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Comparative Analysis of Computer Models for Arterial Signal Timing

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ABSTRACT

The state-of-the-art computer models TRANSYT-7F, MAXBAND, and PASSER-II for arterial signal timing are evaluated considering their capabilities in developing optimal timing plans, input data requirements, and output options. These models were applied on an 11-signal arterial to optimize various combinations of the signal control variables for two-phase and multiphase signal operation. It was found that the timings from TRANSYT-7F were better in terms of traffic performance than the settings from the bandwidth models, under fixed phasing. The settings from MAXBAND and PASSER-II produced very similar results. A number of experiments were also performed to investigate ways for concurrent use of the programs to further improve signal timing. The results indicated that the optimization capabilities of TRANSYT-7F can be improved if the input cycle length and sequence of phases have been optimized with the other models. Suggestions are made for improving the optimization capabilities and the practical application of the selected models.

Signal timing optimization is one of the most efficient ways for reducing fuel consumption and improving traffic operations on urban arterials and networks (1,2). A statewide Fuel Efficient Traffic Signal Management (FETSIM) program is currently under way in California that provides grants to local agencies to optimize their signal systems. Forty-one cities participated in the 1983 FETSIM program, which involved retiming 1,535 signals. The benefits included savings of nearly 6 million gal of fuel and significant reductions in delays and stops (3). The overall first year benefit-cost ratio was 16 to 1, which demonstrates the cost-effectiveness of optimizing the timing plans of existing signal systems.

Several computer models have been developed for improving traffic signal timing. A literature search revealed the following models as readily available, well-documented, and in use for signal timing optimization and evaluation: TRANSYT-7F, PASSER-II(80) MAXBAND, NETSIM, SOAP/M, and SPAN. Other programs under development include the SIGOP-III model, and the Arterial Analysis Package (AAP).

Initial examination of these models showed that TRANSYT-7F, MAXBAND, and PASSER-II can be used directly to determine optimal signal settings on signalized arterials. NETSIM is a stochastic microscopic network simulation model (4). It simulates individual vehicle movements according to car-following, queue discharge, and lane changing laws, and predicts delay, number of stops, fuel consumption, and emissions. NETSIM cannot optimize signal timing; it is most suited as a tool to evaluate alternative control strategies (i.e., pretimed and traffic-adjusted signal control) and to test the effectiveness of different optimization techniques. SOAP/M (5) provides optimal timing at isolated intersections, based on Webster's method (6). This program is particularly useful to determine the number of phases at each signal, and it may be used as an auxiliary tool for timing arterial systems. SPAN may be also considered as an auxiliary program. It optimizes only offsets on an arterial, considering local progression, such as bands that do not extend throughout the system (5).

The TRANSYT-7F model (7,8) has been used as the basic tool in most of the signal retiming projects. The PASSER-II model (9) is increasingly being used for arterial signal timing, and Rogness (10) reported that PASSER-II produces good timings compared with TRANSYT-7F. Recent results reported by Cohen (11) showed that the MAXBAND model (12) gives effective timing plans and substantially enhances the optimization capabilities of TRANSYT-7F when these programs are used concurrently. Concerns have also been raised by practicing engineers that TRANSYT-7F is a complicated program to use, and it does not provide the maximum bandwidth, which historically is the popular solution to the arterial coordination program.

The study described in this paper has two objectives: (a) to evaluate the state-of-the-art computer models for arterial signal timing, considering their capabilities in optimizing the signal control parameters, input data requirements, and output options; and (b) to investigate ways for concurrent use of these computer models to assist the traffic engineer to select the best timing plan for an arterial signal system.

The TRANSYT-7F, PASSER-II, and MAXBAND models are evaluated and their strengths and weaknesses are discussed. Next the results from the application of the selected models on a test arterial are presented. In the last section the findings from the study are summarized and recommendations for further research are given.

DESCRIPTION OF THE MODELS

TRANSYT-7F is a macroscopic deterministic simulation and optimization model, which operates in two modules. The traffic model uses network geometry, traffic volumes, and dispersion of traffic platoons to simulate the existing conditions along an arterial or network of signals and estimates performance by using a set of measures of effectiveness (MOEs)--travel time, delay, stops, and fuel consumption. The signal optimizer uses a hill-climbing technique to adjust splits and offsets to minimize a performance index (PI), which is a linear combination of delays and stops. The optimization process uses an iterative gradient search algorithm and does not guarantee that the true optimal signal settings will be obtained.

MAXBAND can be classified as a macroscopic optimization model. It uses mixed-integer linear programming to simultaneously optimize cycle length, sequence of phases, and offsets to maximize the bandwidth in both directions of an arterial. The optimization algorithm guarantees that the global optimum solution will be found. Splits are not optimized because the bandwidth approach does not provide criteria for setting green times on the side streets. The model allows for directional bandwidth weighting and deviation of the overall progression speed on individual links. Modeling of traffic flow does not account for turning volumes, dispersion and shape of platoons, and secondary traffic volumes.

PASSER-II is also a macroscopic optimization model, based on the bandwidth principle. It provides the best phasing sequences and offsets for maximal bandwidth along an arterial by minimizing the sum of interferences to the bandwidth (13). The optimal cycle length is obtained from multiple computer runs. Splits are calculated for minimum delay at each intersection on the basis of a modified Webster's delay formula (6). The model also allows for variations in the overall progression speed and weighting of the directional bands. Modeling of traffic flow is similar to that with the MAXBAND model.

COMPARISON OF THE MODELS

This section contains a discussion on the application of the selected models to develop optimal signal settings and their respective strengths and weaknesses. Table 1 contains a summary of the capabilities of the models regarding the optimization of the control parameters, for example, the number of phases, sequence of phases, cycle length, phase lengths (splits), and offsets.

Development of Signal Timing Plans

The number of phases at each signal is input to all arterial models. The determination of the number of phases is commonly based on volume, delay, and safety criteria at the particular intersection. SOAP/M may be used to analyze the impact of different numbers of phases. However, it should be noted that no computerized or manual procedure exists for the determination of the number of phases that include consideration of the system performance, and adding phases to improve the operation of a particular intersection may create adverse impacts for the entire arterial. There is a need to develop and incorporate a procedure into the existing arterial models to predict these system-wide impacts and to assist in the selection of the number of phases.

TABLE 1 Optimization of Control Variables with the Selected Models

	Model		
Control Variable	TRANSYT-7F	MAXBAND	PASSER-II
Number of phases	Input	Input	Input
Sequence of phases	Input	Optimized	Optimized
Cycle length	Optimized[a]	Optimized	Optimized[b]
Splits	Optimized	Computed[c]	Optimized
Offsets	Optimized	Optimized	Optimized

[a] No explicit optimization; range of cycle lengths is examined and the one with the lowest PI is selected.

[b] Optimization is performed through multiple runs.

[c] Splits are computed for equal degrees of saturation.

The sequence of phases may consist of numerous combinations of protected and permissive movements, such as leading left turns, lagging left turns, and combinations of lead/lag operation. Other options include permissive-protected or protected-only operation, and unprotected movements. PASSER-II and MAXBAND directly optimize phase sequences with and without overlapping to maximize arterial progression. Phase sequences are required inputs to TRANSYT-7F. Repeated runs are needed to evaluate alternative phase sequences that are selected manually by examination of the flow profiles and time-space diagrams. Protected-permissive operation may be approximated in all models by using only the protected phase for the left turns, such as considering the protected left-turn phases and volumes. Unprotected only operation can be approximately modeled with TRANSYT-7F. MAXBAND and PASSER-II do not explicitly consider left-turn volumes unless a separate left-turn phase is present.

MAXBAND directly optimizes the cycle length for maximum bandwidth. PASSER-II optimizes the cycle length through repeated runs, and the optimal cycle is selected on the basis of the bandwidth efficiency. TRANSYT-7F does not explicitly optimize the cycle length; it evaluates a range of values and selects the cycle that results in the lowest PI after splits and offsets have been optimized. TRANSYT-7F also allows for double cycling where some signals operate on a cycle that is one-half the system cycle length.

Phase lengths (splits) are optimized in TRANSYT-7F for minimum stops and delay in the system. PASSER-II optimizes splits for minimum delay at each intersection after the maximum bandwidth has been established. MAXBAND does not optimize green times; splits may be input or computed to equalize the degrees of saturation on the conflicting critical approaches.

In offset optimization, the objective of both PASSER-II and MAXBAND is to find the offsets that maximize the weighted sum of the directional green bands on an arterial. TRANSYT-7F optimizes offsets to minimize the delays and stops in the system, and the solution may not produce the wide green bands preferred by a number of traffic engineers. The opposite is true for the bandwidth models; maximizing through progression does not necessarily result in systemwide minimum delays and stops.

Another parameter of interest in signal timing is the intergreen interval, that is, the yellow and any all-red periods. These values are usually predetermined on the basis of local conditions. TRANSYT-7F, because it deals explicitly with traffic flow, can analyze the impacts of intergreen intervals as well as the effects of start-up, lost time, and green extension. The other models have default values that cannot be changed. TRANSYT-7F also allows the division of splits into fixed and variable intervals, such as Walk and Flashing Don't Walk.

Input Requirements and Output Options

All models operate on mainframe computers and require structured coding of the input data. TRANSYT-7F and PASSER-II also run on 16-bit microcomputers. TRANSYT-7F can handle up to 50 intersections in a line or a grid network, whereas PASSER-II and MAXBAND can accommodate up to 20 signals along an arterial. MAXBAND can also handle triangular networks for up to 17 nodes. Table 2 contains a summary of the input requirements for all models, and the output from each model is given in Table 3.

TRANSYT-7F requires a substantial amount of data, including network geometry, turning movements at each intersection, saturation flows, link-to-link volumes, speeds, and signal timing data. The network should also be coded into a link-node scheme. Although TRANSYT-7F has American terminology of signal settings, and input data are grouped per intersection, data processing and input coding require a substantial effort. Data on traffic performance are also needed to calibrate the model before the timing plans are optimized. TRANSYT-7F, however, gives the most complete output of traffic performance and signal settings. Information on several MOEs is given for each link and summarized for each intersection and the whole system. Signal controller tables are printed to facilitate field implementation of the optimized signal timings. The model provides both flow profiles and time-space diagrams for visual inspection of the quality of the signal settings. Interpretation of the output is relatively straightforward; the main problem areas seem to be understanding the estimates of the maximum back of queue, random delay, and the meaning of the flow profiles.

TABLE 2 Input Data Requirements for Signal Optimization Models

	Model		
Input Data	TRANSYT-7F	MAXBAND	PASSER-II
Network data			
Number of signals	X	X	X
Intersection spacing	X	X	X
Timing data			
Cycle length	X^a	X^a	X^a
Number of phases	X	X	X
Sequence of phases	X	X^b	X^b
Splits	X^c	X^d	X^e
Offsets	X^c		
Minimum green times	X	X^b	X
Lost time	X		
Queue clearance		X^b	X^b
Volume data			
Saturation flows	X	X^b	X
Turning movements	X	X^b	X
Link-to-link volumes	X		
Speed data			
Free speeds	X	X	X
Speed tolerance		X^b	X^b

[a] Range (a single value may also be input).
[b] Optional.
[c] The STAR1 routine is used to generate initial timings.
[d] If splits are not input, then volumes and saturation flows are required.
[e] Existing splits may be used for minimum green times to optimize offsets.

TABLE 3 Output from Signal Optimization Models

	Model		
Output	TRANSYT-7F	MAXBAND	PASSER-II
Traffic performance			
Delay for each movement	X		X
Delay per intersection	X		X
Total system delay	X		X
Number of stops	X		
Fuel consumption	X		
Travel time	X		
Degree of saturation	X		X
Maximum back of queue	X		
Level of service			X
Queue clearance			X
Signal settings			
Cycle length	X	X	X
Phasing sequence	X	X	X
Splits	X	X	X
Offsets	X	X	X
Interval lengths	X		
Graphical output			
Flow profiles	X		
Time-space diagram	X		X
Other			
Progression speed		X	X
Bandwidth		X	X

Note: Output on basis of information at the time of study.

Field data required for PASSER-II to produce a complete timing plan are similar to that for TRANSYT-7F, namely, distance between signals, turning movements, saturation flows, cruise speeds, and minimum green times. The model does not require link-to-link volumes, and the input coding is considerably simpler than that for TRANSYT-7F. PASSER-II provides information on the degree of saturation, average delay, level of service, and probability of queue clearance for each approach, total delay for each intersection, and the total system delay. The output also gives the optimal signal settings and a time-space diagram including the green bands and the progression speed. The form of the output is familiar to most traffic engineers, and the results can be easily analyzed.

MAXBAND requires about the same amount of field data as the other programs: turning movements, saturation flows, minimum green times, intersection spacing, and cruise speeds. If the splits are kept fixed, then the model requires the minimum amount of data compared with the other programs; only signal spacing and speeds are needed. Input coding is straightforward, similar to that for the PASSER-II program. Output from MAXBAND includes the optimized signal settings at each signal, bandwidth, and progression speeds and times along each direction of the arterial. The program does not, however, predict delays, stops, and other MOEs, nor does it provide a time-space diagram. Considerable analysis may be required to interpret the developed plan by either manually constructing a time-space diagram or by using a simulation model to predict traffic performance before field implementation.

APPLICATION OF THE MODELS AND RESULTS

The Study Arterial

San Pablo Avenue, State Highway 123, in Berkeley was selected as the study arterial. This is an important parallel route to the Eastshore freeway system, and also carries a significant number of local buses. San Pablo Avenue extends from Oakland in the south through Berkeley to Albany, El Cerrito, and Richmond in the north. The study section has three lanes in each direction with left-turn bays, a total length of 2.8 miles, and 11 intersections. The average spacing is about 1,500 ft, ranging from 450 to 2,300 ft. Figure 1 shows the intersection spacing and the total volumes on each approach for the system.

All of the 11 signals in the study section have two phases and operate on a common cycle length of 70 sec. The required data on arterial geometry, saturation flows, speeds, volumes, and signal settings were collected in 1983 as part of an Institute of Transportation Studies research project on signal control sponsored by the California Department of Transportation and FHWA. The p.m. peak period was

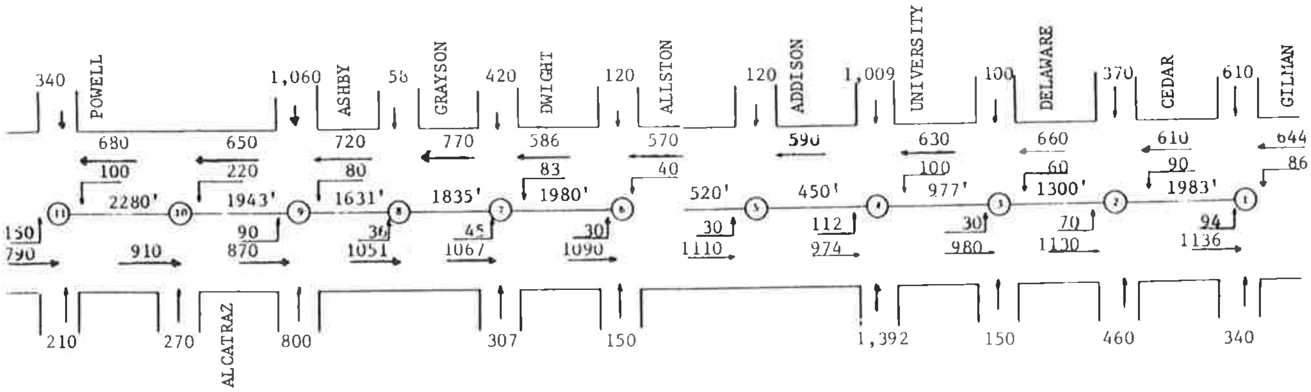

FIGURE 1 San Pablo Avenue: link spacing and traffic volumes.

selected for model applications because of the bad traffic conditions. The average traffic volumes on the arterial were approximately 1,000 vehicles per-hour (vph) in the northbound direction and 700 vph in the southbound direction. Intersections 4 and 9 had high side-street volumes and may be considered as the critical locations. The other intersections had relatively low side-street volumes (Figure 1).

Objective Function

The TRANSYT-7F, MAXBAND, and PASSER-II optimization models were applied to develop improved signal settings for the test arterial, and the performance of the timing plans was evaluated by using the TRANSYT-7F simulation model. The NETSIM model was also used to test the effectiveness of several optimized plans.

PASSER-II and MAXBAND optimize signal timing for maximum bandwidth, which tends to improve perceived progression except the bandwidth is not directly relevant to the TRANSYT-7F objective function. The objective function in TRANSYT-7F for developing optimal timing plans was set for minimum fuel consumption, that is, PI has the meaning of excess fuel consumption as a result of delays and stops, which is expressed as

$$PI = \sum_{i=1}^{n} (k_{1i} d_i + k_{2i} s_i) \qquad (1)$$

where

n = number of links in the system,
k_{1i} = fuel coefficient for delay (gal/hr),
d_i = delay on link i (vehicle-hr/hr),
k_{2i} = fuel coefficient for stops (gal/stop); and
s_i = stops on link i (stops/hr).

This objective function was selected for the following reasons: (a) optimization for minimum fuel was considered important in this study, which was performed in support of the FETSIM program; (b) optimization for minimum fuel tends to provide a reasonable balance between delays and stops (on the average, one stop is equivalent to 25 sec of delay); and (c) experience has shown that the resulting TRANSYT-7F timings provide good progression. The selected objective function would also enable better comparisons with the results of the other models. Optimization for minimum delay tends to overlook stops, and it is more appropriate for dense grid networks than for arterials. It is also known that TRANSYT-7F may provide unacceptable timings when optimized for minimum number of stops.

Experiment 1: Optimization of Splits and Offsets

In this experiment, first the offsets only and then the splits and offsets are optimized for the existing two-phase operation and the common cycle length of 70 sec. The objective of this experiment is to assess the performance of the splits and offsets developed by the selected models and to investigate the effect of using different initial settings in TRANSYT-7F optimization. Summaries of the computer runs performed are given in Table 4, where Run 1 represents the existing conditions. The results of the MOEs are given in Table 5, and the changes in the TRANSYT-7F PI are shown in Figure 2.

TABLE 4 Design of Experiment 1: Optimization of Splits and Offsets for Existing Cycle Length—Two-Phase Scenario

Run No.	Control Variable Optimized	Source of Initial Settings		Final Optimization
		Splits	Offsets	
1[a]	–	Existing	Existing	–
2	Offsets	Existing	Existing	TRANSYT
3		Existing	None	MAXBAND
4		Existing	None	PASSER-II
5	Splits/ Offsets	Existing	Existing	TRANSYT
6		Default	Default	TRANSYT
7		None	None	MAXBAND
8		None	None	PASSER-II
9		Existing	MAXBAND	TRANSYT
10		Existing	PASSER-II	TRANSYT
11		MAXBAND	MAXBAND	TRANSYT
12		PASSER-II	PASSER-II	TRANSYT

[a] Existing conditions.

TABLE 5 Results from Experiment 1: Optimization of Splits and Offsets (C = 70 sec)

Run No.	Measures of Effectiveness				Improvement in Performance Index[a] (%)
	Delay (vehicle-hr/hr)	Stops (stops/hr)	Fuel (gal/hr)	PI	
1	118.36	18,152.8	407.80	190.84	-
2	101.37	15,112.4	376.20	159.22	16.6
3	107.12	16,803.5	390.76	173.83	8.9
4	107.74	16,700.5	390.29	173.36	9.2
5	96.11	14,909.4	369.49	152.73	20.0
6	97.40	14,601.6	368.93	152.19	20.3
7	106.85	16,581.3	388.81	171.95	9.9
8	102.28	16,003.7	381.44	164.63	13.7
9	94.21	14,486.1	366.15	149.44	21.7
10	94.64	14,535.6	360.60	149.87	21.5
11	97.32	15,063.6	371.43	154.71	18.9
12	97.11	15,098.6	371.26	154.51	19.0

[a] From existing conditions.

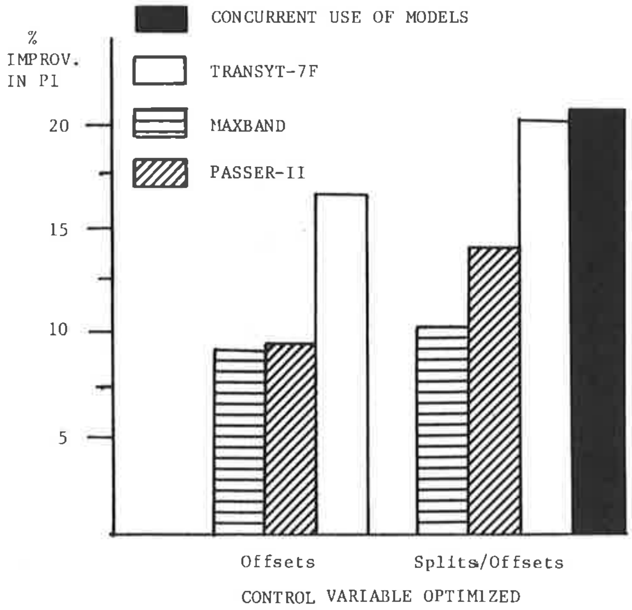

FIGURE 2 Optimization of splits and offsets.

In the offset optimization, with the splits kept fixed as the existing ones, the settings from all models improved the traffic performance. TRANSYT-7F offsets improved the overall system performance by 16.6 percent and the other models by about 9 percent (Figure 2). Comparisons of the results show that the TRANSYT-7F solution was better than those of both MAXBAND and PASSER-II. Delays were less by 6 percent, stops by 10 percent, and fuel by 4 percent. The offsets from the two bandwidth models produced almost identical results in all the MOEs.

When both splits and offsets are optimized (Runs 5, 7, and 8), TRANSYT-7F improved the system performance by 20 percent, whereas PASSER-II improved the PI by 13.7 percent and MAXBAND by about 10 percent (Figure 2). PASSER-II outperformed MAXBAND by 3.5 percent in delays and stops and 2 percent in fuel consumption; this may be attributed to the better procedure in the PASSER-II model for determining signal splits. TRANSYT-7F timings again produced better results than those of the other models. Delays and stops were reduced by 10 percent and fuel consumption by 5 percent compared with the performance of the MAXBAND settings; delays were also reduced by 6 percent, stops by 7 percent, and fuel by 3 percent compared with the PASSER-II timings.

Next, the results obtained from TRANSYT-7F optimizations with starting values for splits and offsets taken as the optimal ones from the other programs were analyzed (Table 5). These results indicate that no substantial improvements were obtained from the concurrent use of the programs compared with the TRANSYT-7F optimum plan from existing settings. The maximum improvement in the PI was about 2 percent (Runs 5 and 9) and the differences in all the MOEs were approximately ±2 percent.

The results from Experiment 1 were further examined by grouping together the values of the PI within 2 percent, assuming that 2 percent is "noise" in the model. The following can be observed for the arterial studied: the best timing plans were all derived by TRANSYT-7F, existing splits provided a better starting solution than the splits produced by the two bandwidth models, and PASSER-II gave the best non-TRANSYT-7F solution.

Experiment 2: Phase Sequence, Split, and Offset Optimization

In this experiment, the programs were applied to develop timing plans for multiphase signal operation to investigate the potential of MAXBAND and PASSER-II to directly optimize the sequence of phases. All signals were assumed to be pretimed with left-turn phases on the arterial. The design of experiment is shown in Table 6. The existing conditions are represented in Run 1, the offsets are optimized in Runs 2 through 4, and the splits and offsets are optimized in Runs 5 through 12, similar to the runs performed in Experiment 1. The sequence of phases and offsets are optimized in Runs 13 and 14. Finally, all the control variables are optimized in Runs 15 through 20. The results are given in Table 7, and the changes in the TRANSYT-7F PI are shown in Figure 3.

In offset optimization, TRANSYT-7F timings improved the PI by 12.3 percent over the existing con-

TABLE 6 Design of Experiment 2: Phase Sequence, Split, and Offset Optimization for Existing Cycle Length—Three-Phase Scenario

Run No.	Control Variable Optimized	Source of Initial Settings			Final Optimization
		Phasing	Splits	Offsets	
1[a]	–	Existing	Existing	Existing	–
2	Offsets	Existing	Existing	Existing	TRANSYT
3		Existing	Existing	None	MAXBAND
4		Existing	Existing	None	PASSER-II
5	Splits/ offsets	Existing	Existing	Existing	TRANSYT
6		Existing	Default	Default	TRANSYT
7		Existing	None	None	MAXBAND
8		Existing	None	None	PASSER-II
9		Existing	Existing	MAXBAND	TRANSYT
10		Existing	Existing	PASSER-II	TRANSYT
11		Existing	MAXBAND	MAXBAND	TRANSYT
12		Existing	PASSER-II	PASSER-II	TRANSYT
13	Phasing/ Offsets	None	Existing	None	MAXBAND
14		None	Existing	None	PASSER-II
15	Phasing/ Splits/ Offsets	MAXBAND	Existing	MAXBAND	TRANSYT
16		PASSER-II	Existing	PASSER-II	TRANSYT
17		None	None	None	MAXBAND
18		None	None	None	PASSER-II
19		MAXBAND	MAXBAND	MAXBAND	TRANSYT
20		PASSER-II	PASSER-II	PASSER-II	TRANSYT

[a] Existing conditions.

TABLE 7 Results from Experiment 2: Optimization of Phase Sequence, Splits, and Offsets (C = 70 sec)

Run No.	Measure of Effectiveness				Improvement in PI[a] (%)
	Delay (vehicle-hr/hr)	Stops (stops/hr)	Fuel (gal/hr)	PI	
1	168.32	20,960.0	460.95	243.43	–
2	150.37	18,400.1	430.95	213.56	12.3
3	157.16	20,086.6	446.77	229.34	5.8
4	160.77	19,727.5	446.74	229.29	5.8
5	148.18	18,144.6	427.35	210.07	13.7
6	147.16	18,534.0	428.39	211.20	13.2
7	158.57	19,486.7	444.79	227.52	6.5
8	154.16	19,421.6	439.46	222.21	8.7
9	148.92	18,189.6	428.72	211.40	13.2
10	150.15	18,352.4	430.34	213.02	12.5
11	146.49	17,832.0	424.71	207.61	14.7
12	149.71	18,308.7	428.40	211.10	13.3
13	151.41	19,198.5	437.40	220.06	9.6
14	150.53	19,013.3	435.44	218.25	10.3
15	143.50	18,077.1	423.73	206.54	15.2
16	145.93	17,944.5	424.81	207.61	14.7
17	149.92	18,771.9	433.22	216.05	11.3
18	144.77	18,504.4	427.23	210.00	13.7
19	139.44	17,925.5	419.83	202.55	16.8
20	139.50	17,995.3	420.08	202.84	16.7

[a] From existing conditions.

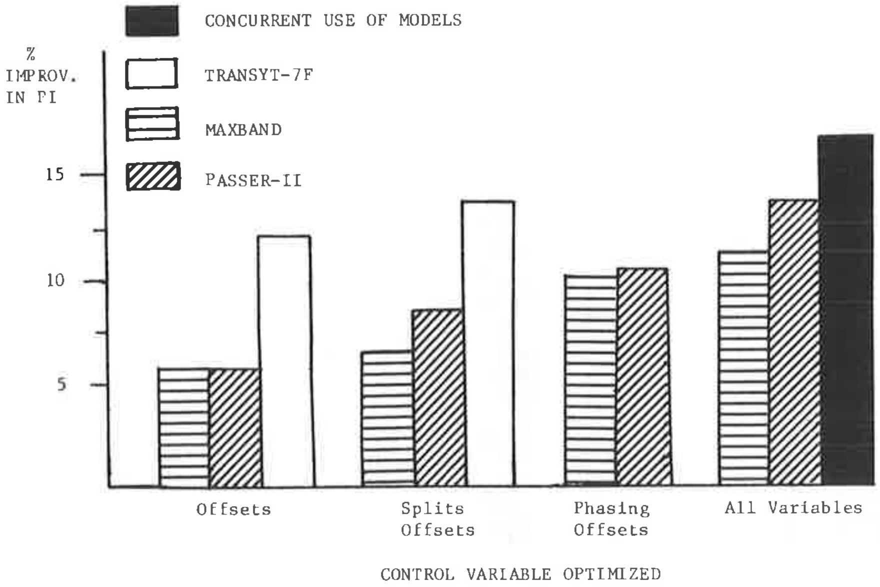

FIGURE 3 Optimization of phasing, splits, and offsets.

ditions, whereas the other models improved the system performance by about 6 percent. Offsets from MAXBAND and PASSER-II produced the same results, less than 1 percent difference in the MOEs. TRANSYT-7F offsets resulted in 5 percent fewer delays and stops compared with the offsets from the bandwidth models.

In optimizing splits and offsets, TRANSYT-7F timings again were better than those of the bandwidth models. TRANSYT-7F outperformed MAXBAND by about 7 percent in delays and stops and 4 percent in fuel consumption. TRANSYT-7F timings also resulted in 4 percent fewer delays, 7 percent fewer stops, and 3 percent less fuel compared with those of PASSER-II. PASSER-II timings had slightly better performance than those of MAXBAND, resulting in fewer delays by 3 percent (Runs 7 and 8). Improved starting values of either offsets or splits and offsets did not affect the final optimization with TRANSYT-7F. The difference in the MOEs was ±1.5, percent and the maximum improvement in the PI was only 1 percent (Runs 5 and 11). This is in agreement with the results obtained from the two-phase scenario (Experiment 1).

When the sequence of phases and offsets is optimized with the splits kept fixed, MAXBAND and PASSER-II had almost identical results in all the MOEs. Optimization of the sequence of phases led to significant improvements; both models improved the PI by 10 percent, which is considerably higher than the 6 percent improvement obtained from the optimization of offsets. The optimized phasing and offsets were then put to TRANSYT-7F for final optimization. The system performance was improved by about 1.5 percent over the TRANSYT-7F optimum solution from existing settings (Runs 5, 15, and 16).

When the splits are optimized with the phasing and offsets, PASSER-II timings were better than those of MAXBAND by about 3 percent in delay and 2 percent in stops and fuel. The PASSER-II settings had the same performance as those of TRANSYT-7F, and MAXBAND's solution was off the TRANSYT-7F optimal by 2.8 percent (Runs 5, 17, and 18). Although this is not a direct comparison because phasing in TRANSYT-7F was not optimized, it indicates that the bandwidth models can be effectively used for timing multiphase signals with different phasing alternatives. The use of the complete timing plan from either MAXBAND or PASSER-II as input to TRANSYT-7F for final optimization led to a further 3.5 percent improvement in the PI. The biggest improvement was a 6 percent reduction in delay; stops were reduced by 1 percent and fuel consumption by 1.7 percent (Runs 5, 19, and 20).

The analysis of the results from Experiment 2 showed that PASSER-II and MAXBAND are very effective in optimizing the sequence of phases and produce similar results when the splits are kept fixed. The use of either of these models to provide initial settings to TRANSYT-7F leads to modest improvements when the optimal phasing is input, and practically no additional improvement was obtained when phasing was kept fixed.

Experiment 3: Cycle Length Selection

Computer runs were performed to determine the optimum cycle length for the system with the three-phase scenario (Table 8). The results are summarized in Table 9. Under the existing phasing, the cycle search routine in TRANSYT-7F involved use of a cycle length of 75 sec as the best one after splits and offsets were optimized. Repeated TRANSYT-7F runs were also made for a range of cycles of 70 to 90 sec by using existing splits and offsets, and the results confirmed that 75 sec was the best cycle derived from the model. PASSER-II produced a cycle length of 80 sec and the optimal cycle from MAXBAND was 77 sec. The timings from the models improved the system performance by 8.5 to 14.7 percent. TRANSYT-7F was better than PASSER-II by 4 percent in delay, 8 percent in stops, and 3.5 percent in fuel consumption. TRANSYT-7F timings resulted in 5 percent fewer stops compared with the MAXBAND settings; total delay was the same. MAXBAND gave better results than PASSER-II.

When the phase sequences were optimized together with the other control variables, the best cycle length from PASSER-II was 85 sec and from MAXBAND 88 sec. PASSER-II timings were better than those of MAXBAND; delays were reduced by 4 percent, stops by 6 percent, and fuel by 2.8 percent (Runs 6 and 7). MAXBAND had a slightly better performance when the splits were kept fixed (Runs 5 and 6). The advantage of the bandwidth models in selecting the best phas-

TABLE 8 Design of Experiment 3: Cycle Length Selection—Three-Phase Scenario

Run No.	Control Variable Optimized	Source of Initial Settings				Final Optimization
		Cycle	Phasing	Splits	Offsets	
1[a]		Existing	Existing	Existing	Existing	
2	Cycle/	None	Existing	Default	Default	TRANSYT
3	Splits/	None	Existing	None	None	PASSER-II
4	Offsets	None	Existing	None	None	MAXBAND
5	All	None	None	None	None	MAXBAND
6	Variables	None	None	Existing	None	MAXBAND
7		None	None	None	None	PASSER-II
8		PASSER-II	PASSER-II	PASSER-II	PASSER-II	TRANSYT
9		MAXBAND	MAXBAND	MAXBAND	MAXBAND	TRANSYT
10		MAXBAND	MAXBAND	Existing	MAXBAND	TRANSYT

[a] Existing conditions.

TABLE 9 Results from Experiment 3: Cycle Length Selection

Run No.	Best Cycle Length (sec)	Measurse of Effectiveness				Improvement in PI[a] (%)
		Delay (vehicle-hr/hr)	Stops (stops/hr)	Fuel (gal/hr)	PI	
1	70	168.32	20,960.0	460.95	243.43	-
2	75	149.05	17,591.4	424.72	207.59	14.7
3	80	157.44	19,077.3	440.16	222.82	8.5
4	77	150.56	18,604.5	433.17	215.81	11.3
5	88	156.25	17,692.5	431.39	214.12	12.0
6	88	152.35	18,016.8	430.92	213.51	12.3
7	85	146.83	16,890.4	419.53	202.38	16.9
8	85	142.21	16,435.5	413.09	195.90	19.5
9	88	143.98	16,606.7	415.53	198.39	18.5
10	88	145.52	16,537.8	415.92	198.78	18.3

[a] From existing settings.

ing is again shown in this experiment. PASSER-II improved the PI by about 17 percent from the base conditions, whereas TRANSYT-7F improved the PI by about 15 percent with existing phasing. MAXBAND also improved system performance by 12.3 percent.

It can be seen from the results shown in Table 9 and Figure 4 that the best alternative for concurrent use of the programs was to input the cycle length and the other timings from PASSER-II as starting values to TRANSYT-7F. The PI was improved by about 6 percent compared with the TRANSYT-7F optimal solution with the 75-sec cycle and the existing phasing. Delays were reduced by 4.6 percent, stops 6.6 percent, and fuel by 2.7 percent. The PI was also improved by 4.5 percent by using the timings from MAXBAND as starting values to TRANSYT-7F. Total delay was reduced by 3 percent, stops by 5.6 percent, and fuel by 2 percent. The same results were obtained when splits were kept fixed and MAXBAND optimized the rest of the control variables. If it is assumed that a 2 percent difference in the TRANSYT7F results is attributed to the noise in the signal optimizer, then either one of the bandwidth models can be used to provide the initial timing plan for TRANSYT-7F optimization.

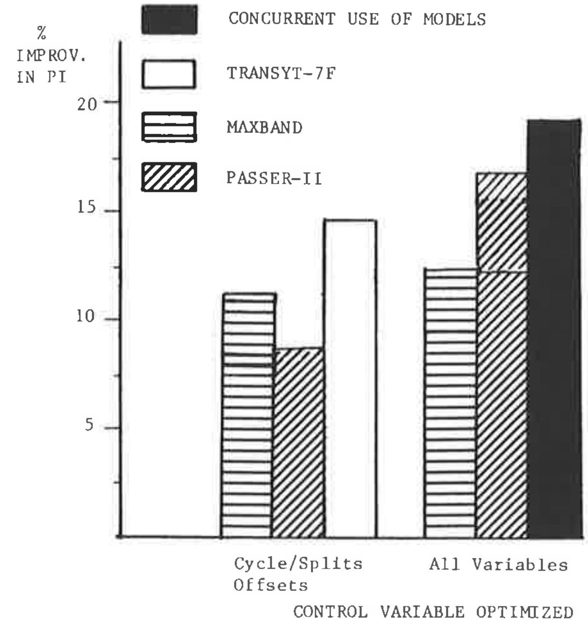

FIGURE 4 Cycle length selection—three-phase scenario.

DISCUSSION

The following comments and suggestions can be made with regard to improvements in the optimization capabilities and the practical use of the selected models:

1. The optimization algorithms of the bandwidth models should be modified to consider system measures, such as delays and stops. One option would be to consider the volume variations along individual links on the arterial instead of overall directional volumes for weighting the bands. Modeling of traffic could also be improved to consider the platoon characteristics of the traffic stream. Another option, currently being implemented in the new version of PASSER-II, is the adjustment of offsets for minimum delay subject to the bandwidth constraints.
2. The TRANSYT-7F model could be extended to "optimize" the sequence of phases. One procedure would be to automatically evaluate alternatives and select promising phasing for full optimization. Another option is to have a bandwidth program to optimize phasing as preprocessor to TRANSYT-7F in a single package.
3. PASSER-II and MAXBAND require considerably less effort in data processing and input coding and they are easier to use than TRANSYT-7F. Neither model, however, can evaluate the performance of the existing timing plan, nor do they provide estimates of the MOEs to quantify the benefits from the signal timing optimization. The practical applications of MAXBAND can be increased if additional output is provided for interpretation of the signal settings, for example, signal controller tables and time-space diagrams. Another improvement for PASSER-II would be the ability to optimize the timing of crossing arterials and triangular networks.
4. TRANSYT-7F is a powerful tool for a range of

applications but substantial effort is required to collect and code the data in the model. Interactive programs to facilitate the input coding and checking for coding errors would make the model much easier to use. These programs would be particularly useful because the model is now available on microcomputers and easily accessible to many users. Graphics packages to display the model results would also increase the application of the model. (Work in these areas is in progress at ITS.)

SUMMARY

The timings from MAXBAND and PASSER-II produced identical results in all the MOEs for all the combinations of the control variables optimized when the splits were kept fixed. PASSER-II showed a slightly better performance when the splits were optimized. Both models significantly improved the traffic performance from the existing settings, and they are particularly useful for timing multiphase arterial systems when the phase sequences are optimized.

The results indicated that the TRANSYT-7F model generated the most efficient timing plans for the arterial studied when splits, offsets, and cycle lengths were optimized. When the phase sequences also are optimized, the bandwidth models produced results comparable to those of TRANSYT-7F. Comparisons of TRANSYT-7F and other models should be interpreted with caution because of the use of TRANSYT-7F as the basic evaluation tool. However, the results from representative NETSIM runs confirmed the general pattern of results. Extensive use of the NETSIM model would require substantial effort because of the stochastic nature of the model and the need for several replications. Another limitation of the study is that one site is considered and the findings may vary when the models are applied on other arterials with different supply and demand characteristics. Further evaluation of these models to obtain more general results is planned at ITS.

The concurrent use of the optimization programs did not result in significant improvements for split and offset optimization under either the two- or three-phase scenario. Different initial settings of splits and offsets did not affect the TRANSYT-7F optimization process. There is a potential for improvements when the bandwidth models optimize the cycle length and phase sequence before the final optimization with TRANSYT-7F. This strategy led to a further improvement of about 5 percent from the TRANSYT-7F optimal settings for the arterial studied. The results also indicated that it is not significant which bandwidth program was used to provide the initial timing plan.

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