Traffic Circle Design Based on Cellular Automata Simulation

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Abstract

Nowadays, with the development of society and the progress of material life, ownership of vehicles is on the increase day by day. In order to solve the problem of traffic jam, we design some solutions of traffic circles. For practical purposes and universality, to begin with, we choose conventional non-controlled traffic circle with single line to research. The whole model is divided into three submodels. Submodel 1 is a dynamic programming model. According to Wardrop Equation, We get the relationship between traffic circle's geometric parameter and maximum traffic volume. The submodel 2 is a traffic circle model based on Cellular Automata. With the help of submodel 1, we design a traffic circle with optimal geometrical parameter. We assume that the vehicle's arrival (i.e., the headway) obey Poisson distribution with mean λ, and we use the value of λ to represent the number of cars. The total delay time is used to measure the total number of stopping vehicles, which is similar to characterize the performance of the whole traffic circle system. In order to solve the problem of submodel 2, we set up submodel 3. It's a Cellular Automata model, using traffic lights to control the intersections. We change the traffic circle in submodel 2 into an intersection with the control of traffic lights. Through the research above, we can draw up a conclusion: It is suitable for a smooth road while intersection with signal lights is suitable for a heavy traffic road. As for this model, its innovation is that we bring in Cellular Automaton to make simulation. Submodel 3 is able to get more parameters by resetting the cycle of signal light and simulating again. Therefore, our model is powerful and reliable for various types of different traffic circles' design.

Keywords

Traffic circle, Wardrop Equation, Cellular Automaton,Poisson distribution.

1. Restatement of the Problem

Helping design a traffic circle is a problem which can be split into two parts: designing its geometry, and optimizing the roundabout traffic capacity. After some discussion, we concluded that we should be able to use the Wardrop Equation which widely applies to the roundabout traffic to analyze the geometry of the traffic circle. Furthermore, we realized that the traffic capacity is closely affected by how many seconds each light should remain green, how many traffic lanes should be set and so on. And all of them can be artificially controlled so that we can keep the roundabout capacity stable in the time of day. In addition, human factors are not considered such as drivers' emotion which has reference value for the traffic circle design.

2. Classification of the Traffic Circle

There are varieties of traffic circles, so clearing our target first is of great importance. To begin with, a specific type of the traffic circle is needed, then we are able to analyze its characteristics. So it is available for us to get a reasonable result, which can be used to other models. The details are as follows.

2.1 Classifying the circle according to its radius

Regular circle

This is the most common type in the traffic design around the world. In the meanwhile, it is usually used to design an intersection with a long mixed section and import channels with the same width, while the diameter of the intersection is above 25m.

Small circle

The diameter of this circle is usually under 25m. And it's convenient for vehicles to broaden the channels when they get into or get out of the circle.

Tiny rotary

The central area of the traffic circle may be other shapes and the radius of the central circle is less than 4m.

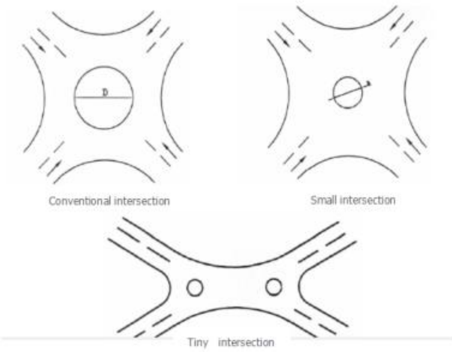

Fig. 1 types of traffic circle

2.2 Classifying traffic circles by the number of import lanes

Traffic circle with multiple lanes

Traffic circle with one lane

2.3 Classifying traffic circles by traffic light control

Traffic circles without signal control

This type is widely applied to the vast majority of nations, which is the traditional management in traffic circle. We divide the traffic circle into two groups—traffic circles without specific stop lines and traffic circle with stop lines. Traffic circles without specific stop lines is also named non-controlled roundabout where vehicles blend with the traffic flow in the roundabout freely. In this case, drivers are able to decide to accelerate or slow down when arriving at the intersection. However, vehicles entering into the roundabout should avoid those moving on the roundabout when the traffic circle sign specific stop lines.

Traffic circles with signal control

It is a management that human adopts traffic signal to control vehicles when they enter into the island. When traffic is heavy, for increasing the number of passing vehicles in unit time and decreasing the waiting time, we use traffic light to control traffic flows.

In order to simplify the problem, first of all, we choose the commonly used roundabout with single lane whose traffic signals are not installed. On this basis, two submodels can be established.

In submodel 1, to enlarge traffic capacity, we should find out the optimum geometry. Under the circumstances, We adopt Wardrop Equation to get the map of geometric profile and best traffic capacity. According to the international standard about the design of roundabouts, we set limits to geometric parameters and establish a dynamic programming model by using Lingo software to get specific designing values.

In submodel 2, to verify the theoretical value mentioned above, we use a simulation method based on Cellular Automata. In such a case, the entire island is spilt into multiple cells, and each of them has two kinds of state--taking up by a car or not. Cars are only allowed to drive in the cellular one by one. After a period of simulation, the final state is available. By setting different traffic flow, simulating different vehicles' state, counting total delay time in each simulation process, we analyze the relationship between traffic flow and delay time. At last, simulation results can be used to direct the design of roundabout traffic lights.

3. Assumptions

(1). There's no suspended vehicle on the road.

(2). The traffic circle is located in the flat area.

(3). Angles of getting in or getting out are in a proper range.

(4). All of the vehicles entering into the circle are the same type and pedestrians are prohibited.

(5). It is average of the traffic flow in every entrance and exit, which obeys the Poisson distribution.

(6). All subjective factors should be ignored such as drivers' emotion so that the vehicles' speed are only affected by traffic signals and vehicle's speed in front of the current one.

Table 1

Parameter	*Definition*
W	the shortest distance between the inner circle and weaving section
l	length of waving section
e_1	the shortest distance between the inner circle and the entrance
e_2	the shortest distance between the entrance to the triangle and the peripheral edge of the circle
P	the ratio of vehicles in weaving sections and the total number of vehicles on the island
$V_i(t)$	the speed of the ith cell at time t
$V_{i+1}(t)$	the speed of the cell in front of ith cell at time t
$X_i(t)$	position of vehicle i at time t
$V_i(t)$	speed of vehicle i at time t
$X_{Stopline}$	position of stop lines
$gap_i(t)$	distance between vehicle i and vehicle i+1 at time t
$state(i)$	directions of vehicle i. 1 means go straight. 2 means turn right. 3 means turn left. 4 means turn around.

4. Modeling

4.1 Roundabout design model

Based on the island's biggest capacity, we adopt the famous Wardrop Equation, which is widely applied to conventional roundabout design.

$$\max Q_M = \frac{280W(1+\frac{e}{w})(1-\frac{P}{3})}{1+\frac{W}{l}}$$

$$s.t.\begin{cases} 6.1 \le W \le 18 \\ 0.12 \le e/W \le 0.4 \\ e = e_1 + e_2 \\ 0.34 \le e_1/e_2 \le 1.41 \\ 0.4 \le P \le 1.0 \\ W, e, e_1, e_2, P > 0 \end{cases}$$

Obviously, the mixed period of maximum capacity is associated with the design parameters. Through changing parameters, we can obtain the maximum capacity of the roundabout. We adopt Lingo software to solve the problem.

4.2 Cellular Automata simulation model

We use this model to simulate the motion of the car inside or outside the circle. Based on past experience, cars' arriving at intersections obey Possion Distribution. We change the probability to find out when we need signal light to control traffic flows entering into the circle.Model details are as follows:Firstly, we address the problem of optimizing a roundabout through separating the roundabout and entrances connected with it into many equally spaced small squares and vehicles are only allowed to move in the small squares one by one. To model the roundabout more easily, we set some rules to control and renew cars' condition.

Rule 1: entering the island

Vehicles entering into the road intersections obey Possion Distribution:

$$P(X=k) = \frac{\lambda^k e^{-\lambda}}{k!} \quad k = 0,1,2\ldots$$

Rule 2: leaving the island

Supposing the number of exports is N around the roundabout. Otherwise, the possibility of leaving each exit is seemed to be the same.

$$P_1 = P_2 = \ldots = P_N = \frac{1}{N}$$

Rule 3: slowing down or stop

If the speed of the current cell is greater than the sum of cell and the grid in front of it, then the car will slow down or even stop.

$$V_i(t) > V_{i+1}(t) + gap_i(t)$$
$$V_i(t) > gap_i(t) - 1$$

Rule 4: accelerating

If the speed of the current cell is slower than the front grid substracting one, then the cell choose to accelerate.

$$V_i(t) > gap_i(t) - 1$$
$$V_i(t) > V_i(t) + 1$$

Based on all the rules above, we use Matlab to simulate.

4.3 Traffic signal lights

Taking flaws in model 2 into account (when headway distance is less than 4, the total delay time of vehicles in traffic circle is long. A discussion of this problem can be found in Section 4.2) , we are supposed to look for a new method to solve the problem. So the intersection traffic light model is created. We set the traffic light in the intersection, and then compare it with traffic circles, which is hoped to make up for previous defects. We also adopt Cellular Automata to simulate the vehicle's arrival and departure.

Traffic circle is replaced by intersections with two ways and two lanes, which is similar to model 2. And graphs are shown as follows:

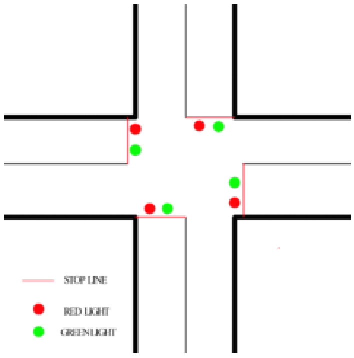

Fig. 2 intersection traffic design

We divide the intersection into many cellulars, whose length is the same as model 2's. Then we set following rules:

Rule 1: arriving rule

Assume that vehicles' arrival at intersection obey Poisson distribution.

Rule 2:leaving rule

There are four directions vehicles can choose, including going straight, turning left, turning right and turn around, and the probability of four directions are equal.

Rule 3:speed rule

When there is vehicle i+1 in front of vehicle i, the speed of vehicle i and its position $(V_{i+1}(t), X_{i+1}(t))$ at time t need to be compared with the speed and position of vehicle i+1 at time t. Under this circumstance, our model can judge whether vehicles need to slow down. When the distance is too small, vehicle i choose to slow down or even stop. On the contrary, vehicle i choose to accelerate.

Rule 4:traffic light rule

If vehicle *i* choose to go straight and its next position $X_{i+1}(t)$ exceed stop lines, then this vehicle need to slow down or stop, while vehicle choosing other directions are out of traffic lights' control. In consideration of regular arrival rules, the probability of leaving from four exits are the same. Based on symmetry principle, we can choose a pair of exit and entrance at random.

Details about rule 3 and rule 4 are elaborated as follows:

if $X_i(t)+V_i(t)<X_{i+1}(t)$

$X_i(t)+V_i(t)>X_{Stopline}$

When *state(i)*=1

$$\begin{cases} V_i(t+1)=0 & X_{Stopline}=1 \\ V_i(t+1)=V_i(t)+1 & X_{Stopline}=0 \end{cases}$$

(rules for stopping or slowing down)

When *state(i)*$\neq 1$

$$V_i(t+1)=V_i(t)+1$$

(rules for turning)

$X_i(t)+V_i(t)<X_{Stopline}$

$$V_i(t+1)=V_i(t)+1$$

(rules for accelerating)

If $X_i(t)+V_i(t)>X_{i+1}(t)$

$$V_i(t+1)=gap_i(t)-1$$

(rules for slowing down)

. Rule 5:position at next time

$$X_i(t+1)=X_i(t)+V_i(t+1)$$

We take all rules into consideration, and then use Cellular Automata to simulate. To begin with, we set all vehicles on the initial lane, at the same time, they obey uniformly random distribution, which means $V_i(0)=rand(1,2,3,4), i=1,2,\ldots n$. The method of simulating time is the same as model 2, and that means each step needs 2 seconds. We need to loop 1000 times. Each simulation will cost 2000 seconds.

4.4 Solution to models

the solution of in Section 2.2

We solve the dynamic programming problem by using Lingo software, and the results are as follows.

Table 2

Parameter	*Value*
Biggest traffic flow	7138.279 *Veh/h*
W	18.000 m
E	18.000m
P	0.400
e_1	9.134328m
e_2	26.85567m
l	80.42020m

At this point, the circumference of the traffic circle is as follows:

$$C=2\pi(\frac{\sqrt{2}}{2}-e_2)=188.4956m$$

the solution of model 2

According to the optimal parameters got in Section 2.2, the circumference of the traffic circle is set to 188.4956m, which can be separated into 48 cellular, of which length is 3.9m. We set 10 cellular at each entrance and their lengths are 39m. The total cycle number is 1000 times and each of it represents an actual time about 2 seconds, whose total time is 2000 seconds. By setting different λ to simulate, we find the relationship between λ and delay time. The results are as follows:

It's clear to see that the relationship between delay time and average space headway is inversely proportional and the headway size can be used to describe road congestion. The smaller the headway is, the heavier the traffic will be.The limited value of headway is zero, which means roads get paralysed and delay time is infinite. When the space headway is greater than 5, there is no big change on delay time, and the number is small too, which means roundabouts are capabale of dealing with the traffic flow. So there's no need to use traffic signal to control it on condition that average space headway is more than 5. On the contrary, we can see a significant rising trend of delay time, so traffic lights are needed to control the traffic flow in the roundabout. To a certain degree, space headway represents a traffic flow in this roundabout. So this curve can be used as a guidance. With the help of it, we can design when to use traffic lights to control traffic flow.

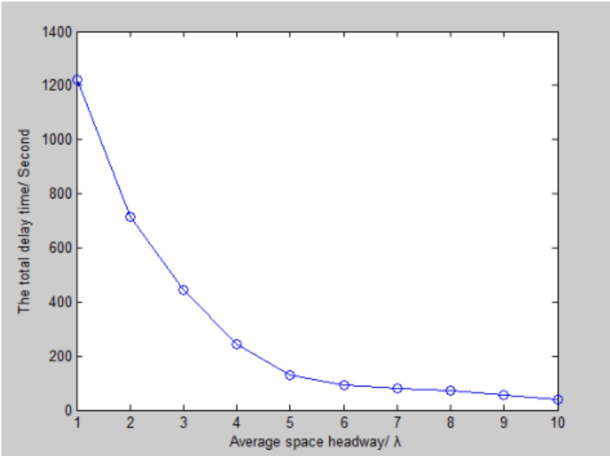

Fig. 3 The delay time of different traffic flow

the solution of model 3

We set 4 lanes, whose length are equal to the length of 10 cellular. Length of each cellular is 3.9m.We regard the intersection of four access lanes as the crossroads with traffic lights. The traffic lights period T is set to be 4. The simulation time is 1000 times, which cost 2000 seconds totally. The following results are concluded by setting different λ:

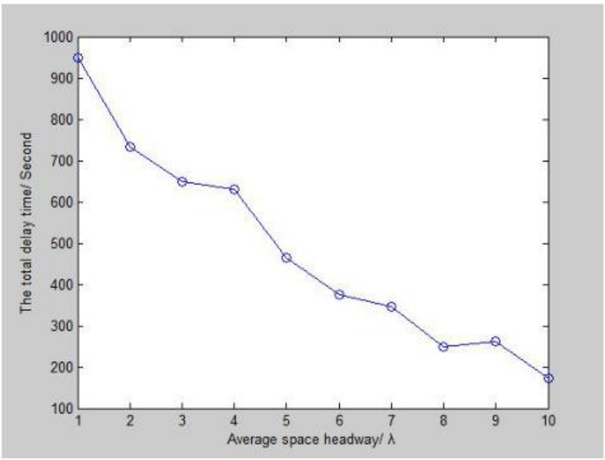

Fig. 4 The simulation results of the λ values corresponding to the total delay time.

4.5 Evaluation of results

Comparing total delay time of traffic circle lanes with intersections'

As we can see, when the value of λ is bigger than 5, the traffic circle is in a good condition and the total delay time is short too. As the value of λ increase, there will be less decrease on total delay time, which matches the physical truth very well. Owing to the small influence of sparse traffic, the total delay time do not reduce significantly along with the augment of λ.

On the contrary, when the value of λ is smaller than 5, the situation of traffic circle becomes worse. It's a significant phenomenon that the total delay time increase sharply as the decrease value of λ, especially when the value of λ is less than 2. So, to replace the previous design of traffic circle, looking forward to another method is of great importance. That's the reason why we adopt model 3 to substitute the conventional traffic circle.

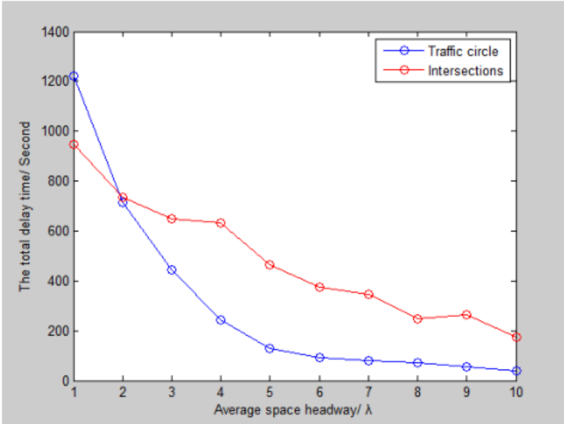

Fig. 5 the comparison of intersection and traffic circle

The simulation result of intersections and traffic circle are put in one graph, from it we are able to find out that when the value of the period of traffic light（T）is set to be 4 cellular, we can improve congestion whose average space headway is less than 2. Nevertheless, we don't solve the problem when 2<λ<5. In order to find a method to deal this matter, we can set different T to simulate continuously.

To sum up, we can draw conclusions that ---when the quantity of the vehicle in the traffic circle is small, traffic circle can reduce total delay time efficiently. As the traffic goes heavy, the traffic circle's fluency will decline dramatically, and that's the time we need to choose traffic circle to relieve traffic pressure. That is to say, the method of traffic lights design is suitable for the road where traffic is usually heavy, while traffic circle is suitable for the smooth traffic.

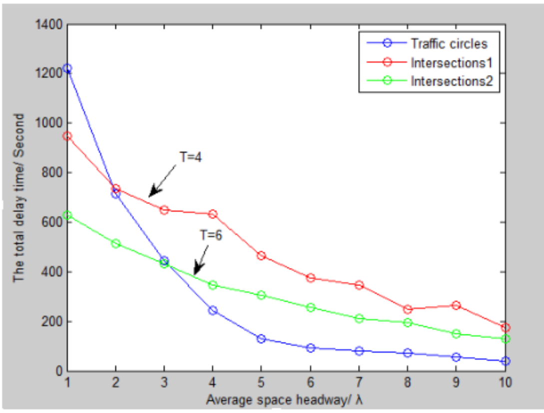

Fig. 6 the result of changing traffic light period T

Now, we can solve traffic jam issue when λ<3 and we should chose the intersection signal lights model in the case of T=6 and λ<3.

5. Testing the Model-Simulations and Sensitivity Analysis

It's widely believed that traffic circles are able to adjust themselves to relieve the traffic pressure and the congestion level can be reduced by setting traffic signals. However, what we expected is really true? With the help of the original experience, Wardrop Equation are chosen to optimize our previous design. On the basis, we adopt Cellular automata model to verify whether the model is correct under different conditions. Through analyzing the model, it's not reasonable to add traffic lights to relieve traffic pressure until traffic flow in the circle being more than its standard capacity. We set up a model from the aspect of qualitative and quantitative analysis to solve the problem of when signals and how many seconds each light should remain green. We proved the subjective conjecture in theory, which also confirmed our model's validity and practicability.

In submodel 3, we set the period of traffic lights is 4. The problem is that, when 2<λ<5, we didn't solve the problem of bad delaying time. So, we will change the period in the next section while remain other conditions unchanged except period. In this background, we do another simulation to find the optimal value. When we increase the period to 6, the results are as follows.

6. Strengths and Weaknesses

Our model is suitable for different cities. Through this model, we can design traffic circles with optimal capacity. At the same time, we apply Cellular automata simulation to test whether its capacity is best only to be given the designing size. According to qualitative and quantitative analysis, we are able to analyze the relationship between delay time and traffic flow. And then a better period of traffic signal can be found, which has certain guiding significance on urban circle design. Nevertheless, there are still some shortcomings about our models. We ignore some objective phenomenon, such as vehicles' irregularity, pedestrian's influence to traffic. In addition, to simplify the model, we only simulate traffic circles with single lane based on all assumptions above. And the period of red light is the same as green light's, which may be different from the real situation.

7. Technical Summary

In order to solve the intersection congestion problem, we come up with two solutions and publish them as follows.

7.1 Conventional single non-control circle

This scheme is suitable for less traffic road especially when average headway time (λ) is bigger than 5. Traffic circle's geometric parameter should be based on Wardrop Equation as follows:

$$Q_M = \frac{280W(1+\frac{e}{W})(1-\frac{P}{3})}{1+\frac{W}{l}}$$

Ideally, we can get an optimal traffic volume under the international standard limit.

Table 3

Parameter	*Reference value*
W	$6.1m \sim 18m$
e/W	$0.4 \sim 1$
W/l	$0.12 \sim 0.4$
e_1/e_2	$0.34 \sim 1.41$
P	$0.4 \sim 1$

And the optimal traffic volume is 7138.279 vehicles per hour. Other parameters are as follows.

Table 4

Parameter	*Value*
Biggest traffic flow	$7138.279\,Veh/h$
W	$18.000\ m$
E	$18.000m$
P	0.400
e_1	$9.134328m$
e_2	$26.85567m$
l	$80.42020m$

Each parameter corresponding to the position below.

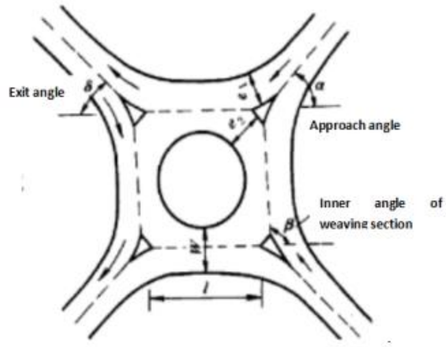

Fig. 7 geometry parameters of traffic circle

7.2 Light control intersection

This scheme is suitable for large traffic road especially when average headway time (λ) is smaller than 3. This scheme is suitable for the two-way two-lane road. The cycle of traffic lights (both red and green) is 6 second. We'll give the schematic in details.

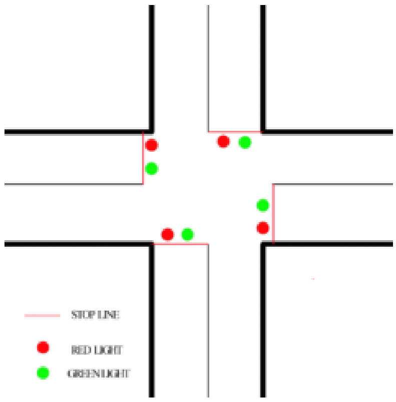

Fig. 8 intersection traffic design

References

[1] Fenfang Liu. The Study of two-line traffic Flow Characteristics Based on Cellular Automaton [D]. Central South University, 2008.

[2] YiPeng Du. The Theory of Traffic Facilities Designs and Study of Case. South China University of Technology. Central South University, 2013.

[3] Bo Zhu. The Study of Multi-Agents Mixed-Traffic Simulation Based on Cellular Automaton [D]. Shandong University, 2006.

[4] Hailan Zhang. The Analysis of Roundabout's Capacity and the Measures of Improvement [D]. Chang'an University, 2012.

[5] Xiaobao Yang, Ning Zhang. Mathematicl Analysis of Effects of Lanes'Number on Expressway Capacity [J]. Journal of Wuhan University of Technology, 2008.