Technical Summary

Our model is established aiming at the general traffic circles, while people have explored many methods to control the traffic streams of traffic circles, especially regular ones so far .Of course our model can be used to regular circles as well. But in terms of more general traffic circles, such as traffic circles with more incoming roads or more complex lanes, our method is more simple and direct while avoid the inaccuracy caused by complexity.

According to different conditions of traffic, the method and steps are listed as following.

Step 1. Preliminary investigation for a certain traffic circle includes the information of,the volume of circular lanes and the length of weaving sections.

Whether there is a dedicated lane for the vehicles which go to the adjunct right road or not.

The number of incoming roads and saturated flow of them.

The O-D matrix data of different moments in a day.

Step 2. It is not necessary to set traffic-control signals if there is not a dedicated lane for a entry. It is indisputable that a YIELD sign is enough for each entry, since there is not conflict between the vehicles which go to the adjunct right lane and other traffic streams.

Step 3. If flows of some incoming roads are obviously smaller than others, usually an order of magnitude, it is more reasonable to mark YIELD than traffic lights.

Step 4. Suppose that only traffic lights are be established at the conflict point. Calculate the signal time configuration based on Webster Formula. Then, judge whether hypothesis is reasonable.

The two following situations are possible:

1.The current method is unreasonable, if the displayed green time of one traffic light is smaller than minimum green time. So change traffic light to YIELD or STOP.

2.Regard the maximum green time as the displayed green time ,if the displayed green time of one traffic light is larger than maximum green time. Calculate status again.

At last, determine the design of traffic-control signals base on discuss above.

Step 5. Design the signal phase based on the determined traffic-control signals of step4. There may be a wide range of designs because of different primary entry and secondary entries.

however above of all:

1.Two entries both with larger green time should avoid to be designed in the same phase.

2.Sum of the number of primary and secondary entries in one phase should not be too small compared with the number of incoming roads. Otherwise, it reflects that Total Green Ratio will be too small which shows that there are defects in current choice of phase.

Step 6. Calculate the total green ratio and service level of road based on the results of Step 5.

Step 7. It is essential to redesign the signal phase, if the traffic evaluating indicators of Step 6 are not satisfactory. The solution is back to Step 5 and calculating new status until the results are satisfactory. All of the steps are easily to be program-control.

Step 8. It is possible that there are different methods about the green time at different time.

We can use two solutions to address this issue,

1.Setting a system which is used to test real-time traffic stream, which can used to calculate the seconds each light should remain green.

2.To establish a daily traffic stream database and set different green time at different time of day based on the database.

To do instructions above step by step, it is feasible to choose the appropriate flow-control method for any specific traffic circle.

A New Traffic-Signal Control for Modern Traffic Circle: Method and Application

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Abstract

The problem of traffic circles has been explored in many methods. But there are no optimal and perfect answers. We create a kind of digraph to describe a actual traffic circles concisely. To design the traffic signals, we improve and utilize Webster Formula to create a general method for both regular and complex traffic circles. The main process should be divided into 3 parts: setting the YIELD signs, calculating the green time and designing signal phases. Then, two typical examples are used to explain how to apply our method in different conditions. The satisfactory results show that our method is reasonable and effective. Finally, we draw a conclusion and discuss the different choices and designs according to the actual situations and provide a technical summary to explain out method to engineers.

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1. Introduction

1.1 Background and Current Models

With the city improving the level of motorization, the relationship between supply and demand for urban road resources becomes increasingly strained. Practice has proved that the road construction can't keep pace with the growth of motor vehicles (shown in Figure 1). This current situation requires people to solve the traffic problem better especially in traffic hub, such as traffic circles and crossroads.

A traffic circle means a road junction at which traffic streams circularly around a central island. Traffic circles have the advantages of traffic safety and capacity. However, traffic circles usually occupy a larger area of land, which conflicts traffic capacity. On the condition of a certain traffic circle area, How to design traffic signals to control the traffic streams around, in and out, in order to reach the optimal capacity, has been the object people explored.

In the current, there are many methods or models studying and discussing the specific traffic circles with regular incoming roads. And some of them are intelligent and effective (shown in Figure 2). But it is not an easy problem to control traffic streams of general traffic circles.

Figure 1: Jam in the traffic circle.

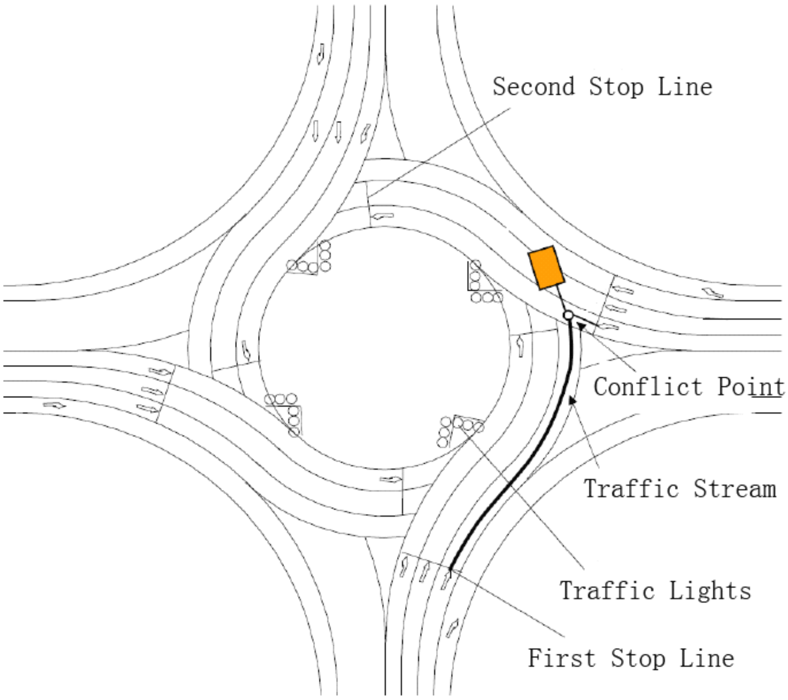


Figure 2: intelligent method to solve the regular traffic circles.

1.2Developing Our Approach

According to the key problem, our goals are:

1. Create a method could be applied to design traffic signals for general traffic circles. The traffic signal can be signal stop, signal YIELD or traffic lights.
2. Draw a conclusion to discuss how to choice the best traffic signals program in different conditions as well as the factor that affects this choice.
3. Apply our method to solve specific examples.

2. Define the digraph

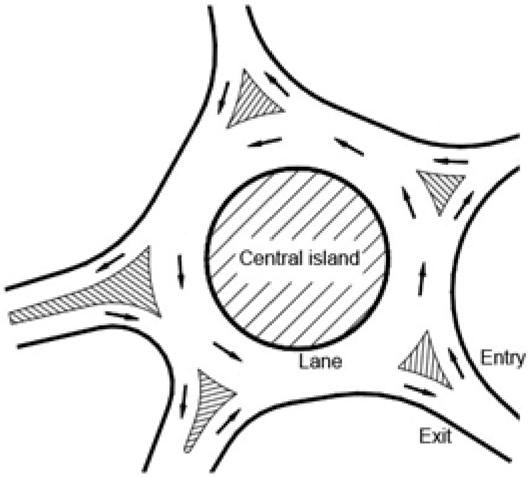


Figure 3: A actual traffic circle with 5 incoming road. The shaded area means a central island in middle and edge islands around it. Small arrows indicate the direction of traffic stream

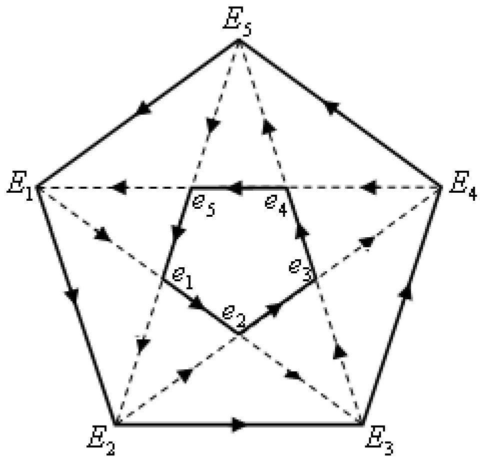


Figure4: A digraph generated by 5 points. It is converted from actual traffic circle map.

In order to discuss and analyses easily, we streamline the traffic circle for the mathematical digraph. The meaning of the directed edges and points of the digraph is described as follows:

- E_i represent entry and exit of a coming road.
- e_i represent the possible conflict between the vehicles entering the traffic circle and the vehicles exiting.
- Directed edges represent the lanes. For example, the vehicles from entry E_1 to E_2 travel through the route E_1E_2 (defined as dedicated lane), while the vehicles from entry to through the routes $E_1e_1e_2e_3E_4$.

For facilitating describing and understanding, we assume a traffic circle with 5 entries, and the traffic circle contains a circular lane. As shown in figure 1. Of course, a dedicated lane for the vehicles which go to the adjunct right road is independent of the circular lane. And vehicles can only move anticlockwise. Then we abstract the traffic circle into digraph as shown in figure 2.

In terms of the digraph above, it match the actual traffic circle system well. Here is a summary of description about the digraph.

- Dashed edges represent the cross between roads in and out of the traffic circle. They also represent the diversion between the circular lanes. We discuss the latter in model extend.

- Solid edges represent the circular lanes around the central island.

- The length of directed edges is independent of actual length of lanes or vehicles capacity.

- vehicles can't travel in the opposite direction of corresponding directed edge.

- All of the possible routes which vehicles can drive in the actual traffic system can be uniquely represented from the digraph.

- The actual meaning of e_i is the conflict point between the incoming traffic stream and the traffic stream already in the circle. So the positions which we design the stop or YIELD signs and traffic lights are rightly points e_i.Note that the position here is abstract rather than actual position of traffic system.

- In fact, there is possible conflictes between the traffic stream linking entry with neighboring exit and the traffic stream coming out from the circular lanes. According to travel priority principle, vehicles of the outside lane have to YIELD to other vehicles. For example, vehicles through E_1E_2 have to YIELD to the vehicles coming out from e_1E_2.

3 Method description

The traffic circles are usually located in the junction of important regions. The regions have a large traffic volume and traffic streams to the left, which usually causes confilcts and accidents. To solve this problem efficiently and economically, traffic signals are used widely. In order to design a properly or even optimal traffic signal program, we create out own method which is introduced in detail in following sections.

3.1 Definition

Signal cycle: the sequencing of a traffic control signal once through its phases.
Signal phase: A time period during which a particular movement, or combination of movements, at a traffic control signal is allowed to proceed.
Primary entry: the flow of this entry primarily released in current phase, which is often considered to be traffic-intensive. In other words, when an entry is just beginning to release, it is a primary entry.
Secondary entry: the flow of this entry has already been released as primary entries in the previous phase. The secondary entry has been released for a period of time in the previous phase so that queuing flow of traffic has been eased in the current phase.
Primary green time: green time while the entry is primary entry.
Secondary green time: green time while the entry is secondary entry.
The primary flow : go in traffic circle from the primary entry of traffic.
The secondary flow :go in traffic circle from the secondary entry of traffic.
Interleaver angle: the average angle between the direction of entering the circular lane and the direction of exiting the circular lane in a certain conflict point.
Yellow light: it means stop, but for those vehicles which are close to the stop line and unable to stop safely, they are permitted to go out of the traffic circle.
All-red time: the interval between the end of yellow phase in the current phase and the beginning of green light in the next phase
Traffic conflict point: an open cash position between two traffic streams.
green ratio： displayed green time/signal cycle

3.2 Assumption

- Setting a dedicated lane for the vehicles which go to the adjunct right lane. There is no traffic signal to control it, so these vehicles can go through the lane all the time.
- there is U-turn lanes before vehicles go in the traffic circle, in other words, in the traffic circle, there are no vehicles which want to turn around or go in the traffic circle from one lane and go out to the same lane.

- if the amount of non-motorized and pedestrian is not too large, we set crossing at the entry of the traffic circle for them.

If the amount of non-motorized and pedestrian is too large, we should set an underpass or flyover for them, according to the specific local conditions and visual landscape effects of the traffic circle.
4Information of a specific traffic circle is known, such as the number of lanes and traffic streams.

3.3 Preparation for model

3.3.1 Introduction for two stops

The design of two stops is an innovation theory of designing for traffic circles. It organizes and controls the traffic by letting the vehicles in the traffic circle wait for two stop signal. It help to avoid the primary conflict to make traffic circles in good condition. Show in **Figure 2**

3.3.2 Define the O-D Matrix

Origin-Destination(O-D)Matrix: Origin-destination matrices for each hour are extracted by using the observed traffic volumes. There are various methods for estimating time-dependent O-D matrices for traffic networks. See [1] for a detailed survey of these methods. However, the study network modeled here is relatively smaller and it does not include multiple lanes between each O-D pair. Therefore, trial and error method is sufficient to determine an accurate O-D matrix for the study network.

3.4 traffic-control method choice

The objective of traffic-control method is to make traffic circle in good condition, so traffic-control signal should be set at the conflict point. And the conflict points are shown in **Figure 5**

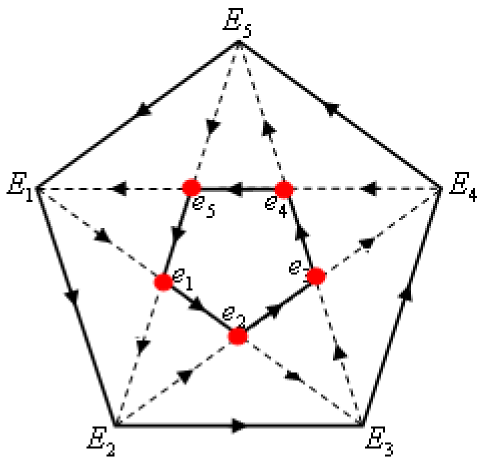


Figure 5: Red dots indicate the conflict points, that is, the position of traffic signals.

The most important way to control the traffic stream of a traffic circle is to choose the right traffic-control method. In order to make the measure is available for any specific traffic circle, our design ideas is: for any traffic circle, firstly we suppose that only traffic lights are used in every conflict point. And according to the two stops design, there are two traffic lights in every conflict point. Secondly, we can calculate the yellow time, all-red time, signal cycle, green time. Thirdly, analyze the status, comparing with the Minimum Green Time and Maximum Green Time, to judge whether this method is reasonable. We change the unreasonable traffic lights to YIELD or STOP to make best control traffic stream in, around, and out of a circle.

3.4.1 Choice of traffic-control signals.

①time configuration

For any specific traffic circle, firstly we suppose that only traffic lights are used in every conflict point.

A. Calculation of yellow time

According to the definition of yellow time, those vehicles which are close to the stop line and unable to stop safely must pass through smoothly during the yellow time.

Suppose the distance of vehicles and stop line before the beginning of yellow time is L_S . t_r represents the loss time of starting, v_0 represents the speed of vehicles during the green light time, a_1 represents acceleration brake. At the yellow time, if vehicle is able to stop before the stop line, the time of yellow light should be larger than L_{y1}:

$$L_{y1} = v_0 \cdot t_r + \frac{v_0^2}{2a_1}$$

Suppose A represents yellow time, if vehicles are able to pass the stop line before changing to the red light, L_s should be smaller than L_{y2}

$$L_{y2} = v_0 \cdot A$$

In order to make sure no doubts to the drivers, the optimal time of yellow light should be A_{opt}, that is let $L_{y1} = L_{y2}$, then

$$A_{opt} = t_r + \frac{v_0}{2a_1} \qquad (1)$$

B. Calculation of all-red time

In order to make sure safety, it is necessary to set all-red time at the intersection of traffic circle. Suppose d_{n_1} represents the distance between the stop line on this phase and potential conflict, which is made by this phase and next phase, d_{n_2} represents the distance between next stop line on this phase and potential conflict, v_0 drepresents the speed of intersection, a represents the start-up acceleration of vehicle.
In order to avoid the conflict between the last vehicle of current phase and the first vehicle of next phase, then all-red time should be:

$$A_{R1} = \begin{cases} \dfrac{d_{n_1} + L_c - d_{n_2}}{v_0} - \dfrac{v_0}{2a} - t_r & \text{当} d_{n_2} \geq \dfrac{v_0^2}{2a} \\ \dfrac{d_{n_1} + L_c}{v_0} - \sqrt{\dfrac{2d_{n_2}}{a}} - t_r & \text{当} d_{n_2} \leq \dfrac{v_0^2}{2a} \end{cases}$$

Because of the d_{n_2} which is designed by human, in order to get the Optimization

Algorithm, we let $d_{n_2} \ge \frac{v_0}{2}$, then all-red is:

$$A_R = \frac{d_{n_1} + L_c - d_{n_2}}{v_0} - \frac{v_0}{2a} - t_r \qquad (2)$$

C. Calculation of signal cycle

1、calculation of total loss of time in each phase i in one cycle
Suppose A_{R_i} represents all-red time in phase i, then
total loss of time in phasei :

$$L_i = t_r + A_{R_i}$$

So that, total loss of time of signal circle is:

$$L = \sum L_i = \sum (t_r + A_{R_i}) = nt_r + \sum A_{R_i} \qquad (3)$$

2、calculation of flow ratio on each phase i
Suppose V_{ij} represents the traffic stream of primary entry of incoming road j in phase i,and S_{ij} represents the saturated flow of incoming road j in phase i;
the flow ratio in phase i:

$$y_i = \max(\frac{V_{ij}}{S_{ij}}) \qquad (4)$$

Then, suppose $S_{o,ij}$ represents the ideal saturated flow ratio of incoming road j in phase i, and f represents the adjustment factor of every different road.
So, the saturated flow of incoming road j S_{ij} :

$$S_{ij} = S_{o,ij} \cdot N \cdot \sum f \qquad (5)$$

D. Calculation for optimal cycle

Suppose Y represents the maximum traffic stream ratio of every phase in on cycle, then

$$Y = \sum^{n} y_i = \sum_{i}^{n} \left(\frac{V_{ij}}{S_{ij}} \right)_{critical} \qquad (6)$$

We Opt the Webster formula to calculate the optimal cycle,
Webster formula is:

$$C = \frac{1.5L + 5.0}{1 - Y} \qquad (7)$$

Until now, we get the signal circle.

E.Calculation for green time

According to the explanation above, suppose total effective green time is g, then

$$g = C - L$$

Suppose the effective green time of each phase i is g_i, then

$$g_i = \frac{g \cdot y_i}{Y}$$

Suppose the displayed green time of each phase i is G_i, then

$$G_i = g_i + L_i - A_i \qquad (8)$$

Next, after the establishment of traffic light time, we should take whether that all the traffic method is traffic light is reasonable.

②Evaluation of traffic light

A. Minimum and Maximum Green Time

It makes a negative influence when the green time is too long or too short. So in order to make the traffic-control method more reasonable, for any specific traffic circle, we can set a minimum green time $G_{i.\min}$ and a maximum green time $G_{i.\max}$ according to the characteristics of the traffic circle and the request of city traffic.

If the displayed green time which we get from current method is smaller than $G_{i.\min}$, we can say current method is unreasonable, then we have to opt other traffic signal control, such as YIELD OR STOP. And if the displayed green time which we get from current method is larger than $G_{i.\max}$, we regard the $G_{i.\max}$ as the displayed green time. Then calculate the yellow time, all-red time and signal cycle.

For example, when the displayed green time of one entry is smaller than $G_{i.\min}$, to some extent, it reflects that the vehicle flow is too smaller, that is it is unreasonable to set traffic light at this entry, because of the negative influence made by the traffic light. So we should change the traffic light to YIELD OR STOP.

B. Service level of road

Service level of road is an important criterion of road evaluation, so it can be used for us to judge whether the traffic light is reasonable.

Average dead-time of vehicles

Suppose X represents the saturation of lane j, m represents adjustment factor of lane j (it is known for a specific road), C_a represents the capacity of lane j. Then we can get the uniform dead-time d_1,

$$d_1 = \frac{0.38C\left[1-\frac{g}{C}\right]^2}{1-\left(\frac{g}{C}\right)X}$$

The increased dead-time d_2:

$$d_2 = 173X^2\left[(X-1)+\sqrt{(X-1)^2+\frac{mX}{c_a}}\right]$$

So the average dead-time of lane j is

$$d_j = d_1 + d_2$$

Service level of leans

We can judge the service level of lane j by using table of service level of road which is listed in table 1.

Table 1: Service level of road

Service level	Dead-time
A	≦5.0
B	5.1 to 15.0
C	15.1 to 25.0
D	25.1 to 40.0
E	40.1 to 60.0
F	>60.0

Our method of designing the traffic-control signal is unreasonable, if the service level of road is too low. So we should design new method , basing on service level of road ,such as changing traffic light to YIELD.

③Change of green time

We can make final design of traffic-control signal after designing traffic-control signal such as, YIELD, STOP and traffic light. Then, calculating the yellow time, all-red time, green time and signal cycle. From the formula, we can see that green time is mainly decided by the traffic stream. So, it is obvious that,

A. Because the traffic stream is different at different time of day, it is possible that a traffic light should be set at the peak traffic stream while not be set at low traffic stream. For address this issue, we can set YIELD and traffic light at the same time or use yellow light flash to control the traffic stream.

B. It is also possible that there are different methods about the green time at different time, we can use two solutions to address this issue.

a. setting a system which is used to test real-time traffic stream, we can use the real-time traffic stream to adjust the real-time green time.

b. we can establish a daily traffic stream database and set different green time at different time of day based on the database.

3.4.2 Choice of signal phase

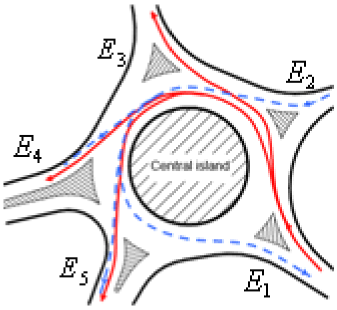
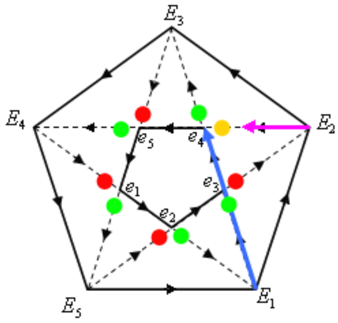
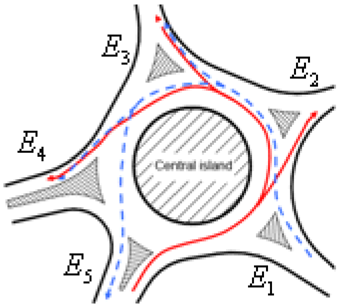
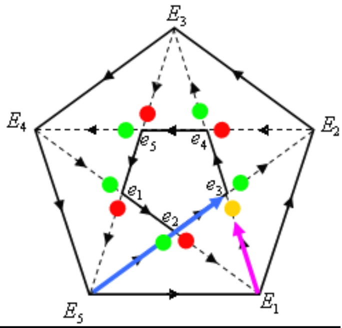
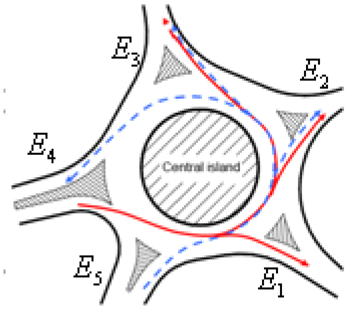
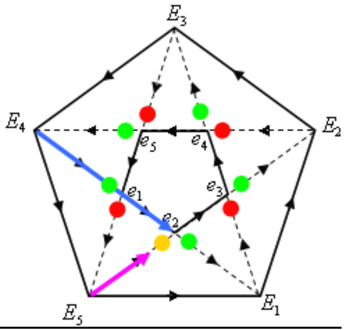
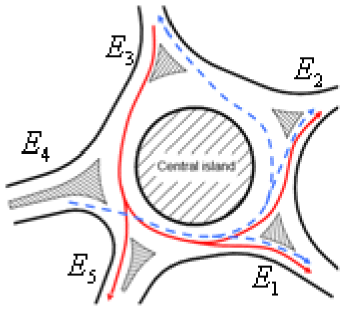
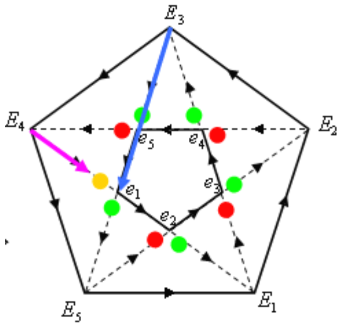
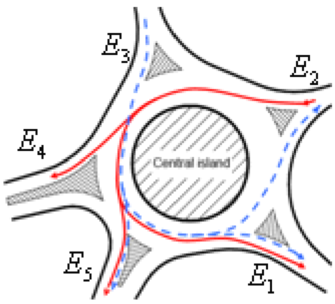
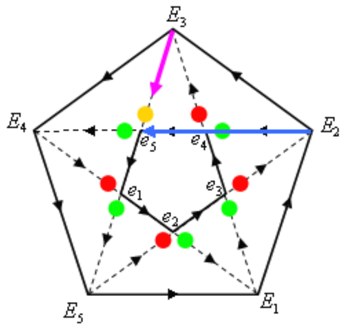
1）Rationale

When we set the signal phase program after the establishment of traffic control, we should consider the traffic order firstly. The advantages of orderly traffic are obvious, such as the improvement speed and reduction of the incidence of accidents etc. However, the traditional control that is trial-by-junction release of the signal light mode can not meet the traffic needs in the peak flow. This makes us take the orderly movement and how to improve the utilization of cross-ring into consideration at the same time , In order to balance them we set the following control methods.

The main characteristic of this idea of control: Let a primary stream of traffic with another signal or more secondary steam of traffic move in the same phase at the same time with least conflicts. Among them, the study of intertwined volume generated by the main stream and secondary stream in the loop at the same time is the key to solve the problem. For different entries, we should investigate the characteristics of the traffic unit. First of all, we should determine the primary stream of traffic in the phase. Furthermore we could make the stream which the intertwined volume and interwoven angle are both less be the secondary stream, and it could move along with the primary stream

In order to state the choice of signal phase clearly, we illustrate a specific example. In current phase, suppose primary traffic stream, then the secondary traffic stream is last primary traffic stream. shown in table 2.

Table 2: Phase diagram

Function Description	Traffic pattern	Geometric Figure
Step1: phase A The primary entry of traffic is E_1, The secondary entry of traffic is E_2.		
Step2: phase B The primary entry of traffic is E_5, The secondary entry of traffic is E_1.		
Step3: phase C The primary entry of traffic is E_4, The secondary entry of traffic is E_5.		
Step3: phase D The primary entry of traffic is E_3, The secondary entry of traffic is E_4.		
Step4: phase E The primary entry of traffic is E_2, The secondary entry of traffic is E_4.		

Notes:
Red solid line: the primary flow of traffic.
Blue dotted line: the secondary flow of traffic.
Red dot: red light.
Green dot: green light.
Yellow dot: the secondary flow of traffic should let the the primary flow of traffic go first.

2）method of choosing the primary flow

Method of choosing the primary flow is a important problem in designing the phases,we can take these factors below into consideration.

①Total Green Ratio

The Total Green Ratio, a perfect target which reflects the capacity of traffic circle, could be regarded as total displayed green time in every phase in one period. It could be a number larger than 1 because that the Total Green Ratio represents displayed green time in one period, which means that a larger Total Green Ratio implies a better capacity of this traffic circle.

Suppose G_{R_i} represents green ratio in phase i, then according to the definition of green ratio,

$$G_{R_i} = \frac{G_i}{C} \tag{9}$$

So total green ratio is

$$G_R = \sum_{i=1}^{n} G_{R_i} \tag{10}$$

According to the formula, the total green ratio has relation to the selected number of primary entry and secondary entry in one phase, which is an extremely marked application in large traffic circle. Taking an 8-entry-traffic-circle for example, the total green ratio can be increased by the design that a primary flow and two secondary flow move simultaneously in a phase, thus to strengthen the capacity of this traffic circle.

②Average speed of vehicles

Average speed of vehicles is an important criterion to evaluate the level of road capacity. While the most effective way to improve the speed is to make traffic situation orderly. In the model above, we have set up the speed of vehicle in the traffic circle is V_0, which is based on traffic conditions of the traffic circle without traffic signals. Now, after the establishment of traffic signal, if in the traffic circle the actual vehicle speed measured by Gun tools is greater than V_0 , we could draw a conclusion that with the traffic signal control, the road capacity has improved. However, if the actual speed is different in different primary or secondary entry, the primary or secondary entries corresponding to greater actual speed are better.

3.5 Conclusion of model

According to the model we establish above, we draw a conclusion which is used to help choose the appropriate flow-control method for any specific circle. That is for any specific traffic circle, firstly we suppose that only traffic lights are used in every conflict point. And according to the two stops design, there are two traffic lights at every conflict point. Secondly, we can calculate the yellow time, all-red time, green time, signal cycle. Thirdly, analyzing the status, comparing with the Minimum Green Time and Maximum Green Time, to judge whether this every traffic light is reasonable. Then we change the unreasonable traffic lights to YIELD or STOP to make best control traffic stream in, around, and out of a circle.

We remain in the rest traffic light after determining the YIELD or STOP. And the design of traffic lights is made of two facets, one is time configuration and the other is choice of phase. We should firstly determine time configuration then choice of phase. In order to determine the choice of phase, we introduce two concepts, primary flow and secondary flow.

Two notes are necessary to state clearly while determine the time configuration of traffic light,

A. Because the traffic stream is different at different time of day, it is possible that a traffic light should be set at the peak traffic stream while not be set at low traffic stream. For address this issue, we can set YIELD and traffic light at the same time or use yellow light flash to control the traffic stream.

B. It is also possible that there are different methods about the green time at different time,we can use two solutions to address this issue.

a. setting a system which is used to test real-time traffic stream, we can use the real-time traffic stream to adjust the real-time green time.

b. we can establish a daily traffic stream database and set different green time at different time of day based on the database.

The main characteristic of this idea of control is to let a primary stream of traffic with another signal or more secondary steam of traffic move in the same phase at the same time with least conflicts. Among them, the study of intertwined volume generated by the main stream and secondary stream in the loop at the same time is the key to solve the problem.

There are two rules while designing the choice of phase,

1. When two entrys both needs a long displayed green time, we should avoid to let these two roads be primary entry and secondary entry, in order to decrease the conflict.

2. When traffic lights are necessary for more incoming roads, sum of the number of primary entries and secondary entries should not be too small. Otherwise, it could decrease the green ratio. Specific choice of phase should be designed based on the

traffic stream of every road.

We get the final design after determining the signal time configuration and the choice of phase, including the YIELD and STOP.

From the description above, we can conclude the steps of designing the traffic-control Signal,

Step1. Fine all the conflict points of traffic circle and set traffic lights only at the conflict point.

Step2. According to step1, calculate the yellow time, all-red time, green time and signal cycle.

Step3. We can judge whether the traffic lights of every entries is reasonable based on the combination the status of step2 and the maximum and minimum green time. Then, we change the unreasonable traffic lights to YIELD or STOP.

Step4. Calculate the time configuration of new method made in step3 and the change of green time during different period of day.

Step5. Design the choice of phase and choose the appropriate primary entry and secondary entry mainly based on the total green ratio.

Step6. Make a best design of traffic-control signals of traffic circle based on the results before.

4. Sample application

4.1 A typical fountain

Firstly, we give an example according to the sample mentioned in the method that the traffic circle has 5 incoming roads. According to the method, the information/data of O-D Matrix and Saturations Flow is needed. One group of representative data is used as a result of different traffic circles.

Table 3: Information of the first example

Pcu / h	Exit1	Exit2	Exit3	Exit4	Exit5	SF
Entry1	0	1240	580	700	1500	9500
Entry2	640	0	1440	990	1320	9000
Entry3	600	700	0	1660	2200	12000
Entry4	1100	2340	1500	0	1800	12000
Entry5	900	700	740	1100	0	7000

SFR: Saturation Flow

From the information above, we find that there is no significant differences among the flows of 5 entries. So these entries are all needed to be determined by calculating results, listed in the following table 4.

Table 4: Results of first example

Entries	Entry1	Entry2	Entry3	Entry4	Entry5	SS
Time/s	41	38	48	51	41	219

SS: Signal Cycle

Besides, the results of evaluation criteria are listed below:

Total Critical Flow Ratio (TCFR)：0.8400
Total Green Ratio：240/219

From the results above, the Primary Green Time are similar as the traffic streams are similar to each other. Meanwhile, the TCFR satisfy the condition: 0.8<TCFR<0.9 and the Green Ratio and Traffic capacity are both reasonable and favorable.

We convert the results for the design of figure below:

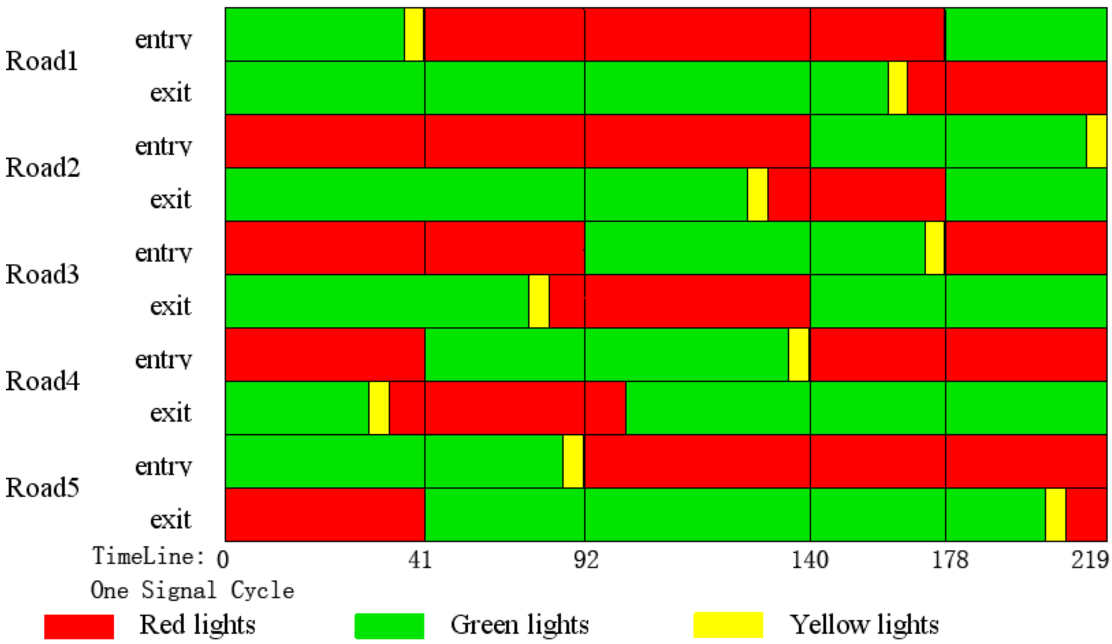


Figure 6: There are 10 traffic lights for 5 incoming roads. The figure above Accurately reflects phase change of all the traffic lights in a signal cycle.

4.2 Another fountain

We give another example to explain. Suppose a traffic circle with 6 entries and exits(It's also possible that the number of exits isn't equal to that of entries). The following table lists the information of O-D matrix and Saturation Flow.

Table 5: Information of the second example

Pcu/h	Exit1	Exit2	Exit3	Exit4	Exit5	Exit6	SF
Entry1	0	1240	580	700	1500	1480	9500
Entry2	440	0	420	300	190	540	11000
Entry3	600	700	0	1660	2200	2342	14000
Entry4	1100	2840	1500	0	1800	2342	15000
Entry5	610	700	740	600	0	540	13000
Entry6	1342	1420	3150	1890	1987	0	15000

SF: Saturation Flow

Results table:

Table 6: The initial results of the second example

Result	Entry1	Entry2	Entry3	Entry4	Entry5	Entry6	SS
PGT/s	46	14	49	55	17	61	242

PGT: primary green time SS: Signal Cycle

Total Critical Flow Ratio： 0.8305
Total Green Ratio： 220/242

From The calculated results, we find that the primary green times of Entry 2 and Entry 3 is too short to set traffic lights. Therefore, in practical application, we must improve the calculated results above. Our method is: change the traffic lights signal of Entry 2 and Entry 3 into YIELD signal; Redistribute the Signal Cycle to the remaining 4 primary green times. The improved results are shown in the table below.

Table 7: Final results of the second example

Entry	Entry1	Entry2	Entry3	Entry4	Entry5	Entry6	SS
Results	53	YIELD	56	63	YIELD	70	242

Finally, we should design the traffic lights phase. From the data in the table above, we found that the flows of Entry 1 and Entry 3 are obviously smaller than those of Entry 4 and flow Entry 6. So we set the two distant entries as the primary entry and the secondary entry at the same phase in order to avoid the conflict between two larger-flow entries.

5.Further Discussion

5.1 .Digraph extension from simple lanes to complex lanes

For the method we have mentioned to describe the actual traffic circle system, it could be extended to more complex lanes. Here, complex lanes mean the different lanes which can be distinguished and control independently by traffic signals. Following figure is a typical example.

Now, we abstract the complex traffic circle shown in the figure 7 into digraph shown in figure 8.

The red pentagon in middle stands for the internal circular lane, and each edge of it also has direction. This digraph can reflect actual complex traffic circle system. For example,there are two reasonable routes from E_1 to E_4, as the blue route shown in figure 8 and figure 9.

Figure 7:The circular lanes of this traffic circle is isolated by several small edge islands into two circles.Clearly, it's necessary to design good traffic signals.

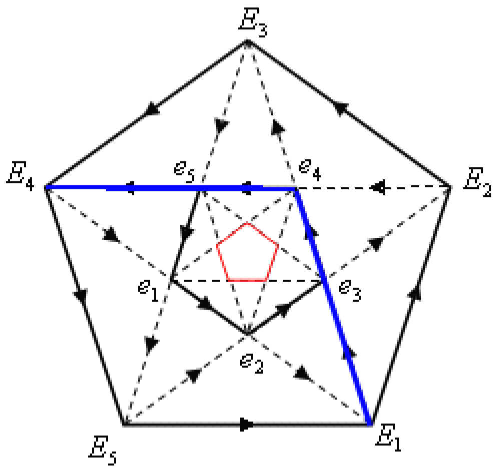


Figure 8: A route from E_1 to E_4 without passing through the inside lanes.

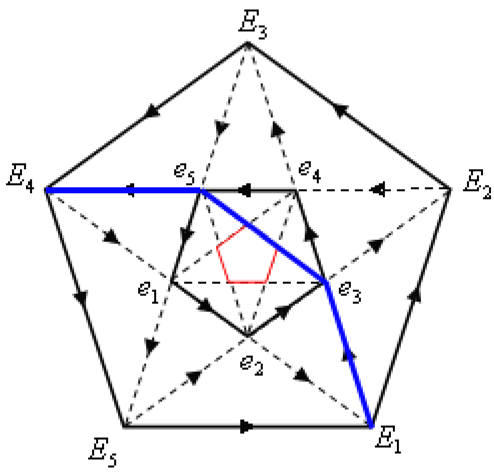


Figure 9:A route from E_1 to E_4 passing through the inside lanes.

But there are more options from E_1 to E_5. Of course, the best route should be following route in blue.

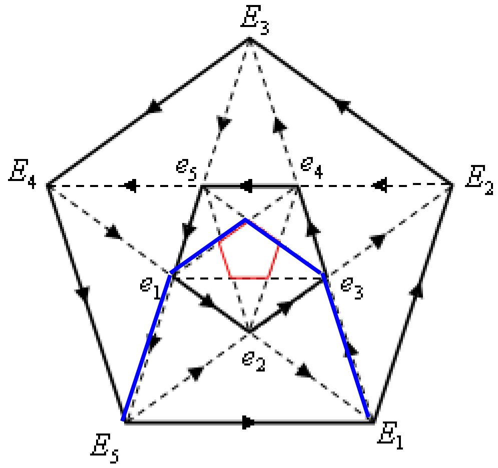


Figure 10: The best route from E_1 to E_5 pass through the inside lanes

It should be noted that vehicles should travel along the internal lanes if the target exit is away from the entry, such as from E_1 to E_5. However, there is no need to go into the internal lanes when the target exit is just two entries away, such as from E_1 to E_3.

In reality, however, it is inconvenient to set and control independent traffic signals for circular lanes. Therefore, our method fails to give the practical application of extended digraph. But the process of constructing the digraph and way of thinking is still worthwhile.

5.2 Considering pedestrian

From the method we create, it's obvious that in order to increase traffic capacity, we fail to take the sidewalk for pedestrians into consideration in our model. However, sidewalk design is a realistic problem, so following simple methods can be adopted.

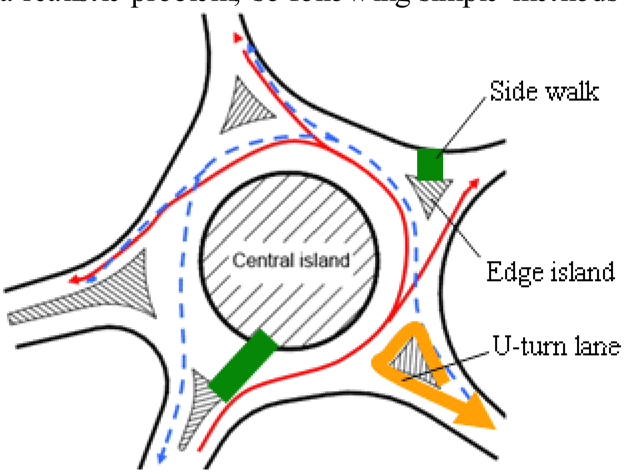


Figure 11: An actual traffic circle. The green lines represent side walk; the yellow line represents U-turn lane; the shaded parts around the central island is edge islands.

1.Sidewalks could be design with the Center Island and edge islands(As indicated in the figure 11),while the Signal phase design must be improved.
2.Set side walks across the incoming road a bit far away from the traffic circle and set the traffic signals as well.
3.Set the underpass or flyover near the traffic circle. But the high costs of this way make it unsuitable to be used.

5.3 Considering u-turn vehicle

Some of the vehicles may want to make a U-turn rather than travel into the traffic circle. Therefore, set U-turn lanes before vehicles travel into the traffic circle (shown in Figure 11).

6.Conclusion

Until now, people have explored many methods to control the traffic streams of traffic circles, especially regular ones. While our method is established aiming at the general traffic circles. Of course it can be used to regular circles as well and is in accordance with classical methods. But in terms of more general traffic circles, such as traffic circles with more incoming roads or more complex lanes, our method is more simple and direct while avoid the inaccuracy caused by complexity.

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