

Research Article

A Regional Coordinated Signal Control Method Based on Game Theory

Ke-Cheng Xu, Jian-Ming Hu and Yi Zhang

Department of Automation, Tsinghua University, Beijing, 100084, China

Abstract: Signal control for multi-intersections is a hot issue in traffic research. Intelligent Vehicle and Infrastructure Coordination System (IVICS) helps us to develop much more accurate and effective signal control strategy. This study presents a system with a new algorithm to optimize the control strategies. This system collects the data in real time and develops strategies in the form of game tree. The evaluation algorithm for the control strategy of each intersection is put forward. And then a new regional coordinated signal control strategy is proposed based on game tree theory. The global optimal strategy can be obtained from the gaming of all the intersections. In other words, all the intersections acquire the optimal set of control strategies when each intersection acquires their own optimal strategy. This study utilizes VISSIM to verify the proposed algorithm. Compared with that of the fixed cycle control system, the simulation study implemented in a road network with five intersections shows that the proposed algorithm is effective in coordinating multiple intersections, especially when the traffic flow density is mean or close to the saturation.

Keywords: Game tree, game theory, IVICS, signal control

INTRODUCTION

In recent years, Intelligent Vehicle and Infrastructure Cooperation System (IVICS), also named as VII (Vehicle Infrastructure Integration) has become a research hot topic in Intelligent Transportation Systems. IVICS is composed by RSUs(Road-Side Unit) and vehicles equipped with OBU (On-Board Unit), which can sense and transmit local traffic parameters to RSU by wireless multi-hop communication. It may provide a brand new idea for traffic control because more precise, accurate and fine-grained vehicle and traffic information can be obtained, communicated and shared among vehicles and roadside infrastructures.

Also we notice that as a successful theory in economics, Game Theory considers individuals related with each other as intelligent agents and analyzes the influences between individuals to find the balanced point. A lot of researchers have shown great interests in how to introduce it to the transportation and traffic engineering, such as route guidance (Anastasios and John, 1991; Eitan *et al.*, 2001; Jeffrey and Victor, 2002), traffic modeling (Fisk, 1984, 1986; Hai, 1995; Michael, 2000; Kita *et al.*, 2002; Lian-Ju and Zi-You, 2007), signal control (Hai, 1995; Owen and Moshe, 2007), risk and security (Francesca, 2007). Compared to the fruitful work in traffic modeling, the collaboration between signal control and Game Theory is relatively less. The major difficult for signal control is that how to design the evaluation function which can represent and evaluate

the complex mutual influences among intersections. Without this function, we can't evaluate the signal control strategies with a unified standard and as a result, we cannot find the optimal one.

This study utilizes Game Theory as the analyzing method, proposes an evaluation function for intersections and demonstrates a new multi-intersection signal control mode based on IVICS information. And this study focuses on a five-intersection area and evaluates the influences among all the intersections and discusses how they coordinate with each other. All the intersections can get the optimal control strategy based on different traffic conditions.

THE MODELING OF SIGNAL CONTROL BASED ON GAME THEORY

This study is based on IVICS information. Five intersections are included in the research area. To simplify the study and validate the efficiency of the proposed signal timing algorithm, we merely focus on the traffic control for vehicles and ignore the pedestrians, bicycles and U-turn vehicles. Besides, there are only red light and green light in each cycle length. No protected left-turn phase is discussed either.

Considering the driving behavior, minimum green time and maximum green time in each phase are defined for each intersection in order to realize green extension and to make sure the vehicles go through the intersection smoothly and safely as well.

Corresponding Author: Jian-Ming Hu, Department of Automation, Tsinghua University, Beijing, China, California PATH, ITS, University of California, Berkeley, 94704, CA, Tel.: (+86)13683278978

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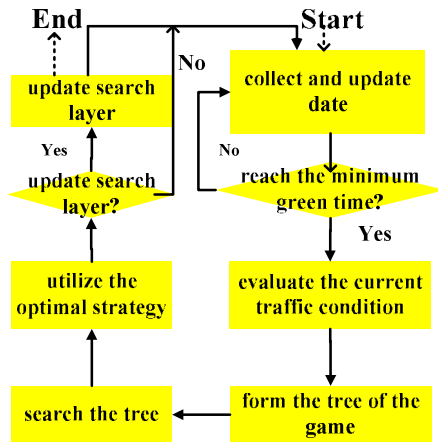


Fig. 1: The flow chart of the signal control strategy optimization based on game tree

If the signal control is regarded as a decision-making process, a signal control model is designed to determine whether to extend the green time or not. Therefore, the process of traffic signals can be considered as a sequential decision-making process in some sense. For the circumstance of multiple intersections, the process of signal control can be treated as a game.

Each intersection can be considered as a player. The decision of each player is to extend the green time of its current phase or change phase according to the game evaluation function which will be discussed in the next section. For the sake of convenience, we choose an intersection as the “target intersection” to control and call the game intersection which has influences on it as the “relative intersection”.

Assuming the signal timing of the current intersection is at phase i and the moment has passed the minimum green time, then the current intersection starts the process of the game and calculates the game equilibrium solution. Certainly, if the minimum green time is not reached, the target intersection should keep waiting.

When the used green time is larger than the minimum green time, the game-tree-based decision process is called. This process can be regarded as a combination of a series of sequential decisions. During the period of decision, the intersection makes its decision in each time unit. Since the decision of the target intersection should consider all the decisions of the other intersections in the games simultaneously, the sequential decision during the decision time is a process of repeated game. If an optimal strategy at a moment is to switch the phase, then the decision process stops and gets into the decision process of the next phase. If the optimal strategy of the decision sequences is still to extend the green time after reaching the maximum green time, then the intersection will switch to the next phase automatically and terminate this decision process.

As time goes, we can get payoffs of all the combinations of strategies from the current time to the end time. This tree composed of the payoffs is defined as a game tree for regional coordinated traffic control.

When the conditions mentioned above are all satisfied, the strategy of the target intersection must be the best because it can get the payoffs of all the combinations of strategies no matter which strategies will be taken by other intersections. The target intersection can always obtain the optimal strategy by backtracking in the game tree.

The control strategy of coordinated signal control system for multiple intersections based on game tree theory is shown in Fig. 1.

Once reaching the decision time, the system will evaluate the current condition with the evaluation function and then develop the game tree according to the searching time and the number of the searching layers to get the payoffs after the expected time. Furthermore, we can backtrack in the game tree to get the optimal strategy. Finally, the optimal strategy is carried out and the data is updated in real time.

COORDINATED TRAFFIC SIGNAL CONTROL STRATEGY BASED ON GAME THEORY

Regarding Game Theory, it is the first and the most important step to define the game players, evaluation function and equilibrium solution.

As is mentioned in section 2, in this study, all the five intersections are game players. And the intersection decides whether to carry out the strategy or not by synthetically considering the possible change of the evaluation function value before and after taking it. The equilibrium of a game is defined as the combination of all the optimal strategies for all the players. We can get each player’s optimal strategy by game tree.

Now, let’s discuss how to get the evaluation function. The evaluation function is determined by two aspects. One is the evaluation value of the target intersection at that decision moment. This evaluation value is usually used to decide green extension or phase change. Green extension can get a higher evaluation value when the queue and delay are long in the current phase. The other is the influence of the adjacent intersections on the target intersection. This influence is mainly determined by the offsets. The more appropriate the offset is, the higher the evaluation value will be.

Denote the evaluation function as $F(\cdot)$, the current phase as i and the next phase as $i+1$. The green queue length for each lane in phase i can be formulated as Eq. (1):

$$L(t + \Delta t) = \max \left\{ \left[L(t) + \sum_{k=1}^{\Delta t} q(k) - s \times \Delta t \right], 0 \right\} \quad (1)$$

where, $L(t)$ is the existing queue length, $q(k)$ is the arrival rate of vehicle in one time unit (such as 1 sec), s is the flow rate of the leaving vehicles in green time, assuming s is a constant in the current phase.

Similarly, the queue length of red lane in phase i is:

$$Q(t + \Delta t) = Q(t) + \sum_{k=1}^{\Delta t} q(k) \tag{2}$$

where,

Q(t) = The queue length of the original vehicles at the moment t

Taking an intersection with four phases in one cycle as an example, the intersection needs to decide whether to extend the current green time or not at the moment t, the green queue lengths in phase i+1, i+2, i+3 all have influence on the current decision, but the influence becomes weaker as the number of phase gets bigger.

The change of the queue length at a certain place apparently cannot thoroughly reflect the current traffic condition, so we define an equivalent queue length in this study. The equivalent queue length can reflect the changing trend of the current queue length. The equivalent queue length is shown in Eq. (3):

$$F(g) = \frac{L_i + \sum_{n=1}^3 Q_{i+n}}{u(g)} \tag{3}$$

where, L is the green queue length at current phase, Q+ is the red queue length (queue length on red). u(g) is the related occupancy rate which can be calculated with Eq. (4):

$$u(g) = \frac{u_i}{u_{i+1} + \alpha u_{i+2} + \beta u_{i+3}} \tag{4}$$

where, $\alpha = 0.7$ and $\beta = 0.3$ in this study. Equation (4) represents the different influences of queue length in different phases.

On the other side, on the red lane (the lane in which the traffic light is currently red), even though the queue length is fairly short, there are still some vehicles waiting too long, which will surely annoy the drivers. So we need to count the number of the vehicles having waited for a long time and define the number as N_{red} , which will have an influence on the decisions of intersections. So, the equivalent queue length can be calculated with Eq. (5).

$$F(g) = \frac{L_i + \sum_{n=1}^3 Q_{i+n} - \mu N_{red}}{u(g)} \tag{5}$$

where, $\mu = 0.5$ in this study, which represents the influence weight.

In addition to the queue length, the used green time will also affect the evaluation value. For example, if the used green time just exceeds the minimum green time, the intersection has a great probability to continue the current phase. On the contrary, if used green time is almost close to the maximum green time, the probability of changing phase will be higher.

In this study, the influence value of the current green time is defined as the following expression.

$$I_{green} = \begin{cases} e^{\frac{t_{current}}{t_{max,green}}}, & t_{current} \geq t_{mingreen} \\ e^{\frac{t_{max,green} - t_{current} + 1}{t_{max,green}}}, & t_{current} < t_{mingreen} \end{cases} \tag{6}$$

So, the equivalent queue length can be calculated with Eq. (7):

$$F(g) = \frac{I_{green} \times \left(L_i + \sum_{n=1}^3 Q_{i+n} - \mu N_{red} \right)}{u(g)} \tag{7}$$

Furthermore, we talk about the influence value of the adjacent intersections on the target intersection. The influence value can be divided into two parts. One is the green time of the adjacent intersections in the current phase. The longer it is, the bigger the flow rate will be. The other is the evaluation value of the current offset. The evaluation value reflects the coordination level. The influence value can be seen as the influence on the future queue length of the target intersection. The influence value of the adjacent intersection can be calculated according to Eq. (8):

$$G(g) = C \times t_{green}^{0.5} \times \frac{t_{i \rightarrow j} - t_{green} - \varepsilon}{t_v} \tag{8}$$

where,

- t_{green} = The current green time of the adjacent intersection
- $t_{i \rightarrow j}$ = The time lag
- ε = The offset and is set by the system
- t_v = The travel time from the adjacent intersection to the target intersection

If $t_{i \rightarrow j} - t_{green} - \varepsilon$ is less than 0, then

$$G(g) = C \times t_{green}^{1.05} \times \frac{t_{i \rightarrow j} - t_{green} - \varepsilon + t_{cycle}}{t_v} \tag{9}$$

where,

t_{cycle} = The average cycle for the current traffic condition

To sum up, the evaluation function can be expressed as Eq. (10):

$$f(g) = \frac{F(g)}{G(g)} \tag{10}$$

SIMULATION AND RESULTS ANALYSIS

Simulation environment based on VISSIM: A road network with 5 intersections is established by using

Table 1: The flow parameters set in simulation

Traffic flow status	North	South	West	East
Low	750	700	750	700
Mean	1800	1800	1800	1800
High	3200	3200	3200	3200

VISSIM. The central intersection is chosen as the target intersection and adjacent four intersections are relative intersections.

VISSIM provides two methods to collect data, i.e., collecting with Data Collection and collecting from Port Com. In this simulation, we utilize Port COM to acquire the average travel time while utilize Data Collection to acquire average delay.

In this study, Visual Basic (VB) is applied to obtain and process the simulation data and store them into the database because the API interfaces of VISSIM have better compatibility with VB. Meanwhile, since the data processing speed of VB is rather slow, we utilize Visual C (VC) to extract the data from the database and calculate the proposed algorithm. VB gets the optimal strategy from VC by loading the dynamic link library and controls the signal in simulation with this strategy.

It is the most important to build and search the game tree for the algorithms in VC. As each intersection has two options, extending green time and switching phase, for a five-intersection network, there are 32 different kinds of strategies, i.e., each node in the game tree has 32 branches towards the next layer. Note that the time cost of searching for the optimum in a 32-branch game tree is relatively expensive, it's very important to simplify the tree. When making decision for each second, every intersection only needs to predict the very short next period of time, which only needs to be about a quarter of a cycle time and in this study is 15 seconds. In this period, we can assume that the signal will change phase no more than once. So if one node of the game tree is to change phase, we don't need to take

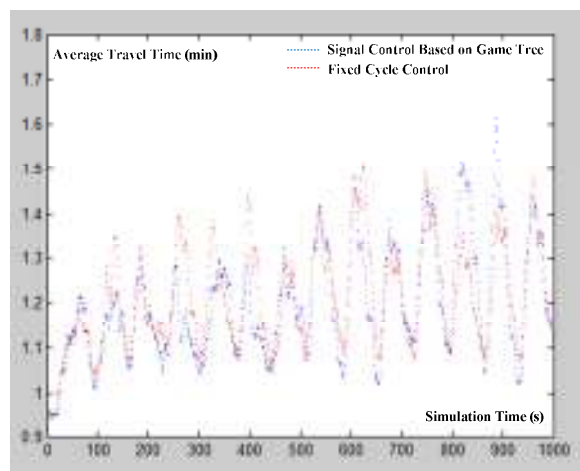
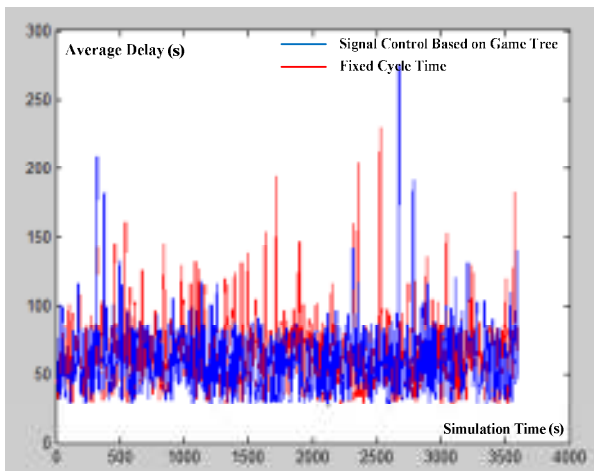
its child-nodes into consideration, which simplifies the tree greatly.

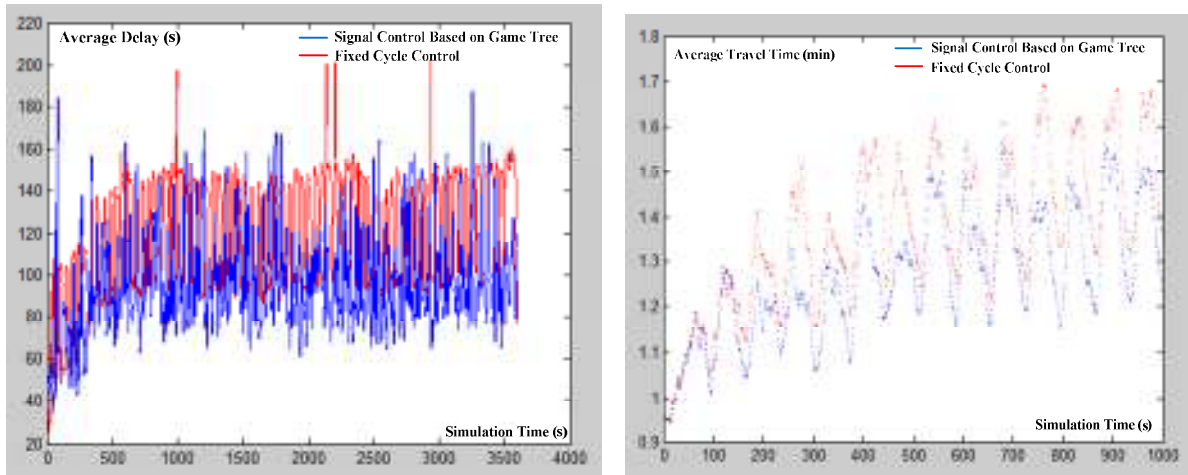
Simulation results and analysis: In General, the saturation flow density for a network is 3600 veh/h. This study presets the flow parameters as shown in Table 1.

The low, mean and high flow density parameters in this simulation are approximately 0.2, 0.5 and 0.9 times the saturation flow respectively. The simulation results are provided in Fig. 2 and the performance of the algorithm is shown in Table 2.

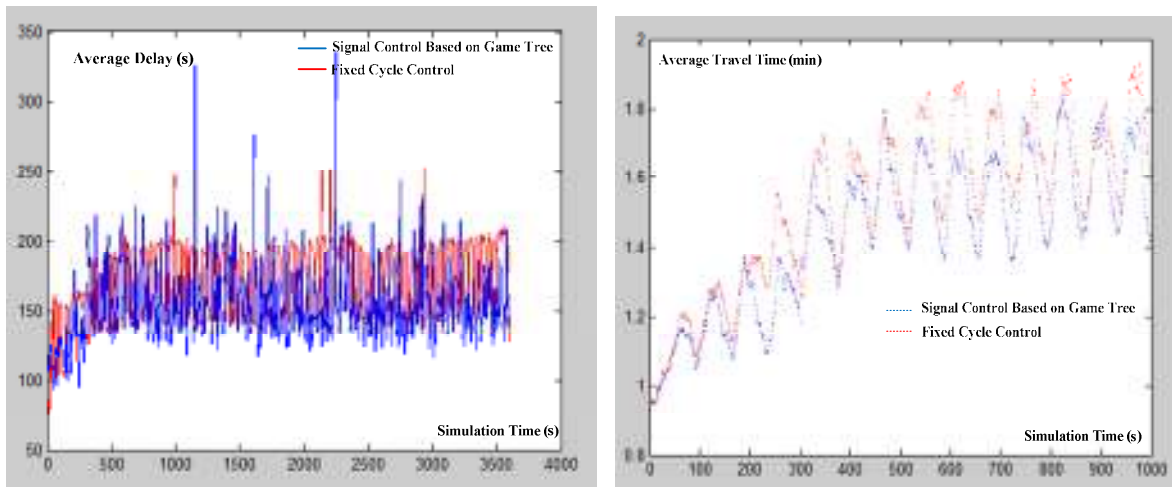
Based on the table and figures above, we can get the following findings:

- When traffic flow density is low, the effect of the proposed system is similar to the fixed time control system. The average delay and the average travel time are improved by only 1.87 and 0.84% respectively. In this case, there is no necessary to coordinated control these intersections.
- When traffic flow density is mean, the effect of the proposed system is much better than the fixed time control system apparently, for average delay is shorten by 8.23% and average travel time is shorten by 7.53%.
- When traffic flow density is high, the effects of both systems are not satisfying while the effect of the proposed system is still better. As we can see from Fig. 2c that average delay is around 150 sec and average travel time closes to 2 min. The performance improves less than that in mean-density is probably because the number of vehicles is very close to the capacity of the network and the room for this method to improve is less, in other words, the available strategies that each intersection can choose are less.





(b)



(c)

Fig. 2: (a) Simulation results for low traffic flow density, (b) Simulation results for mean traffic flow density, (c) Simulation for high traffic flow density

Table 2: The performance improvement percentage

Traffic flow status	Average delay (%)	Average travel time (%)
Low	1.87	0.84
Mean	8.23	7.53
High	6.82	4.41

- Note that we can find the fluctuation of the proposed system in the figures of average delay is larger than that in the figures of average travel time, for there are several extremely high points in the average delay figures. It is because the average delays are acquired by setting data collection in VISSIM while the average travel times are acquired from Port COM. The latter utilizes all the vehicles data to calculate while the former utilizes a part of the data.

CONCLUSION

This study presents a new algorithm to evaluate intersection conditions for regional traffic control. Based on IVICS information, the proposed system can get the timely vehicle information such as longitude, latitude, speed, lane, headway and so forth to evaluate the condition for the whole network. The system figures out the evaluation values for all the strategies and searches for an efficient strategy in the form of the game tree. Based on Game Theory, we only need to focus on the influences between the target intersection and the relative intersections and the algorithm aims to evaluate these influences. The simulation result shows that, by the algorithm based on Game Theory, we find a new idea to deal with the regional traffic control.

The future task is to optimize the algorithm furthermore as the influences are really complex. And as our simulation is connected with a simple situation but there are various situations in the real world, we need to perform simulations in other situations.

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