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Ant colony algorithm for traffic signal timing optimization

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ABSTRACT

In order to separate the conflict of the traffic flow effectively, time delay, number of stops and traffic capacity are chosen as performance indexes, and the objective function related to the cycle time and the saturation of an intersection is established by using the weighting coefficients. Then, based on the uncertainty and convergence analysis of ant colony algorithm (ACA), computational experiments are conducted and numerical comparisons are made for the values of performance indexes achieved by the signal timing optimization problem with Webster algorithm, genetic algorithm (GA) and ACA. Numerical results show that ACA is a simple and feasible method for signal timing optimization problems.

1. Introduction

With the rapid development of economy, traffic congestion has become one of the most serious problems in many cities at present. Traditionally, the congestion problem was dealt by adding more lanes and new links to the existing transportation network [1,2]. Since such a solution can no longer be considered for limited availability of space in urban centers, greater emphasis is nowadays placed on traffic management through the implementation and operation of intelligent transportation systems such as TRANSYT, which has been widely recognized as one of the most useful tools in studying the optimization of traffic control [3,4]. Nowadays, with the development of artificial intelligence technology, ant colony algorithm (ACA) has been applied to signal timing optimization problems, as well as genetic algorithm (GA) [5].

As is known to all, the main places responsible for traffic congestion are urban intersections, and the primary reason for traffic congestion of urban intersections is the irrational cycle time of traffic lights. In order to separate the conflict of the traffic flow effectively and improve traffic capacity, how to assign the red and green time in a cycle is obviously important when dealing with traffic control problems [6]. Generally, the longer cycle time, the greater traffic capacity, but time delay and number of stops also increase with increasing of the cycle time. In other words, when the saturation of an intersection is small enough, the increase of the cycle time does not go far enough towards traffic capacity, and it only leads to the increase of time delay. Therefore, the cycle time of traffic lights should be justly distributed so as to minimize time delay and number of stops.

Ant colony algorithm (ACA), which was first brought forward by Dorigo et al. [7] in the early 90s, is a new simulated evolutionary optimization algorithm with the characteristics of positive feedback, distributed computing and strong robustness [8]. However, with the defects of an acute pheromone shortage in early period, less slow solution speed, stagnation and easy to fall in local optima, it has being obtained comprehensive attention from domestic and alien scholars. Recently, ACA has been successfully applied to many combinatorial optimization problems such as TSP, vehicle routing problem, set covering problem, graph coloring and so on [9–12]. But to our knowledge, GA has been rarely used for traffic signal timing optimization.

This paper is organized as follows. In Section 2, some basic parameters for traffic signal control are briefly described. In Section 3, ACA and its rule are both presented after the optimization model of signal timing is created. Furthermore, the uncertainty and convergence of ACA are analyzed in detail in Section 4. In Section 5, numerical results based on Webster algorithm, GA and ACA are discussed thoroughly. Finally, some conclusions are drawn by the analysis of numerical results in Section 6.

2. Basic parameters for traffic signal control

2.1. Signal phase

In traffic signal control, not all the traffic flow has the right of way in a signal cycle so as to avoid the conflict among the traffic

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flow in every direction. Generally, the traffic flow with the same colored signal lights in a signal cycle has the same signal phase.

2.2. Saturation

The saturation of an intersection, also known as the flow ratio, means the ratio of the traffic flow to the saturation flow in unit time [13]. Here, the traffic flow means the number of vehicles passing by the intersection in unit time, and the saturation flow means the maximum number of vehicles passing by the intersection when the green light is on in a signal cycle.

2.3. Time delay

During the traffic signal control, time delay has a direct bearing on the traffic access. Therefore, we often take it as a key index of traffic benefit. In recent years, traditional Webster signal intersection delay formula has been widely used in traffic field.

$$D_i = \frac{c(1-g_i)^2}{2(1-y_i)} + \frac{y_i^2}{2q_i g_i (g_i - y_i)} \tag{1}$$

where c is the cycle time, g_i is the ratio of the effective green light time to the cycle time, q_i is the traffic flow of the phase i, y_i is the saturation of the phase i.

However, Webster formula is available only when the saturation is smaller. Therefore, it is improved by Yang [14], and time delay is defined as follows:

$$D_i = \frac{cq_i(x-y_i)^2}{2x^2(1-y_i)} + \frac{x^2}{2(1-x)} \tag{2}$$

where x is the saturation of an intersection.

2.4. Number of stops

As is known to all, number of stops is inversely proportional to the saturation. In other words, the less number of stops, the better effect of traffic control. Then, according to the research by Jindong Yang, number of stops for the phase i is defined as follows:

$$H_i = \frac{y_i(x-y_i)}{2x^2(y_i - x^2)} \tag{3}$$

2.5. Traffic capacity

Traffic capacity, as it is called, is traffic reaching. Generally, vehicles can only pass the stop line during the effective green light time. Therefore, according to the relationship between number of stops and traffic capacity, traffic capacity can be expressed as follows:

$$Q_i = s_i \cdot \left[1 - \frac{y_i(x-y_i)(1-y_i)}{1.8x^2(y_i - x^2)}\right] \tag{4}$$

where s_i is the saturation flow of the phase i.

3. Signal timing optimization based on ant colony algorithm

3.1. Optimization model of signal timing

In view of the actual traffic demand, the smallest time delay, the fewest number of stops and the largest traffic capacity are chosen as the ultimate aims. Here, time delay, number of stops and traffic capacity are all functions with respect to the cycle time c and the saturation of an intersection x. In order to maximize traffic capacity and minimize time delay and number of stops, the signal timing optimization problem can be translated into a minimization problem in the form of a fraction, thus the objective function turns into a single objective function with two design variables c and x by introducing three weighting coefficients which vary with different traffic demands. Therefore, the optimization model of signal timing can be written as:

$$\min f(x,c) = \frac{\sum_{i=1}^{n}(K_i^1 D_i + K_i^2 H_i)}{\sum_{i=1}^{n} K_i^3 Q_i} \tag{5}$$

subject to $x \in [0.6, 0.8]$, $c \in [40, 120]$.where 0.6 is to avoid the increases of time delay and number of stops caused by the smaller saturation, 0.8 is to avoid traffic congestion caused by the bigger saturation; the interval of cycle time is often defined as $[40, 120]$ [15]; K_i^1, K_i^2 and K_i^3 are respectively the weighting coefficients of time delay, number of stops and traffic capacity, and they can be calculated as follows [16]:

$$K_i^1 = 2 \cdot (1-Y) \cdot \sqrt[7]{s_i} \tag{6}$$

$$K_i^2 = \sqrt[7]{s_i} \cdot \frac{1-Y}{0.9} \tag{7}$$

$$K_i^3 = 2Y \cdot \frac{c}{3600} \tag{8}$$

where $Y = \sum_{i=1}^{n} \max y_i^j$, and y_i^j $(j = 1, 2, \ldots)$ is the saturation in a direction for the phase i. Thus it can be found that $f(x,c) \geqslant 0$ and $\min f(x,c) \geqslant 0$.

3.2. Determination of weighting coefficients

For the reason that weighting coefficients represent the tradeoff between efficiency and robustness [17], the determination of weighting coefficients K_i^1, K_i^2 and K_i^3 is also important. Here it is made under the following considerations.

(1) We hope that K_i^1 and K_i^2 decrease with increasing of the saturation y_i, but K_i^3 increases with increasing of the saturation y_i, so as to improve traffic capacity during the rush hours and reduce time delay and number of stops during the rest hours.
(2) Considering that it is more likely to cause time delay at heavy intersections during unsaturated hours, we hope that K_i^1 increases with increasing of the saturation flow s_i, so as to reduce time delay at heavier intersections.
(3) As is known to all, the longer cycle time, the larger traffic capacity. Therefore, the cycle time c is introduced into K_i^3, so as to improve traffic capacity to some extent.

3.3. Ant colony algorithm

Ant colony algorithm (ACA) [18] is a promising metaheuristic and great amount of research has been devoted to its empirical and theoretical analysis. The ants can carry on indirect communication through a chemical substance pheromone, which is accumulative and also evaporative. The ants travel a shorter path on which the pheromone accumulates faster than on the longer one. Therefore, the faster the pheromone increases on the short path, the greater the probability that the ants travel this path. The pheromone can deposit unceasingly and evaporate as time goes on. At the same time, the ants also can unceasingly secrete the pheromone in their travel process, thus the pheromone can be updated unceasingly. The pheromone on the path which few ants travel decreases more and more, but the pheromone on the path which more ants travel increases more and more. This forms a positive feedback process, and finally causes all the ants to travel the shortest path.