An Effective Method of Traffic Signals Control in Traffic Circle

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Summary
As we all know, traffic circle has been widely used among cities and communities. But how to design traffic circle and control traffic flow are a kernel issue. In this paper, we study mainly how to control traffic flow by using traffic rules and signal lights. We comparative study two methods of adopting traffic lights and positioning a yield sign in the circle at each entrance road to give priority to incoming traffic. Traffic lights are installed to control the traffic flow of entries and the left-turn traffic flow on circulatory roadway. Left-run vehicles on circulatory roadway will stop before red signal to avoid weaving. By this method the green time of signal and the running lane of circulatory roadway are utilized optimally.

Key words:
Traffic circle, Signals control, Average waiting time, Genetic algorithm.

1. Introduction

Many cities and communities have traffic circles-from large ones with many lanes in the circle (such as at the Arc de Triomphe in Paris and the Victory Monument in Bangkok) to small ones with one or two lanes in the circle. A nice traffic circle design is always a very beautiful sight, even becomes the symbol of the city. It is more important that a traffic circle designed well can provide better safety and performance for drivers making left turns and control traffic flow better. Therefore how to design a nice traffic circle is very important problem, many countries and regions in the world have been set up design standard or guide, such as Highway capacity manual[1], Canadian Capacity Guide for Signalized Intersection [2], Traffic Signals Capacity and Timing Analysis[3], Florida Roundabout Guide[4], etc. Traffic circles have many forms, typical traffic circle is designed generally to a circular central island and many lanes around it. Generally speaking, the traffic circle is often the locus that the vehicles gather and turn. For the traffic circle given (designed), complex transportation characteristic causes often traffic congestions and accidents, which reduced the road net passing capacity and becomes the entire urban road bottleneck region. Therefore it is a key issue to design a good rule of passing traffic circle. At present, there are mainly two kinds of methods, one use traffic lights to control vehicles passing, and other method have no lights. The method of no traffic light positions a stop sign or a yield sign on every incoming road that gives priority to the vehicles already in the circle. Some researchers studied to control traffic flow by using traffic signals and obtained some useful results. Yang X. G. etc. researched the control method of traffic flow for four-leg traffic circle, formed a systematic theoretical research results, and successfully applied to Lianban traffic circle, Xiamen City in China [5-8]. Compared to the four-leg traffic circle, the control method using a signal separation of the traffic flow in five-leg traffic circle is more difficult. In this paper, we will build a model which describes how to control traffic flow by using traffic signals for five-leg traffic circle. We comparative study two methods of adopting traffic lights and having no traffic lights. For the case using traffic lights, we build optimization model and determine optimal open the moment and duration of every green light at the entrance. Furthermore, according to different vehicles flow (large, medium and small) we will calculate average waiting time of vehicles of vehicles according to use traffic light and no traffic light respectively.

2. The minimum waiting time model of the vehicles

For convenience, in this study, we have assumptions as follows:

- The speed of the vehicle entering the circle road is no more than 30 kilometers per hour. This assumption is very close to reality.
- The traffic signals are 100% effective. That is do not consider the traffic signals are suddenly not working.
- Consider that only the traffic flow impact on the traffic lights remain green, do not account for other factors, such as accident, weather, etc.

2.1 The Standard of Classification

Through investigation and analysis, we find that the traffic rules adopted are relevant with the traffic condition. So we

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define the saturation(q/s). q is the actual flow (unit pcu/hr). s is the saturated flow of the intersection (unit pcu/hr). The higher of the saturation the worse the traffic circle is. So we take the saturation as the standard to classify, as follows:

(1) saturation < 0.5
(2) saturation between 0.5 and 0.8
(3) saturation >0.8

We use formula s = 3600/L(unit pcu/hr) to calculate the saturated flow(s). At the same time, the time-headway (L) is relevant to the width and the radiuses of the lane. So we can find the relation through observing the time- headway at different widths and radiuses.
Considering the liner correlation between the saturated flow and the speed and the direct proportion between the speed and the square of radiuses, We take widths(d) and radiuses(r) as independent variables, and the time-headway (L) as dependent variable to establish a binary quadratic regression model.
Now the observing records(ShangHai) are listed in Table 1.
The results of the regression analysis are as follows: (formula(1) and figure(1))

$$L = 11.2425 - 4.6895d + 0.0156r + 0.6133d^2 - 0.0009r^2 \quad (1)$$

The root mean square errors is 0.1552, so we can see that the saturation flow can be well described by the model.

Table 1: The time-headway at different widths and radiuses(ShangHai)

Width/*m*	Radiuses/*m*	the Time-headway/*s*
3.40	20	2.3500
3.10	20	2.4194
3.00	20	2.7137
3.00	15	2.8829
3.50	25	2.3060
4.25	20	2.3122
4.25	15	2.1654
4.60	10	2.8117
2.80	40	2.0936
4.30	25	2.3197
3.35	25	2.2403
3.40	15	2.1723
2.95	35	2.1793
2.85	30	2.3189
3.50	20	2.3980
3.20	15	2.6400

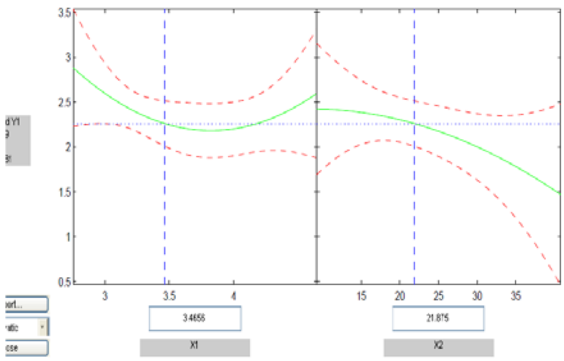

Fig. 1 Result of regress-model

2.2 Basic rules of vehicle driving

According to the common sense, we establish the driving rules as follows (as illustrated in the figure2):

* Vehicles B and C must yield to vehicle A.
* Vehicle E must yield to vehicle D, while vehicles F and D proceed together.
* Vehicle H must yield to vehicle G.
* Enter into the right hand lane of a traffic circle when you in tend to leave at the first or second available exit point.
* If you are planning to proceed to the second exit or beyond, it is recommended that you use the left-hand lane.
* When entering or leaving a traffic circle be aware there may be marked pedestrian crosswalks.
* Vehicles entering the circle must yield to vehicles already in the circle. When you are leaving the traffic circle, you use your right turn signal. This tells other drivers what you intend to do.

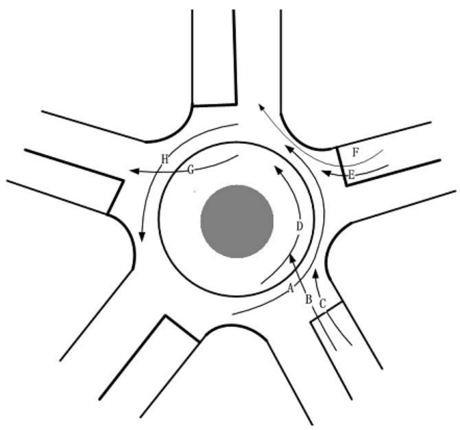

Fig.2 Schematic diagram of driving rules of five-leg traffic circle

2.3 The minimum waiting time model of the vehicles

When the saturation is between 0.5 and 0.8, We adopt the method of adding signal rights in the coming road to control the traffic flow. Keep the traffic circle clear by time-sharing adjustment. So we establish a nonlinear programming model to get the optimal assignment. Specific analysis is as follows.

According to the results of the binary quadratic regression model, take the minimum value of the total waiting time as the object to establish a optimization function. We can get the average waiting time(d) according to the Webster's formula :

$$d = \frac{c(1-\lambda)^2}{2(1-\lambda x)^2} + \frac{x^2}{2q(1-x)} \qquad (2)$$

Where the first term is uniform waiting time(the arrival rate of vehicles is a constant), and the second term is the random waiting time(the arrival rate of vehicles is different), c is the length of Signal Cycle(unit s), λ is green ratio, q is flow (unit pcu/hr), x is the saturation of vehicles.

The formula of calculating the total waiting time is as follows(taking 4 phases for example):

$$D = \sum_{i=1}^{4}\sum_{j=1}^{2}\left\{[\frac{c(1-\lambda_i)^2}{2(1-\lambda_i x_{ij})^2} + \frac{{x_{ij}}^2}{2q_{ij}(1-x_{ij})}]q_{ij}\right\} \qquad (3)$$

Where q_{ij} is the flow of the j entrance of the i phases (unit pcu/hr). x_{ij} is the saturation of vehicles of the j entrance of the i phases. λ_i is the green rate of the i phases.

Objective function:

$$\min D \qquad (4)$$

End conditions are as follows:

First, considering the safety, the minimum green time of every phase is not below a certain number (eg.10s). So the time sharing of every phase must meet to

$$10 \le t_i \le c - L - 10\times 3,\ i = 1,2,3,4 \qquad (5)$$

where t_i is the effective green time of the i phases(units), L is the total lost time(unit s).

Second, the maximal control to saturation should be considered. The reasonable designing for time sharing and the cycle in a period must ensure that the saturation of every phase will be suitable in order to avoid overcrowded. Suppose the saturation of every entrance of every phases is less than 0.9.

$$x = \frac{q}{N} = \frac{q}{s\frac{g_e}{c}} = \frac{cq}{sg_e} \le 0.9 \qquad (6)$$

where q is the actual flow(unit pcu/hr), N is the ability to transit(unit pcu/hr), s is the saturated flow(unit pcu/hr), g_e is the effective green time(unit s). that is

$$g_e \ge \frac{cq}{0.9s} = \frac{cy}{0.9} \qquad (7)$$

where y is the flow rate. The maximal y should be substituted into it to get the minimum green time, that is

$$t_i = g_{e_i} \ge \frac{cy_{i\max}}{0.9},\ i = 1,2,3,4 \qquad (8)$$

to sum up, the end conditions are as follows:

$$\begin{cases} 10 \le t_i \le c - L - 10\times 3 \\ t_i = g_{e_i} \ge \dfrac{cy_{i\max}}{0.9} \end{cases} \quad i = 1,2,3,4 \qquad (9)$$

2.4 The solving algorithm based on Genetic Algorithms

Use Genetic Algorithms to optimize and solve the nonlinear Programming problem given in the formula (4).

(1) Encoding

Using real-coded schema, the length of codes is the number of the variables. Taking a four-phase intersection for example, t_1 , t_2 , t_3 are the optimized variables (t_1, t_2, t_3 are the green time of the relevant phase). In the condition of what the cycle is fixed and the lost time is given, the effective green time of the 4th phase is $t_4 = T - t_1 - t_2 - t_3 - L$. The code is (t_1, t_2, t_3).

(2) Fitness Function

As the purpose is to find the minimum of the objective function, we take $F(i) = C_{\max} - O(i)$ as the fitness of the i individual, $O(i)$ is the objective function value of the individual, $C_{\max}$ is the sufficient large constant.

(3) Genetic operations

- Selection operation

Elite strategy: Reserve the optimal individuals at the present generation, we reserve two optimal individuals. Adopt arithmetic operator based on sorting roulette, sort all individuals by fitness from high to low, so the i individual's survival probability is calculated by the formula (10)

$$P_{rob}(i) = q(1-q)^{i-1} \qquad (10)$$

where $q \in (0,1)$, is selection pressure. After every individual's survival probability was determined, we can calculate the individual's selection probability by formula (11)

$$P_i = \frac{P_{rob}(i)}{\sum P_{rob}(i)} \quad (11)$$

At last, we produce children by roulette method.

• Crossover operation

Assume P_c is the rate of crossover, all the individuals are randomly matched. When the number of the individuals is odd, an individual will be rejected randomly. A random number r is produced in [0,1] for every pair parents. If $r < P_c$, the pair will cross according to formula (12).

$$\begin{aligned} P_1^{'} &= cP_1 + (1-c)P_2 \\ P_2^{'} &= (1-c)P_1 + cP_2 \end{aligned} \quad (12)$$

Where P_1, P_2 are parents, $P_1^{'}, P_2^{'}$ are offspring.

• Mutation operations

Suppose the probability of mutation is P_m, a random number r is produced in [0,1] for every individual i in this population. If $r < P_m$, the individual will be mutated by using the formula (13).

$$P_1^{'} = P_1 + n \quad (13)$$

Where n is a random number produced by normal distribution, P_1 is parent, $P_1^{'}$ is offspring. Here we adopt a competition between the parent and the child, and take the individual having high fitness as next generation parent.

The algorithm used in this paper can be described as follows:

Step 1: Randomly generate an initial population $M(0)$.

Step 2: Compute and save the fitness $F(i)$ for each individual i in the current population $M(t)$.

Step 3: Calculate selection probabilities $p(i)$) by formula (11) for each individual i in $M(t)$, and implement selection operation.

Step 4: Carry out crossover operation by the formula (12).

Step 5: Perform mutation operation by the formula (13).

Step 6: Repeat step 2 to step5 until end condition is satisfied.

3. Cooperative control model of signal lights

When the saturation is over 0.8, that shows only using the incoming traffic lights can not make the traffic circle clear, so that we setup traffic lights in the traffic circle.

Because of the intersection of the traffic circle is wide generally, we can reduce waiting time by cooperative signal lights between the entry and the circle, the circle signal light each other and the entry lights each other. In this way, the vehicles in the traffic circle can get out quickly, reduce the time of stop. In addition, in order to increase the ratio of sequence flow time, the circle light should light green.

3.1 Coordination between the Entry signal light and the circle signal light

If we want to cooperative control the entry signal light and the circle signal light, we should consider two cases: the first, the space between the entry stop line and the circle stop line can be used for increasing the dispersing time of queuing vehicles. When the vehicles flow before the stop line arrive the point of conflict with the circle flow, we can stop the circle flow later. The second, in the traffic circle signal light control scheme, we need to correspond to the entry signal light and the adjacent circle signal lights on direction of vehicles flow headway, guaranteeing the vehicles passed the stop line can successfully pass the adjacent circle lane's stop before the end of the entry green light.

3.2 Coordination between the each circle signal light

In the traffic signal light control scheme, we not only need to correspond the entry signal light and the adjacent circle signal lights on direction of vehicles flow headway, but also the circle signal light each other. The coordination of the circle signal light each other also have two cases: at first, in order to guarantee the vehicles in the traffic circle can get out of the intersection before the green time over, and reduce the needless vehicles' waiting time and stops in the course of driving as a result of the state of signal light becomes red, we need to coordination between each circle signal light. The second, when the vehicles on the downstream stop line arrive the upstream stop line and the queue dispersing on the downstream, the down stream's signal light state need to correspond with the up stream's.

When the saturation is between 0.5 and 0.8, we adopt the method of adding signal lights in the coming road to control the traffic flow. Keep the traffic circle clear by time-sharing adjustment. So we establish a nonlinear programming model to get the optimal assignment. Specific analysis is as follows.

4. Experimental Results

At first, we calculate L by using formula(1), and further determine the saturated flow $s = 3600/L$ as follows:

$$s = \begin{bmatrix} 1300 & 1300 & 1500 \\ 1450 & 1500 & 1500 \\ 1600 & 1400 & 1600 \\ 1500 & 1600 & 1700 \\ 1500 & 1400 & 1700 \end{bmatrix}$$

The following are discussed according to the size of traffic flow.

4.1 Small Vehicles Flow

(1)Without Signal lights

We can get the waiting time is 0.6125×10^3 through the Webster's formula.

(2) Using Signal Lights in the Coming Road
Assume the vehicle flow is

$$r = \begin{bmatrix} 128 & 78 & 42 \\ 272 & 434 & 96 \\ 516 & 88 & 126 \\ 224 & 242 & 208 \\ 312 & 125 & 212 \end{bmatrix}$$

Let T_{maw} represents the minimal average waiting time, T_{vgs} represents vector consisting of every valid green signal time.
We run the Genetic Algorithms source. The results are as follows:

$$T_{maw} = 3.7593 \times 10^3$$
$$T_{vgs} = (59.2399, 75.1699, 90.4793, 98.0320, 111.0436)$$

(3) Using Signal Lights in the Coming Road and the Circle Road
Assume the vehicle flow is

$$r = \begin{bmatrix} 103 & 95 & 87 \\ 64 & 32 & 64 \\ 78 & 105 & 49 \\ 86 & 64 & 75 \\ 88 & 69 & 94 \\ 59 & 84 & 67 \\ 59 & 89 & 57 \\ 100 & 79 & 95 \\ 68 & 96 & 105 \\ 76 & 78 & 69 \end{bmatrix}$$

The results obtained by Genetic Algorithm are as follows:

$$T_{maw} = 6.3142\text{e}+003$$
$$T_{vgs} = (9.5618, 41.5553, 44.0295, 47.0392, 65.4436, 73.7924, 75.6564, 83.0483, 91.9956, 92.7902)$$

4.2 Medium Vehicles Flow

(1)Without Signal lights

We can get the waiting time is 9.5624×10^4 through the Webster's formula.

(2)Using Signal Lights in the Coming Road
Assume the vehicle flow is

$$r = \begin{bmatrix} 705 & 650 & 840 \\ 550 & 450 & 561 \\ 424 & 680 & 510 \\ 605 & 540 & 384 \\ 564 & 681 & 540 \end{bmatrix}$$

The results obtained by Genetic Algorithm are as follows:

$$T_{maw} = 4.3620\text{e}+004$$
$$T_{vgs} = (31.4901, 46.0682, 51.0364, 71.2948, 97.5571)$$

(3)Using Signal Lights in the Coming Road and the Circle Road
Assume the vehicle flow is

$$r = \begin{bmatrix} 261 & 253 & 241 \\ 274 & 324 & 471 \\ 286 & 305 & 267 \\ 259 & 312 & 299 \\ 287 & 259 & 286 \\ 297 & 286 & 306 \\ 269 & 249 & 281 \\ 294 & 286 & 284 \\ 294 & 296 & 315 \\ 288 & 294 & 305 \end{bmatrix}$$

The results obtained by Genetic Algorithm are as follows:

$$T_{maw} = 5.7011\text{e}+004$$
$$T_{vgs} = (29.7569, 45.4610, 55.0572, 55.9919, 59.0258, 72.3998, 74.4310, 76.7388, 80.5279, 91.0304)$$

4.3 Large Vehicles Flow

(1)Without Signal lights

We can get the waiting time is 2.531×10^5 through the Webster's formula.

(2)Using Signal Lights in the Coming Road
Assume the vehicle flow is

$$r = \begin{bmatrix} 1054 & 978 & 1200 \\ 1192 & 993 & 1013 \\ 984 & 994 & 934 \\ 1026 & 912 & 964 \\ 987 & 1065 & 983 \end{bmatrix}$$

The results obtained by Genetic Algorithm are as follows:

$$T_{maw} = 8.8094\text{e}+004$$

$$T_{vgs} = (50.2423, 64.3604, 73.5731, 79.8865, 81.6440)$$

(3)Using Signal Lights in the Coming Road and the Circle Road
Assume the vehicle flow is

$$r = \begin{bmatrix} 500 & 451 & 466 \\ 363 & 423 & 471 \\ 452 & 461 & 512 \\ 521 & 531 & 496 \\ 487 & 503 & 492 \\ 486 & 510 & 495 \\ 488 & 491 & 462 \\ 453 & 468 & 491 \\ 492 & 476 & 466 \\ 475 & 463 & 494 \end{bmatrix}$$

The results obtained by Genetic Algorithm are as follows:

$$T_{maw} = 5.3552\text{e}+004$$

$$T_{vgs} = (21.7969, 36.0144, 37.5379, 40.2347, 48.5875, 54.9187, 64.3047, 68.9740, 85.9427, 97.8067)$$

5. Conclusions

In this paper, we build the model which describes how to control traffic flow for five-leg traffic circle, comparative study two methods of adopting traffic lights and having no traffic lights for different vehicles flow (large, medium and small), and calculate average waiting time of vehicles according to use traffic light and no traffic light respectively.

• We use genetic algorithm to optimize the time of the traffic lights remain green, so it is more easily to get the global optimal solution than conventional optimization methods.

• For the traffic circle, experimental results show that if the traffic flow is smaller than threshold given, need not the traffic lights, otherwise traffic lights are used. For the case of using traffic lights, we build optimization model, its variables are duration of every green light at the entrance, and objective function is to minimize average waiting time of vehicles.

• In fact, the traffic rules adopted are relevant with the traffic condition. This paper introduces the saturation(q/s), and takes the saturation as the standard to describe traffic condition.

Under large vehicles flow, traffic lights on the entry and the circle should be used. Under medium vehicles flow, traffic lights on the entry should be used. Under small vehicles flow, there is no need to use traffic lights, the vehicle should obey the traffic rules.

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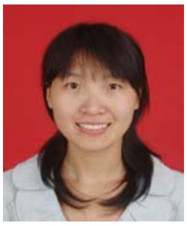

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