

Multiple Intersections Traffic Signal Timing Optimization with Genetic Algorithm

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Abstract — Traffic congestion in the urban area occurs more frequent than the past due to rapidly increasing on road vehicle usage rates. It could seriously hinder the development of urban area if a well management system has not being established. These scenarios necessitate the development of advance traffic management systems to increase the performance of signalized intersection. Traffic signal timing management (TSTM) system which comprise of genetic algorithm based optimization is proposed. Using a proper TSTM system, network traffic flow can be improved with considerably less cost than other infrastructural improvements. The proposed genetic algorithm based optimization approach allows signal timing parameters such as offset, cycle time, green split and phase sequence to be optimized with objective of minimum delay and better traffic fluency. The proposed GATSTM system has the ability to handle and manage the dynamic changes of the traffic networks condition by calibrating the system parameters accordingly.

Keywords – Traffic Flow Control; Traffic Signal Timing Plan; Genetic Algorithm

I. INTRODUCTION

Traffic congestion has become a serious problem with the rise of traffic user especially in urban settings. High densities of traffic flow could effectively being handled by a good signalized control of intersections. However, the efficiency of traffic movements depends on the signal timing plan. Improper manipulation of signal timing plan will degrade the performance of signalized intersections.

Majority of the traffic control systems implemented in Malaysia are pre-timed control systems consist of fixed cycle lengths, preset phase intervals and operates according to predetermined timing plans. This type of control system disregards the dynamic nature of the traffic load and cannot respond adequately to unpredictable changes in sudden traffic demand [1]. In other words, pre-timed control system implemented in Malaysia cause excessive delay to vehicles where there exists a high degree of variability in the traffic flows. It is essential for Malaysia to have an efficient transportation system as a key factor to the economic development in the country.

Thus, this scenario necessitates the development of a traffic signal timing management (TSTM) system which will

be tailored based on Malaysia traffic component. Besides, the proposed traffic control scheme will be designed with a view toward application in real time adaptive traffic control system to replace the existing pre-timed traffic control system in Malaysia.

II. TRAFFIC SIGNAL TIMING PLAN MANAGEMENT

Traditionally, congestion problem is solved by extending traffic infrastructures. In most cases, it is not viable because the existing road infrastructure is often strained to its limits and expansion is infeasible due to spatial, environmental, and economic constraints. Instead, signalized control of intersections is the most cost-effective solution [2]. High densities of traffic flow could effectively being handled by an effective signalized control of intersections. However, the efficiency of traffic movements depends on the signal timing plan. According to Sánchez, J.J. *et al.* [3], many initiatives have been developed to provide traffic network with new management facilities for its better exploitation which are categorised as the Intelligent Transport Systems.

However, less emphasis on traffic management has been carried out in Malaysia. Leong *et al.* [4] state that “Approach adopted for the signalized intersection timing plan design and analysis by Ministry of Works in Malaysia is based on the U.S. Highway Capacity Manual (U.S. HCM 1994 and 1997 Update) and the new metric version, HCM (2000). Most of this study is based on a method developed by Webster and Cobbe from the United Kingdom in the 50s and 60s.” Due to the different traffic components such as drivers’ behaviour, roadways characteristics, and mixed traffic composition in Malaysia and other countries, the signal timing plan evaluated from these approaches is likely to be underestimated or overestimated. Furthermore, Malaysia has been implementing fixed-timed control system in most of the traffic intersections which acted upon the statistical traffic parameters and lacked of the ability to adapt into the fluctuations of traffic demands within the traffic network [1,5].

Hence, traffic signal timing management (TSTM) system which comprise of genetic algorithm based signal optimization in Malaysia is proposed with the nature characteristic of genetic algorithm to search the most optimum solution by evolutions.

III. GENETIC ALGORITHM

A. Fundamental of Genetic Algorithm

Genetic algorithm is known to be an algorithm for locating the best optimal solution throughout the evolutionary process of the possible solutions [6]. The problem of interest is modelled as an imitated biological environment where all the possible solutions are treated as individual chromosomes in a population. The concept of genetic algorithm allows the population of solutions to compete and survive through the evolution, and only the fit and strong solutions will be left surviving at the end of the evolution [7,8]. The characteristic of genetic algorithm has the advantage to optimize the flow of the complex and dynamic traffic network environment.

B. Structure of Genetic Algorithm Chromosomes

Chromosomes are the possible solutions that form the whole population in the genetic algorithm process. A single chromosome is used to encode the entire information of a solution. In the genetic algorithm based optimization traffic signal timing management, a chromosome contains intersections' signal timing parameters such as cycle time C , green split S , phase sequence o and offset F as these are the parameters which tend to be optimized in the genetic algorithm for the traffic signal timing plan [9]. Integer coding is selected to encode the chromosome. Fig. 1 shows the arrangement of the proposed chromosomes.

C. Fitness Function

The proposed fitness function derived for the genetic algorithm evaluates the individual chromosome based on traffic delay and fluency. To ease the derivation of the fitness function, the following interpretation of traffic control system had been made.

Traffic signal control system is treated as a group of service agents. Vehicles are the customer to be served by the agents and act as the only source of income for the agents. Vehicle considered served only when they have successfully being sent to their desired destination and agent will be paid according to the distance travelled. On the other hand, time spent on serving the customer is the cost for the agents. So, the total net profit is equal to the total income, minus total cost, accumulated. Logically, the aim for the agents is to maximize the profit, which can be archived by either minimizing the cost or maximizing the income.

The above mentioned idea is then being modelled into equations as below,

$$G = P - Q \quad (1)$$

$$P = mD \quad (2)$$

$$Q = wT \quad (3)$$

where, G is fitness profit value calculated from the income, P and the cost, Q with m as the weight of the travelled distance, D while w is the weight of the waiting time, T .

Offset, F	Cycle Time, C	Phase Sequence, o	Green Signal Split, S
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Figure 1. Chromosome structure.

Hence, the proposed optimization scheme enables the cycle time C , green split S , phase sequence o and offset F of each intersection being optimized with traffic delay and fluency consideration.

D. Selection Process

Roulette wheel selection method is the common method employed for selection process. However, literatures state that this method is not feasible to handle traffic problem since it limits the chances of poor chromosome to be selected when the population is dominated by much better chromosomes. Instead, the proposed selection algorithm is the combination of ranking and elitist selection method. In the proposed algorithm, poor chromosome has higher chances to be selected compared to the Roulette wheel selection method. The proposed algorithm ensures that only the highest rated individuals is likely to be chosen and small group of best two individuals are cloned to the next generation. The intention is to preclude similarity of the individual fitness within one generation and prevent good individual from destroy. Elitism accelerates the evolution process of genetic algorithm in searching the fittest solution with the process crossover and mutation to produce new chromosomes where the previous chromosomes information is preserved.

The proposed selection algorithm is designed as follow. The entire individuals will be ranked first. Then, new fitness value is assigned to each individual based on their ranking. Fitness 1 will be assigned to the least fit individual, continue with the second least fit individuals obtaining fitness value of 2 and the best fit will have the number of total population as the fitness value. So, individuals with higher fitness are likely to be selected for reproduction. The two best individuals are guaranteed to be selected so that the best individuals for the next generation will inherit the fitness strength from previous generation. This architecture is very suitable for the proposed traffic problem among a set of selection strategies tested.

E. Recombination Process

During this process, selected individuals will be given chances to exchange genetic information with other individuals to produce offspring via crossover operator with probability, P_c . The proposed crossover strategy is four points crossover, which increase the resolution of crossover operation, so that small changes on the solution can be made.

Crossover operator is designed as a random point at each parameters group will be chosen for crossover. Besides crossover, individual will be given a chance to mutate with probability, P_m . This operator avoids the solution being trapped at local maxima by allowing small changes of deviation to be added to the selected genes. Then the mutated chromosomes will be involved in the evolution process. At the end of evolution process, changes caused by mutation are very

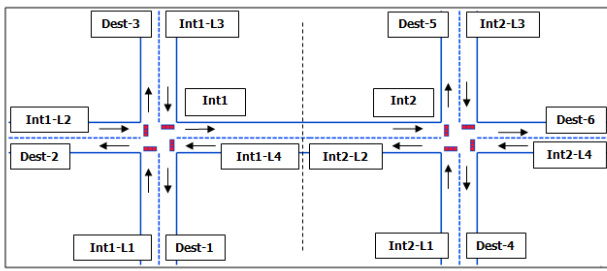


Figure 2. Intersections structure.

small and the solution can be fine tuned to locate the optimum value. The number of points chosen for the proposed mutation process is ranged from 0 to 4, at most 1 in each parameters group.

IV. SIMULATIONS

A. Traffic Intersection

Simulation on the proposed genetic algorithm traffic signal timing plan management (GATSTM) is run on a 2-intersections traffic network which is shown in Fig. 2.

B. Simulation Results

In order to test the performance of the GATSTM, simulations are run and analysis are done by comparing the proposed GATSTM with the conventional signal timing planning which is the fixed time traffic signal timing plan. The simulation is run on an intersection instead of 2 intersections traffic network as the objective of the simulation is to test the performance of GATSTM

The simulations are run with the same conditions which are shown in Table I. A summary of the traffic analysis for both signals timing plan was tabulated in Table II where the first column represents the signal timing evaluated from the proposed GATSTM optimization module and the second one represents the signal timing evaluated from the conventional fixed time traffic signal planning approach.

TABLE I. TRAFFIC PARAMETER FOR PERFORMANCE ANALYSIS

Network Type	1-intersection-4-link-3-lane
Link Flow rate (veh/s)	$g_1 = 0.08$; $g_2 = 0.3027$; $g_3 = 0.144$; $g_4 = 0.177$

TABLE II. PERFORMANCE ANALYSIS FOR GATSTM

Signal Timing	GATSTM	Fixed Time
Total Profit	1889	-437
Total vehicle served	53	39
Average Speed (km/h)	36	18
Timing Plan	Total cycle = 104 s (exclude 16s time lost) Phase sequence = [1 2 4 3] Green split = [14 48 4 38]	

Based on the obtained traffic analysis results for both signal timing plans, GATSTM yielded higher profit, 1889 than fixed time traffic signal plan which produced only -437. Intersection operates under GATSTM will cause lesser delay and better traffic flow than fixed time traffic signal plan. The performance of GATSTM is further convinced by higher total vehicle served which are 53 vehicles and higher average traffic speed of 36 km/h, which are higher than the fixed time traffic signal plan. This implied that traffic delay is lower and more fluent for GATSTM. Thus, the GATSTM is outperforming the fixed time traffic signal plan.

Moreover, the fixed time traffic signal plan is developed for pre-timed control which is unable to adapt into the dynamic changes of the traffic demands with the uncertainty of the traffic network environment unlike the GATSTM which is able to allocate and distribute optimum traffic signal timing plan to the intersection according to the current traffic demand. Hence, signal timing plan evaluated by the proposed GATSTM optimization module performed better than the fixed time traffic timing plan.

V. RESULTS AND DISCUSSIONS

A. Results of Simulations

This section presents the application of proposed GATSTM system to control the traffic network with several traffic conditions as shown in Table III. Performance of the optimized signal timing plan will be analyzed and the control strategy employed by the proposed TSTM system will be discussed each case study. Through the different scenarios in the case study, the performance for the proposed GATSTM system's ability in the dynamic environment of traffic network is further analyzed and studied.

B. Results of CS-1 Simulation

Traffic control system can handle traffic links that have equal traffic demand. In such cases, equal amount of split time could be logically assigned to each links. However, it is quite often when particular links are busier than the others. This study is conducted to investigate the control strategy proposed by GATSTM system and employ to control the traffic when such situation occurs at a particular intersection. Fig. 3 represents the traffic network used for CS-1. In Fig. 3, Int2-L4 defined as intersection 2-lane 4 which is the dominant phase in this simulation where most of the traffic demands is introduced. The traffic condition is treated as an unsaturated traffic network as only 1 of the intersection experience high traffic demand from the road users.

Parameter values as shown in Table IV are used to simulate the results of GATSTM for CS-1. The optimized signal timing and the simulated traffic data were tabulated in Table V.

TABLE III. CASE STUDY FOR TSTM SYSTEM

CS-1	Undersaturated Traffic network
CS-2	Oversaturated Traffic network

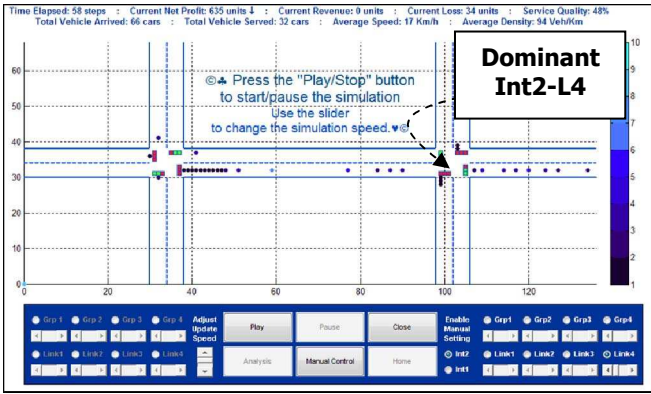


Figure 3. Traffic network for CS-1.

From the results, the control strategy employed by the proposed GATSTM system is successful. Dominant signal group is assigned with a higher green signal as it has more incoming traffic demands while signal group with no traffic demand such as Int1-L4 will not assigned any green signal. GATSTM system recognizes Int2-L4 as dominant link by assigning longer green period to release more vehicles from Int2-L4. Since most of the vehicles in dominant link will eventually sink at Int1-L2, GATSTM system successfully assigned Int1-L2 with green signal of 86% from its cycle time to ensure traffic flow is more fluently from Int2 to Int1.

C. Results of CS-2 Simulation

There are often the cases where traffic demands increase rapidly (oversaturated) and certain destination is more favoured over the others. Such traffic condition can be observed

TABLE IV. TRAFFIC SYSTEM PARAMETER FOR CS-1

Parameter	Value
Link Flow Rate (veh/s)	$g^1_1 = 0.4; g^1_2 = 0.2;$ $g^1_3 = 0.1; g^1_4 = 0;$ $g^2_1 = 0.1; g^2_2 = 0;$ $g^2_3 = 0.2; g^2_4 = 0.5$
Initial Vehicles	$iveh^1_1 = 5; iveh^1_2 = 5;$ $iveh^1_3 = 5$ $iveh^2_1 = 5; iveh^2_2 = 5;$ $iveh^2_3 = 5;$
Destination Probability	$PD^1_1 = [0 \ 0 \ 1 \ 0 \ 0 \ 0];$ $PD^1_2 = [0.2 \ 0 \ 0.05 \ 0.05 \ 0.3 \ 0.4];$ $PD^1_3 = [0.2 \ 0.05 \ 0 \ 0.05 \ 0.3 \ 0.4]$ $PD^2_1 = [0 \ 1 \ 0 \ 0 \ 0 \ 0];$ $PD^2_2 = [0 \ 0 \ 0 \ 1 \ 0 \ 0];$ $PD^2_3 = [0 \ 1 \ 0 \ 0 \ 0 \ 0];$ $PD^2_4 = [0 \ 1 \ 0 \ 0 \ 0 \ 0]$
Local Dominant Signal Group	Int2-L4 $\rightarrow S^2_1$

TABLE V. OPTIMIZED SIGNAL TIMING AND SIMULATED TRAFFIC DATA FOR CS-1

Optimized Signal Timing	
Offset	$\mathcal{F}^2 = 7$
Cycle Time	$\mathcal{C}^1 = 75, \mathcal{C}^2 = 14$
Green Split (%)	$S^1_1 = 86, S^1_2 = 10$ $S^1_3 = 0, S^1_4 = 4$ $S^2_1 = 80, S^2_2 = 2$ $S^2_3 = 0, S^2_4 = 18$
Phase Sequence	$\sigma^1_1 = 4, \sigma^1_2 = 2$ $\sigma^1_3 = 3, \sigma^1_4 = 1$ $\sigma^2_1 = 3, \sigma^2_2 = 4$ $\sigma^2_3 = 2, \sigma^2_4 = 1$
Profit	5445
Average Speed (km/h)	31.06
Average Density (veh/m)	82
Average Flow rate (veh/(m * lane))	2538
Total Served Vehicle (veh)	101
Total Vehicle Arrived (veh)	122

at the beginning of peak hour. Current fixed time traffic signal plan system implemented in most of the area in Malaysia underperforms in such situation and causes severe traffic congestion. Hence, investigation on the reaction of the proposed GATSTM system towards such situation is important to be analyzed. Fig. 4 presents the traffic network used for CS-2, where the peak destination located at Int1-L2 or destination 2 is the final destination of the most traffic demand. The traffic parameter settings are tabulated at Table VI.

From the results shown in Table VII, the control strategy employed by the proposed GATSTM system is discussed as follow. GATSTM releases the link with lowest demand (Int2-L1) to clear the waiting vehicle before the links with higher demand (Int2-L4) is getting crowded. This strategy is working

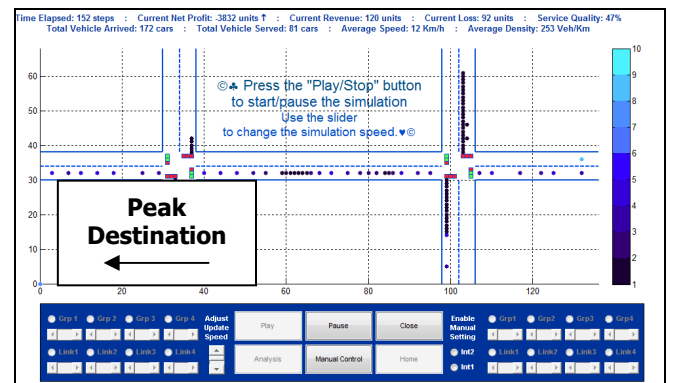


Figure 4. Traffic network for CS-2.

because it allows the queue formed at Int2-L4 when Int2-L1 is released. This ensures that the Int2-L4 will achieve maximum saturation flow rate for releasing more vehicles [10]. GATSTM maximizes the use of green time by releasing vehicle at higher flow rate.

Next, Int2-L4 is treated before the queue getting longer and unmanageable. When time step reached 78, the downstream is going to over saturate as shown in Fig. 5. Queue spillback will occur at that stream if vehicle continue to arrive. Spillback is a phenomena of traffic flow exceeds the capacity of the traffic road and start to accumulate at the intersection causing a hinderance for other traffic phases. Spillback will cause the upstream to be congested and should be avoided in any traffic control. Indeed, management of queue spillback is required especially during the oversaturated conditions [10]. Thus, GATSTM system change the direction of queue build-up by stopping vehicle from Int2-L4 and release vehicle at Int2-L3 to avoid spillback as shown in Fig. 6. For the entire simulation period, no queue spillback occurs under GATSTM's control.

VI. CONCLUSIONS

The implementation of the proposed GATSTM system has been introduced, tested and analyzed. Common signal timing planning strategy such as fixed time traffic signal planning system is used to compare with the GATSTM system. The results show that GATSTM has several advantages over the fixed time traffic signal timing plan system. One of the main advantages is the ability of GATSTM to react toward the dynamic nature of unpredictable traffic network environment.

TABLE VI. TRAFFIC SYSTEM PARAMETERS FOR CS-2

Parameter	Value
Link Flow Rate (veh/s)	$g^1_1 = 0.1; g^1_2 = 0.05;$ $g^1_3 = 0.05; g^1_4 = 0;$ $g^2_1 = 0.3; g^2_2 = 0;$ $g^2_3 = 0.4; g^2_4 = 0.6$
Initial Vehicles	$iveh^1_1 = 2; iveh^1_2 = 2;$ $iveh^1_3 = 2$ $iveh^2_1 = 5; iveh^2_1 =$ $30; iveh^2_1 = 10;$
Destination Probability	$PD^1_1 = [0 \ 0 \ 1 \ 0 \ 0 \ 0];$ $PD^1_2 = [0 \ 0 \ 0 \ 0 \ 0 \ 1];$ $PD^1_3 = [0 \ 0 \ 0 \ 0 \ 0 \ 1];$ $PD^2_4 = [0 \ 1 \ 0 \ 0 \ 0 \ 0]$ $PD^2_1 = [0 \ 1 \ 0 \ 0 \ 0 \ 0];$ $PD^2_2 = [0 \ 0 \ 0 \ 0 \ 0 \ 1];$ $PD^2_3 = [0 \ 1 \ 0 \ 0 \ 0 \ 0];$ $PD^2_4 = [0 \ 1 \ 0 \ 0 \ 0 \ 0]$
Peak Destination	Dest-2

TABLE VII. OPTIMIZED TIMING PLAN AND THE SIMULATED TRAFFIC DATA FOR CS-2

Optimized Signal Timing	
Offset	$\mathcal{F}^2 = 11$
Cycle Time	$\mathcal{C}^1 = 55, \mathcal{C}^2 = 96$
Green Split (%)	$\mathcal{S}^1_1 = 88, \mathcal{S}^1_2 = 0$ $\mathcal{S}^1_3 = 0, \mathcal{S}^1_4 = 11$ $\mathcal{S}^2_1 = 54, \mathcal{S}^2_2 = 8$ $\mathcal{S}^2_3 = 1, \mathcal{S}^2_4 = 20$
Phase Sequence	$\mathcal{O}^1_1 = 1, \mathcal{O}^1_2 = 4$ $\mathcal{O}^1_3 = 3, \mathcal{O}^1_4 = 2$ $\mathcal{O}^2_1 = 1, \mathcal{O}^2_2 = 3$ $\mathcal{O}^2_3 = 4, \mathcal{O}^2_4 = 2$
Profit	-4468
Average Speed (km/h)	12.97
Average Density (veh/m)	211
Average Flow rate (veh/(m * lane))	2738
Total Served Vehicle (veh)	97
Total Vehicle Arrived (veh)	190

In CS-1, GATSTM able to prioritize the dominant signal group that experiencing higher traffic demands than the other signal group by distributing more green signal to the signal group. This ability of GATSTM allows the system to release or serve a total of 101 vehicles out of the 122 arriving vehicles. In addition, the strategy employed by the proposed TSTM system to manage queue spillback during the oversaturated conditions in CS-2 is encouraging the involvement of genetic algorithm in traffic flow optimization in the future. GATSTM prioritize the movements and control the directions of queue build-up to avoid spillback as simulated in CS-2. In short, GATSTM

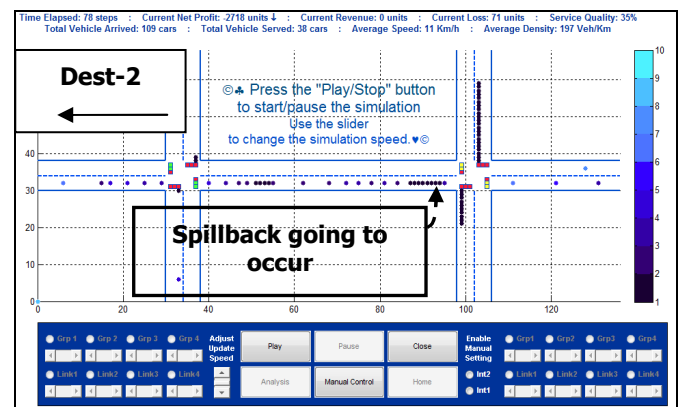


Figure 5. Queue spillback almost occur at downstream.

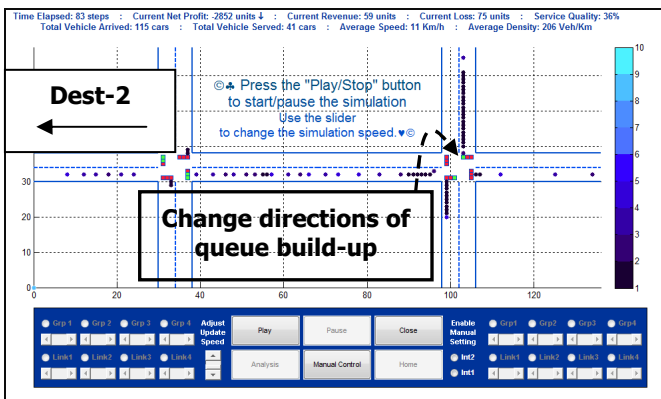


Figure 6. TSTM system change the directions of queue build-up to avoid queue spillback.

system shows higher degree of performance in the traffic flow control of multiple intersections of traffic network.

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