The Bandwidth-Constrained TRANSYT Signal-Optimization Program

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ABSTRACT

A discussion is presented of previous attempts to combine bandwidths and delay and stop considerations as criteria for computing signal-timing plans for arterial signal systems. In particular, deficiencies in these previous attempts are pointed out. A new approach that involves constraining the TRANSYT-7F model to preserve the two-way band computed by a bandwidth program is described. This new approach was tested on 10 widely varying arterial data sets by using the MAXBAND program to develop the green bands, and the NETSIM model to evaluate the effectiveness of the resultant signal-timing plans with a weighted combination of delay and stops as the measure of performance. It is shown that no statistically significant improvement in arterial performance is obtained by adjusting offsets only, even in the case of short block spacing. However, if both offsets and green times are adjusted, statistically significant improvements in arterial performance are obtained.

The TRANSYT model is the most widely used computer program for developing signal-timing plans for urban signal systems (1). An Americanized version of the program, TRANSYT-7F was developed for use in the United States and has been successful (2). The TRANSYT program is based on delay and stops in that a macroscopic traffic model is used to estimate delay and stops, based on volumes, capacity, and signal timing. A weighted combination of delay and stops, called the performance index (PI), is the criterion used. Offset and green-phase times are adjusted to make the estimate of PI as small as possible (e.g., optimize PI).

However, some reluctance has been evident in the traffic engineering community about applying the TRANSYT program to signalized arterials because the program often does not produce good progression bands. As an example, consider the space-time diagram in Figure 1. The signal offsets for the eight-intersection network were developed by using the TRANSYT program. This can be compared with the space-time diagram for the same network and traffic conditions shown in Figure 2. Here, the offsets were obtained by using a bandwidth-based program, MAXBAND (3). A substantial number of practicing traffic engineers prefer a timing plan such as the one shown in Figure 2 over a timing plan such as that shown in Figure 1. Engineers often take the signal-timing plans produced by TRANSYT and make offset and even green-time adjustments to improve the progression bands. These adjustments, which are made in an ad hoc manner, will degrade the performance of the signal-timing plans relative to delay and stops. They also do not produce the widest green band that could be achieved. For instance, it is unlikely that one could make adjustments by hand on the timing plan shown in Figure 1 and arrive at progression bands as wide as those shown in Figure 2.

Because many traffic engineers want arterial signal-timing plans to have good progression bands, they prefer to use maximal bandwidth-based programs such as MAXBAND and PASSER II (4), which optimize the total two-way green band on signalized arterials, but give delay and stops consideration only insofar as the computation of green time is concerned.

Based on these comments, it is evident that it would be useful to combine the delay-stop optimization approach and the bandwidth optimization approach in some way to be able to produce signal-timing plans that combine the best features of both. The purpose of this paper is to report on an approach that does this.

DISCUSSION OF PREVIOUS RESEARCH

A number of research studies have been done in the field of combining delay-stops and bandwidth considerations. These studies may be divided into two categories:

1. Those that modify a delay-based program to give consideration to bandwidth (or more generally, progression).
2. Those that adjust bandwidth-based signal-timing plans to reduce further delay.

In the first category, an obvious approach is to use a bandwidth solution as a starting point for a TRANSYT optimization. One researcher (5) has previously performed a study in which this approach was taken. Based on the somewhat limited sample of two test arterials, some indication was evident that using a bandwidth solution as a starting point for TRANSYT had some potential for giving signal-time plans that were an improvement over those obtained using the default zero offsets. However, this approach in no way guarantees that there will be progression bands, much less maximal progression bands. For example, consider Figure 3, which is a space-time diagram for the same arterial with volume and capacity conditions the same as in Figures 1 and 2. The timing plan shown in Figure 3 was developed by using the TRANSYT program with the timing plan shown in Figure 2 as the starting solution. It can be ob-

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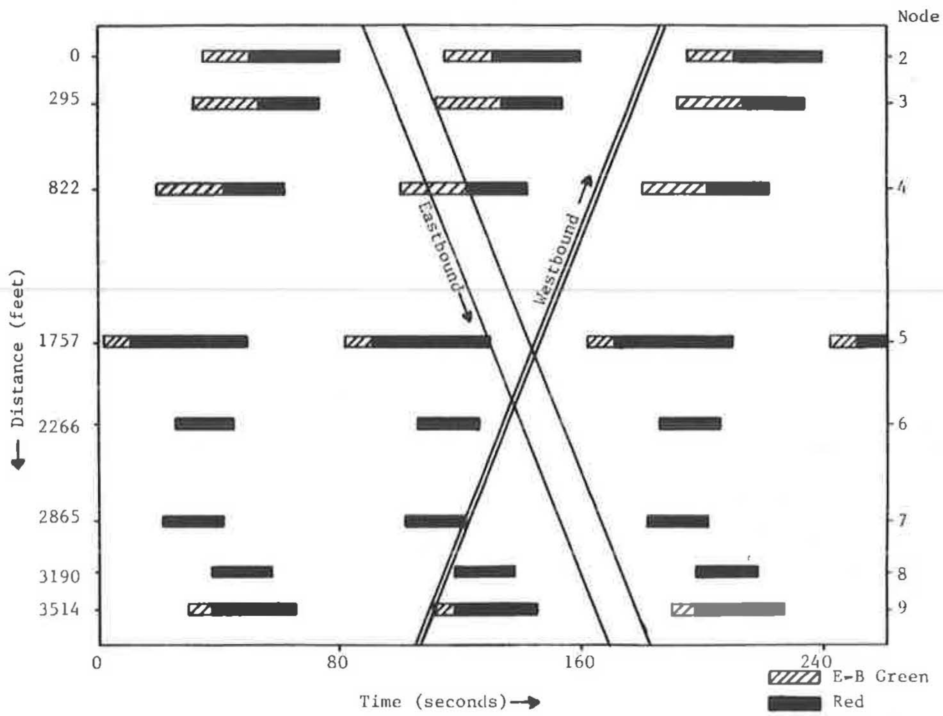

FIGURE 1 Time-space diagram of TRANSYT-7F-generated signal policy.

served that the progression bands are better than in Figure 1, but not as good as those in Figure 2.

A better approach has been taken by Wallace and his associates (6), who replaced the minimization of PI in TRANSYT with the maximization of PROS/PI. The quantity PROS, which stands for PRogression Opportunities, is defined as follows: extend the concept of progression to include progression opportunity, which is defined as "the opportunity presented at a given traffic signal and a given point in time to travel through a downstream signal without stopping." The quality PROS is defined as the sum of all such progression opportunities.

In maximizing PROS/PI, the TRANSYT program will try to achieve a value of PI that is as small as possible, while at the same time trying to achieve a

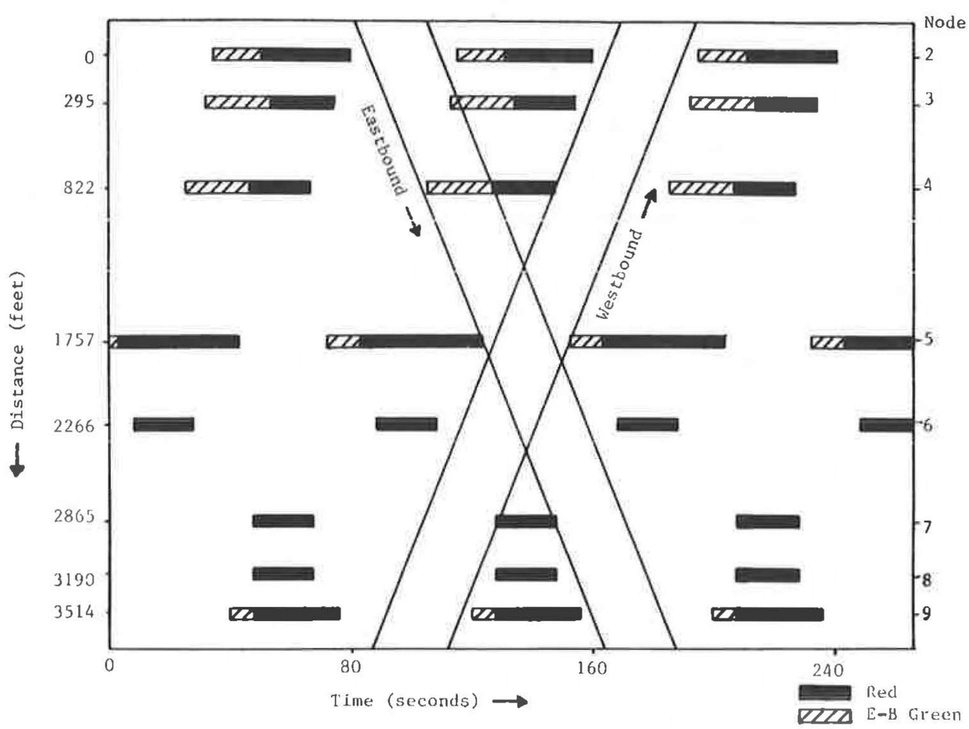

FIGURE 2 Time-space diagram of MAXBAND-generated signal policy.

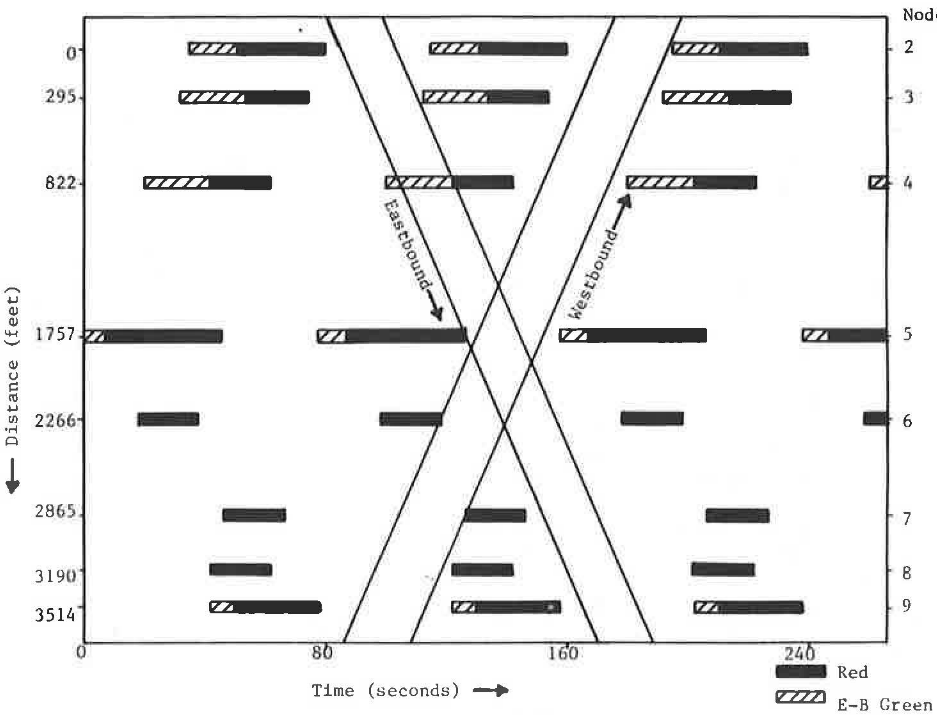

FIGURE 3 Time-space diagram of TRANSYT-7F-generated signal policy using MAXBAND results as the initial setting.

value of PROS that is as large as possible. Obviously, bandwidth alone could have been used in place of PROS in this approach. The results, based on 5 arterial networks that had a range of from 5 to 20 intersections, were promising. Delay measures of effectiveness, as measured by TRANSYT, were improved over the PASSER II bandwidth solutions. Furthermore, bandwidths were at least equal to those produced by PASSER II. However, putting PROS (or bandwidth) directly into the TRANSYT objective function has the disadvantage that, when green times are optimized, the side streets tend to be discriminated against in that they will get less green time. The reason for this is as follows: the quantity (1/PI) as a function of side-street green time increases to some optimum value and then decreases as side-street green time is increased; PROS (or bandwidth) is a monotonically decreasing function of side-street green; thus, the product [PROS * (1/PI)] will have an optimum value shifted toward smaller values of side-street green.

The second category of approaches depends on the observation that bandwidth solutions do not lead to a complete specification of the offsets. This is because many, if not most, of the intersections on an arterial will have slack green time available. Slack green time is defined as "green time available at an intersection that is outside the band." This is shown in Figure 2, which depicts an eight-intersection arterial. There are 26.3-sec bands in both directions, and the cycle length is 80 sec. It can be observed that the two-way band touches the left and right edges of the arterial green at Intersections 4, 5, and 7, but that the other intersections have slack green time. The slack green times range from 6.4 sec at Intersection 2 to 15.4 sec at Intersection 8. Thus, the offsets at Intersections 2, 3, 6, and 9 may be adjusted within the slack green time allowances without affecting the through band.

One approach to utilizing the slack green time was taken by Wallace (7) in the development of the PROS model that was described previously in this section. In this work, PROS was compared with the results of PASSER II on five arterials. The result was that optimizing PROS gave through bands that were equivalent to the through bands given by PASSER II. However, at the same time, when the TRANSYT model was used to compare the delay statistics, it was found that PROS provided only small improvements over PASSER II-74, as measured by reductions in delay. The results of the study may be summarized as follows: maximizing PROS, in most cases, has the effect of giving through bands comparable with PASSER II, with slack green times adjusted in order to provide the maximum amount of secondary progression.

Consideration of secondary progression was added to PASSER II in 1980, and to the MAXBAND program in 1982. In this approach, the band is centered so that an equal amount of slack green time is available on both sides of the two-way band. This is shown in the time-space diagram given in Figure 2. The amount of improvement to be expected over a random assignment such as was found in the original MAXBAND program is given in Table 1. In this table, two arterial networks [described by Cohen (5)] were used to determine the improvement to be expected relative to reduced delay and stops (or, more generally, PI) in

TABLE 1 Comparison of MAXBAND and MAXBAND Centered Signal-Timing Plans

Network	Program	Delay (sec/veh)	Stops (stops/veh)	PI (= delay + 4 * stops) (vehicle-hr/hr)
Hawthorne Boulevard	MAXBAND	68.3	1.77	138.3
Hawthorne Boulevard	MAXBAND-C	62.8	1.63	127.0
University Avenue	MAXBAND	41.7	1.44	87.3
University Avenue	MAXBAND-C	39.4	1.38	82.6

centering the bands produced by MAXBAND. The measures of effectiveness were obtained using the NETSIM model. Based on the admittedly limited sample, it can be seen that the improvements in PI were about 7 to 8 percent for both arterials, which is a fairly substantial improvement.

The major problem with these approaches to adjusting slack green time is that the effect of actual traffic volumes and traffic patterns, especially those turning onto the arterial from side streets (called secondary flow), are not taken into account. The PROS and centering approaches provide secondary progression opportunities, of which secondary flow may take advantage, but they do not directly respond to traffic patterns.

Another approach to adjusting slack green time has been suggested by Chang (8,9). In this approach, a simple delay model based on the delay-offset relation has been added to PASSER II. It explicitly models secondary flow from the intersections immediately upstream of an intersection and adjusts the offset at that intersection within the slack green time allowance to minimize the delay so calculated. Thus, the two-way band is explicitly preserved and the intersections with slack green time have their offsets adjusted to further reduce delay. However, results cited in the paper were based on a limited sample of one four-intersection arterial.

Nevertheless, Chang's approach has a number of advantages over the other approaches described previously in this paper. Unlike the bandwidth starting solution for TRANSYT described by Cohen (5), the two-way band is preserved. Unlike the PROS/PI approach described by Wallace and Courage (6), the side streets are not discriminated against because the green times are held fixed. Unlike the secondary progression approaches--PROS and centering--traffic effects, particularly secondary flow effects, are explicitly considered.

However, Chang's approach has some defects, namely

1. In adjusting offsets at a given intersection, only the effects on the intersections immediately upstream are included.
2. In the delay-offset model, the platoon structure is not modeled.
3. No capability exists for making adjustments to green time while at the same time preserving the bands.

The purpose of this paper is to propose an alternative approach to Chang's, an alternative that addresses the problems just cited.

CONSTRAINED MODEL LOGIC

The authors start with the approach taken earlier by Cohen (5), namely, using a bandwidth solution generated by the MAXBAND program as a starting solution for TRANSYT-7F. To facilitate further discussion, TRANSYT's optimization submodel will first be briefly described.

The optimization process in TRANSYT-7F is controlled by a subroutine, HILLCL, in which the offset and/or green times are changed iteratively by specified amounts. The new or revised timing values are simulated by TRANSYT's traffic simulation model located in subroutine SUBPT. The resulting PI is compared with the previous value to determine whether the last change was an improvement. This process is repeated for all hill climb step sizes that were input from Card Type 4. Figure 4 shows a flow chart of the program logic of subroutine HILLCL relevant to the current study (10).

The incorporation of a two-way progression band

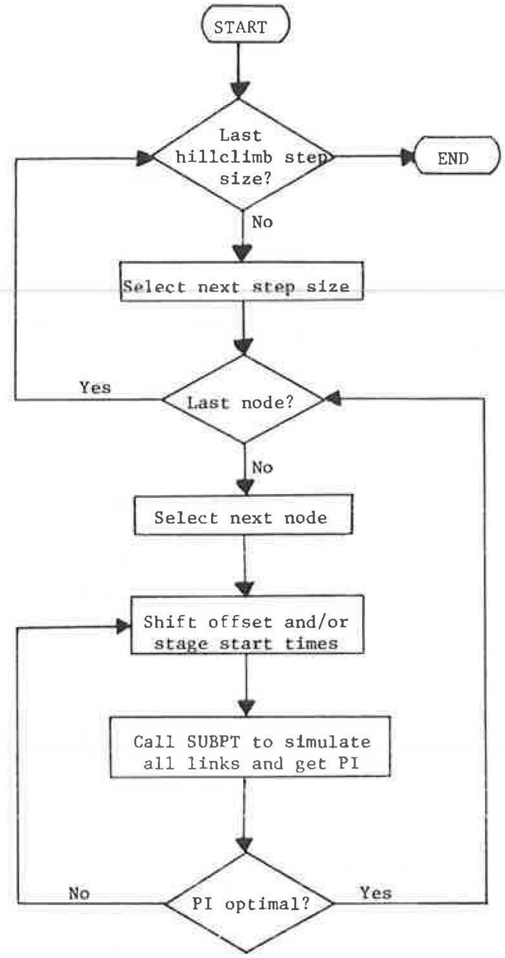

FIGURE 4 Existing subroutine HILLCL.

into the optimization structure just described involves, first as required input to TRANSYT, the desired bandwidths of both directions of travel and the progression speeds. This is actually accomplished by specifying the starting and ending time points (there is a maximum of four) at each intersection of the two-way band in an additional input stream. This information is readily available from MAXBAND or any other progression-band-based arterial model.

The constrained model, in essence, is to simply provide a check after each shift of timing values. As long as the shift does not cause any red time (including dual left-turn green time) to encroach on the through band, arterial progression is preserved. Care should be taken here that in situations with phase overlap, left-turn green time for one direction would be considered red for the other and vice versa. One can easily visualize the constrained optimization process as to first plot or "nail down" the MAXBAND's two-way band on an empty time-space diagram and then enable TRANSYT to generate timing plans within the band constraints. It should be noted that this approach allows the possibility of unequal bands in the two directions in order to accommodate unbalanced flows.

A total of three additional routines were added to TRANSYT-7F to perform the constraining functions. Modifications were also made to subroutine HILLCL, including some error checking pertaining to progression band input. The modified HILLCL logic is shown in Figure 5.

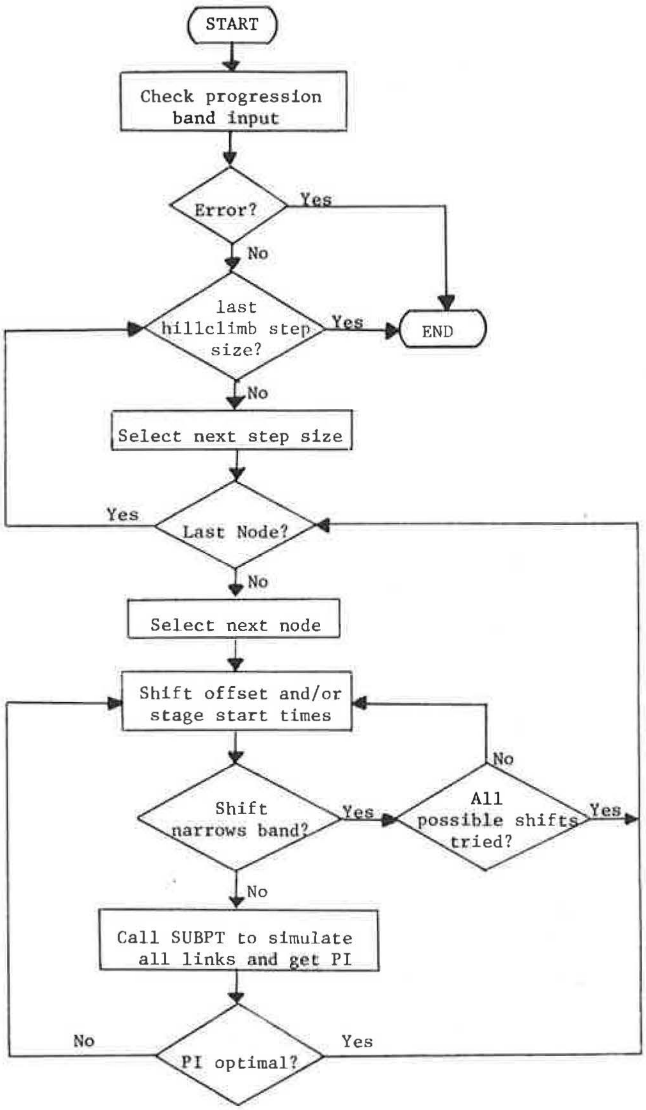

FIGURE 5 Constrained subroutine HILLCL.

CONSTRAINED TRANSYT RESULTS WITH OFFSET ADJUSTMENT

The constrained TRANSYT model, hereafter referred to as TRANSYT-7F(C), was first run with all positive hill climb step sizes. This would prohibit TRANSYT from changing MAXBAND's green split, enabling it to perform offset adjustments only.

Ten arterial data sets were available, including seven that have been described previously (11). The additional three arterials were added because they are characterized by short block spacing (average spacing 500 ft or less). One of the findings by Chang et al. (8) was that slack green time adjustments show the greatest potential for improvement in short block situations. Table 2 gives a brief description of each arterial.

The NETSIM model was run for the MAXBAND and TRANSYT-7F(C) timing plans for each arterial data set. A stop weighting factor of four was used in TRANSYT; the results are given in Table 3. It can be seen that the percentage improvement, as estimated by TRANSYT, is quite small, averaging approximately +3 percent over all networks. The average over all NETSIM runs was only +0.9 percent. To test whether the change due to slack green time adjustment is significant, a Wilcoxon matched-pairs test was done comparing MAXBAND and TRANSYT-7F(C) as estimated by NETSIM. The result was that no significant difference was found at the 5 percent level of significance. Therefore, it may be concluded that no evidence exists that slack green time adjustment alone will significantly reduce delay or stops over centering the band. Further, the changes in PI for North Michigan Avenue (which had average block spacing of 300 ft) were smaller than the average change over all networks, which contradicts the assertion by Chang et al. (8) that the largest improvements due to slack green adjustment may be expected on arterials with the shortest block length.

CONSTRAINED TRANSYT WITH OFFSET AND GREEN TIME ADJUSTMENT

When negative hill climb step sizes are intermixed with positive ones on Card Type 4, both offset and green time are optimized by TRANSYT. The 10 arterials described in the previous section were again run with the TRANSYT-7F(C) under this scenario. It is noted that in this case, it could happen that the bandwidth actually increases, if it is advantageous for TRANSYT to shift green time to the arterial through movements. However, it should also be noted that any increase in arterial through green will occur only if it is advantageous from the point of view of reductions in PI. It could happen that green time may be shifted to the side streets, especially in cases in which a large slack green time is available. This is to be contrasted with the PROS/PI approach vehicle, which will always shift green time to the main street to improve PROS, regardless of its effect on PI. The constrained model is in no way bounded to produce exactly the same input progression bandwidth, although it may be the case. Rather, as mentioned earlier, the notion is to prevent red time encroachment on the band. Table 4 gives a summary of the results of the run.

TABLE 2 Arterial Descriptions

Arterial	Location	Signalized Intersections	Lanes	Progression Speed	Cycle Length	Signal Spacing Range (ft)	Average Signal Spacing (ft)
Hawthorne Boulevard	Los Angeles, California	13	8	45	90	560-2,600	1,189
University Avenue	Provo, Utah	10	4	30	80	480-1,440	820
Nicholasville Road	Lexington, Kentucky	12	4	35	80	520-2,160	1,177
North 33rd Street	Salt Lake City, Utah	9	4/6	35	75	353-1,605	1,131
Frederica Road	Owensboro, Kentucky	12	4	45	80	582-2,310	1,167
Fannin Boulevard	Houston, Texas	15	6	35	80	300-1,900	711
San Felipe Road	Houston, Texas	12	4	35	80	250-1,400	741
K Street	Washington, D.C.	11	6/4	28	80	323-679	525
M Street/Key Bridge	Washington, D.C.	8	4	30	80	285-935	502
North Michigan Avenue	Chicago, Illinois	13	8/6	30	90	280-325	304

TABLE 3 MAXBAND versus TRANSYT-7F(C): Offsets Only Optimized

Arterial	TRANSYT PI MAXBAND	TRANSYT PI TRANSYT(c)	Difference (%)	NETSIM PI MAXBAND	NETSIM PI TRANSYT(c)	Difference (%)
Hawthorne Boulevard	233.6	224.3	4.0	263.4	255.1	+3.2
University Boulevard	83.2	81.7	1.8	98.0	97.6	+ .4
North 37 Street	235.7	234.9	.3	242.3	241.9	+ .2
Nicholasville Road	184.7	175.0	5.2	209.0	212.7	−1.8
Fredrica Road	119.9	115.8	3.4	109.9	105.2	+4.3
Fannin Boulevard	181.2	173.8	4.0	176.0	172.9	+1.8
San Felipe Road	229.6	220.8	3.8	170.3	171.5	− .7
M Street/Key Bridge	54.8	54.0	1.4	55.1	55.9	−1.5
K Street	219.1	210.4	4.0	230.9	224.5	+2.8
North Michigan Avenue	174.5	169.9	2.6	171.0	169.9	+ .6
Average			+3.0			+0.9

Note: PI = performance index.

TABLE 4 MAXBAND versus TRANSYT-7F(C): Offsets and Greens Optimized

Arterial	TRANSYT PI MAXBAND	TRANSYT PI TRANSYT(c)	Difference (%)	NETSIM PI MAXBAND	NETSIM PI TRANSYT(c)	Difference (%)
Hawthorne Boulevard	233.6	208.0	11.0	263.4	242.7	+ 7.8
University Boulevard	83.2	78.5	5.6	98.0	92.3	+ 5.8
North 23 Street	235.7	227.4	3.5	242.3	248.4	− 2.6
Nicholasville Road	184.7	167.1	9.5	209.0	204.5	− 2.2
Fredrica Road	119.9	108.5	9.5	109.9	109.6	+ .3
Fannin Boulevard	181.2	151.9	16.1	176.0	158.4	+10.0
San Felipe Road	229.6	207.4	9.7	170.3	167.2	+ 1.8
M Street/Key Bridge	54.8	51.0	6.9	55.1	53.8	+ 2.3
K Street	219.1	198.7	9.3	230.9	221.8	+ 3.9
North Michigan Avenue	174.5	151.6	12.1	171.0	152.0	+11.1
Average			+9.4			+ 4.2

Note: PI = performance index.

It can be observed that the changes (as measured by TRANSYT PI) produced by both offset and green time adjustments are three times as large as those produced by offset adjustment alone. Further, a Wilcoxon test was performed comparing the NETSIM estimates of MAXBAND versus TRANSYT-7F(C) with green times and offsets optimized. It was found that the results for the 10 arterials were significantly different at the 5 percent significance level. Therefore, it may be concluded that adjusting both offsets and green times while preserving the two-way band has the capability of significantly improving the performance, relative to PI, of centered bandwidth timing plans.

The question might be raised as to what price in terms of delay and stops is being paid by constraining TRANSYT. To investigate this question, TRANSYT was run unconstrained on the 10 networks, optimizing both green times and offsets. The resultant timing plans were compared with the constrained TRANSYT timing plans, as shown in Table 5. The average difference in NETSIM PI was −2.4. A Wilcoxon test showed no significant difference in PI at the 5 percent level over the 10 networks, although, in individual instances (e.g., Fannin Boulevard), some difference may have existed.

TABLE 5 TRANSYT-7F versus TRANSYT-7F(C): Offsets and Greens

Arterial	NETSIM PI TRANSYT	NETSIM PI TRANSYT(c)	Difference (%)
Hawthorne Boulevard	234.1	242.7	−3.7
University Boulevard	87.2	92.3	−5.8
North 33 Street	246.7	248.4	−0.7
Nicholasville Road	213.2	204.5	+4.1
Fredrica Road	102.5	109.6	−6.9
Fannin Boulevard	145.3	158.4	−9.0
San Felipe Road	168.5	167.2	+0.8
M Street/Key Bridge	53.7	53.8	−0.2
K Street	219.6	221.8	−1.0
North Michigan Avenue	150.4	152.0	−1.1
Average			−2.4

Note: PI = performance index.

CONCLUSION

From the research conducted in this work, it can be concluded that the constrained TRANSYT approach to combining bandwidth and delay considerations in developing arterial signal-timing plans has a number of advantages over other approaches that have been examined:

1. Unlike the bandwidth starting approach, this approach guarantees that the progression band is preserved.
2. Unlike the PROS/PI approach, this approach does not discriminate against the side streets because side-street green time may increase at intersections with slack green time if such adjustments improve PI.
3. Unlike the PROS or centering approaches, this approach explicitly adjusts for traffic patterns.
4. Unlike the delay-offset approach, this approach explicitly considers platoon structure and effects on intersections beyond the nearest ones, and allows adjustment of green times in addition to offsets.

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Discussion

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The paper by Cohen and Liu was a review of several alternatives for combining bandwidths, delay, and stop as criteria to optimize arterial signal-timing plans. Two major approaches were made to combine the minimum-delay and maximum-progression considerations by modifying the delay-based program to maximize bandwidth or adjusting the bandwidth-based signal-timing plans to minimize delay. A method was evaluated in their paper by constraining TRANSYT-7F to minimize system delay, while preserving the two-way progression solution optimized by MAXBAND.

In the first approach, TRANSYT was used with PASSER II, MAXBAND, and the PROS/PI function to provide the maximum progression. The PROS/PI method maximizes the sum of all the progression opportunity (PROS) at all traffic signals in a given time for traveling to downstream signals without stopping. However, putting PROS/PI or bandwidth directly into the TRANSYT objective function may result in less green time for the cross street because the PROS/PI or bandwidth is automatically increased if the arterial green time is increased.

The second approach fine tuned the green times available at noncritical intersections to reduce system delay by using

1. The PROS/PI model in TRANSYT,
2. The arbitrary bandwidth centering in MAXBAND, and
3. The system delay-offset optimization model in PASSER II-84.

In general, these methods can provide good through bandwidths with slack green times adjusted to maximize the secondary arterial progression. The PROS and progression bandwidth centering approaches allow the maximum secondary flow to utilize the secondary progression opportunities, but they do not directly put traffic signal patterns or the side-street traffic in the optimization process. The other approach suggested by Chang explicitly preserved the two-way progression bands and adjusted offsets to reduce the total system delay based on the PASSER II calculations. Unlike the PROS and arbitrary bandwidth centering approaches, traffic effects from the secondary flow are explicitly considered without discriminating against the side-street traffic demand.

To enhance Chang's approach, an alternative method was studied in their paper to provide a constrained offset optimization with TRANSYT-7F's optimization submodel by using the MAXBAND green split and offsets as a starting solution. The two-way progression band coordinate was input into the TRANSYT-7F optimization by specifying the starting and ending time points at each intersection. The constrained model checks the bandwidth coordinates after each shift of timing values. This constrained TRANSYT optimization process could be described as first plotting or "nailing down" the MAXBAND's two-way band on an empty time-space diagram, and then allowing TRANSYT to optimize offsets or the combinations of offsets and green times within the band constraints. The arterial progression is preserved so that the shift does not cause any red time to interfere with the through band and the dual left turn. The constrained TRANSYT offset or offset-green optimization was made to optimize only the offsets or to optimize both offset and green splits without affecting the MAXBAND progression solution.

It was indicated in this study that no statistically significant improvement is obtained by adjusting only the offsets. However, significant improvements in arterial performance are obtained if both offsets and green times are adjusted. Overall, this study shows a feasible approach for incorporating the maximum bandwidth and minimum delay analysis.

However, additional discussion of Chang's approach (1) is needed:

1. Unlike the usual delay-offset analysis, a system offset optimization method using the sectioning method was formulated in PASSER II-84.
2. The platoon arrival was considered by a simplified platoon projection model in PASSER II-84. The platoon propagation on intersections beyond the neighboring intersections is considered by PASSER II.
3. The adjustment to green time splits to account for the progression effect was considered in

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the PASSER II initial progression calculations. The 1984 study made by Skabardonis and May at the University of California at Berkeley demonstrated the superiority of green split calculations and less delay of PASSER II to MAXBAND (2).

In the system offset optimization process, PASSER II-84 first identifies the offset slack-time allowance ranges for each intersection in the arterial. The algorithm then optimizes the offsets within the slack time for each intersection from the lowest possible optimum offset while keeping all the other offsets constant. When the solution of the minimum arterial system average delay is found for a particular signal within the slack-time allowance, the search continues on to the next intersection until no further reduction of the total arterial system delay can be found. The major benefit of this system offset optimization process is that the search always continues for minimizing the arterial system delay within the slack-time constraint in PASSER II-84. The optimization algorithm is constantly focused on the system optimization objective instead of on the local optimization objective. An interconnected signal system may result in nonuniform but controlled platooned traffic during different signal cycles.

Many field studies indicated that delay can be controlled by compacting random flow into a platoon along arterial streets with good progression. At first, it is desired to achieve one coherent platoon of traffic per cycle, preferably a length not exceeding the through green for the maximum progression flow. It is also desirable to obtain the repeated arrival of these platoons in green and not in red through proper signalization. For pretimed signal systems, implementation of an optimized set of cycle, green times, phase sequence, and offsets is desired. For coordinated actuated systems, either prescheduled time-space solutions or platoon-identification techniques applied in real-time computerized traffic signal control are required.

PASSER II considers the effect or delay of arterial progression by estimating the progressive movements arriving at the through green onto the downstream intersections. Three principal factors are included in the platoon projection model of PASSER II-84:

1. Proportion of the total traffic in the progression platoon,
2. Platoon size and rate of platoon dispersion, and
3. Progression quality between each consecutive intersection.

The percentage volume that progressed is calculated by percentage of total through traffic in the arterial progression band, length of the platoon leaving the upstream intersection, and time period for the arterial through saturation flow to clear the upstream intersection. The platoon's length at the downstream intersection depends on the original platoon length leaving the upstream intersection, average travel time, and number of vehicles in the platoon. The platoon dispersion rate increases with increasing travel time and with smaller platoon size in the arterial progression bandwidth.

The progression quality between two intersections could best be described by the amount of through-green time being used for progression. The time period used by the progressed platoon depends on the platoon length arriving at the upstream intersection, length of the through-green time at the downstream intersection, and progression quality between the two intersections. The optimal time-space diagram can be used to examine the quality of progression. Good progression would result in a larger progression bandwidth and bad progression might result in a smaller band or no progression bands.

Based on the NETSIM evaluations in the PASSER II-84 study, it appeared that the effects of slack-green adjustment would depend on how the original green-time splits were first calculated by PASSER II or MAXBAND. It should also be noted that the NETSIM evaluation of average delay and stops on the whole system and total arterial direction might indicate different results. That is, when the total arterial study delay is fine tuned based on the PASSER II-84 or MAXBAND progression solution, the delay measurement may decrease on some links but may increase on other links. When fine tuning intersection slack green time or offsets to optimize secondary progression on the arterial directions, the method and objective function used played a decisive role in reducing the total system delay or initially the arterial delay.

A consistent and satisfactory trend of delay estimation was noted between PASSER II-84 and NETSIM in the PASSER II-84 enhancement study. However, PASSER II-84 predictions of delay reduction were somewhat higher than those predicted by NETSIM. From Chang's limited NETSIM evaluations, the greatest improvement was found in the arterial system performance instead of in the total system delay reduction. The arterial system delay was found to be reduced from 0 to 23 percent. As has been noted, Chang's study results may be different when the performance of various signal system operations are evaluated only on the total system basis. Therefore, this constrained TRANSYT-7F study might indicate different results if NETSIM evaluations were also made separately for both arterial directions and total arterial system. Results might also be different if this study began with the PASSER II-84 progression solution instead of with the MAXBAND solution.

REFERENCES

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Authors' Closure

Chang's discussion mainly concerns the authors' discussion of the model used in PASSER II-84 to fine tune the offsets to provide further reductions of delay over that achieved by the centered bandwidth approach used in MAXBAND and PASSER II-80. In the authors' paper, three points were made concerning this model, all of which are disputed by Chang. Each of these three points will be discussed here.

1. "In adjusting offsets at a given intersection, only the effects on the intersections immediately upstream are included." This statement is essentially correct. Chang's model considers upstream intersec-

tions only insofar as the assumption that there is a green band that passes through them. His model does not take into account the possible changes in delay at up-stream intersections caused by fine tuning at a given intersection, provided that such fine tuning does not encroach the band. TRANSYT does take into account such changes.

2. "In the delay-offset model, the platoon structure is not modeled." This statement is essentially correct. Chang's model assumes that the platoon is rectangular in shape and that platoon dispersion can be modeled by assuming that the rectangular platoon increases in length and decreases in height uniformly as it travels down the arterial. Such a model is only a crude estimate of actual platoon shapes that are much more irregular and that disperse in nonuniformity and in irregular patterns as they traverse sections of roadway. The histogram-based platoon structure and exponential smoothing platoon dispersion model in TRANSYT give a substantially better description of actual platoon behavior than that found in PASSER II-84.

3. "No capability exists for making adjustments to green time while at the same time preserving the bands." In Chang's discussion, he argues that green time is adjusted during the bandwidth optimization procedure and that the green phase times computed by PASSER are better than those computed by MAXBAND. This statement is true, but irrelevant. One of the authors' basic conclusions was that, given the maximum, centered, two-way green band on an arterial, fine tuning of offsets alone does not on the average produce a statistically significant improvement in system delay. Chang argues that a different result might have been achieved had PASSER-II been used instead of MAXBAND. This is possible because the heuristic optimization technique used in PASSER does not produce the widest possible green bands, unlike MAXBAND, which guarantees a global optimum. Therefore, PASSER-II solutions will, in general, have larger amounts of slack green time available for fine-tuning adjustments, and thus more opportunities for delay improvements. This appears counterproductive to the intent of both the authors' approach and Chang's approach, which was to attain the lowest possible delay consistent with the widest possible green band.