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Enhanced Genetic Algorithm for Signal-Timing Optimization of Oversaturated Intersections

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Enhancements were provided to a previously developed genetic algorithm (GA) for traffic signal optimization for oversaturated traffic conditions. A broader range of optimization strategies was provided to include modified delay minimization with a penalty function and throughput maximization. These were added to the initial delay minimization strategy and were further extended to cover all operating conditions. The enhanced program was evaluated at different intersection spacings. The optimization strategies were evaluated and compared with their counterpart from TRANSYT-7F, version 8.1. A microscopic stochastic simulation program, CORSIM, was used as the unbiased evaluator. Hypothesis testing indicated that the GA-based program with average delay minimization produced a superior signal-timing plan compared with those produced by other GA strategies and the TRANSYT-7F program in terms of queue time. It was also found from the experiments that TRANSYT-7F tended to select longer cycle lengths than the GA program to reduce random plus oversaturation delay.

Oversaturated conditions are becoming increasingly common on many urban arterials in the United States during peak hours. Traffic signal optimization has proved to be a cost-effective means of alleviating congested conditions, especially when physical capacity additions are not feasible. Rouphail and Akcelik (*1*), Prosser and Dunne (*2*), and Messer (*3*) have developed models of oversaturated conditions at intersections. However, all such models assume that signal-timing plans are given and, therefore, have no optimization capabilities.

Foy and colleagues applied a genetic algorithm for signal-timing design by minimizing total delay (*4*). The test network consisted of four intersections with two-phase controls, and phase sequence and proportion of green time were optimized. Hadi and Wallace developed a hybrid genetic algorithm (GA) and the TRANSYT-7F program (*5*). In their work, the GA optimized cycle length, phase sequence, and offsets, whereas TRANSYT-7F optimized green splits. Abu-Lebdeh and Benekohal (*6*) developed a dynamic signal optimization procedure for oversaturated conditions that works for one-way arterials by use of a GA algorithm. They optimized cycle length, green split, and offset. Park and colleagues developed a GA-based traffic signal optimization program that simultaneously optimizes four signal parameters (i.e., cycle length, green split, offset, and phase sequence) for oversaturated intersections (*7*). The program was evaluated under different demand levels but was limited to minimization of average delay for closely spaced intersections. In this study, the program is extended to deal with three different optimization strategies and is tested for various intersection spacings.

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GENETIC ALGORITHMS

GAs are search techniques based on the mechanics of natural selection and evolution (*8*). Since Holland (*9*) developed the GA in the early 1970s at the University of Michigan, GA has been widely used and developed in various fields, especially in the optimization area (*8, 10*). The GA is a computation model that emulates biological evolutionary theories to solve optimization problems (*8, 11, 12*). It can be classified as a guided random-search algorithm that seeks to optimize any form of an objective function.

The steps of the GA used in this study are summarized as follows:

- Initialization (random with binary string),
- Retrieval of fitness (i.e., objective function value) from mesoscopic simulator,
- Selection process (tournament selection),
- Crossover (uniform crossover),
- Mutation, and
- Elitist selection method.

Tournament selection (*13*) uses relative fitness values instead of absolute fitness values. In each tournament, two individuals are selected from the population and the fitter one is chosen for crossover and mutation. Uniform crossover proposed by Syswerda (*14*) is an alternative to single-point crossover or two-point crossover, and it is known to be superior to other crossover operators in most cases. The elitist selection method (*15*) keeps the best individual from generation to generation. The detail descriptions of GAs can be found in the work by Goldberg (*8*).

Rudolph (*16*) and Cerf (*17*) studied the convergence of genetic algorithms. Rudolph (*16*) analyzed the convergence of GAs by means of a homogeneous finite Markov chain and concluded that GAs converge to the global optimum when an elitist selection method is used. Cerf (*17*) also provided an asymptotic theory that the GA converges to the global optimum in probability if an adequate population size is used. The upper bound for the population size is given to be the length of binary digits used in GA coding.

Problem Formulation

Three types of objective functions are considered. They are throughput maximization, average delay minimization, and modified average delay minimization with a penalty function. It is known that the system throughput maximization is a promising strategy during oversaturated conditions. However, it may not be applicable for undersaturated conditions, because movements with light traffic demand will endure severe delays. The third strategy penalizes the movements that experience volume-to-capacity ratios of 0.9 or higher. This strategy tries to prevent movements serving light traffic from being delayed unrealistically.

The objective function for the modified delay minimization has been updated from previous work (*7*) and is shown in Equation 1. An exponential-type penalty function is multiplied by each movement delay. The penalty function is greater than 1 if the volume-to-capacity ratio is greater than 0.9. Otherwise, the exponential penalty function is equal to 1. This strategy then penalizes movements with higher volume-to-capacity ratios to prevent low demand movements from being unrealistically delayed. It is noted that the fitness value (FV) of the system throughput maximization strategy is just the denominator part of the modified average delay with a penalty function in Equation 1.

GAs maximize the FV. Thus, in the case of the minimization problem, the fitness function must be transformed into a maximization problem. In this case, the original objective function is multiplied by a minus value (e.g., −1) for transformation.

$$\underset{C,g,\theta,p}{\text{Minimize}}\ \text{Obj} = \frac{\sum_{i}^{N_i}\sum_{j}^{N_m}\left\{\sum_{t}^{N_t} q_{ij}^{t}(C,\hat{g}_{ij},\theta,p)\times \exp\left[I(v/c)_{ij}\times(v/c)_{ij}\right]\right\}}{\sum_{i}^{N_i}\sum_{j}^{N_m}\sum_{t}^{N_p} D_{ij}^{t}(C,\hat{g}_{ij},\theta,p)} \tag{1}$$

$$\Leftrightarrow \text{Maximize FV} = -\text{Obj}$$

subject to

$$G_{i1} + G_{i2} = G_{i5} + G_{i6} \qquad \text{for } i = 1,\ldots,N_i \tag{2}$$

$$G_{i3} + G_{i4} = G_{i7} + G_{i8} \qquad \text{for } i = 1,\ldots,N_i \tag{3}$$

$$\sum_{j=\text{ring}} G_{ij} = C \qquad \text{for } i = 1,\ldots,N_i \tag{4}$$

$$G_{ij} \geq MG_{ij} \qquad \text{for } i = 1,\ldots,N_i \text{ and } j = 1,\ldots,N_m \tag{5}$$

$$0 \leq \theta_{i,i+1} < C \text{ and } \theta_{i+1,i} = C - \theta_{i,i+1} \qquad \text{for } l = 1,\ldots,N_l \tag{6}$$

$$\text{Min } C \leq C \leq \text{Max } C \tag{7}$$

$$g_{ij}, C, \theta \geq 0 \text{ and integer} \tag{8}$$

where

$I\left(\frac{v}{c}\right)_{ij}$ = index function; if the volume-to-capacity ratio (v/c) is >0.9, then $I(v/c)_{ij}$ is equal to 1; otherwise, $I(v/c)_{ij}$ is equal to 0;
C = cycle length (s);
$\hat{g}_{ij}$ = effective green time for movement j at intersection i (s);
$\theta_{i,i+1}$ = offset between intersection i and $i + 1$ (left to right; s);
p = phase sequence (predefined 16 possible cases per four-leg intersection);
i = intersection;
j = movement (j = 1, . . . ,12; National Electrical Manufacturers Association phase plus right turns);
t = simulation time interval;
l = links;
N_i = total number of intersections;
N_m = total number of movements;
N_t = total simulation time period (s);
N_l = total number of links;
N_p = total number of phases;
q_{ij}^{t} = queue length at j during time t at i (number of vehicles);
D_{ij}^{t} = (unimpeded) departed vehicles at j during time t at i (number of vehicles);
G_{ij} = green time (only integer values) for j at i (s);
MG_{ij} = minimum green time for j at i (s);
Min C = minimum cycle length (s); and
Max C = maximum cycle length (s).

Equations 2 and 3 indicate the signal-timing barrier, whereas Equations 4 and 5 are the cycle length and minimum green time constraints, respectively. Equation 6 indicates that the offset should be between 0 and cycle length − 1, whereas Equation 7 confines the cycle length to between a user-specified minimum and maximum cycle length. Finally, Equation 8 restricts green times, cycle length, and offset to integer values. Phase sequences are determined from 16 possible left-turn treatments for both main and minor streets. The detailed description of the fraction-based decoding scheme can be found in a previously published paper (*7*).

Genetic Algorithm-Based Signal Optimization Program

The GA-based program consists of two components: a GA optimizer and a mesoscopic simulator. A GA optimizer is an optimization routine based on GAs, whereas a mesoscopic simulator produces system performances for a given signal setting. The differences between GA-based program and TRANSYT-7F version 8 (T7Fv8.1) are summarized as follows:

- The GA optimizer simultaneously optimizes cycle length, offset, green split, and phase sequence, whereas T7Fv8.1 performs a sequential optimization of each variable, one at a time.
- The mesoscopic simulator explicitly models different vehicle arrivals, whereas T7Fv8.1 uses analytical equations to account for random and oversaturation queue effects. In other words, the mesoscopic simulator actually simulates random plus oversaturation conditions by allowing varying arrival rates.

A detailed description can be found in the work by Park et al. (*7*).

EXPERIMENTAL DESIGN

The three different GA-based signal optimization strategies that have been proposed are tested and compared with T7Fv8.1. The CORSIM microscopic simulation program, developed by FHWA (*18*), is used as the unbiased evaluator. The experimental design is examined, including geometric conditions, demand volumes, and parameters used in the genetic optimizer. Experimental design issues are also discussed in this section.

Geometric Design

To test the GA-based program, an arbitrary arterial system consisting of four intersections was selected. As shown in Figure 1, the

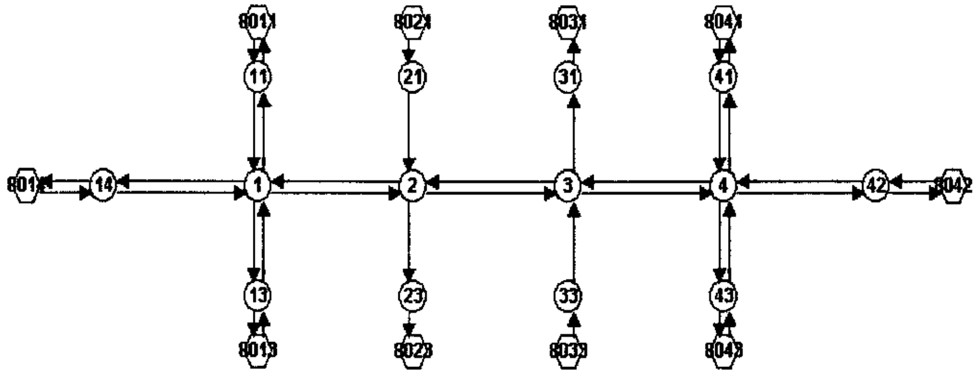

FIGURE 1 Experimental site (CORSIM coding).

arterial system has a diamond interchange (or two one-way cross streets) and two two-way cross streets. Interior link lengths of 100, 200, and 300 m are tested. All links have two through lanes with both left-turn and right-turn bays where applicable. The lengths of the right-turn and left-turn bays are 40 m (about 130 ft) and 150 m (about 500 ft), respectively. In the case of interior links, one-half of the interior spacing is used for the left-turn bay length.

Traffic Demands

Previous work (*7*) investigated three levels of demand volumes: low, medium, and high. It was found that the GA-based program worked well for all three conditions. In this paper, only high-demand conditions under different intersection spacings are investigated. The demand volumes for oversaturated conditions are summarized in Table 1 (where LT is left turn, TH is through, and RT is right turn, and N/A is not applicable). The selected traffic pattern has approximately 80 percent arterial traffic and 20 percent cross-street traffic, which is thought to be typical of an urban arterial. It is noted that the volume-to-capacity ratios (i.e., the degree of saturation) for most movements range from 1.0 to 1.2. The volume-to-capacity ratios are a function of volume, saturation flow rate, green time, and cycle length. Even though volume and saturation flow rates are constant, the volume-to-capacity ratio varies according to the optimization results for green time and cycle length.

Genetic Algorithm Design

The GA optimizer requires parameters including the maximum number of generations, the number of individuals, the crossover probability, and the mutation probability. It is known that a higher mutation probability results in a random search. As to crossover probability, lower crossover probabilities slow the evolution, whereas the higher crossover probability may destroy the good component in the individuals. In this experiment, the GA optimizer used a maximum of 250 generations with a population size of 10, a crossover probability of 0.4, and a mutation probability of 0.03. Previously, Park showed that the solutions are not sensitive to the typical parameter values used in this paper (*19*).

TRANSYT-7F Version 8.1

T7Fv8.1 can evaluate a range of cycle lengths, but it does sequentially optimize this parameter. To save computation time, a cycle length range of 50 to 120 in 10-s increments was initially examined. Then, on the basis of the prescreened cycle lengths, the range was again evaluated in 1-s increments to find an optimum cycle length. During the optimization, the default hill-climb step sizes were used (*20*). The phase sequence obtained from the GA-based program is used because T7Fv8.1 does not optimize it efficiently.

Even though T7Fv8.1 provides four disutility index definitions and six performance index definitions, they all require user-specific weight values to be input. Thus, to maintain a fair comparison between the proposed GA-based algorithm and T7Fv8.1, only the average delay minimization strategy is evaluated in the study described in this paper.

Mesoscopic Simulation Model Design

All simulation runs were performed for a duration of 15 min. This 15-min time period was selected in keeping with the *Highway Capacity Manual* analysis duration (*21*). It should be noted that a fixed initialization period was used in this experiment. Since traffic

TABLE 1 Traffic Demands for Oversaturated Conditions (in vehicles per hour)

Int.	East Bound			West Bound			South Bound			North Bound		
	LT	TH	RT	LT	TH	RT	LT	TH	RT	LT	TH	RT
1	200	1200	100	200	1200	100	200	1200	100	200	1200	100
2	N/A	1300	200	300	1300	N/A	300	1000	200	N/A	N/A	N/A
3	300	1300	N/A	N/A	1300	200	N/A	N/A	N/A	300	1000	200
4	200	1200	100	200	1200	100	200	1200	100	200	1200	100

demand always exceeds capacity, the traffic network will never reach a steady-state equilibrium condition. An initialization period of 3 min was used to allow an initial single vehicle to pass through the system. This initialization period was applied to all programs tested in the study described in this paper.

During oversaturated conditions, the declaration of queue blockage is very crucial in optimizing a traffic signal-timing plan for closely spaced intersections. In this experiment, link blockage due to queue spillback is declared if the length of queued vehicles exceeds 90 percent of the through and left-turn storage capacity. In the case of 100-m spacing, the reduced queue storage capacity allows two more vehicles per lane to be stored without causing intersection blockage. It is noted that, after careful observation of CORSIM simulation runs, the right-turn bay area was not considered a part of storage capacity for either the GA-based program or the T7Fv8.1 program.

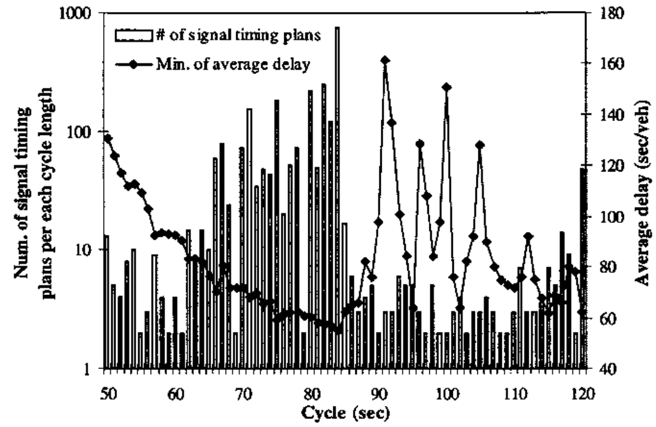

FIGURE 2 Number of signal plans and minimum of average delay per each cycle length (100-m spacing GA-based program with delay minimization).

Measurement of Effectiveness Selection

Comparisons of the T7Fv8.1 and GA strategies are made on the basis of the CORSIM model. During the analysis of the CORSIM simulation results, it was found that the average delay per movement, especially for right-turn movements into the interior link, gave suspect average delay. For example, the northbound right-turn movement at Intersection 1 showed large average delay variations because of extreme blockage of the receiving link. At times, no single right-turning vehicle departed the intersection. During such times, CORSIM reports zero delay for that movement. This is because CORSIM reports average delay for the vehicles after they depart the subject link. As a consequence, if a comparison is based on the average delay obtained from CORSIM results, the conclusions may be invalid.

To overcome this problem with CORSIM, queue time, which is defined as the total time accumulated in a queue caused by signal control (*22*), was adopted as a surrogate for average delay. The number of throughput vehicles was also used.

GENETIC ALGORITHM MODEL EVALUATION

The purpose of the study is to demonstrate how the GA works for signal optimization. Then, the three different optimization strategies were tested under three different intersection spacings: 100, 200, and 300 m.

Genetic Algorithm-Based Program

The GA-based program searched 2,500 signal-timing plans (250 generations × population size of 10). In the case of the average delay minimization strategy for the 100-m spacing, the GA program produced an optimum cycle length of 84 s. As shown in Figure 2, the GA optimizer searched cycle lengths mostly in the range of 70 to 85 s. The bar graph in Figure 2 indicates the number of signal-timing plans per cycle length searched by GA, whereas the line graph shows the minimum average delay found at each cycle length. It is noted that the minimum average delay plotted in Figure 2 is not the optimal delay per each cycle length but is the minimum delay obtained from signal-timing plans searched by the GA-based program at each cycle. It is also noted that the GA-based program evaluated less than 10 signal-timing plans for cycle lengths between 51 and 63 s and between 86 and 118 s. A high average delay variation was revealed for cycle lengths between 86 and 118 s, whereas a smooth average delay curve is noted for cycle lengths between 51 and 63 s. This is because a short cycle length will have less variability in green split and offset than a long cycle length. The GA-based program searched 750 plans for a cycle length of 84 s to further refine the other parameters: green split, offset, and phase sequence.

The convergence of the GA-based program for delay minimization with interior spacing for the 100-m case is plotted in Figure 3. Within 20 generations, the average system delay for 25 individuals dropped very rapidly and then maintained fairly similar values with some random variations. The minimum delay becomes stable after 100 generations, and the improvements after that seem negligible. It is noted that since the elitist algorithm was used, the best solution was maintained. The stopping criterion is not readily available for GA optimization; thus, eye examination of the GA convergence curve shown in Figure 3 was used. The computation time required for the GA-based program (for 250 generations) was about 5 min when a computer with a Pentium II (350-MHz) processor was used.

In Figure 4, the evolution of queue lengths for major arterial eastbound through movements was plotted. It is noted that the queue lengths plotted in Figure 4 were obtained not from CORSIM but from the mesoscopic simulator developed in this study. It was found that eastbound Intersection 1 kept all excess demand vehicles to prevent spillback at downstream Intersections 2, 3, and 4. A similar phenomenon occurred for westbound movements. This indicated that the best strategy during oversaturated conditions would be metering from the outside of the system. This will ensure stable flows at interior links, as shown in Figure 4*b* to 4*d*.

Evaluation Results

Three different strategies were evaluated: throughput maximization, average delay minimization, and average delay minimization with a penalty function. The evaluation was performed on the basis of multiple CORSIM simulation runs. As noted in the section on measure-of-effectiveness (MOE) selection, queue time is mainly used for evaluation of GA strategies. It is noted that for the cases with spacings of 100 and 200 m, CORSIM results occasionally revealed queue spillback because of link blockage and, at times, intersection blockage.

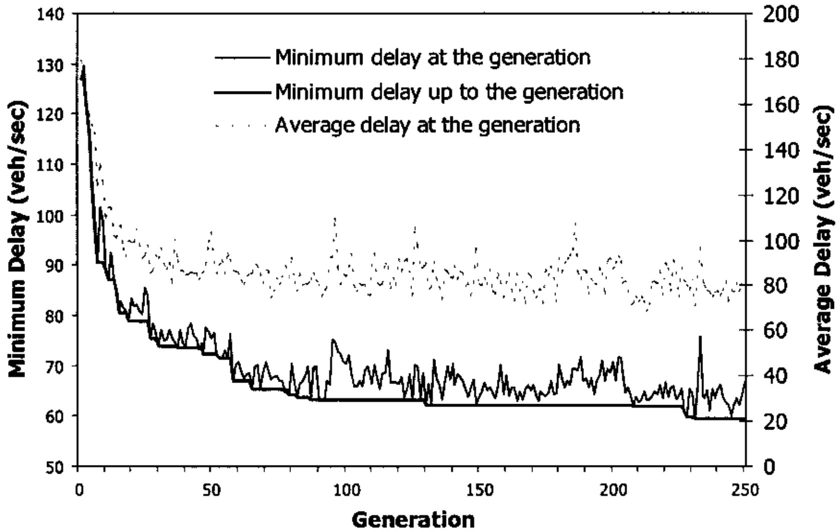

FIGURE 3 Convergence of GA-based program (100-m spacing).

The queue time per approach, obtained from the CORSIM simulation runs, for the three optimization strategies was noted. It appears that the delay minimization strategy worked very well because it produced less queue time than the other two strategies.

With 100-m spacing, the throughput maximization strategy revealed an intersection blockage for the southbound movements at Intersection 2 (Figure 1). The delay minimization with a penalty function strategy also revealed intersection blockages for the northbound movements at Intersection 1 and the southbound movements at Intersection 2. The average delay minimization strategy showed relatively low queue times for most movements, indicating that no severe intersection blockage had occurred.

With 200-m spacing, intersection blockage occasionally occurred for the delay minimization with a penalty function strategy. This strategy yielded intersection blockage for the southbound movements at Intersection 4. However, the intersection blockage was less severe compared with that with 100-m spacing. The throughput maximization and delay minimization strategies produced 20 and 36 percent less queue times, respectively, than the delay minimization with a penalty function strategy.

None of the three signal-timing plans showed intersection blockage with 300-m spacing. This is because the queue storage capacity is sufficient to prevent queue blocking. The delay minimization strategy yielded about 9 percent less queue time than the other two strategies.

Hypothesis tests were conducted to investigate whether the differences are statistically significant. Since the variances are not equal, a *t*-test based on the Smith-Satterthwaite procedure was used (*23*). The hypothesis test results are summarized in Table 2 (where H_0 is the null hypothesis and H_A is the alternative hypothesis). In terms of queue time, it is found that the delay minimization strategy is superior to the other two optimization strategies tested.

The system throughputs were also examined for the three optimization strategies. The CORSIM simulation results showed that the throughput maximization strategy produced slightly higher system throughput than the other two strategies did for an interior spacing of 100 m. Even though the GA-based program with the throughput maximization strategy produced more throughput than the other strategies did, the difference is less than 2 percent compared with that for the delay minimization strategy on the basis of CORSIM simulation runs.

It is noted that the CORSIM simulation revealed not only link blockage but also intersection blockage for an interior spacing of 100 m. Because the GA-based program models only the link blockage that results from queue blockage, it is not surprising that the throughput obtained from the GA-based simulation program does not always follow that obtained from the CORSIM simulation. This is because the CORSIM simulation explicitly models intersection blockage. The throughput maximization strategy likely gives more green time to heavy demand movements (through movements, in this case).

For spacings of 200 and 300 m, the throughput maximization strategy produced higher throughputs than the other two strategies did. This is because no severe intersection blockages occurred because of adequate queue storage capacity. This indicates that the throughput maximization strategy would have worked well even with the interior spacing of 100 m if the intersection blockage could have been prevented.

MODEL COMPARISON

In a comparison of the GA-based program and T7Fv8.1, only the delay minimization strategy is used to ensure a fair comparison between the two models.

With intersection spacing of 100 m, as obtained from CORSIM simulation runs, several intersection blockages were observed. As a result, the northbound movements at Intersections 1 and 3 experienced large queue times. In the case of the T7Fv8.1 signal-timing plan for the 100-m spacing, the CORSIM simulation revealed extreme intersection blockage, as shown in Figure 5. Even though cross-street vehicles see the green lights, they are not able to cross because of severe intersection blockage on the westbound movement. It is noted that the current version of CORSIM, version 4.2, cannot completely avoid link spillback.

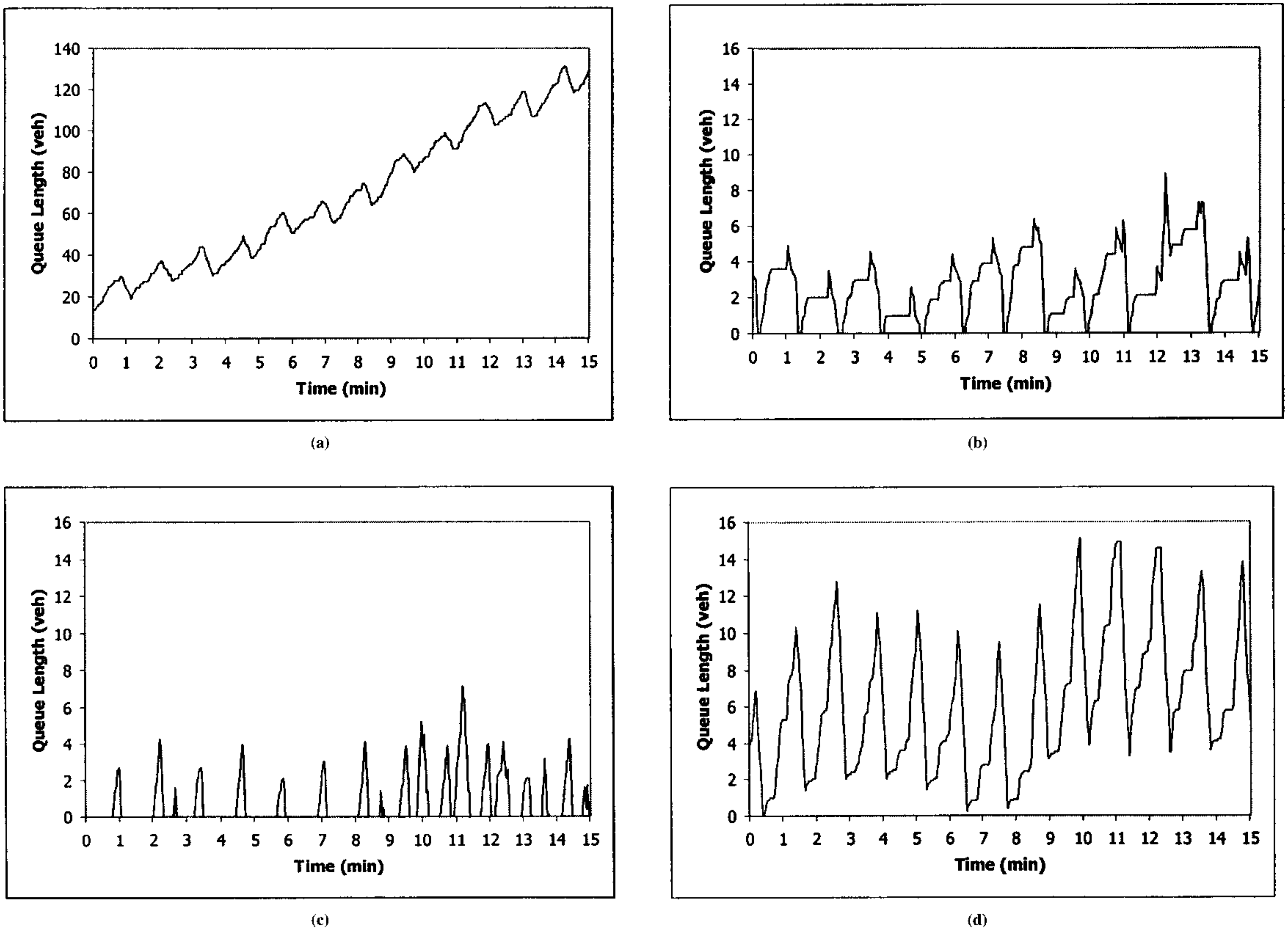

FIGURE 4 Queue length evolution for eastbound through movements (GA-based program): (*a*) Intersection 1; (*b*) Intersection 2; (*c*) Intersection 3; (*d*) Intersection 4.

TABLE 2 Hypothesis Test Results for Model Performance (Comparison of Queue Time and 100-, 200-, and 300-m Spacings)

Spacing	Test	Hypothesis (H_0, H_A)	d.f. (γ)	t-stats (T_γ)	t-table α=0.05	Result	Conclusion
100 meters	GA-delay vs. GA-throughput	$\mu_{GAD} = \mu_{GAT}$ $\mu_{GAD} < \mu_{GAT}$	38	2.620	1.686	Reject Ho	$\mu_{GAD} < \mu_{GAT}$
	GA-delay vs. GA-mod. delay	$\mu_{GAD} = \mu_{GAM}$ $\mu_{GAD} < \mu_{GAM}$	34	19.285	1.691	Reject Ho	$\mu_{GAD} < \mu_{GAM}$
	GA-delay vs. TRANSYT-7F	$\mu_{GAD} = \mu_{T7F}$ $\mu_{GAD} < \mu_{T7F}$	36	16.966	1.688	Reject Ho	$\mu_{GAD} < \mu_{T7F}$
200 meters	GA-delay vs. GA-throughput	$\mu_{GAD} = \mu_{GAT}$ $\mu_{GAD} < \mu_{GAT}$	33	10.615	1.692	Reject Ho	$\mu_{GAD} < \mu_{GAT}$
	GA-delay vs. GA-mod. delay	$\mu_{GAD} = \mu_{GAM}$ $\mu_{GAD} < \mu_{GAM}$	22	11.334	1.717	Reject Ho	$\mu_{GAD} < \mu_{GAM}$
	GA-delay vs. TRANSYT-7F	$\mu_{GAD} = \mu_{T7F}$ $\mu_{GAD} < \mu_{T7F}$	30	3.355	1.697	Reject Ho	$\mu_{GAD} < \mu_{T7F}$
300 meters	GA-delay vs. GA-throughput	$\mu_{GAD} = \mu_{GAT}$ $\mu_{GAD} < \mu_{GAT}$	35	7.585	1.690	Reject Ho	$\mu_{GAD} < \mu_{GAT}$
	GA-delay vs. GA-mod. delay	$\mu_{GAD} = \mu_{GAM}$ $\mu_{GAD} < \mu_{GAM}$	37	5.520	1.687	Reject Ho	$\mu_{GAD} < \mu_{GAM}$
	GA-delay vs. TRANSYT-7F	$\mu_{GAD} = \mu_{T7F}$ $\mu_{GAD} < \mu_{T7F}$	29	11.534	1.699	Reject Ho	$\mu_{GAD} < \mu_{T7F}$

μ_A: Average delay obtained from 20 CORSIM simulation runs based on A strategy
GAT: GA-based program with the throughput maximization strategy
GAD: GA-based program with the delay minimization strategy
GAM: GA-based program with the modified delay minimization with penalty strategy
T7F: TRANSYT-7F version 8.1

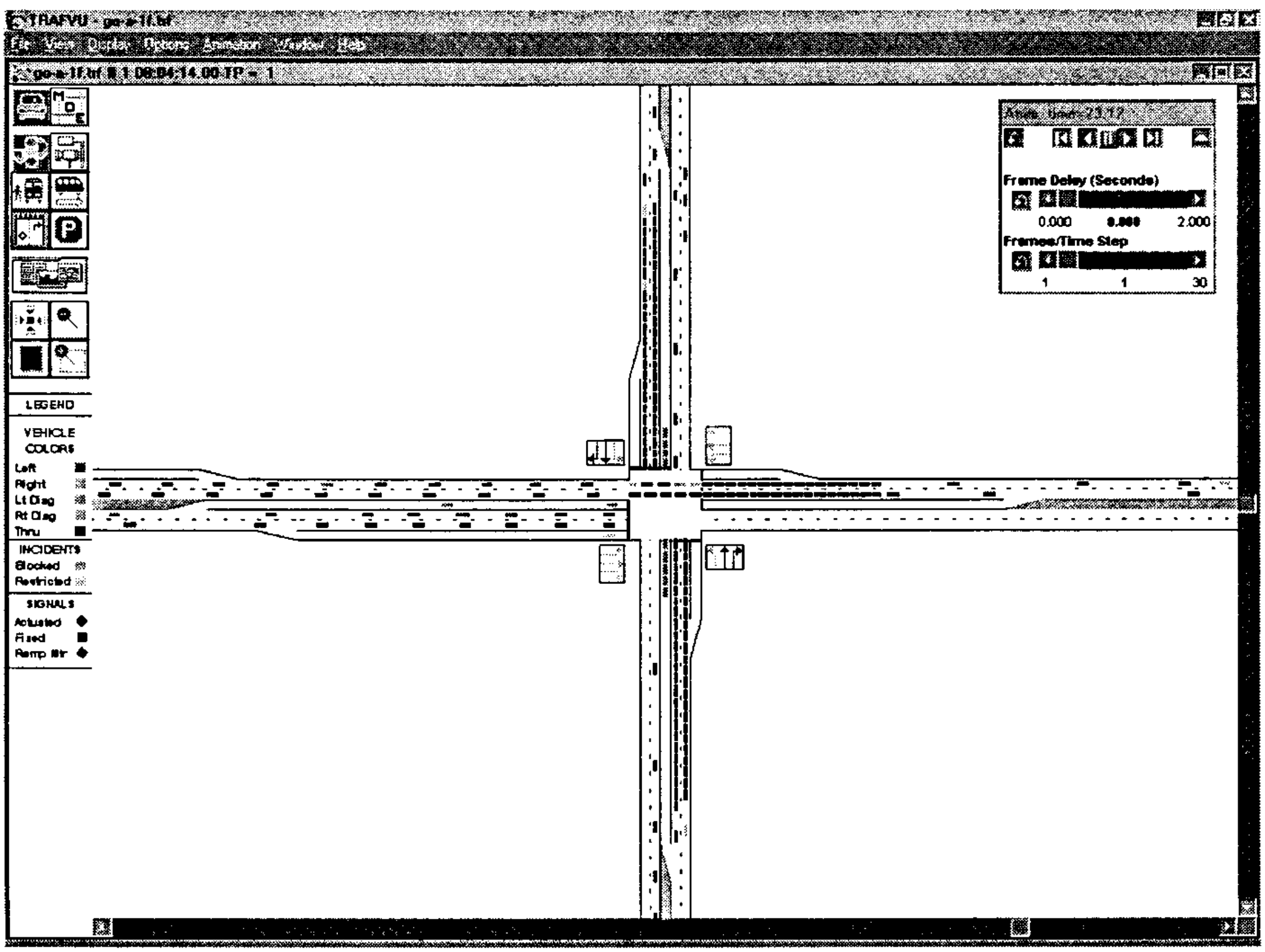

FIGURE 5 Example of CORSIM intersection blockage with T7Fv8.1 signal-timing plan (100-m spacing).

Again, T7Fv8.1 tended to select longer cycle lengths to reduce random plus oversaturation delay. A longer cycle length mathematically ensures larger phase capacity and decreases random plus oversaturation delay. The delay formula used in T7Fv8.1 revealed that the overflow delay is dominant over the uniform delay during oversaturated conditions (*20*).

Because of the longer cycle length, the T7Fv8.1 signal-timing plan produced higher traffic demands per cycle than the GA-based program did. This increases the likelihood of blockage of links as well as intersections, especially at short intersection spacings. It is noted that queue blocking occurs when the queue length on the link exceeds the fixed queue storage capacity. Thus, T7Fv8.1 produced larger queue times than the GA-based program did because of severe intersection blockage caused mainly by the selection of a longer cycle length.

With an intersection spacing of 200 m, the two models produced very comparable results. Apparently because of the adequate spacing between the intersections, severe intersection blockage did not occur.

With interior spacing of 300 s, the T7Fv8.1 signal-timing plan yielded higher queue times on the basis of CORSIM simulation runs. The westbound movements at Intersection 1 and the southbound movements at Intersection 2 experienced extremely high queue times. During the CORSIM simulation runs, it was visually observed that the westbound movements had not sufficiently progressed. It appears that the offset between Intersections 1 and 2 was not optimal for the westbound movements. Thus, the queue on the westbound movements builds up until it blocks the upstream intersection. The intersection blockage occasionally occurs at the end of the simulation period. This observation explains the higher queue time noted for the southbound movement at Intersection 2.

With interior spacing of 100 m, the GA-based program produced less queue times and more throughputs than T7Fv8.1 did. This is mainly because intersection blockage occurred during CORSIM simulation runs with the T7Fv8.1 signal-timing plan. It is noted that the optimum cycle lengths for the GA-based program and T7Fv8.1 were 84 and 117 s, respectively. Because a longer cycle length allows more vehicle arrivals per cycle, it is more likely to incur intersection blockage when the queue storage is limited. This is because the signal-timing plan obtained from T7Fv8.1 experienced more queue time than that obtained from the GA-based program.

With an interior spacing of 200 m, the queue time and throughput obtained from CORSIM simulation runs showed that the GA-based program yielded less queue time and less throughput than T7Fv8.1 did. It seems reasonable that the GA-based program yielded less throughput than T7Fv8.1 because the optimum cycle length of the GA-based program (83 s) was much smaller than that of T7Fv8.1 (117 s). In other words, since the signal-timing plan with a smaller cycle length experiences more lost time during a fixed time period, the system throughput is likely to be less than that of a longer cycle length. The GA-based program produced less queue time than T7Fv8.1 did on the basis of the CORSIM simulation. This indicates that the signal-timing plan obtained from the GA-based program is better than that obtained from TRANSYT-7F in terms of queue time.

As mentioned before, with an interior spacing of 300 m, the T7Fv8.1 signal-timing plan experienced higher queue times for the westbound movements at Intersection 4. Furthermore, the westbound movements occasionally caused intersection blockage at the end of a simulation period.

Total queue time and total system throughput for the GA-based program with delay minimization and T7Fv8.1 are provided in Figure 6. On the basis of the CORSIM simulation runs, the GA-based program yielded better performance in terms of queue time and provided comparable results in terms of system throughput. A comparison of the results between the GA-based program and T7Fv8.1 with the three different spacings is also summarized in Table 3.

The hypothesis test results for all three different spacings are provided in Table 2. The results indicate that the GA-based program produced a signal-timing plan better than that produced by T7Fv8.1 in terms of average delay. The comparison is based on an average of 20 CORSIM simulation runs.

CONCLUSIONS AND RECOMMENDATIONS

For the GA-based program, three different optimization strategies were tested: throughput maximization, delay minimization, and modified delay minimization with a penalty function. Intersection spacings of 100, 200, and 300 m were considered. With a spacing of 100 m, apparent queue blocking exists because of an inadequate spacing, and occasionally, intersection blockage occurred during CORSIM simulations. However, with interior spacings of 200 and 300 m, no severe intersection blockage occurred.

An investigation of the optimization strategy and intersection spacing relationship revealed that the GA-based program with the delay minimization strategy produced less queue times for all spacings examined. However, none of the strategies provided dominant performance in terms of system throughput. It should be noted that the minimum queue time did not correspond to maximum throughput.

During oversaturated conditions with apparent spillback occurrence, CORSIM generates suspect delay for low demand movement because of complete blockage (resulting from intersection blockage) during the evaluation period. Depending on the severity of intersection blockage, cross-street through movement and right-turn movement to the interior link may experience extreme variations in delay.

Three different GA-based optimization strategies were proposed and evaluated. On the basis of the evaluation, the delay minimization strategy is recommended since it is applicable to both undersaturated and oversaturated conditions. In the case of the modified delay minimization strategy, the penalty function needs to be further calibrated with respect to the degree of saturation to improve model performance.

The GA-based program and T7Fv8.1 were compared. Statistically, the GA-based program yielded less queue time than that from T7Fv8.1 on the basis of multiple CORSIM runs. It is found that T7Fv8.1 tends to select longer cycle lengths to reduce random plus oversaturation delay, which tends to promote queue storage overflow and intersection blockage.

The evaluations and comparisons presented in this paper are limited in scope. Thus, a further evaluation and validation study for wider ranges of traffic demands and geometric conditions should be conducted. In particular, the relationships among traffic demand level, intersection spacing, geometry, and optimization strategy should be further investigated to provide, if possible, general guidelines for traffic signal optimization during oversaturated conditions.

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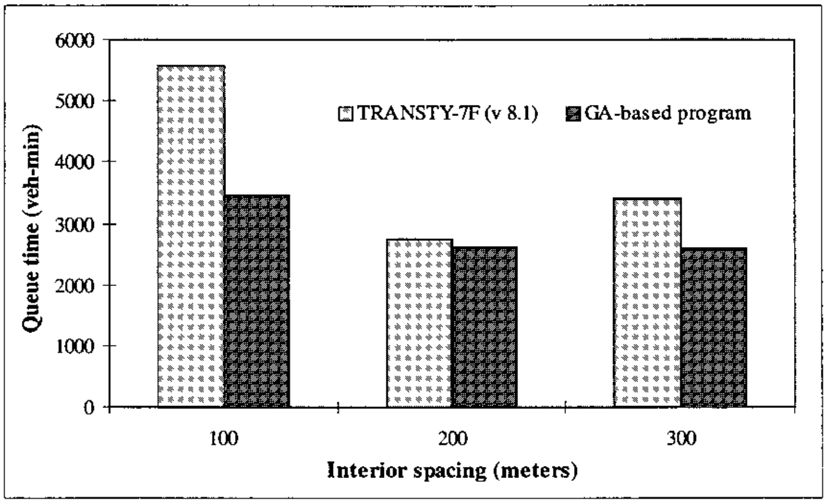
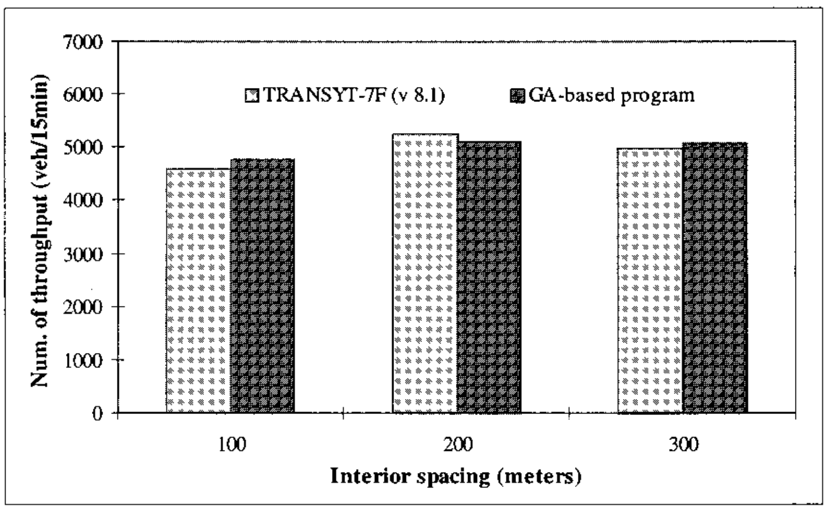


(a)



(b)

FIGURE 6 Comparison of GA-based program and T7Fv8.1 (average of 20 CORSIM runs): (*a*) queue time and interior spacing; (*b*) system throughput and interior spacing.

TABLE 3 Comparison of Results of GA-Based Program and T7Fv8.1 (Average of 20 CORSIM Runs)

Spacing (meters)	MOE	GA	TRANSYT	[GA-T7F]÷T7F (% differences)
100	Cycle	84	117	-28.2%
	Queue time	3461	5584	-38.0%
	Throughput	4770	4594	+3.8%
200	Cycle	83	117	-29.1%
	Queue time	2614	2744	-4.7%
	Throughput	5094	5243	-2.8%
300	Cycle	84	119	-28.2%
	Queue time	2595	3396	-23.6%
	Throughput	5075	4993	+1.6%

REFERENCES

1. Rouphail, N. M., and R. A. Akcelik. Preliminary Model of Queue Intersection at Signalized Paired Intersections. *Proceedings of Australian Road Research Board*, Vol. 16, Part 5, 1992, pp. 325–345.
2. Prosser, N., and M. A. Dunne. Procedure for Estimating Movement Capacities at Signalized Paired Intersections. *Proc., 2nd International Symposium on Highway Capacity*, Vol. 2, Sydney, Australia, 1994, pp. 473–492.
3. Messer, C. J. Extension and Application of Prosser-Dunne Model to Traffic Operation Analysis of Oversaturated, Closely Spaced Signalized Intersections. In *Transportation Research Record 1646*, TRB, National Research Council, Washington, D.C., 1998, pp. 106–114.
4. Foy, M. D., R. F. Benekohal, and D. E. Goldberg. Signal Timing Determination Using Genetic Algorithms. In *Transportation Research Record 1365*, TRB, National Research Council, Washington, D.C., 1992, pp. 108–115.
5. Hadi, M. A., and C. E. Wallace. Hybrid Genetic Algorithm to Optimize Signal Phasing and Timing. In *Transportation Research Record 1421*, TRB, National Research Council, Washington, D.C., 1993, pp. 104–112.
6. Abu-Lebdeh, G., and R. F. Benekohal. Development of Traffic Control and Queue Management Procedures for Oversaturated Arterials. In *Transportation Research Record 1603*, TRB, National Research Council, Washington, D.C., 1997, pp. 119–127.
7. Park, B., C. J. Messer, and T. Urbanik II. Traffic Signal Optimization Program for Oversaturated Conditions: Genetic Algorithm Approach. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1683*, TRB, National Research Council, Washington, D.C., 1999, pp. 133–142.
8. Goldberg, D. E. *Genetic Algorithms in Search, Optimization, and Machine Learning.* Addison-Wesley Publishing Co., Reading, Mass., 1989.
9. Holland, J. *Adaptation in Natural and Artificial Systems.* University of Michigan Press, Ann Arbor, 1975.
10. Gen, M., and R. Cheng. *Genetic Algorithms and Engineering Design.* John Wiley and Sons, Inc., New York, 1997.
11. Beasley, D., D. R. Bull, and R. R. Martin. An Overview of Genetic Algorithms: Part 1, Fundamentals. *University Computing*, Vol. 15, No. 2, 1993, pp. 58–69.
12. Filho, J. R., P. Treleaven, and C. Alippi. Genetic Algorithm Programming Environments. *IEEE Computer Journal*, Vol. 27, June 1994, pp. 28–43.
13. Brindle, A. *Genetic Algorithms for Function Optimization.* Ph.D. dissertation. University of Michigan, Ann Arbor, 1982.
14. Syswerda, G. Uniform Crossover in Genetic Algorithms. *Proc., 3rd International Conference on Genetic Algorithms*, George Mason University, 1989, Morgan Kaufmann Publishers, Inc., San Mateo, Calif., pp. 2–9.
15. Dasgupta, D., and Z. Michalewicz. Evolutionary Algorithms—An Overview. In *Evolutionary Algorithms in Engineering Applications*, Springer-Verlag, New York, 1997.
16. Rudolph, G. Convergence Analysis of Canonical Genetic Algorithms. *IEEE Transactions on Neural Networks*, Vol. 5, No. 1, 1994, pp. 96–101.
17. Cerf, R. An Asymptotic Theory for Genetic Algorithms. In *Artificial Evolution: Lecture Notes in Computer Science 1063*, Springer, New York, 1995, pp. 37–53.
18. *CORSIM User's Manual, Version 1.03.* Intelligent Systems and Technology Division, FHWA, U.S. Department of Transportation, McLean, Va., April 1997.
19. Park, B. *Development of Genetic Algorithm-Based Signal Optimization Program for Oversaturated Intersections.* Ph.D. dissertation. Department of Civil Engineering, Texas A&M University, College Station, 1998.
20. Wallace, C. E., K. G. Courage, M. A. Hadi, and A. C. Gan. *TRANSYT-7F User's Guide.* Transportation Research Center, University of Florida, Gainesville, March 1998.
21. *Special Report 209: Highway Capacity Manual*, 3rd ed. TRB, National Research Council, Washington, D.C., 1994.
22. Showers, R. H., and K. G. Courage. CORSIM Treatment of Gap Acceptance and Delay. Presented at 77th Annual Meeting of the Transportation Research Board, Washington, D.C., 1998.
23. Milton, J. S., and J. Arnold. *Introduction to Probability and Statistics.* McGraw-Hill, Inc., New York, 1995.

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