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Highway Maintenance Scheduling Using Genetic Algorithm with Microscopic Traffic Simulation

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Abstract: This paper introduces a hybrid genetic algorithm-microscopic traffic simulation methodology for scheduling of pavement maintenance activities involving lane closures aiming to minimize network traffic delay. Genetic algorithm is implemented as an optimization tool for the generation and selection of maintenance schedules. For each possible schedule, a microscopic traffic simulation model is used to simulate traffic operations in the network to estimate the delay caused by the lane closures. This concept has been implemented with the genetic algorithm written in the C language and simulation carried out by PARAMICS. The hybrid model has been tested with an example problem that requires the scheduling of three maintenance crews to 10 links within a 24-hour period, in a network comprises 160 links. It recommended a schedule that has avoided peak periods of traffic flow. The example problem has demonstrated the applicability of this hybrid methodology in pavement maintenance scheduling.

1. INTRODUCTION

Highway maintenance scheduling is a complex constraint optimization problem. In the past, resource allocation, due to limited budget, manpower, materials, equipment and/or time constraints have been a major focus of research in highway maintenance scheduling *(1, 2)*. Highway maintenance activities, especially those involving lane closures, may result in speed reduction or even traffic congestion, causing delay to motorists. Recently, attentions have been paid to the impacts on traffic operations when planning for such activities.

Two scheduling methodologies have been proposed to minimize the disruption caused by lane closures to traffic operations *(3, 4)*. Fwa et al. used the genetic algorithm technique to search for a near optimum lane closure schedule for pavement maintenance activities in multiple links in a network *(3)*. The objective was to minimize total traffic delay in the network. Individual work zone delay was calculated based on a set of analytical equations developed from queuing theory. This method has been applied to schedule three teams among 10 work zones in a day, and subsequently expanded to assign six teams for 100 work zones in a week *(5)*. However, the delay calculation method ignores the influence of lane closure on adjacent links (for example, spilt over queue) and the interactive effects of work zones nearby. Chang et al. developed an alternative approach using the Tabu search technique *(4)*. The network traffic delay was estimated from a dynamic traffic assignment model. This methodology has been applied to schedule two construction crews two six work zones in a day. As the Tabu search technique is more suitable for integer combinatorial problems, it has the disadvantages of requiring the day to be divided into shifts, and all the jobs (lane closures) in the same shift to start and end at the same time. In reality, highway maintenance activities performed by different work teams may not start or end concurrently.

This study is motivated by the need to improve the scheduling of maintenance activities that involve lane closures in the affected links. As in the above existing methodologies, the objective of the maintenance or lane closure scheduling is to minimize total traffic delay in the network. Our proposed scheduling methodology uses genetic algorithm as the solution generation and search engine, coupled with a microscopic traffic simulation model to estimate total traffic delay in the network. The methodology is flexible enough to handle (1) multiple lane closures that occur simultaneously at different links in a network; (2) different maintenance requests each requiring a different duration (number of hours) of closure; and (3) different starting and end times of lane closures in each affected link. In particular, the microscopic traffic simulation model is able to represent the interacting effect of adjacent work zones in the estimation of traffic delay, and account for the delay imposed by the work zone on surrounding links.

The hybrid genetic algorithm-microscopic traffic simulation (hereafter referred to as GA-simulation) methodology has been tested with an example problem of assigning three maintenance crews to 10 maintenance requests in a day, in a network consisting of 160 links. The objective of this paper is to introduce the methodology, and investigate several factors that affect the rate of convergence to the recommended solution. These include the number of repetitions of simulation runs with different random number seeds, the population size and number of generations in GA evolution.

2. THE HYBRID GA-SIMULATION MEHODOLOGY

This hybrid methodology combines two different approaches: genetic algorithm (GA) and microscopic traffic simulation.

GA is a heuristic optimization technique based on the mechanics of natural selection and evolution *(6)*. In GA, feasible solutions of a problem are each represented by a chromosome string. Each chromosome string carries a genetic code that represents the characteristics of an individual. A number of chromosome strings collectively forms a population. Strings in the current populations are ranked and better ones selected to produce the next generation of solutions, emulating the survival of the fittest mechanism. The use of multiple feasible solutions reduces the likelihood of the solution converging to a local minimum and increases the probability of finding the global optima. Another advantage of GA is that the objective function and constraints may not necessarily be expressed in mathematical form. This makes GA highly suitable for highway maintenance scheduling problem that has many constraints.

In this methodology, Version 3.0 of PARAMICS microscopic traffic simulation model was used to estimate the average network total delay to road users under different maintenance schedule. PARAMICS is a suite of software tools for high performance microscopic traffic simulation *(7)*. In PARAMICS, the movements of individual vehicles are represented in detail, enabling the modeling of speed reduction, lane changing and queuing behavior due to lane closure in a link. PARAMICS is selected for implementation due to its relatively fast simulation speed and ability to interface with external programs (in this case, the GA program) or customized routines.

The framework of the hybrid GA-simulation scheduling methodology is presented in FIGURE 1. A network consisting of links to be partially closed for maintenance must be first coded into the simulation model.

Traffic demand over a 24-hour period, in the form of trip origin-destination (O-D) matrices, and other important inputs such as signal timing parameters, are defined in the simulation input files. On the other hand, the types and locations of maintenance requests, manpower, material, equipment and other constraints are coded into the GA program. Note that, all the maintenance activities discussed in this research involve the closure of at least one traffic lane. As soon as the simulation and GA inputs are ready, the GA program can start to drive the optimization process.

In each GA generation, a population of schedule is generated. Each schedule refers to the spatial and temporal scenario of lane closures in a network over a 24-hour period. Each lane closure schedule is simulated several times, each with a different random number seed. This is to average out any bias in the results (total traffic delay) caused by the random number seed in the simulation input. At the end of each simulation run, the total travel time is fed back to the GA program for delay calculation. GA then evaluates the relative merit of each lane closure schedule by comparing the average total traffic delay, and uses the relatively better schedules to produce the next generation of solution. The process continues until a pre-defined generation size is met. Then the schedule with the least total traffic delay found in the search is recommended.

To arrive at a near optimal lane closure schedule, the GA search process needs to evolve through many generations, and each generation contains a population of chromosomes. For each unique chromosome, several simulation runs need to be carried out with different random number seeds. Therefore, hundreds of simulation runs are anticipated.

3. EXAMPLE PROBLEM

The application of the scheduling methodology is demonstrated through an example problem. In this problem, it is assumed that 10 links in a network with various pavement distresses have been earmarked for maintenance treatments by three teams, each with a different standby working hour. This scheduling exercise is to work out a day’s work plan for the three maintenance teams with the objective of minimizing total traffic delay to all the vehicles in the network. The program code is written in the C language, and implemented in a personal computer with a Pentium 733 MHz processor.

3.1 Road Sections Under Maintenance

The road network selected for this demonstration was modeled after the Clementi town network in Singapore. It is assumed that there are 10 links with maintenance jobs to be scheduled in the day of interest. The job numbers, locations, affected lanes, and hours required are listed in Table 1. Note that, depending on the availability of the teams and constraints, not all the 10 jobs may be scheduled in one day, but the standby hours of the teams are utilized as much as possible.

3.2 Standby Hours

Routine road maintenance work is carried out by a contractor who is required to supply three maintenance teams covering 24 hours a day. The standby hours of the teams are

Team 1: 6:00 a.m. to 6:00 p.m. (12 hours)
Team 2: 7:00 a.m. to 5:00 a.m. (22 hours)
Team 3: 8:00 p.m. to 6:00 a.m. (10 hours)

Work scheduling is made to achieve a desired minimum of six working hours and a maximum of ten working hours within the standby period.

3.3 Resources Constraints in Maintenance

In this hypothetical problem, it is assumed that the maintenance requests are relatively simple, and can be completed within a few hours, or, all the teams have sufficient resources for any assignment. However, the following constraints must be taken into account:

(1) A job can only be assigned to a team in a day;
(2) In a link, there can only be one period of lane closure in a day;
(3) A team cannot be assigned to more than one job at any time;
(4) For each team, the total duration of work should not go beyond the standby period;
(5) For each team, the total number of working hours should be between six and 10 hours.

4. TRAFFIC SIMULATION

4.2 Network Coding

The selected road network is represented in detailed in PARAMICS by nodes and links, as presented in FIGURE 2. There are 74 nodes, 160 links, 13 signalized intersections, and 13 O-D zones in the coded network. A road section in which one or several lanes to be closed should be coded as an individual link, although the length may be shorter than the distance between two intersections.

4.3 Modeling of Lane Closure

In PARAMICS, a lane closure is coded by changing its link attributes. Lanes are closed and opened to traffic at hourly intervals. When some lanes are to be closed, related entries in the link attribute file in PARAMICS are modified by the GA program.

4.4 Signal Planning

PARAMICS is able to model the cycles, phases and offsets of traffic signals at intersections. Actuated signal control was coded for all the intersections in the simulated network. The signals in the network are coordinated with fixed offsets. The cycle time varies between 60 seconds and 140 seconds, according to the overall traffic demand.

4.5 Trip Demand

In the simulation, it is assumed that the O-D trip distribution varies hour by hour, but remains constant within an hour. Therefore, 24 hourly trip distribution matrices are provided. To simplify this task, the trip distribution matrix in a certain hour, e.g., the morning peak hour, may be used as the "based matrix". Trip demands for several hours before and after this "based hour" may be taken as a fraction of the based matrix. Based on partial link traffic count data within the network, a hypothetical trip distribution matrix for the morning peak period between 8:00 a.m. and 9:00 a.m. was derived for this example problem. The trip demand at other hours of the day was assumed to be a fraction of this based matrix.

4.6 Traffic Assignment

The maintenance activities under consideration in this problem are all short-term maintenance activities. Therefore, a lane closure will not last more than several hours. It is assumed that the drivers in the network will not be informed in advance on such temporary lane closures. Therefore, the all-or-nothing traffic assignment method is applied to assign all vehicles for an O-D pair along its shortest route. The shortest route is calculated by PARAMICS based on the free-flow link travel times.

4.7 Performance Measures

In this scheduling methodology, total delay is used to assess the impact of the 24-hour maintenance scheduling on traffic operation. The total delay is calculated from the difference in trip travel time with and without lane closure. So trip travel time for each vehicle that arrives at its destination is recorded through the measurements provided by PARAMICS.

4.8 Simulation Time

As explained in Section 2, a scheduling optimization requires the number of simulation runs equal to the product of number of GA generations, population size, and number of repetitions with different random number seeds. To reduce the consumption of computational resource, the 24 hours of traffic operations is reduced to 12 hours in the simulation coding. It has been mentioned that the trip distribution matrices are specified on hourly basis. For each trip distribution matrix, instead of carrying out simulation for one hour of traffic operations, PARAMICS has been coded to run for half an hour of traffic operations. The network total travel time or delay is then multiplied by a factor of two. From our initial tests, with three randomly generated lane closure schedules but repeated for the same set of 20 random number seeds, this compressed simulation duration always underestimated the total travel time by 11% to 12%. This is because, if the simulation is allowed to carry on for one hour per time period, there will be longer time for congestion queue to build up, and the more severe congestion needs longer time to recover. Nevertheless, the under estimation is always a constant factor and this does not change the results in the recommended schedule. With the compressed simulation period, PARAMICS runtime is reduced by 50%. A simulation run for 24 hours of traffic operations in the compressed time mode took 14 minutes in a personal computer with a Pentium 733 MHz processor.

5. GENETIC ALGORITHM PROGRAMMING

The difficulty of maintenance activity scheduling arises due to the large number of variables and constraints, the discrete nature of variables, and the non-linearity in the objective function and constraints. GA is particularly suited for this scheduling problem because it allows the coding of objective functions and constraints through a combination of mathematical equations and heuristics. The GA program is originally adopted from *(8)*. At the programming stage, the genetic representation, constraint handling method, method of generating initial population, fitness function, selection scheme, and crossover and mutation operations have to be customized for the maintenance scheduling problem. The structure of the GA program is depicted in Figure 3.

5.1 Genetic Representation

The string structure was defined according to the standby hours of different maintenance teams, as shown in FIGURE 4. The total number of genes (or cells) in the string corresponds to the total available team-hours per day. In the example problem, the standby hours for the maintenance teams are 12, 22 and 10 hours respectively. Thus, there are altogether 44 genes in the string. Each gene represents one hour of the standby time. The integer value in each gene (R_i) is the job number (between 1 and 10, see Table 1) assigned to the team during that hour. A value of zero means that the team concerned is not assigned any job during the hour.

5.2 Fitness Function

The objective of this maintenance (and hence, lane closure) scheduling is to minimize the total traffic delay to the vehicles in a network in a day. Hence, the total traffic delay to all the vehicles is selected as the GA's fitness function. The equation of average network total traffic delay (*ANTTD*) computation is

$$ANTTD = N * \frac{\sum_{i=1}^{r}\left[\sum_{j=1}^{n_i^1} t_{ij}^1 \Big/ n_i^1\right]}{r} - N * \frac{\sum_{i=1}^{r}\left[\sum_{j=1}^{n_i^0} t_{ij}^0 \Big/ n_i^0\right]}{r} \quad (1)$$

where

ANTTD is the average network total traffic delay in one day;

N is the total number of trips in one day (define in simulation input file);

t_{ij}^1 is the trip travel time of the *j*th vehicle in the *i*th simulation run with lane closures;

t_{ij}^0 is the trip travel time of the *j*th vehicle in the *i*th simulation run without lane closures;

n_i^1 is the number of completed trips in the *i*th simulation run with lane closures;

n_i^0 is the number of completed trips in the *i*th simulation run without lane closures;

r is the number of repeated simulations, with different random number seeds.

5.3 Selection, Crossover and Mutation

In this GA program, the rank-based selection scheme is employed to pair up the parents. First, the chromosomes are sorted in ascending order of their ANTTD. The first pair of parents is formed from the best chromosome (the one with the lowest ANTTD) and one randomly selected from the rest in the top half of the sorted list. The second pair of parents consists of the second one in the ranked list and one chosen from the rest in the entire list (except the first individual in the ranked list). Then the selected pairs of parents are removed from the ranked list for the creation of next generation. This selection process is performed repeatedly based on the same approach until the number of selected parents is the same as the population size. Chromosomes that are ranked in the first half of the list have higher chances to be selected. Two points crossover is adopted in this research, which crosses the parents at two randomly selected cell partitions within a chromosome. The mutation rate was set to be adaptive, which changed within the range of [0.05, 0.25] according to the similarity between the child and parent. The similarity is the number of genes in the child that are similar to the genes in the same positions in the parent. The similarity value is first divided by the length of chromosome, and then multiplied by 0.25. The result is the mutation probability. If this value is less than 0.05, then the value of 0.05 will be used.

5.4 Constraints Handling in GA

The Decoders and Repair Algorithm Method (DRAM) is adopted in this study to rectify a chromosome that violates any of the constraints. In this method, a gene (or a group of genes) in a chromosome that violates any of the constraints is discarded. A new value is randomly generated and assigned to the replaced gene. The constraint checking and gene replacement process is repeated until all the constraints are satisfied.

6. IMPACTS OF RANDOM SEEDS ON DELAY ESTIMATION

PARAMICS uses random numbers to generate the released vehicles, assign behavioral characteristics and determine vehicle routes. The random number stream is split into two, with one stream controlling vehicle releases, and the other stream controlling driver/vehicle behavior.

A test to investigate how the random number seeds influence the delay estimation was carried out before the implementation of the hybrid GA-simulation methodology. With a randomly selected feasible lane closure schedule, simulation was conducted for 60 times, each with a different random seed. The ANTTD were calculated based on equation (1) and plotted in FIGURE 5. The average trip travel times with and without lane closure are presented. It was found that, without any lane closure, the difference between the maximum and minimum trip travel time per vehicle was 47.1 seconds. With lane closures, this difference was 36.0 seconds. The cumulative average trip travel times with and without lane closure are also plotted in FIGURE 5. The average delay is the differences between the cumulative average trip travel times with and without lane closure. The standard deviations of the average delay are plotted against the increase in simulation runs in FIGURE 6. This figure shows relatively high fluctuations in the standard deviation of average delay in the first several runs. After 15 simulation runs, the standard deviation trend to converge to a stable value. FIGURES 5 and 6 demonstrate that the best way to reduce the variances in delay estimation due to the random number seed is to increase the number of simulation runs, and use the average travel times from these repeated runs in delay calculation. Based on this the results of this test, it was decided that twenty simulation runs each with a different random number seeds was necessary to provide a reasonably accurate estimation of average trip delay, for the same lane closure schedule.

7. METHODOLOGY PERFORMANCE

The proposed methodology was applied to the network with population size of four for 10 generations. For each schedule generated by GA, twenty simulation runs were carried out, and ANTTD was calculated based on equation (1).

Table 2 presents the results of applying the proposed hybrid scheduling methodology. As shown in this table, after 5 generations, the hybrid method arrived at a solution that reduced the fitness or ANTTD from the initial best value of 516.3 veh-hr from the 4 chromosomes to the final best value of 11.8 veh-hr. The average network total travel time without lane closures was 11968.0 veh-hr. As spelt out in Table 2, the average total travel times with lane closures were reduced from 12484.2 veh-hr to 11979.7 veh-hr. The recommended lane closure schedule represents an increase in total travel time of only 11.7 veh-hr, or less then 1% of the original travel time. This recommended schedule remained unchanged for the next 5 generations. FIGURE 7 presents the process of convergence.

The best schedule is graphically depicted in FIGURE 8. In this figure, the standby period of each team has been shaded. The assigned hours of maintenance and link identifications are highlighted in boxes. Only 8 out of 10 jobs were assigned to the three teams, with both Team 1 and Team 2 responsible for three sites and team 3 for two sites. The compliance of all the scheduling constraints has been checked manually. All the maintenance tasks selected are assigned to the off-peak hours, avoiding the morning and evening peak traffic demands. In this recommended schedule, all these three teams are required to work for 7 hours within their respective standby period.

Table 2 presents the network travel time and delay for each schedule of maintenance activities generated in chronological order. As shown in this table, the worst schedule (the one that gave highest ANTTD) occurred with the fourth chromosome at the third generation. This schedule caused an average delay of 167.6 seconds to each vehicle. While the best schedule found in the third chromosome at the fifth generation in this experiment only contributed an average delay of 0.3 second to each vehicle.

The evolution of the maintenance schedule can be seen from Table 3. The best schedule showed in each generation included the best one found in all the previous generations. In this table, all the lane closures that fall within the periods of peak traffic demand (between 0800 hrs and 1000 hrs in the morning, and between 1700 hrs to 1900 hrs in the evening) are shaded. From the initial schedule to the final recommended schedule, the GA search has directed the schedules to avoid the peak traffic periods. As in FIGURE 8, all the recommended lane closures have avoided the period of peak traffic demand.

8. FINDINGS

The experiments detailed above have demonstrated the applicability of the hybrid GA-simulation methodology. The GA search of the methodology can arrive at a good solution for the example problem.

This research has implemented the concept of hybrid GA-simulation methodology in the scheduling of highway maintenance or lane closure activities with the objective of reducing the increase in total network travel time. The experience of initial implementation has suggested several possible directions of improvement. The most urgent task is to reduce the simulation time. Computer scheduling of daily activities should not take more than a day to complete. One way to speed up the convergence is to make use of heuristics rules to improve the initial solutions. Another technique is to implement parallel simulations using a multiprocessor machine, with the number of parallel simulation runs equal to the population size.

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List of Tables and Figures

TABLE 1. List of Maintenance Job Requests

Job no.	Link Start Node	Link End Node	Maintenance Time (hours)	Total no. of Lanes	Lanes Closed
1	8	66	2	3	Left & Middle
2	11	10	2	3	Left & Middle
3	21	22	2	3	Left & Middle
4	22	21	3	3	Left & Middle
5	39	71	3	3	Left & Middle
6	66	8	3	3	Left & Middle
7	71	39	4	3	Left & Middle
8	72	26	2	3	Left & Middle
9	73	74	4	2	Right
10	78	76	3	2	Right

TABLE 2. Fitness Values at Each Generation & Travel Time for All the Individuals Generated

Generations	Average Network Total Travel Time (veh-hr)	Average Network Total Traffic Delay (veh-hr)	Individuals	Average Trip Travel Time Per Vehicle (sec)	Average Traffic Delay Per Vehicle (sec)	ANTTD (veh-hr)
1	12484.2	516.3	1	266.3	12.0	567.0
			2	279.8	25.6	1204.7
			3	265.2	11.0	516.3
			4	310.9	56.7	2667.8
2	12209.5	241.6	1	259.3	5.1	241.6
			2	271.9	17.7	834.2
			3	316.0	61.8	2907.2
			4	272.9	18.7	878.0
3	11997.9	29.9	1	294.8	40.6	1911.1
			2	328.7	74.5	3508.5
			3	254.9	0.6	29.9
			4	421.8	167.6	7890.2
4	11997.9	29.9	1	283.5	29.3	1379.5
			2	294.6	40.4	1899.6
			3	296.8	42.6	2006.4
			4	374.4	120.2	5658.2
5	11979.7	11.8	1	359.6	105.4	4960.9
			2	271.1	16.9	794.8
			3	254.5	0.3	11.8
			4	267.7	13.5	635.5
6	11979.7	11.8	1	254.5	0.3	11.8
			2	281.3	27.0	1273.2
			3	262.5	8.3	388.7
			4	254.5	0.3	11.8
7	11979.7	11.8	1	264.6	10.3	486.6
			2	359.7	105.5	4964.6
			3	273.5	19.3	906.4
			4	270.8	16.6	779.3
8	11979.7	11.8	1	321.8	67.6	3181.7
			2	275.3	21.1	991.9
			3	265.8	11.6	546.8
			4	343.6	89.4	4208.4
9	11979.7	11.8	1	261.3	7.1	335.5
			2	294.1	39.9	1876.1
			3	337.1	82.9	3901.0
			4	257.9	3.7	173.4
10	11979.7	11.8	1	294.6	40.4	1899.9
			2	264.5	10.3	483.5
			3	322.7	68.5	3224.6
			4	259.5	5.3	247.4

TABLE 3. Best Schedules at Each Generation

Generations	Average Network Total Delay (veh-hr)	Schedules			
		LinkID	Team	Start Time (o'clock)	Repair Time (hrs)
1	516.3	9	1	6	4
		5	2	11	3
		4	1	15	3
		2	3	21	2
		7	2	22	4
		6	3	23	3
		3	3	27 (3 in the 2nd day)	2
2	241.6	1	1	8	2
		5	2	11	3
		8	1	11	2
		4	1	13	3
		2	3	21	2
		7	2	22	4
		6	3	23	3
		3	3	27 (3 in the 2nd day)	2
3~4	29.9	1	1	6	2
		3	1	10	2
		9	2	11	4
		10	1	14	3
		7	3	20	4
		8	3	25 (1 in the 2nd day)	2
		2	2	27 (3 in the 2nd day)	2
5~10	11.8	1	1	6	2
		3	1	10	2
		2	2	14	2
		10	1	14	3
		8	2	20	2
		7	3	21	4
		5	2	22	3
		6	3	27 (3 in the 2nd day)	3

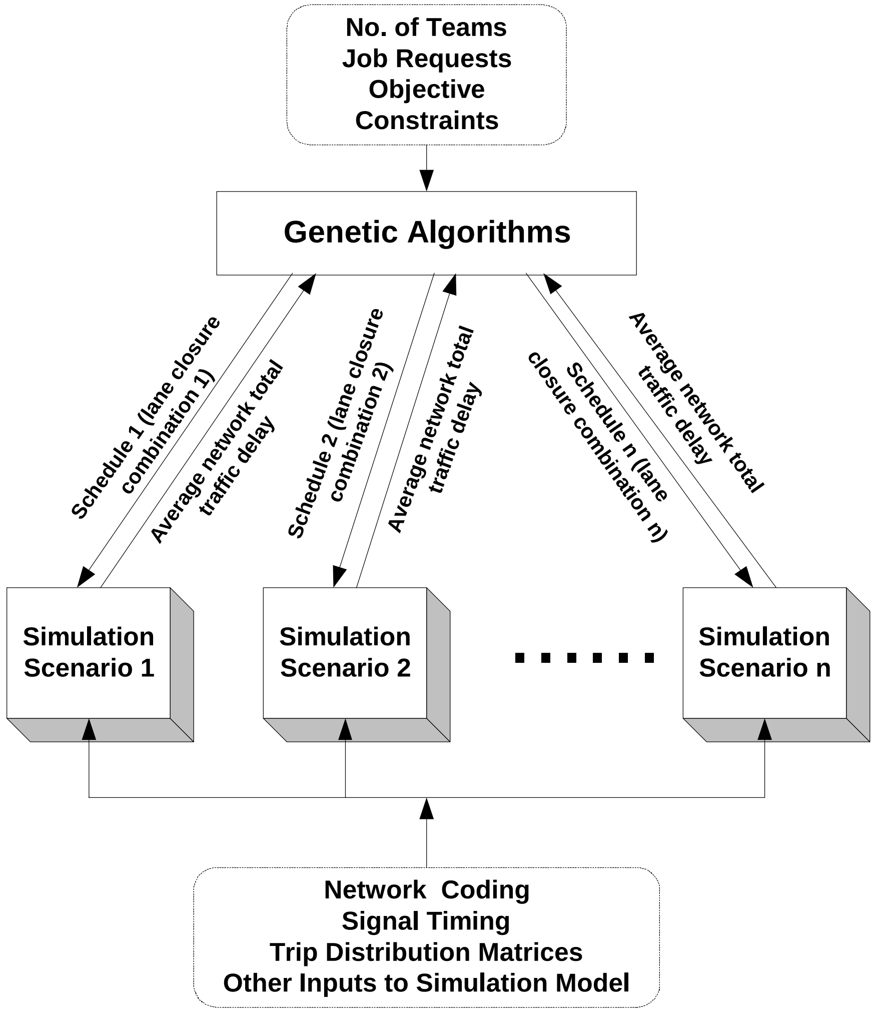

FIGURE 1. Framework of the Hybrid GA-Simulation Scheduling

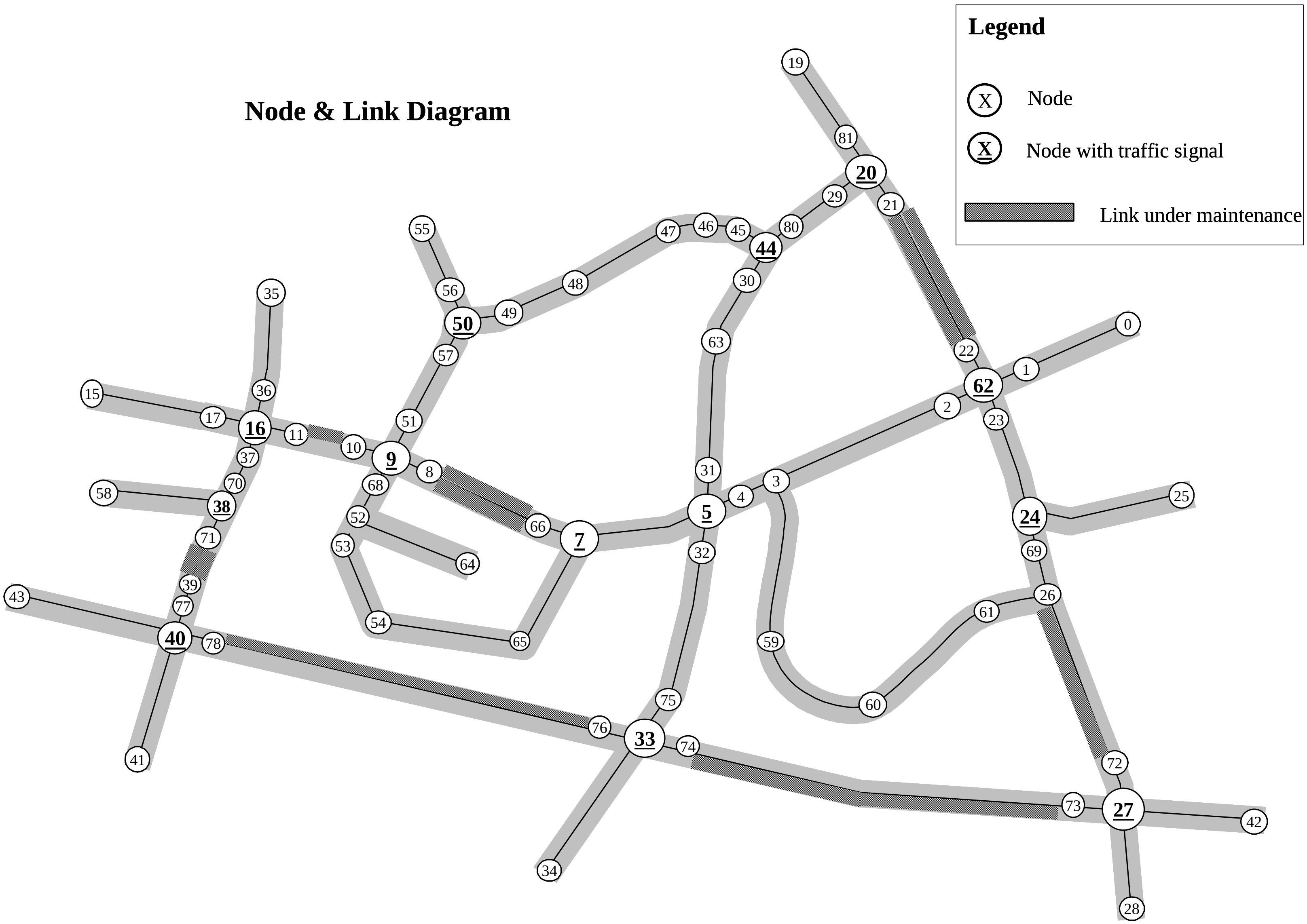

FIGURE 2. CODED NETWORK IN PARAMICS

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Paper revised from original submittal.

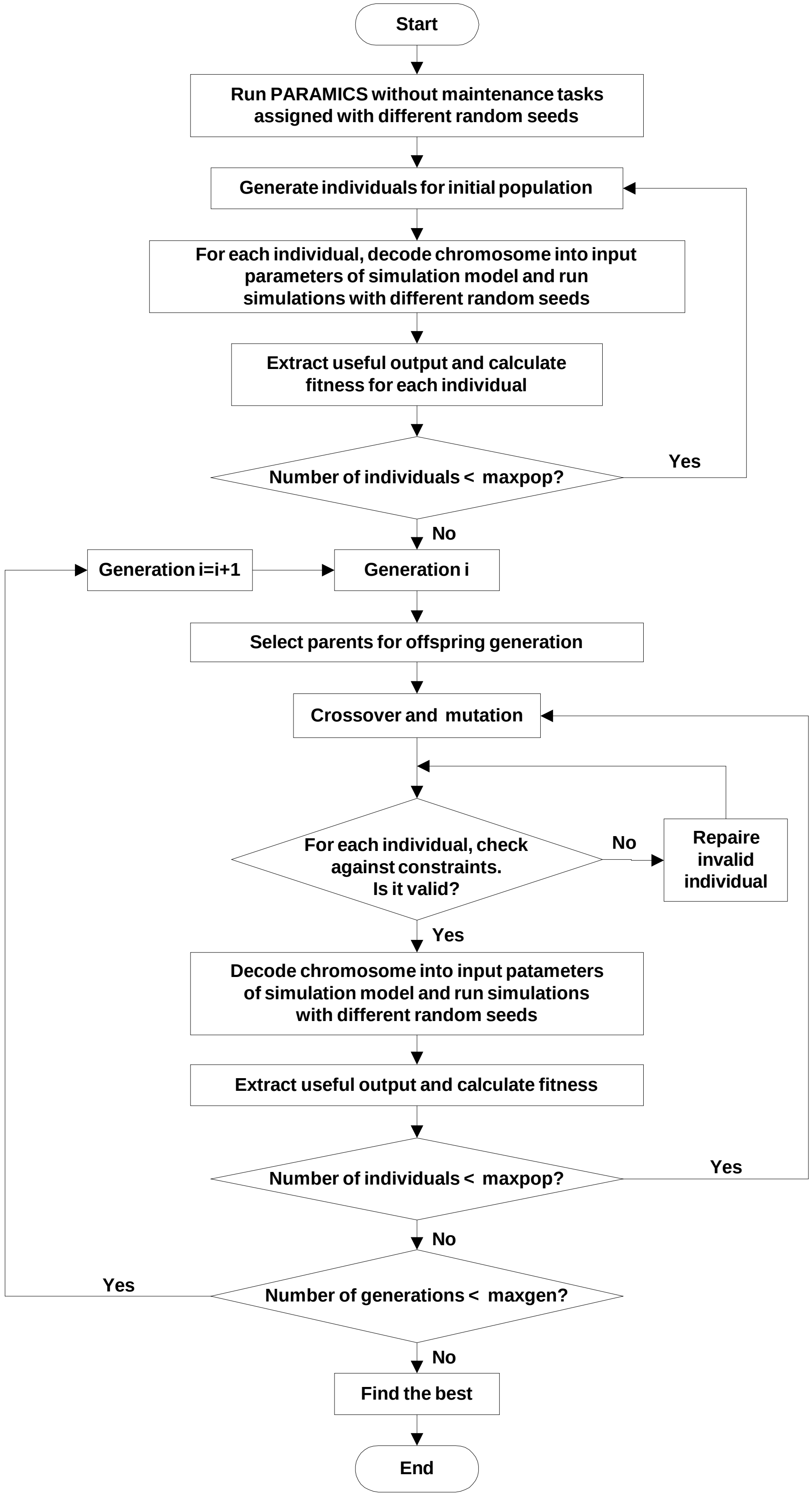

Figure 3. Structure of GA Program

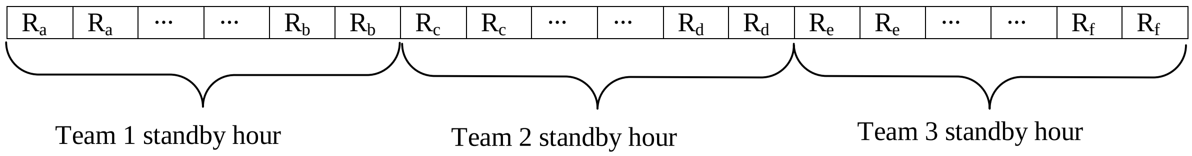

FIGURE 4. Structure of a Chromosome

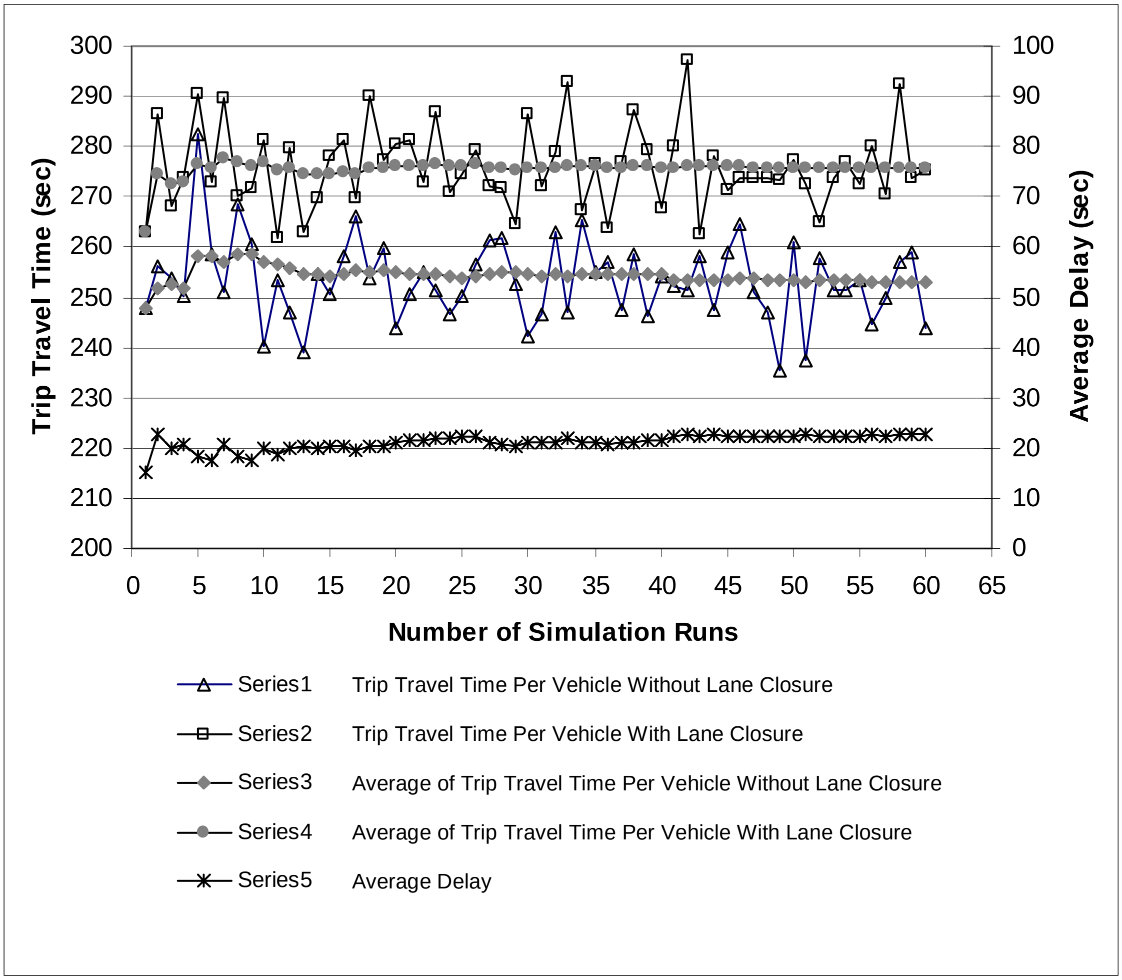

FIGURE 5. Trip Travel Times and Average Delays Over Runs with Different Random Seeds

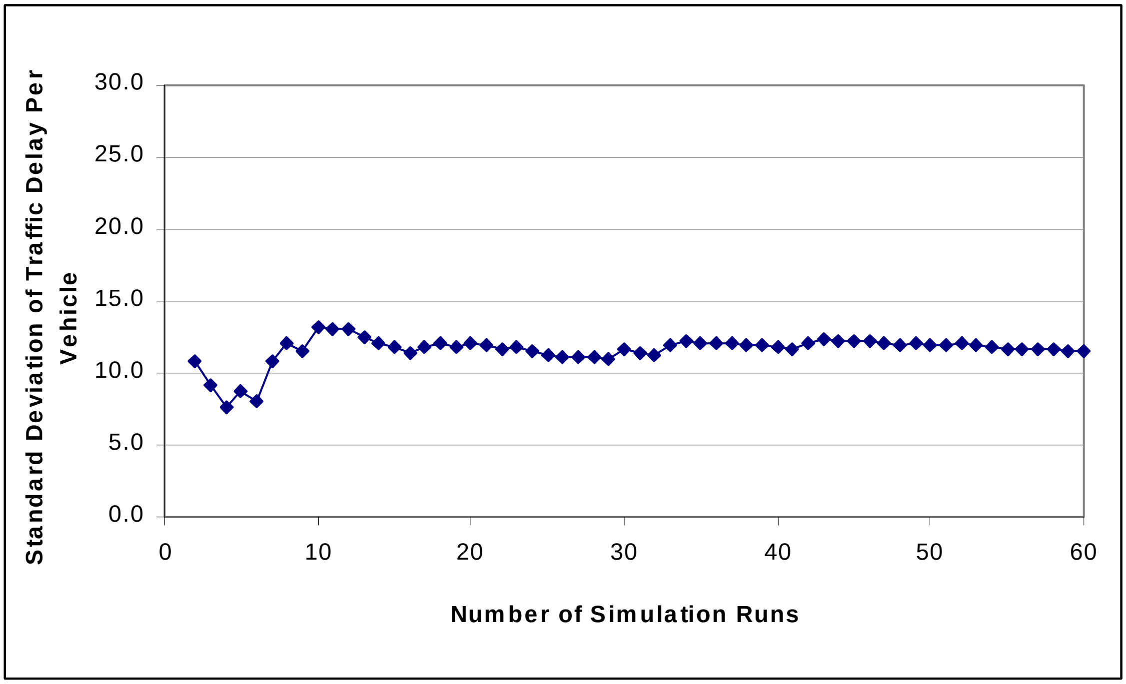

FIGURE 6. Variance in Standard Deviation of Average Delay

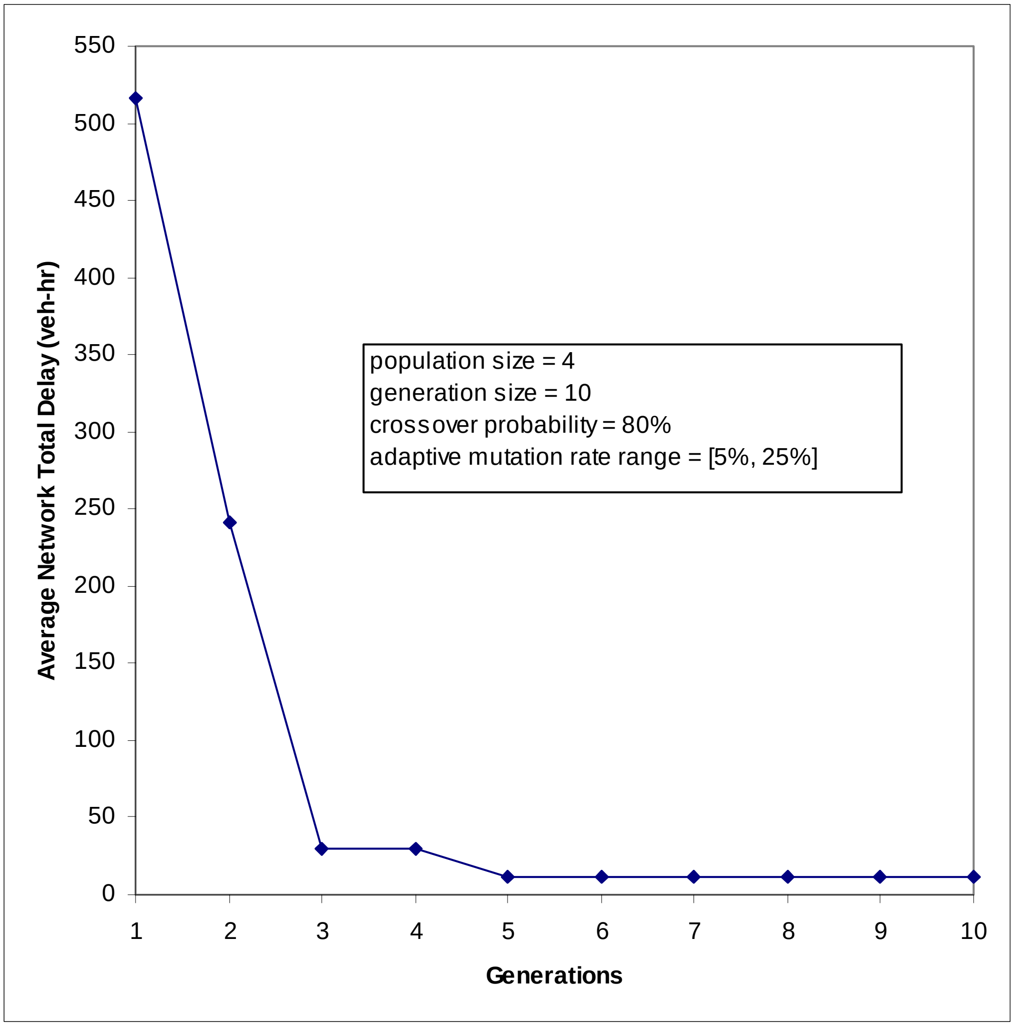

FIGURE 7. Convergence of GA Search

Team \ Time	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5
1	**Link 8:66**				**Link 21:22**				**Link 78:76**															
2									**Link 11:10**						**Link 72:26**		**Link 39:71**							
3																**Link 71:39**						**Link 66:8**		

FIGURE 8. Recommended Maintenance Schedule