			PI (vehicle-hr/hr)		
Arterial	Before	After	Change (%)	Before	After	Change (%)	Before	After	Change (%)	Before	After	Change (%)
Hawthorne	0.284	0.548	+93	80.16	64.94	-19	2.21	1.74	-21	263.4	212.7	-19
University	0.231	0.498	+116	42.40	35.39	-16	1.53	1.29	-16	98.0	82.4	-16
Nicholasville	0.368	0.480	+30	75.64	71.38	-5	2.27	2.00	-12	209.0	195.4	-7
North 33rd	0.092	0.268	+191	51.64	51.57	0	1.33	1.29	-3	242.3	247.0	-1
Frederica	0.470	0.718	+54	66.28	62.63	-6	2.10	1.95	-7	109.9	103.4	-6
Fannin	0.392	0.597	+52	63.59	54.28	-15	1.99	1.77	-11	176.0	151.0	-14
San Felipe	0.423	0.600	+42	51.44	49.60	-4	1.59	1.52	-4	170.3	163.8	-4

6. Steps 2-4 were repeated by using the optimized phase sequence patterns obtained in step 5.

GENERAL REMARKS

Before the results are discussed, two comments are necessary particularly with respect to the use of the NETSIM model.

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 speeds, queue discharge headways, start-up delays, left-turn gap acceptance, and so forth. For this reason, estimates of MOEs such as delay and stops will have a certain amount of variability in them depending on the particular sequence of random numbers used. Past experience with the model on undersaturated networks of size comparable with the ones used in this work has shown that this variability is approximately 3.5 percent. This means that when different timing plans are compared for the same network, a difference of 4 percent or less is probably not statistically significant. A review of the 15- and 30-min cumulative statistics for the seven arterials studied indicated that the network statistics were stable.
2. The traffic models used in TRANSYT-7F and SIGOP-III are macroscopic and deterministic and, by necessity, represent oversimplifications of traffic behavior in networks. Thus it can happen that apparent improvements predicted by them may not appear when a more detailed model such as NETSIM is used. This is not of any practical significance if one is looking at small discrepancies. In Table 3 for example, TRANSYT-7F predicted an improvement of 4 percent in PI for San Felipe Road, whereas NETSIM showed no improvement in delay and stops. It is not at all improbable that a 4 percent effect predicted by TRANSYT-7F could be washed out by those factors that were taken into account by NETSIM. On the other hand, evidence of large discrepancies indicates a potential problem with the macroscopic traffic model. For example, in Table 4 SIGOP-III predicted an improvement of 27 percent in DIS for University Boulevard, whereas NETSIM showed a decline of 19 percent. This indicates a very substantial difference between the behavior of traffic on the arterial as simulated by the two models.

INTRAMODAL RESULTS AND DISCUSSION

Tabulations of before-and-after phase sequence optimization results for each of the programs are given in Table 2 for MAXBAND, Table 3 for TRANSYT-7F, and Table 4 for SIGOP-III. Table 2 gives tabulations on the changes in bandwidth and NETSIM estimated delay, stops, and PI as a result of phase sequence optimization. Table 3 gives tabulations on the changes in NETSIM estimated delay, stops, and PI and TRANSYT-7F PI as a result of phase sequence optimization. Table 4 gives tabulations on the changes in NETSIM estimated delay, stops, and PI and SIGOP-III DIS. The results are summarized in the following paragraphs.

MAXBAND

1. As expected, optimizing phase sequence increased total two-way bandwidth because the MAXBAND formulation guarantees a global optimum (i.e., the largest possible bandwidth). Bandwidth increases ranged from 30 to 191 percent.
2. Arterial delay was reduced substantially in five of the seven arterials with reductions that ranged from 5 to 19 percent. The reduction in stops of from 7 to 21 percent was even more impressive, as might be expected, because the major effect of increasing bandwidth is to reduce the number of vehicles in the through platoon that have to stop.
3. Improvements in NETSIM PI ranged from 6 to 19 percent for the same five arterials.

TABLE 3 Before-After Phase Sequence Results for TRANSYT-7F

	TRANSYT-7F			NETSIM								
	PI (vehicle-hr/hr)			Delay (sec/vehicle)			Stops (stops/vehicle)			PI (vehicle-hr/hr)		
Arterial	Before	After	Change (%)	Before	After	Change (%)	Before	After	Change (%)	Before	After	Change (%)
Hawthorne	194.6	180.4	-7	71.89	64.04	-11	1.89	1.72	-9	234.7	210.4	-10
University	89.1	71.5	-20	38.93	36.12	-7	1.89	1.72	-8	90.4	84.0	-7
Nicholasville	167.2	161.4	-4	79.82	72.55	-9	2.28	2.07	-9	219.4	199.2	-9
North 33rd	226.2	219.0	-3	51.86	50.35	-3	1.36	1.29	-5	243.9	235.8	-3
Frederica	109.8	103.4	-6	66.46	62.96	-5	2.08	1.91	-8	109.7	103.9	-5
Fannin	159.7	152.8	-4	54.88	54.72	0	1.75	1.78	+2	152.0	152.2	0
San Felipe	207.6	202.6	-2	55.57	53.78	-3	1.55	1.60	+3	181.5	176.8	-3

TABLE 4 Before-After Phase Sequence Results for SIGOP-III

	SIGOP-III			NETSIM								
	DIS (sec/hr)			Delay (sec/vehicle)			Stops (stops/vehicle)			PI (vehicle-hr/hr)		
Arterial	Before	After	Change (%)	Before	After	Change (%)	Before	After	Change (%)	Before	After	Change (%)
Hawthorne	299,580	260,560	-13	78.57	84.12	+7	2.25	2.29	+2	259.6	275.7	+6
University	77,040	56,160	-27	41.45	49.44	+19	1.44	1.75	+21	95.4	114.0	+19
Nicholasville	223,020	207,248	-7	83.94	82.23	-2	2.38	2.30	-3	230.0	225.4	-2
North 33rd	210,936	201,288	-5	57.09	54.05	-5	1.43	1.36	-5	266.9	253.0	-5
Frederica	222,805	221,410	-1	65.47	69.01	+5	2.12	2.19	+3	108.6	114.6	+6
Fannin	158,558	15,630	-3	57.23	67.13	+17	1.89	2.01	+6	159.8	184.7	+16
San Felipe	160,335	166,185	+4	52.02	49.44	-5	1.55	1.50	-3	171.1	163.4	-4

TRANSYT-7F

1. Improvements in delay and stops were generally less significant than in the case of MAXBAND; NETSIM estimated that delay, stops, and PI were reduced on four out of the seven arterials.
2. Improvements ranging from 3 to 20 percent in the TRANSYT-7F PI were seen in all seven arterials.

SIGOP-III

Increases in delay and stops were seen in four of the seven arterials. This is particularly disturbing because improvements in DIS were predicted on the same four arterials by the SIGOP-III traffic model. The greatest difference was for University Boulevard where SIGOP-III estimated an improvement of 27 percent and NETSIM estimated a decline of 19 percent. The remaining three arterials had only minor improvements and only one of those (5 percent) was significant. On the basis of these results, it would appear that a serious problem exists in the SIGOP-III traffic model relative to the treatment of multiphase arterials. It would appear that further research (outside the scope of this study) is needed in this matter.

INTERMODAL RESULTS AND DISCUSSION

Before the results of the models are compared with each other, the following caveat is required: The MAXBAND runs use equal directional bandwidth weighting and equal allocations of slack green phase time. Here, slack green phase time is defined as the amount of arterial major phase green time that lies outside of the two-way bands. Preliminary studies have shown that adjustment of directional weighting can provide signal timing plans with lower delay. This is currently under further study in an FHWA contract. It has also been shown that adjustments of slack green in signal timing plans computed by bandwidth methods to accommodate queues may reduce delay (9). Therefore, it is likely that the MAXBAND results given below, especially for the the before-phase sequence optimization case where slack greens are larger, could be improved.

Given this caveat, the intermodal comparison shown in Table 5 is based on a TRANSYT-7F/SIGOP-III-like PI computed from NETSIM-generated delays and stops. It may be seen that the performance of all three models was fairly equivalent before optimization of the left-turn phase sequence, with TRANSYT-7F having a slightly better overall performance for the seven networks studied. MAXBAND and TRANSYT-7F again performed fairly equivalently after phase sequence optimization and performed substantially better than SIGOP-III in six of the seven arterials. For the San Felipe arterial, MAXBAND and SIGOP-III were equivalent and performed better than TRANSYT-7F.

CONCLUSIONS

From the results of this study, the following conclusions as applied to the seven arterials studied may be drawn:

1. Optimizing phase sequence can substantially improve the performance, both in terms of increased bandwidth and decreased delay and stops, of bandwidth optimization programs such as MAXBAND.
2. By using phase sequence patterns optimized by MAXBAND in TRANSYT-7F, the potential for improving signal timing plans produced by the latter program can be recognized.
3. By using phase sequence patterns optimized by MAXBAND in SIGOP-III, the potential for producing signal timing plans with reduced performance can be recognized.

FURTHER RESEARCH

Based on the findings of this paper and Rogness (7) and Cohen (8), the feasibility of extending the MAXBAND program to grid networks and integrating the resulting program with TRANSYT-7F into a single package can be assessed. The combined program would

TABLE 5 Comparison of Model Results Both Before and After Phase Sequence Optimization

	Before Phase Sequence Optimization (vehicle-hr/hr)			After Phase Sequence Optimization (vehicle-hr/hr)		
Arterial	MAXBAND	TRANSYT-7F	SIGOP-III	MAXBAND	TRANSYT-7F	SIGOP-III
Hawthorne	263.4	234.7	259.6	212.7	210.4	275.7
University	98.0	90.4	95.4	82.4	84.0	114.0
Nicholasville	209.0	219.4	230.0	195.4	199.2	225.4
North 33rd	242.3	243.9	266.9	241.0	235.8	253.0
Frederica	109.9	109.7	108.6	103.4	103.9	114.6
Fannin	176.0	152.0	159.8	151.0	152.2	184.7
San Felipe	170.3	181.5	171.1	163.8	176.8	163.4

have a common input stream and would have the capability of using the MAXBAND module to compute an initial timing plan and optimum phase sequence for the TRANSYT-7F module that could then fine-tune the offsets and green phase times for optimum PI.

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