Optimization of Signal Phasing and Timing Using Cauchy Simulated Annealing

MOHAMMED A. HADI AND CHARLES E. WALLACE

Off-line optimization of signal timing plans involves the selection of cycle length, phase sequences, offsets, and green splits. None of the available signal timing optimization models explicitly optimizes all four parameters, and a combination of these models is usually used to obtain a total optimal design. One of the most effective programs used to optimize traffic signal timing is TRANSYT-7F. A major limitation of the program, however, is its inability to select signal phase sequences. Previous research applied genetic algorithms to phase sequence and timing optimization. This approach was functionally promising, but (at least in its experimental version) not very computationally efficient. The possibility of introducing a phase sequence optimization capability to TRANSYT-7F using the Cauchy simulated annealing algorithm was investigated. This is an optimization technique that makes an analogy between optimization problems and the annealing of physical solids. The simulated annealing algorithm is implemented to optimize cycle length, phase sequences, and offsets simultaneously on the basis of the progression opportunities calculated by TRANSYT-7F. The results suggest that the algorithm has potential for optimizing signal phasing and timing for arterial streets as well as multiarterial networks. The model is recommended for implementation in a future version of TRANSYT-7F, further advancing the utility of this important traffic signal timing tool.

Several optimization models have been developed for off-line selection of signal timing plans. These models have used two basic optimization approaches in the selection:

- Maximizing progression, an approach that includes maximizing bandwidth efficiency in programs such as PASSER II (*1*), MAXBAND (*2,3*), and PASSER IV (*4*), or maximizing progression opportunities (PROS) in TRANSYT-7F (*5,6*).
- Minimizing a disutility index (DI), which has generally been a function of a combination of delay, stops, or fuel consumption. This approach includes models such as TRANSYT-7F (*5*) and TRANSYT/9 (*7*).

Signal timing plan optimization involves selection of cycle length, splits, offsets, and phase sequences. None of the existing models can simultaneously (that is, explicitly) optimize all of these parameters. All optimize some parameters but in design either simply set others according to fixed rules or ignore them altogether.

PASSER II, MAXBAND, and PASSER IV can optimize cycle length, phase sequences, and offsets; however, these models do not optimize green splits. This is because they select signal timing plans on the basis of maximizing bandwidth efficiency, which does not provide appropriate criteria for setting green times for minor movements. They do, however, calculate splits on the basis of manipulating the degrees of saturation of conflicting movements.

TRANSYT-7F can optimize cycle length, offsets, and splits on the basis of optimizing the DI or PROS/DI. It can also optimize offsets and cycle length on the basis of the PROS value. The optimization process in TRANSYT-7F uses a technique known as hill climbing. This is an iterative gradient search procedure that makes changes to signal timing parameters to determine whether a performance index (DI, PROS, or PROS/DI) is improved. By adopting only those changes that improve the performance index, the procedure tries to find a set of timing that optimizes the performance, subject to any limits placed on the process.

Although TRANSYT-7F has been proven effective for timing optimization, it does not optimize phase sequences. Cohen and Mekemson (*8*) noted that adding a phase sequence optimization capability to TRANSYT-7F would involve combining a linear gradient search technique with a combinatorial optimization problem. They concluded that this appears computationally infeasible because there are 4^n possible phase sequence combinations at n intersections, assuming four possible phase sequences—namely, leading lefts, lagging lefts, leading in one direction, and lagging in the other, and vice versa.

To optimize signal phasing and timing, some engineers have used bandwidth-based optimization programs such as PASSER II or MAXBAND to select phase sequences and TRANSYT-7F to determine cycle length, offsets, and splits. Previous studies have shown that this approach can produce good signal timing plans (*8–10*).

TRANSYT/9 (*7*), the latest release of the British version of TRANSYT, permits the user to specify allowable phase sequences at each node. Then, TRANSYT/9 performs quick optimization runs, to evaluate each allowable combination of phase sequences, and selects the one that produces the best result. The runs are made shorter by using a modified hill-climbing optimization routine.

Recently, Hadi and Wallace (*11*) proposed the use of a genetic algorithm (GA) with TRANSYT-7F to select all signal timing design elements including phase sequences. GAs are heuristic search strategies based on the mechanics of natural selection and natural genetics. Applications of the algorithm suggested that it has potential for optimizing signal phasing and timing for arterial streets and multiarterial networks, but this experimental version (in which the GA used TRANSYT-7F as a black box with many resulting optimization runs) was not computationally efficient. Further work was suggested to improve the efficiency and performance of the method.

In the present study another optimization strategy, simulated annealing (SA), was investigated for its potential in optimizing signal phasing and timing.

Transportation Research Center, University of Florida, 512 Weil Hall, Gainesville, Fla. 32611.

ELEMENTS OF SIMULATED ANNEALING

SA (*12,13*) is a general purpose optimization technique that makes an analogy between the solutions of an optimization problem and the energy states of a physical solid that is slowly being cooled. It has been proven that the SA algorithm is capable of obtaining solutions close to the global optima. These solutions do not depend strongly on initial solutions, as is the case in other optimization algorithms such as TRANSYT-7F hill climbing.

SA was first suggested by Kirkpatrik et al. (*14*) in 1983 to solve combinatorial optimization problems. Since then it has emerged as a viable optimization technique and has been applied successfully to a variety of optimization and artificial intelligence problems.

SA Algorithm

In condensed-matter physics annealing denotes a thermal process for obtaining low energy states of a solid in a heat bath. First, the solid is heated until it melts. At this high temperature the substance is in a liquid state and all particles arrange themselves randomly. Then, the temperature is slowly lowered until the particles arrange themselves in the minimum energy state of the solid, which is called the ground state. In this state the particles are arranged in a crystalline lattice structure.

When the temperature is lowered too fast the resulting crystals may have many defects or may even lack all crystalline order. Thus, the cooling schedule should be slow enough to prevent this phenomenon.

The SA algorithm assumes an analogy between a solid and an optimization problem based on

- Solutions to the optimization problem equivalent to states of a solid and
- Value of the objective function of a solution equivalent to the energy of a state.

In a signal timing optimization problem, solutions to the problem are alternative signal timing plans tested by the SA algorithm to determine whether they are kept or discarded. The objective function in the process can be selected as any measure of effectiveness of the timing plans such as PROS, DI, or PROS/DI.

In SA an artificial temperature is defined for the system under consideration. This temperature governs the energy state of the system (the objective function value) just as temperature governs the energy of solids.

"Artificial temperature" in traffic signal timing optimization has no physical meaning. It is just a variable for which a value is selected by the SA algorithm at each optimization stage. The value of artificial temperature determines the amount of shifts in problem parameters at a given optimization stage. In signal timing optimization shifts in cycle length, offsets, and phase sequences during optimization are selected randomly on the basis of the artificial temperature. The higher the temperature is, the larger the shifts. Initially, a high artificial temperature is selected for the process; thus, large shifts in problem parameters are made. As the optimization proceeds the process gets closer to the optimal solution and the temperature is lowered, causing smaller shifts in problem parameters.

The distribution of energy states at any given temperature in the annealing process is determined by the relationship

$$P(E) = A \cdot \exp(-E/kT) \tag{1}$$

where

$P(E)$ = probability that the system is in a state with energy E,
T = temperature,
E = energy state, and
A, k = constants.

At high temperatures, $P(E)$ approaches unity for all states. This means that the probabilities of getting low energy states (good solutions) and high energy states (bad solutions) are the same. As the temperature decreases the possibility of getting high energy states vanishes and the probability of finding near-optimal solutions increases.

The SA algorithm can be summarized as follows:

1. A large initial artificial temperature is specified.
2. An initial solution is generated at random, and the objective function is calculated for that solution. In signal timing optimization cycle length, offsets, and phase sequences are generated at random and the selected objective function is evaluated for the resulting signal timing plan.
3. A random change is made to one of the problem parameters (in the present case either a phase sequence, an offset, or the cycle length). The random change is obtained as a function of the artificial temperature at this stage. This function will be addressed later.
4. If a better value of the objective function is produced by the change, the solution with the new parameters is kept.
5. If a worse value of the objective function is produced by the change, it is generally discarded in other procedures, such as the TRANSYT-7F hill climbing algorithm. In SA, however, the resulting solutions are kept some of the time to break out of local minima. The probability of accepting these solutions is calculated from the Boltzman distribution as follows:

$$P(c) = \exp(-c/bT) \tag{2}$$

where

$P(c)$ = probability of accepting a change of c in the objective function (e.g., a decrease of amount c in PROS value),
T = artificial temperature, and
b = constant.

To determine whether the change is accepted, a random number r is selected from a uniform distribution between 0 and 1. If $P(c)$ is greater than r the solution is kept; otherwise, the algorithm returns to the previous solution.

6. Steps 3 to 5 are repeated until a stopping criterion is achieved.
7. The artificial temperature is decreased.
8. Steps 3 to 7 are repeated until a stopping criterion is achieved.

The random changes to the problem parameters of Step 3 can be determined as a function of artificial temperature by using the Gaussian distribution. Szu and Hartley (*15*) used the Cauchy distribution instead of the Gaussian distribution to determine the random changes. Mathematical proofs showed that use of this distribution permits faster convergence to optimal solutions. The method developed by Szu and Hartley is called the *fast simulated annealing*, or the *Cauchy simulated annealing* and was used in the present study.

It should be mentioned that SA requires a large number of objective function evaluations compared with those required by other optimization routines, even compared with those required by the TRANSYT-7F hill-climbing approach. Theoretical studies *(12,13)* presented proof that SA will converge to the global optimal solution with a probability of 1. However, these results indicate that an infinite amount of computation time would be necessary to guarantee this convergence to the global optimum. In practical implementations the algorithm is not guaranteed to find a global optimal solution. In any case applications of the algorithm indicate that it can perform better than traditional optimization algorithms if the latter are allowed the same amount of computation time as that of the SA algorithm *(12,13)*.

Cooling Schedule

In condensed-matter physics the ground state of the solid (the state with minimum energy) is obtained only if the maximum temperature is high enough to melt the solid and the cooling is sufficiently slow. If the solid is not allowed to reach equilibrium at each temperature value, the solid will be frozen into a metastable state instead of into the ground state.

This same discussion is applied to SA. If the initial artificial temperature is not high enough and the "cooling" from the initial temperature to the final temperature is not sufficiently slow, or both, the process may "freeze" in a suboptimal solution. The following parameters should be specified for the SA algorithm:

- The initial artificial temperature. This value affects the starting amount of shifts to signal timing parameters.
- The temperature decrement in Step 7 of the SA algorithm presented in the previous section. As the temperature decreased the amount of shifts in signal timing parameters decreased.
- The equilibrium condition at each temperature at which the temperature can be decreased. This is the stopping criterion in Step 6 of the SA algorithm presented in the previous section and is based on the requirement that at each value of the artificial temperature equilibrium must be restored. If equilibrium is not achieved the system might converge to a suboptimal solution. In signal timing optimization shifts in phase sequences, cycle length, and offsets are generated on the basis of a given value of artificial temperature until equilibrium is achieved at that temperature. At this point the temperature is decreased and shifts in cycle length, offsets, and phase sequences are generated on the basis of the new (that is, the lower) temperature.
- The final temperature. This is the stopping criterion in Step 8 of the SA algorithm.

A choice of these parameters is referred to as a *cooling schedule.* Several approaches have been suggested for determining the cooling schedule. Some of these approaches are conceptually simple and are based on empirical rules. Others are more elaborate and are theoretically based *(12,13)*.

In the present study a simple empirical approach for determining the cooling schedule was used. Similar approaches were used in previous implementations of the algorithm *(12,13)*. The following is a description of this approach:

- The initial value of artificial temperature was determined in such a way that a large proportion of all proposed transitions was accepted. This is because at high temperatures all energy states have the same probability of existing as explained before. This method involved the calculation of an acceptance ratio, which was defined as the number of accepted solutions divided by the number of proposed solutions. The initial temperature was selected such that the acceptance ratio was higher than 0.8.
- The temperature was decreased by the following equation:

$$T_{K+1} = \alpha \cdot T_K \qquad (3)$$

where

T_K = temperature at step K,
T_{K+1} = temperature at step $K + 1$, and
α = constant that is less than, but close to, 1.

- The equilibrium condition was satisfied by specifying a constant number of proposed transitions at each temperature. This number was specified as a function of the problem size. Problems with more variables required more transitions to reach equilibrium and thus longer execution times.
- The stopping criterion was to stop the process if the last solutions for a number of consecutive temperatures were identical.

MODEL IMPLEMENTATION

The Cauchy SA algorithm described was implemented in the present study to optimize signal phasing and timing. The objective function used in the optimization was the PROS value calculated by TRANSYT-7F. A separate computer program was written to exercise the SA algorithm and call TRANSYT-7F to calculate the PROS value for each proposed solution.

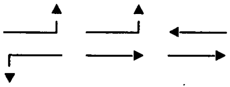
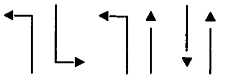
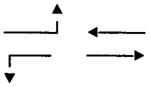
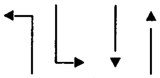
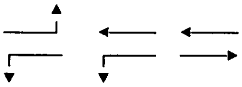
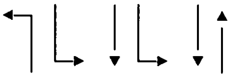
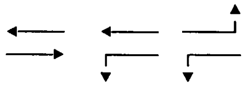
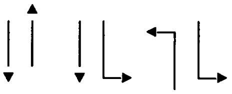
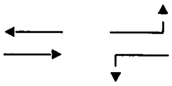
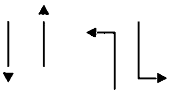
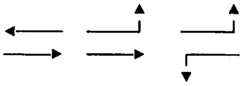
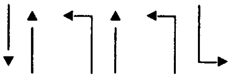
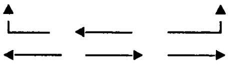
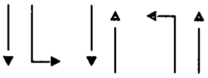
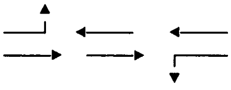
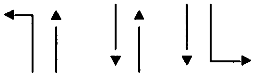
Other functions, such as combinations of delay and stops (DI) or progression (PROS), could have been used as objective functions in the SA optimization; however, the PROS objective function was selected because it requires less computer time compared with that required by other objective functions. The optimization could also have been based on bandwidth efficiency, which is calculated along with PROS by TRANSYT-7F.

The parameters optimized by the SA algorithm were the cycle length, phase sequences, and offsets. Because PROS optimization, as is the case with other progression-based optimization strategies, does not provide criteria for setting green splits, they were not optimized in this implementation. The splits used were calculated by the TRANSYT-7F internal timing routine on the basis of equalizing the degrees of saturation on the critical movements. This approach is similar to the ones used by the MAXBAND and PASSER II programs for setting green splits. If the objective function selected for the optimization had included a consideration of delay or stops, splits in conjunction with other signal phasing and timing parameters could have been optimized by using the SA algorithm. (Splits could also be optimized separately as a last step to fine tune the solution, but the objective of the study was not to find the absolute best solutions.)

Phase sequences were selected by using a look-up table. Real numbers from the SA procedure were first converted to the nearest integer values. Then, each number was mapped into a phase sequence by using Table 1.

The cooling schedule used in this implementation was based on the conceptually simple cooling schedule approach presented in the previous section. The initial value of the artificial temperature was

TABLE 1 Look-up Table Used to Transform Integer Numbers to Phase Subsequences

Integer	Phase Subsequence E-W Artery	 N-S Artery
0		
1		
2		
3		
4		
5		
6		
7		

selected to be 50. This value produced an acceptance ratio of more than 0.80 for all cases investigated. The final value of the artificial temperature was selected to be 0.7 unless no change in the objective function was obtained in three consecutive temperatures before reaching this temperature. The temperature decrement (α in Equation 3) was selected to be 0.95 on the basis of recommendations from previous implementations of the algorithm (*12,13*).

The number of proposed transitions at each temperature (NPT) was selected as a multiple of the number of variables to be optimized (n). For example, given a seven-intersection artery, the variables that had to be optimized were cycle length, seven phase sequences, and seven offsets. Thus, n in this case was 15. NPTs of $4n$, $6n$, $8n$, $10n$, $12n$, and $16n$ were compared to determine the NPT that produced the best objective function value.

MODEL APPLICATIONS

Five real-world traffic systems (all in Florida) were used to evaluate the SA model presented in this paper. These were

- Cape Coral Parkway, a seven-intersection artery in Cape Coral,
- Volusia Avenue, a 12-intersection artery in Daytona Beach,
- Monroe Street, a 12-intersection artery in Tallahassee,
- Gandy Boulevard, a four-intersection artery in Tampa, and
- A nine-intersection network in Daytona Beach that includes two parallel arteries, each with four intersections, and a three-intersection artery that intersects the two parallel arteries.

In most cases the existing phase sequences were leading dual lefts without overlap. For the purpose of the present study several permitted-only left turns were changed to protected, even though they were not warranted, to provide multiple phasing. This was done to increase the sensitivity of the PROS-based phase sequence optimization.

The designs obtained by the SA optimization of signal phasing and timing were compared with those obtained by TRANSYT-7F hill-climbing optimization of signal timing. The TRANSYT-7F optimization was performed with the existing phase sequences and the phase sequences selected by PASSER II-90. As noted earlier the objective function used in the optimization for all cases compared was the PROS value calculated by TRANSYT-7F. The comparison was based on perceived progression as measured by the PROS value and the bandwidth efficiency—a policy consistent with all maximal bandwidth models. For readers not readily familiar with PROS or bandwidth efficiency, they are defined as follows:

$$\mathrm{PROS}_e = \frac{\sum_{i=1}^{M} \sum_{K=1}^{2} \sum_{j=1}^{N_i} \sum_{t=1}^{C} \mathrm{PROS}_{ikjt}}{\sum_{i=1}^{M} C \cdot N_i \cdot (N_i - 1)} \tag{4}$$

where

PROS_e = effective PROS,
PROS_{ikjt} = ability presented at time t to enter intersection j on green and expected to travel through the next downstream intersection on artery i in direction k without stopping,
M = number of arteries in the system,
N_i = number of intersections for artery i, and
C = cycle length (in sec).

$$E = \frac{B_R + B_L}{2 \cdot C} \tag{5}$$

where

E = bandwidth efficiency,
B_R, B_L = bandwidth efficiency in the right and left directions, respectively, and
C = cycle length (sec).

The following comparison is based on the effective PROS and bandwidth efficiency calculated by using Equations 4 and 5, respectively.

In the comparative study the green splits used were always those calculated by the TRANSYT-7F internal initial timing routine. For all systems investigated the cycle length range was 100 to 120 sec with 5-sec increments. The present study was an initial attempt to investigate the ability of SA to optimize phase sequences, cycle length, and offsets simultaneously. Wider cycle length will be investigated in future work.

RESULTS

Tables 2 and 3 present the results of the comparative study. From these tables it can be seen that in all cases the shortest NPT investigated (4*n*) was enough to produce good results. When using this length significant improvements in the PROS value and the bandwidth efficiency were obtained compared with those obtained by TRANSYT-7F optimization with the existing phasing.

On the other hand the results demonstrate that in some cases, when the NPT was below a certain value, the optimization converged to a suboptimal solution. This is observed when optimizing the Monroe Street system with NPTs of 6*n* and 8*n*. In these cases the (effective) PROS values obtained were 37 and 38, respectively. These were lower than the maximum PROS value (40), which was obtained when the NPT was 10*n* or higher. In the following discussion of the results the comparison will be based on running the SA with an NPT of 12*n* to avoid comparison with suboptimal solutions.

Tables 2 and 3 and Figure 1 indicate that in all cases investigated the SA optimization procedure produced higher PROS values and bandwidth efficiencies compared with TRANSYT-7F optimization with the existing phase sequences. The PROS improvements achieved were 36 percent (34 versus 25), 30 percent (43 versus 33), 29 percent (40 versus 31), 13 percent (34 versus 30), and 23 percent (37 versus 30) for the five systems investigated, respectively. Bandwidth efficiency improvements were 100 percent (26 versus 13), 227 percent (36 versus 11), 63 percent (36 versus 22), and 4 percent (27 versus 26) for the four arterial systems investigated, respectively. For the Daytona Beach network the increases in bandwidth efficiency for the three arterial subsystems were 66 percent (35 versus 21), 31 percent (21 versus 16), and 27 percent (23 versus 18), respectively.

The SA optimization was also compared with TRANSYT-7F timing optimization (only) by using PASSER II's optimized phasing. The results, again shown in Tables 2 and 3 and Figure 1, indicate that the SA algorithm was able to produce higher PROS values in all cases investigated. The improvements in PROS were 10 percent (34 versus 31), 5 percent (43 versus 41), 5 percent (40 versus 38), 10 percent (34 versus 31), and 6 percent (37 versus 35) for the five systems investigated, respectively. The bandwidth efficiency produced by the SA algorithm was equal to or slightly higher than that produced by the combination of TRANSYT-7F timing with PASSER II-selected phasing for all systems investigated except for the second arterial subsystem in the Daytona Beach network. However, the PROS value (which is the objective function used in the SA optimization) on this artery was equal for both SA and PASSER II-selected phasing.

Although the SA and PASSER II optimized phase sequences produced solutions with comparable PROS values and bandwidth efficiencies, the selected phase sequences, cycles, and offsets differed significantly. In some cases running the SA optimization with different numbers of transitions also resulted in significant differences in the three parameters, although the PROS value and the bandwidth efficiency were close among all solutions. These observations suggest that multiple progression-based solutions close to the optimal solution can exist for the same problem.

To give some idea of resource requirements, a 12-intersection artery run took 23,100 PROS evaluations when running the SA with the selected cooling schedule and an NPT of 12*n*. Although SA requires more objective function evaluations than a normal TRANSYT-7F hill-climb optimization, the use of SA for PROS optimization does not require a long run time. This is because the PROS optimization is very fast. If the PROS were calculated in the program without a need to call TRANSYT-7F externally, it would take about 1 μ sec for one PROS calculation on a 33-MHz 80486 machine. Thus, for a 12-intersection artery, it would take about 33 sec to run the SA algorithm, assuming that 23,100 evaluations are required.

Use of DI or PROS/DI as the objective function will naturally take much longer. (This demonstration of SA was external to TRANSYT-7F, requiring complete simulation runs for each trial. Once it is internalized and coupled with other enhancements, the performance would be improved measurably.)

CONCLUSIONS AND RECOMMENDATIONS

From the results of the present study it can be concluded that SA has potential for use in signal timing optimization for arterial streets and

TABLE 2 Comparison of Results Obtained When Optimizing PROS for Four Arterial Systems by Different Optimization Methods

System	Sequence Source[a]	Nodes	No. of Transitions	Effective PROS (%)			Bandwidth Efficiency (%)		
				Right[b]	Left[b]	Average	Right[b]	Left[b]	Average
Volusia Avenue	Existing	12	-[c]	24	25	25	18	7	13
	PASSER II		-[c]	28	34	31	24	25	25
	SA		4n	33	33	33	24	25	25
	SA		6n	33	32	33	25	24	25
	SA		8n	33	35	34	26	27	26
	SA		10n	33	35	34	26	27	26
	SA		12n	33	35	34	26	27	26
	SA		16n	32	36	34	26	27	26
Cape Coral Parkway	Existing	7	-[c]	40	26	33	21	0	11
	PASSER II		-[c]	31	51	41	22	45	33
	SA		4n	35	47	41	3	32	18
	SA		6n	38	47	42	26	42	34
	SA		8n	39	45	42	36	38	37
	SA		10n	34	48	41	2	33	18
	SA		12n	34	51	43	27	45	36
	SA		16n	38	47	42	25	43	34
	SA		18n	36	51	43	27	45	36
Monroe	Existing	12	-[c]	46	15	31	43	0	22
	PASSER II		-[c]	42	34	38	40	30	35
	SA		4n	45	34	39	42	12	27
	SA		6n	39	34	37	27	23	25
	SA		8n	43	34	38	37	28	33
	SA		10n	45	36	40	43	29	36
	SA		12n	45	34	40	44	28	36
	SA		16n	46	35	40	44	28	36
Gandy	Existing	4	-[c]	29	31	30	26	25	26
	PASSER II		-[c]	30	32	31	25	27	26
	SA		4n	36	31	33	28	26	27
	SA		6n	34	33	33	28	26	27
	SA		8n	33	34	34	28	26	27
	SA		10n	35	32	34	28	26	27
	SA		12n	35	33	34	27	27	27
	SA		16n	35	33	34	27	27	27

[a] Signal timing is optimized using TRANSYT-7F with the existing and PASSER II selected phase sequences. SA optimizes signal timing and phasing simultaneously.

[b] Right and Left refer to the right-bound and left-bound travel on the artery.

[c] "-" means that the number of transitions is not applicable in this case

multiarterial networks. It performed at least as well as TRANSYT-7F hill climbing to optimize timing with PASSER II's optimized phasing. This is significant because it demonstrates a complete design capability within the TRANSYT-7F environment.

The SA model performs better than the GA model presented elsewhere (*11*). Compared with the GA for optimizing cycle length and phase sequences and TRANSYT-7F for optimizing offsets, the SA is much more efficient in terms of computer time and produces solutions that are at least as good. Compared with the GA for optimizing all three parameters, the SA produces better solutions, although it requires more PROS evaluation runs and more time.

The SA model runs efficiently on microcomputers; however, research is needed to investigate the possibility of using a more efficient cooling schedule. This might include the examination of several cooling schedules proposed in the literature.

A more efficient cooling schedule will be particularly useful if the SA is used to optimize signal phasing and timing on the basis of TRANSYT-7F DI and PROS/DI. These require much more computer time for optimization compared with that required for PROS optimization. The use of SA to optimize signal phasing and timing on the basis of DI and PROS/DI should be investigated. This optimization will permit the selection of splits with other phasing and timing parameters.

PROS, DI, and PROS/DI are all undersaturation optimization strategies. The use of simulated annealing to optimize objective functions suitable for congested conditions in which spillback and

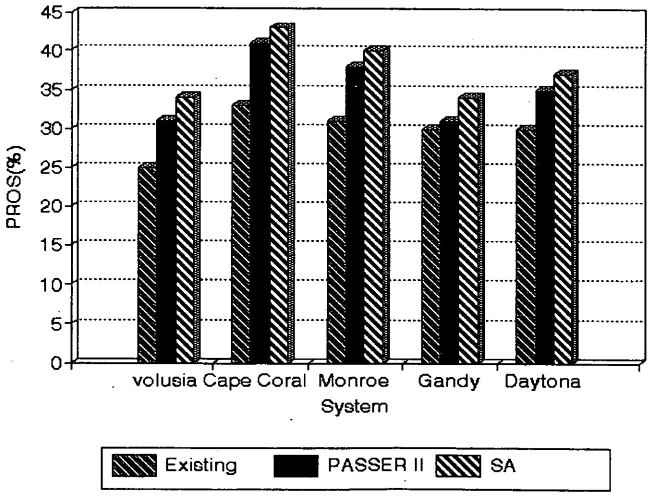
TABLE 3 Comparison of Results Obtained When Optimizing PROS for Daytona Beach Network by Different Optimization Methods

Sequence Source[a]	No. of Transitions	Artery No.	No. of Nodes	Effective PROS (%) Right[b]	Effective PROS (%) Left[b]	Effective PROS (%) Average	Bandwidth Efficiency (%) Right[b]	Bandwidth Efficiency (%) Left[b]	Bandwidth Efficiency (%) Average
Existing	-[c]	1	4	31	37	30	15	28	21
		2	4	16	37		0	32	16
		3	3	21	36		0	35	18
PASSER II	-[c]	1	4	45	33	35	45	26	35
		2	4	31	36		27	35	31
		3	3	34	28		30	14	22
SA	4n	1	4	40	38	35	28	28	28
		2	4	34	33		21	21	21
		3	3	37	26		37	8	22
SA	6n	1	4	43	40	36	37	33	35
		2	4	32	36		18	24	21
		3	3	33	30		26	19	23
SA	8n	1	4	44	39	36	41	29	35
		2	4	28	39		11	31	21
		3	3	34	28		28	17	23
SA	10n	1	4	44	39	36	41	29	35
		2	4	31	37		13	28	21
		3	3	35	29		30	15	23
SA	12n	1	4	42	41	37	34	36	35
		2	4	33	34		19	23	21
		3	3	36	28		33	13	23
SA	16n	1	4	43	39	37	38	32	35
		2	4	36	34		29	33	31
		3	3	33	31		23	22	23

[a] Signal timing is optimized using TRANSYT-7F with the existing and PASSER II selected phase sequences. SA optimizes signal timing and phasing simultaneously.

[b] Right and Left refer to the right-bound and left-bound travel on the artery.

[c] "-" means that the number of transitions is not applicable in this case.



Note: existing and PASSER II in the above graph refer to TRANSYT-7F optimization with the existing and PASSER II selected phase sequences, respectively.

FIGURE 1 Comparison of PROS values achieved by different optimization methods.

blockage occur should be investigated. In short, it is recommended that the SA model be implemented in TRANSYT-7F to provide the program with a phase sequence optimization capability.

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