

Multi-agent System based Urban Traffic Management

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Abstract—Road Traffic congestion can occur anywhere from normal city roads, freeways to even highways. Traffic congestion can also be accentuated by incidents like terrorist attacks, accidents and breakdowns. This paper summarizes the use of various evolutionary techniques for traffic management and congestion avoidance in Intelligent Transportation Systems. Evolutionary algorithms with their inherent strength as optimization techniques are good candidates for solutions to road traffic management and congestion avoidance problems. A number of approaches involving the use of Genetic algorithms, Learning Classifier Systems and Genetic Programming have been discussed for solutions to different problems in this domain. This paper proposes a multi-agent based real-time centralized evolutionary optimization technique for urban traffic management in the area of traffic signal control. This scheme uses evolutionary strategy for the control of traffic signal. The total vehicle mean delay in a six junction network was reduced by using evolutionary strategy. In order to achieve this the green signal time was optimized in an online manner. Comparison with a fixed time based traffic controller has been made and was found to produce better results.

I. INTRODUCTION

Intelligent transportation Systems vary in technologies applied, from basic management systems such as car navigation, traffic light control systems, container management systems, variable message signs or speed cameras to monitoring applications such as security CCTV systems, and then to more advanced applications which integrate live data and feedback from a number of other sources, such as weather information, bridge de-icing systems, and the like. Additionally, predictive techniques are being developed, to allow advanced modeling and comparison with historical baseline data. Interest in Intelligent Transportation Systems also comes from the problems caused by traffic congestion worldwide and a synergy of new information technologies for simulation, real-time control and communications networks. Traffic congestion has been increasing world-wide as a result of increased motorization, urbanization, population growth and changes in population density. Congestion reduces utilization of the transportation infrastructure and increases travel time, air pollution and fuel consumption. Evolutionary computation methods offer solutions for management of traffic networks and also augment other approaches in real time control of smooth flow of traffic. The paper has been organized into six sections.

Section II discusses about the application of different evolutionary approaches to the problems of congestion avoidance and urban traffic management. Section III discusses the motivations for the paper. Section IV discusses the idea of using evolutionary strategy for traffic signal optimization, simulation and results. Section V contemplates on the open research areas. Section VI concludes with a discussion on what has been proposed.

II. EVOLUTIONARY TECHNIQUES APPLIED TO ROAD TRAFFIC MANAGEMENT

Evolutionary techniques work well with reinforcement learning, multi-agent systems and rule based systems in urban traffic management. The applications include traffic signal control, freeway ramp metering and hazard response systems. This section discusses the various approaches using evolutionary techniques that have been employed for traffic management.

A. Evolutionary Techniques with Reinforcement Learning

Genetic algorithms coupled with reinforcement learning can effectively adapt to the congestive traffic environment and subsequently improve traffic volume. Traffic signal control optimization with the objective of maximizing the total traffic volume is a complex problem. This problem was presented as a multi-agent type real-time planning problem in [1], with no explicit model given. The problem also presented the difficult trade off between cooperation and autonomy of planning agents. To illustrate this, if each signal determines its phases (green, yellow, or red) from only its local traffic flow sensor, traffic congestion may easily occur over the whole area because the improvement of the local traffic flow is not directing to cooperate with the other signals. The other possibility is that each signal simultaneously communicates with others concerned and controls its phases according to the change of global traffic flow. This leads to the total traffic volume of the area well optimized. In traffic control problems, however such frequent communication and a large scale real-time planning is not available because the number of signals is usually large. This large scale real-time planning can be realized by
letting each signal learn through reinforcement learning and acquire long-term cooperation through the combinatorial search by genetic algorithms.

Using the approach discussed above in [1] the periodic modification of parameters for reinforcement learning for different signals was done by a central controller. The central controller received a cumulative performance evaluation for the local agent after a certain period. After receiving the performance evaluation from all agents, the central controller prepared a new parameter set to improve global performance and transmitted them to each of the signals. Genetic Algorithm (GA) was used by the central controller to find good parameters and the next population of parameter sets was prepared. The GA was able to find robust parameters for dynamically changing traffic environments. The rate of improvement for each learning agent also increased after the genetic search had been saturated.

Another interesting approach which combines both reinforcement learning and evolutionary computing techniques is Learning Classifier Systems (LCS) which is described in [2]. Learning Classifier Systems (LCS) can be used for optimization in a way that holds promise for application in adaptive traffic-responsive signal control. Traffic signal control should be sufficiently flexible to respond rapidly when traffic conditions change in a fundamental way. An example of this is at the start of a peak period, without being unduly sensitive to short-term variations in flow. A combination of reinforcement learning and evolutionary computing techniques forms a good candidate for a solution to this problem. Learning Classifier Systems (LCS) offer the automated rule development in the same way as neural networks. Additionally they provide the transparency of production system rules. The importance of this approach for traffic control is that it offers a means by which signal control strategies can be developed directly according to their performance and also be evaluated using detailed microscopic simulation. This closed-loop approach to the development of control strategies offers several advantages over traditional explicit optimization formulations. These include flexibility in respect of objectives so that multiple and varying needs can be accommodated, ability to use various different kinds of detector data according to their availability, and freedom from dependence on a single explicit evaluation formula that is intended to embody the whole of a traffic model.

The simulator that was used in [2] represented a small network of four crossroads junctions, each controlled by a separate set of traffic signals. Two kinds of Classifier systems ZCS [3] and XCS [4] were tested as individual junction controllers. The size of the rule-bases, parameters of the evolutionary algorithm like mutation rate and the learning rate for reinforcement learning were varied and their effects were studied. XCS has been found to perform better than ZCS in all cases tested here. Neither ZCS nor XCS contained explicit mechanisms by which they could consider the context of the current stimulus from the environment. In view of this, the utility of incorporating mechanisms aimed at enabling XCS to maintain internal memory - rule-linkage and the memory register - in the distributed road traffic junction control task to further improve performance were studied. These mechanisms were found not to aid performance. Various parameters like reward function and objective function for the LCS were varied in order to compare it to already established approaches. The XCS was found to give a lesser mean delay time than the conventional approaches.

B. Self-organizing multi-agent Systems

Another approach to the problem of traffic management is given in [5]. This paper presented a cooperative, hierarchical, multi-agent system for real-time traffic signal control of a complex traffic network. The traffic signal control problem was divided into various sub-problems due to its large scale. An intelligent agent with fuzzy neural decision-making module handled each sub-problem. The decisions made by lower-level agents were mediated by their respective higher-level agents. A cooperative distributed problem solving approach aiming to achieve coordinated control by the agents was achieved. The multi-agent architecture had to adapt itself continuously to the dynamically changing problem domain. For this a multistage online learning process for each agent was implemented involving reinforcement learning, learning rate and weight adjustment. It also included a dynamic update of fuzzy relations using evolutionary algorithm. In this paper, the evolutionary algorithm performed the fuzzy rules adjustment process online. This was done throughout the running of the simulation in order to accommodate possible fluctuations of the system dynamics. New fuzzy relations were generated by the evolutionary algorithm fuzzy relation generator (EAFRG) based on the reinforcements received by the agents, thus changing the knowledge representation for each agent as the traffic network evolves.

Hercog [6] introduced a system where heterogeneous agents, learnt from traffic reports, co-evolved and produced traffic self-organization using inductive reasoning. Inductive reasoning is one of the best solutions to solve ill-defined problems where formulation of a mathematical model is not trivial. This paper introduced a model based on a multi-agent system that learns using an extended classifier system (XCS) known as MAXCS. This system was implemented in Mexico City. MAXCS is a multi-agent system that learns using a Learning Classifier System (LCS), with each agent is represented by an XCS. LCSs learn by evolving simple strings encoded as if-then rules using a genetic algorithm (GA) and a Reinforcement Learning Algorithm (RLA) in the paper to determine the usefulness of the rules. The RLA is used to update the rules’ fitness that is the reward that the rule generates when it is activated by the state that the system perceives from the environment. XCS [4] is a LCS that uses three parameters to measure a classifier’s usefulness: the prediction of the reward, the error of the prediction and the fitness. The fitness of the rule is an
inductive reasoning with evolutionary reinforcement approach was exciting due to the fact that it combined reward received, rather than the tolerance of the agents. This authority suggests, the avenue usage depended on the most of the agents did not pay attention to what the agents), the comfort threshold in the avenues is achieved. As what the authorities suggest (heterogeneous less-tolerant authorities (homogeneous agents) or they are less tolerant to the agents paid attention to the suggestions made by the mode to improve).Experimental results showed that when all the agents paid attention to the suggestions made by the authorities (homogeneous agents) or they are less tolerant to what the authorities suggest (heterogeneous less-tolerant agents), the comfort threshold in the avenues is achieved. As most of the agents did not pay attention to what the authorities suggest, the avenue usage depended on the reward received, rather than the tolerance of the agents. This approach was exciting due to the fact that it combined inductive reasoning with evolutionary reinforcement learning.

C. Evolutionary programming for optimizing rule sets

Ramp metering control is an effective way to reduce freeway congestion. It involves varying the number of vehicles on the freeway sections according to the load. In early stages of ramp metering control implementation, it was commonplace to have fixed metering rates that were based on the set of recurring demands. In the event of accidents or sudden thin traffic, the traffic flow would remain the same. An effective metering system would be responsive to the conditions prevalent in the global traffic network. An evolutionary addition to this rule based approach would be ideal to solve this kind of problem. A technique which applied evolutionary programming to the rule based ramp metering control strategy is presented in [7]. It allowed for optimization of freeway ramp metering rates to maximize total freeway throughput. The rule based ramp controller took into account feed forward information from the upstream sensors and feedback information from the downstream sensors and then adjusted the metering rates. It also took into account adjacent freeway occupancy levels. The initial controller parameters are encoded in the form of a vector. The vector was then evolved according to the conditions prevailing in the traffic network.

A parallel implementation of evolutionary programming for evaluating ramp metering control strategies was undertaken because even with an initial population of 10 and over a small run of 100 generations large amounts of resources were needed. The experiments were carried out in INTRAS (Integrated Traffic Simulation) a sophisticated traffic simulation model. The technique was applied to a uniform freeway segment without any ramp queues and surface street congestions. A number of scenarios simulating high and moderate freeway traffic load, with and without accidents were studied. The measure of effectiveness was the total number of vehicles exiting the system in an hour. A rise in the number of vehicles exiting the system was observed over the normal fixed metering rates case in different scenarios. An important observation made was that maximizing the total traffic throughput did not always yield the best results for total vehicle-miles, total vehicle-minutes, average speed, and delay.

D. Evolutionary Algorithms for optimizing cellular automata

Another aspect of the problem of urban traffic management is traffic management of transportation systems under emergency conditions. Transportation systems operating under emergency conditions evacuation conditions exhibit behavior that is quite different from typical modes of transportation systems operations. It has been argued in [8] that the approach to model, analyze and optimize such systems is very different. Cellular automata with agents have been successfully used to model self-organizing behavior in many practical systems. They carry substantial promise for modeling the behavior of traffic management and hazard response systems. Effective operational strategies can be developed for robust hazard response systems using Cellular Automata (CA). Evolutionary algorithms can be used to identify optimal CA models in vast solution spaces, which are shown in [8]. A self-organizing traffic management hazard response system with states of traffic signals within several signal blocks can be represented as a two dimensional Cellular Automata. The spatial (north-south-east-west) relationships among elements of the traffic control systems and their relative distances (1 block away, 2 blocks away, etc) can be represented explicitly by the cells of the CA.

A model for the above system was represented in a computer system called Emergent Designer. The cellular automata representation of a simple urban traffic network was developed and combined with an evolutionary algorithm. The evolutionary design process came up with solutions which consisted of initial configurations of traffic signal states and two dimensional CA rules which updated the configurations of traffic signals at multiple phases of the traffic simulation process. The number of vehicles which left
the affected area during the course of simulation as well as the total travel time of vehicle in the allowed area was a measure of fitness. These measures provided a feedback for an evolutionary algorithm and defined the quality, or fitness, of solutions, produced during the evolutionary design process. In order to evaluate the scheme a simple transportation network of an urban area spanning several city blocks was developed. Several simulations were performed to identify effective evolutionary strategies for this urban area. It was found that there was a reduction of total travel time between the initial and final solutions generated by the evolutionary design process. This work stood out for the uniqueness of its approach and the problem it solved.

E. Evolutionary algorithms for real-time vehicle guidance and signal phasing

Real-time route guidance is a promising approach to alleviating congestion on the highways. Dynamic traffic assignment models are extremely important for the development of guidance strategies. Genetic algorithms (GAs) are used to provide a solution to the dynamic traffic assignment model developed for a real-world routing scenario in Hampton Roads, Virginia [9]. The results of this GA approach are presented and discussed, and the performance of the GA is compared with an example of commercially available nonlinear programming (NLP) software. GAs offered certain tangible advantages when used to solve the dynamic traffic assignment problem. GAs allowed solving the problem analytically by the relaxation of many of the assumptions that were needed by traditional techniques. GAs also handled problems of larger scale than some of the commercially available NLP software packages were unable to. This approach demonstrated the feasibility of GAs to solve dynamic network flow modeling problems when applied to the field of road traffic management.

The use of a genetic algorithm to find a good assignment of signal control stages to links in the traffic network for TRANSYT (Traffic Network Study Tool). TRANSYT tunes its optimum settings by a ‘hill climbing’ process. The optimizer systematically altered signal offsets and/or allocation of green times at signals to search for the timings which reduce the Performance Index to a minimum. Minimum green time at a signal and other constraints were also taken into account. During the genetic process, the partially matched crossover operator and exchange mutation operator maintained the feasibility of the sequence of evolved phases. This paper demonstrated the possibility of using GA in the optimization of Signal Phasing in the area of traffic signal control.

III. MOTIVATIONS

Usually a model depicting the dynamic nature of traffic is desired. This model has to take into account the phase considerations and the influence of previous occurrences on traffic flow. A dynamical traffic flow model of a single two-way intersection with multi-lanes was proposed in [11]. The traffic lights at the signal intersection had four phases. This model focused on the dissipation and formation of retained vehicles in the different lanes at the end of different phases. The problem tried to minimize the number of vehicles retained at a traffic junction by optimizing the time for which the green light becomes on in the different phases. Usually the time for which the green light becomes on is fixed. A real coded genetic algorithm (RGA) was used for optimization of the signal timing i.e., the time for which the green light becomes on. The use of RGA eliminates the process of encoding and decoding as required by a binary GA thereby reducing the complexity. For solving the problem, the arrival of vehicles at a traffic intersection was taken to be a Poisson distribution. The results obtained by applying the RGA were found to show a marked improvement over the fixed time control of signals.

The approach discussed above was shown for a single four phase signal junction. The application to a large scale traffic junction network was not shown. The complexity of the method increases as the number of junctions increase. This paper builds upon the work in [11] to present an efficient solution to the problem when applied to a large scale traffic network.

IV. EVOLUTIONARY STRATEGY BASED APPROACH

The problem of urban traffic congestion has been experienced worldwide. Delay time on the road has a direct relationship with the number of accelerations and decelerations of the car with in the network. By reducing delay time, we can also reduce the fuel consumption. The emission of green house gases can also be reduced. This work seeks to provide an extension to the approach by [11] developed for queue reduction in a single intersection to a larger network having six intersections. The objective function has been modified to reduce the total delay time of the vehicles in the network. The method employed was a centralized control based multi-agent system with each junction acting as an agent. The agents serves to collect the data from the network in real-time and give it to a centralized controller. The centralized controller, the optimum value of the green timing in each phase of the junction is evolved. This green time can reduce the overall delay experienced by the vehicles in the network.

The attractiveness of this approach to traffic management is the real-time evolution of the green signal values. This makes the approach adaptive. Another most important advantage is the online learning capacity of the system. The system adapts itself based on the fitness value calculated from the dynamic traffic flow model.

A. Problem Formulation

The traffic network considered here for the evaluation of the evolutionary strategy based centralized traffic signal control was a typical Manhattan type network with six intersections each of which are signalized. All approaches to
the intersection are two way. All the links are major link type with each link having three lanes. Fig.1 shows the outline of the entire network. Fig.2 shows a single intersection with all the lanes. For simplicity in evaluation of traffic in each lane, it was assumed that each lane allows one directional movement only. This was to avoid the ambiguity of signal phase synchronization and order of phases’ issue. Fig.2 shows the typical distribution of flow in an intersection. The number of phases was restricted to four. The sequence of phases was maintained the same order and no attempts were made to change the signal phasing sequences as this would complicate the entire problem and fitness function design for such a case would be difficult.

**B. Fitness Function**

The traffic signal intersections are influenced by the conditions that were prevalent in the previous state. This necessitates a method to take into consideration the traffic flow rate say in the previous N cycles and utilize them to predict the condition of traffic. The number of vehicles in a queue along any lane of a link will depend on the flow rate of the vehicles under prevalent conditions and also the saturated flow rate.

Saturated flow rate can be defined as the flow rate with which vehicles will pass the intersection, if the green light of the signal were to be on condition for a long period of time. This gives us a realistic estimate of the maximum number of vehicles that could flow under the existing conditions of the link. The saturated flow rate calculation is complex and depends to a great extent on the saturated headway between vehicles. Usually for a saturated headway of 2 seconds, the saturated flow rate in a major link is calculated as approximately 1900veh/hour. This value was used throughout for all the lanes in all links as it has been accepted widely.

Based on the discussions above regarding saturated flow rate it can be seen that the number of vehicles that are made to wait at the intersection can be given as the product of difference in the arrival flow rate and the saturated flow rate of the lane (having the green signal) and the green time for each corresponding phase.

\[
Q_{sijk}^l = q_{sijk}^l - \left( \mu_{sijk}^l \ast \lambda_{sijk}^l \right) \ast \frac{g_i^l}{sijk}
\]  

Where \(Q_{sijk}^l\) is the queue length formed after \(S = 1..10\) (number of cycles), with \(i=1,2,3,4\) (phases), \(j=1,2,3,4\) (number of links) and \(k=1,2,3\) number of lanes. \(l\) represents the cycle, \(q_{sijk}^l\) is the arrival rate of vehicles corresponding
to the lane, link, phase and sample period. \( \lambda_{sijk} \) is the saturation flow rate for the lane \( k \). The value of \( \mu_{sijk} \) depending on the signal condition corresponding to the particular lane. It is 1 if signal was green and 0 otherwise. \( g_i \) is the value of green time corresponding to the phase.

So the problem becomes finding the value of green time that causes the overall queue to be reduced in every junction.

\[
\sum_{i=1}^{N} \sum_{k=1}^{J} \sum_{l=1}^{I} \max \left[ 0, \frac{1}{N} \sum_{j=1}^{J} g_{ijk} - \left( \mu_{sijk} \lambda_{sijk} \right)^* g_i \right] = \text{(2)}
\]

Equation (2) gives a clear picture of the total queue length that needs to be minimized by utilizing the evolved values of green time. For avoiding the fitness function from becoming negative and to convert it into maximization problem the final fitness function can be written as shown in (3).

\[
M - \sum_{i=1}^{N} \sum_{k=1}^{J} \sum_{l=1}^{I} \max \left[ 0, \frac{1}{N} \sum_{j=1}^{J} g_{ijk} - \left( \mu_{sijk} \lambda_{sijk} \right)^* g_i \right] = \text{(3)}
\]

Where \( M \) is a large value typically of 1000000.

C. Simulation & Results

Evolutionary strategy was used for the evolution of the green time. This method was used over GA as it is best suited in applications that involve real valued functions. It can directly use these functions. Moreover the selection is influenced only by the fitness function and no probabilistic approach is employed. This increases the speed of convergence as it is one of the critical necessities of the application. \( \mu + \lambda \) strategy was employed here. This strategy is used because the better individuals are retained for a larger span of generations.

The inputs to the chromosome were the green signal timing corresponding to each of the intersection. The structure of the chromosome is depicted in Fig.4. Only mutation was used and no crossover was employed. The mutation performed was standard mutation using self-adaptive mutation parameters.

A population size of 7 was used and the number of offspring’s produced was 49. The green time value of the chromosome was restricted between 7 and 60 seconds. The upper bound on the cycle time was 260 seconds. No lower bound was kept as the minimum green time would ensure a large enough cycle time.

The flow of the evolutionary strategy is as given below.

1. Initialize the size of population to be 7
2. Initialize the parent chromosome with green time values between 7 and 60 seconds. Set the adaptive mutation sigma parameter to be between 1 and 10 seconds.
3. Calculate the fitness value of the parents.
4. Increase the offspring size to seven times of population size.
5. Perform the mutation over the sigma parameter
6. Mutate the green time stored in the chromosome using the mutated sigma values
7. Calculate the fitness values of offspring chromosome
8. Compare and select the best seven individuals from parent and offspring and introduce back into the loop.

The termination criterion used was 100 generations. This is a practically feasible operation as other criterions would increase the run time indefinitely and when the green time are evolved, it may not be optimum solution at that point as longer time would have lapsed. The total runtime was for six hours. PARAMICS software was used for the simulation of the traffic condition and MATLAB was used for running the evolutionary strategy algorithm.

Fig.5 shows the comparison between the delay time when the simulation was conducted with and without the agent. It can be seen from the plot that the simulation run with agent running in the background produced better results. It can also be seen that during the initial period of simulation the delay in the vehicles are the same for the run with and without simulation.

The evolution of the green time was performed by sampling the real world data for a period of 10 minutes. During this period both the algorithms run using the green time value and hence show similar pattern. It can also be seen that in simulation run without agent, the total vehicle mean delay keeps increasing. The variation produced was narrow because of the traffic demand pattern assumed but it can be positively verified from data that the delay keeps increasing. When the agent was present the delay kept decreasing. A maximum of twenty percent reduction in the delay time was noticed. This is a considerable increase. The reduction in the delay time was due to the optimized value of green time evolved.
VI. CONCLUSION

The availability of large number of literatures on application of evolutionary computational techniques to traffic management gives us a good overview of its potential. In this paper we have attempted to exploit the advantage of evolutionary techniques when applied to six junction network green signal optimization. Evolutionary technique that can perform a combined optimization of signal phasing offset and timing is one of the future research works to be carried out. Heuristics based and reinforcement learning based evolutionary techniques are still in its primitive stage of development and could lead to a plethora of opportunities for research in future.

REFERENCES