Traffic Circle Design based on Simulation Approach

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Abstract

The paper establishes a model to determine how best to control the traffic flow in, around, and out a circle. A criteria for judging the controlling method of the traffic flow on traffic circle is given. The paper analysis the main factors which affect the traffic flow and focus on the basic model for the small traffic circles. In the basic model, an ideal situation is introduced and be regarded as the busiest condition. Based on the ideal model, the Gap-acceptable theory and the concept of headway and entry capacity, Cowan's M3 distribution is assigned to the cumulative probability of headway. And it could give the expectation of the number of inserting vehicles and the entry capacity of the intersection. Further, the criteria for judgment is set up by making use of the expectation of the number of inserting vehicles and the relation between the incoming flow and the out flow under the uncontrolled status. Further more, the paper give a method to determine the best time of green light for every traffic light. Finally, for the large traffic circle, the paper also gives a rough description based on the basic model..

Keywords: Entry capacity;Headway;Gap-acceptable;Traffic circle design

1 Introduction

A traffic circle is an intersection with a circular shape and, usually, a central island. In some traffic circles two-way traffic is allowed within the circle. However, it is much more common that traffic is allowed to go in one direction only around a central island. A stop sign and a yield sign may be used in some of these traffic circles. A yield sign indicates that a vehicle driver must slow down and prepare to stop if necessary. A stop sign instructs drivers to a full stop and then to proceed only if the way ahead is clear.

Traffic circles have been part of the transportation system in United States since 1905, when the Columbus Circle designed by William Phelps Eno opened in New York City. Subsequently, many large circles were built in the United States. The prevailing design enabled high-speed merging and weaving of vehicles. Priority was given to the traffic entering the circle, facilitating high-speed entries. High crash experience and congestion in the circles led to rotaries falling out of favor in America after the mid-1950's [3].

However,, the experience with traffic circles was equally negative, with many countries experiencing circles that locked up as traffic volumes increased. The experience with traffic circles with the priority given to the traffic entering the circle in the US was almost entirely negative, characterized by high accident rates and congestion problems. By the mid 1950s, construction of traffic circles had ceased entirely. In 1966, the United Kingdom adopted a mandatory 'give-way' rule at all circular intersection, which required entering traffic to give way, or yield, to circulating traffic. This rule prevented circular intersections from locking up, by not allowing vehicles to entering the intersection until there were sufficient gaps in circulating traffic. These changes improved the safety characteristics of the circular intersections by reducing the number and particularly the severity of collisions.

Now, as the pressure of the traffic is increasing, it is necessary to deal with the large traffics. Some experts divert their attention back to the traffic circle. But how to re-design the traffic circle is the urgent problem. Then, the paper we expand the discussion about the design of traffic facilities, especially the design of stop sign, yield sign and the traffic light.

2 Assumptions and Definitions

For the sake of the description, we will introduce some basic assumptions and definitions.

2.1 Assumptions

1. Suppose the center of the traffic circle is circularity, and the width between center and curbside is always the same.
2. Suppose all the vehicles running on the traffic circle have almost the same speed.
3. Suppose all the vehicles comply with the traffic rules strictly and ensure the safety of traveling.
4. Suppose the drivers will use the same method to deal with the similar cases at any time. That is, if the vehicle is asked to enter the gap which is acceptable, then the driver won't refuse a acceptable gap first and accept a smaller gap later.
5. Suppose the priority rules in the intersections on a traffic circle are always the same.

2.2 Definition

1. **Entry capacity**(C) The number of the vehicles which enter the next segment of the traffic circle per second.
2. **Gap** The area between a vehicle and its proximate ahead vehicle.
3. **Headway** The distance in time that separates two vehicles traveling the same route.
4. **Incoming flow**(I) The traffic flow with the direction pointing to the center on the incoming road.
5. **Out flow**(O) The traffic flow with the direction lapsing from the center on the incoming road.

3 Problem Design

The number of lanes on the traffic circle, the priority rules and the control method all affect the traffic conditions on the traffic circle. We try to use a model which is with an eye to all the factors, however the effect of the factors are so complicated. In order to touch the essence factor of the problem, we will start from a basic model.

3.1 Basic model: Small traffic circle

In the part we will focus on the circles whose scale is small. That means there are one or two lanes in the circles, so it is reasonable for us to regard it as a bigger traffic circle with only one lane. Here we neglect the conflict happen in the moment of change lanes. This neglect is acceptable for the size of the traffic circle is small. To sum up, we only need to consider the condition that there is only one lane with n intersections on the traffic circle.

3.1.1 Parameters

I_i, O_i The incoming flow and the out flow of the i th intersection respectively.

IN_i The traffic flow which could enter the circle at the i th intersection.

$f_{i,i+1}$ The traffic flow on the segment between the i th and the $i+1$ th intersection.

E The expectation of the number of inserting vehicles.

B_{ij} The rate of vehicles which come from the i th intersection and leave at the j th intersection.

B The matrix with the size of $n \times n$ consisting of the element of B_{ij}. We could call it rate matrix.

h_i The traffic flow on the traffic circle which is between the way-in lane and the way-out lane of the i th intersection.

Δ The lower limit of headway. That contains the length of vehicle and the safe distance.

T The headway which could allow just one vehicle to insert

T_0 The headway which the following vehicles need to insert.

Here is a graph to explain some variables.

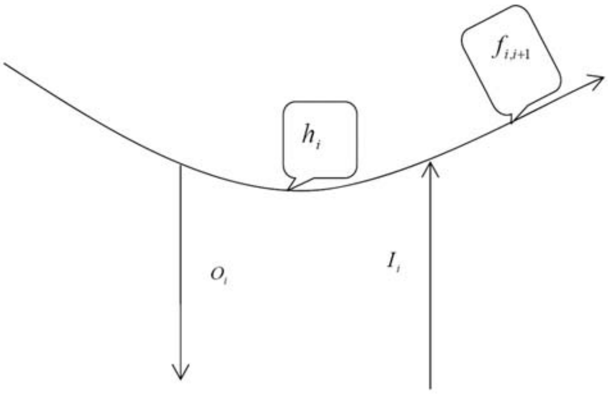

Figure 1: The graph of some variables

3.1.2 Abandoned visualization

Our purpose is to maximize the entry capacity through the control method such as a stop sign, a yield sign and a traffic light. At first, we see about the state without any restrictions. It is worth to note that the vehicle is considered as a point with no length and allows the coming ones enter. That is we consider the traffic circle as an ideal circle which has large enough space.

Under these hypotheses, we focus our energy on the stable state. Combining with the rate matrix B, we could get the following equations:

$$f_{12} = I_1 + B_{22} I_2 + (B_{32} + \cdots + (B_{n2} + B_{n3} + \cdots + B_{nn}) I_n$$
$$f_{23} = (B_{11} + B_{13} + B_{14} + \cdots B_{1n}) I_1 + I_2 + \cdots + (B_{n3} + B_{n4} \cdots + B_{nn}) I_n$$
$$\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots$$
$$f_{n1} = B_{11} I_1 + (B_{21} + B_{22}) I_2 + \cdots I_n$$

where to each segment we add all the traffic flow coming from different intersections. For example, to the traffic flow f_{n1}, all the traffic coming from the n th intersection will go through this segment; however only the traffic flow which come from the 1st intersection and leave at the 1st intersection too will go through this segment. If we mark this rate to be b_{n1}, then $b_{n1} = B_{11}$. Go on the similar analysis, we could obviously get the above equations.

For the similar reason, we could calculate the out flow of each intersection.

$$O_1 = B_{11}I_1 + B_{21}I_2 + \cdots + B_{n1}I_n$$
$$O_2 = B_{12}I_1 + B_{22}I_2 + \cdots + B_{n2}I_n$$
$$\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots$$
$$O_1 = B_{1n}I_1 + B_{2n}I_2 + \cdots + B_{nn}I_n$$

Then, according to the stability of the total traffic flow, we could get

$$h_i = f_{i,i_1} - O_i = f_{i,i+1} - I_i$$

Hence, under the abandoned visualization, we could know the traffic flow of each segment on the traffic circle.

3.1.3 Entry Capacity of Incoming road

Of course, considering the traffic safety and the carrying capacity of the traffic circle in fact, the abandoned visualization is just an ideal. But we could regard it as the worst situation and the busiest situation. Now, we will go further discussion based on the ideal condition.

As we has introduced above, the traffic circle is a method of intersection. And the priority rules will affect the entry capacity. Looking back to the history of traffic circle, we can find that it is easy to lead to congestion. As a result, and considering some traditional rules, we default that vehicles on the traffic circle has the priority.

Under this default, we generally have 3 kind of basic theories to deal with it[1]:

1. **Interwoven theory**. Use the maximum interwoven flow of the part of interwoven to reflect the entry capacity. The typical is Wardrop Formula
2. **Gap-acceptable theory.** Use the maximum number of vehicles which could enter the traffic circle to reflect the entry capacity
3. **Regression model**. Be built up on the foundation of a large amount of data which reflect the traffic flow on the circle and the entry capacity of intersection.

Here, considering the function of yield sign, we choose the Gap-acceptable theory. That means the vehicle on the incoming road is secondary traffic flow and the vehicle on the circle is the main traffic flow. The secondary flow could enter the main flow if and only if there is a gap which is bigger than the critical gap.

Based on the gap-acceptable theory we could conduct the **mathematics Description**.

In early time of the study for the development of traffic flow, people always suppose the incoming vehicles satisfied Poisson distribution. Then the headway should be exponential distribution. However, this would lead to much headway between 0 and 1. And this doesn't correspond to reality. In consideration of the lower limit of headway Δ, we revise the exponential distribution to M3 distribution which was proposed by Cowan.

In the special distribution, Cowan introduce the rate of free vehicles α (the rate of vehicles which don't troop). So the cumulative probability of the headway is

$$F(t) = \begin{cases} 1 - \alpha e^{-\lambda(t-\Delta)} & t > \Delta \\ 0 & t \le \Delta \end{cases} \text{---------------------------------------(1)}$$

where $\lambda = \dfrac{q\alpha}{1 - q\Delta}$, here q represent the traffic flow.

Next, we focus our on the traffic circle. Then the probability of the distance in distance of the gap at the i th intersection which is restrict less than t_0 is

$$H_i(t_0) = P(t \le t_0) = F(t_0) = 1 - \alpha_i \lambda_i e^{-\lambda_i (t_0 - \Delta_i)} \text{----------------(2)}$$

where $\alpha_i, \Delta_i, \lambda_i = \dfrac{q_i \alpha_i}{1 - q_i \Delta_i}$ are the corresponding explains, and here $q_i = h_i$

Then, we could go a further step to get

$$P_i(k) = H(T + kT_0) - H(T + (k-1)T_0) \text{-------------------------------------(3)}$$

where $P_i(k)$ represent the probability that i th intersection could just enter k vehicles into the traffic circle.

In general sense, we could think all the vehicles are free. So we could just $\alpha = 1$, and (1) can be revised as

$$F(t) = \begin{cases} 1 - e^{-\lambda(t-\Delta)} & t > \Delta \\ 0 & t \le \Delta \end{cases} \text{---(4)}$$

where $\lambda = \dfrac{q\alpha}{1 - q\Delta}$

In order to a further simplification, we could roughly get the equation between Δ, T, T_0

$$T_0 = \Delta \qquad \text{---(5)}$$

$$T = 2\Delta \qquad \text{---(6)}$$

which could be easily understood by the following graph.

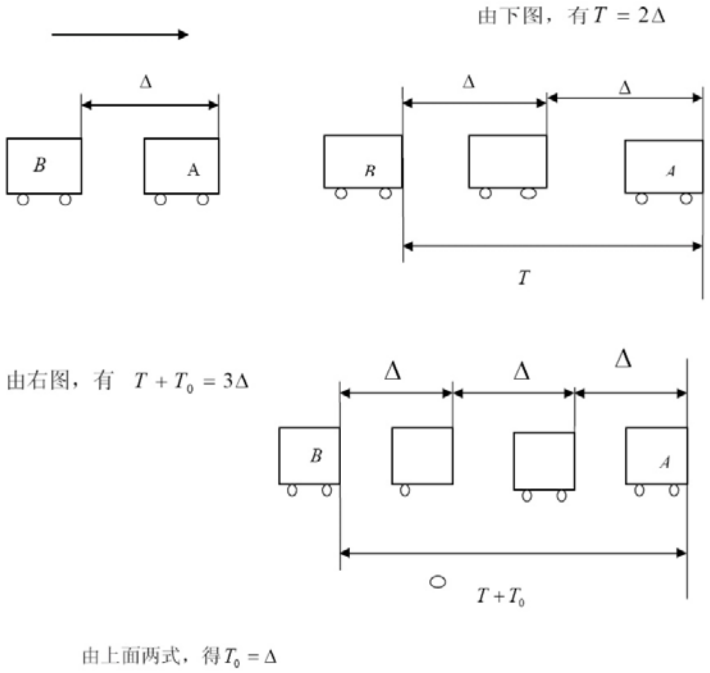

Figure 2: The explanation for the above two equations

Then (2) could be simplified as

$$H_i(t_0) = P(t \le t_0) = F(t_0) = 1 - \lambda_i e^{-\lambda_i (t_0 - \Delta_i)} \text{--(7)}$$

where $\lambda_i = \dfrac{h_i}{1 - h_i \Delta}$

Combining (7) and (3),(6),(5), we could get

$$P_i(k) = H_i((k+2)T_0 - H((k+1)T_0) \qquad \text{--------------------------------------(8)}$$

$$= e^{-\lambda_i (k+1)T_0}(e^{\lambda_i T_0} - 1) \qquad \text{--(9)}$$

Finally, we could express the expectation of the number of inserting vehicles at the i th intersection

$$E_i = \sum_{k=1}^{\infty} kP_i(k) \qquad \text{---------------------------------------(10)}$$

And basing on the expectation E_i and the traffic flow in the corresponding segment on the circle h_i , we could get the entry capacity

$$C = h_i E_i \qquad \text{---(11)}$$

$$= h_i \sum_{k=1}^{\infty} kP_i(k) \qquad \text{---(12)}$$

3.1.4 Judgment criterion and method choice

As the expectation could be regarded as an average state, the expectation of the number of inserting vehicles can reflects the average level of entry capacity.

Taking into account the safety, the rules of priority and the meaning of control method, we know that a yield sign is a basic remind sign. This sign could be used for those not busy intersections. However, as a stop sign asked the driver a full stop and then wait for the acceptable-gap to go. What's more the stop sign is often used on the not too busy intersection. Finally, to the most commonly used traffic lights are often used to control the traffic flow on the busy intersection.

Compare with the difference of the control method and considering the purpose of maximum the entry capacity, we could summarize the following criterion for judgment:

When $E \geq 1$, we choose a yield sign to control the traffic flow waiting to enter the traffic circle.

When $E < 1$ and $I < O$, we choose a stop sign to control the traffic flow waiting to enter the traffic circle.

When $E < 1$ and $I \geq O$, we choose a traffic light to control the traffic flow waiting to enter the traffic flow.

It is obvious that this kind of criterion conduce to our purpose. First, $E \geq 1$ means in average sense there will be an acceptable gap for the driver to enter. Hence we could think the traffic flow isn't busy. So there is no need for the vehicle on the incoming road to stop. That means a yield sign is a better choice.

Second, $E < 1$ means in average sense there won't be a acceptable gap for the incoming car to enter immediately. So, we should try to reduce the traffic flow on the circle in order to let the vehicles on the incoming road could have more chance to enter. Further, considering that $I < O$ indicates the number of vehicles which could enter the circle IN must less than O. So, it just needs a little longer waiting for the flow reduction. This was because that $IN < O$ will lead the self-regulation of traffic flow on the circle. Hence, we just need to position a stop sign.

Last, when $E < 1$ and $I \geq O$, the traffic flow on the circle is busy and can't self-regulate. So, the vehicles on the incoming road must be complied to yield within some time in order to reduce the flow on the circle. And the position of a traffic light is a good choice to achieve this goal.

To sum up all above cases, we are sure that it is reasonable to set up the criterion.

3.1.5 Determine the time of green light

Obviously, when a intersection is controlled by a traffic light, the time of the light which remain green is the most important factor of controlling traffic flow on the traffic circle. Next, our task is to determine the time the light should be green in order to get the maximum entry capacity.

As we consider about a period of time during which the traffic flow on all the incoming roads don't have obvious change, it is reasonable for us to believe that the color of traffic light changes in a certain cycle. So, the first of all, we should determine the proportion of green time in the entire cycle.

In order to determine the proportion, we suppose in an entire cycle the time for green is g and the time for red is r. Then, based on the worst condition, that is the abandoned visualization condition, we could know the out flow O in the stable state according to the incoming flow I. Considering that our purpose is to maximum the entry capacity of the intersection, so we should let the vehicles entering the circle as many as possible. Further, we could know that the number of the vehicles which leave the traffic circle during the cycle of traffic light should be

$$Leave = (g + r)O$$

On the other hand, as the right light will stop the vehicles on the incoming road. So the maximum number of vehicles which have the probability to enter the traffic circle should be

$$Enter = gI$$

As we should increase the entry capacity of intersection as large as possible, so during the whole cycle $Enter$ should be as many as possible. However, we can't ignore the aim of reducing the traffic flow on the traffic circle. That indicates that

$$Leave \geq Enter$$

Taking into account of all the purposes, we could see that the critical state should be

$$Leave = Enter$$

That is

$$(g + r)O = gI \qquad \text{--(13)}$$

Simplify (13), we could get the rate we want

$$\frac{g}{r} = \frac{O}{I - O} \qquad \text{--(14)}$$

For the criterion of choosing light ask the inequality $I > O$, the proportion $\frac{g}{r}$ reasonable.

Next, we will search for the best time for the green light during the entire cycle. For the sake of description, we introduce some addition symbols and assumptions.

Table 1: The introduction of the parameters

m	The number of intersections which we have determined to position a traffic light.
r_i	The time of the i th light which remain red during an entire cycle
g_i	The time of the i th light which remain green during an entire cycle
R_i	The proportion of the time of the green light to the red light. That is $R_i = \frac{g_i}{r_i}$
Q	The sum of Q_i. Of course, if Q get its max, then we can control the traffic flow best.
$C_i(t)$	The entry capacity of the i th intersection at the time t. Here, we regard 1 second as the unit of the change of time, then the t would be the integer with the changing from 1 to 3600.

Some assumptions:

1. The state of the traffic circle and the incoming road almost keep the consistency during the unit time.

2. Each unit time there is a state of traffic circle and the next state of the traffic circle is determined by the previous state.

3. The traffic light is always kept green at the beginning of the discussion period of time, say 1 hour.

As we have known control method at each intersection and the correspond incoming flow, Q is a function of r_i and g_i. Considering that we could get the best choice of the proportion R_i, $g_i = R_i r_i$. Then, Q will be simplified to a function whose variables are $\{r_i\}_{i=1}^{m}$ and our purpose is to find $(r_1^*, r_2^*, \cdots, r_m^*)$ which will let the Q get its max. We will realize it by the following steps:

1. Initialization. For the abandoned state is the basis of the choice for the controlling method, we have enough reasons to set the abandoned state as the first state. That is

$$C_i(0) = I_i (i = 1,2,\cdots,n)$$

2. As $C_i(t)$ represent the entry capacity at the moment of t under the Gap-acceptable theory. Further, it reflects the traffic flow which could really enter the traffic flow. Therefore, we could regard it as the equivalent actual incoming flow of the next moment of $t+1$. As this flow will completely enter the next segment of the traffic circle once, we could similarly deal with it according to the state of abandoned visualization, and get the traffic flow of each segment on the circle $(\hat{h}, \hat{f}, \hat{O})$. Again make use of the equation (12), we could get correspond $\hat{C}$.

3. If we position a stop sign or a yield sign at the i th intersection, then the flow on the incoming road could enter the next segment of the circle. So $C_i(t+1) = \hat{C}$. If we position a traffic light at the i th intersection and the traffic light is green, we deal with it the same case for the stop sign and yield sign. That means $C_i(t+1) = \hat{C}$. If we position a traffic light at the i th intersection and the traffic light is red, then the vehicles is complies to stay on the incoming road. Then, only the vehicles which are still on the circle at the intersection could enter the next segment. That means $C_i(t+1) = \hat{h}$.

4. Repeat the 3rd step 3600 times, then we could get the matrix $(C_i(t))_{4\times3600}$. And

considering that check the states every one second, so

$$Q_i = \sum_{t=1}^{3600} C_i(t) \times t_0$$

where $t_0 = 1$ with the unit of s. And we get $Q = \sum_{i=1}^{4} Q_i$.

5. Try to find the maximum points $(r_1^*, r_2^* \cdots, r_n^*)$ of the function. Then, we could use their correspond proportion R_i get the best for green light $(R_1 r_1^*, R_2 r_2^* \cdots, R_n r_n^*)$

3.1.6 Stochastic simulation

In order to check the validly of the model, we will use a stochastic simulation to simulate the situation for a real traffic circle. In the simulation we replace the expectation of the inserting vehicles by the random ones to get the entry capacity. Here ,we get the random number of the inserting vehicles by making use of the corresponding probability density function of the present moment which is determined by h_i .And it is just the entry capacity corresponding to the next moment.

Then, based on the data of a traffic circle with 4 incoming road, we can get the final result as follow:

Table 2: The comparison between the model ant the reality

	Our Model	Realistic Circumstance
I	0.4, 0.6, 0.5, 0.5	0.4, 0.6, 0.5, 0.5
Method Choice	S,L,S,L	Y,L,Y,Y
r	/, 40, /, 60	/,55,/,/
Q	6508	5500

From the table above, we can know that using our model to determine which one among the stop sign, the yield sign and the light on every incoming road and the time of lights which remain green, Q change from 5500 in the realistic circumstance to 6508, which means that can be well applied in the realistic circumstance and therefore improve the efficiency of the traffic circle.

3.1.7 Sensitivity analysis

In order to realize the essential elements which influence the results, that is, the sensibility of the parameters, we begin the work as follow.

Firstly, we will discuss how r_i influence Q

According to what we have known, we can get the figure about how the time of the light which remain red influence the number of vehicles entering the traffic circle when the number of the incoming road is 4 and 8 respectively as follow:

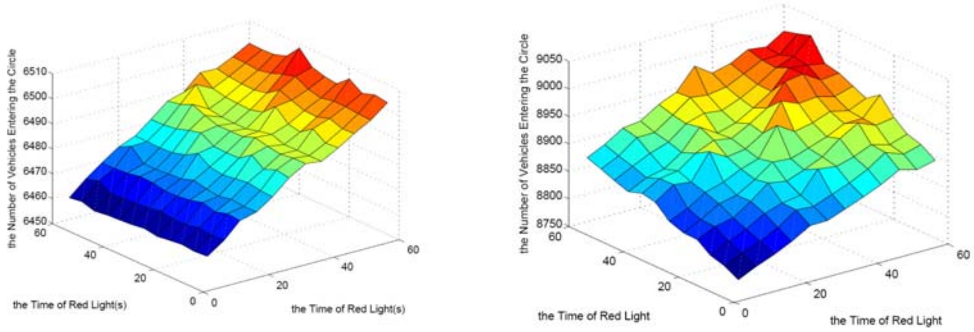

Figure 3: How r_i influence Q

From the figure, we can know that when the number of the incoming road is 4, if the time of each light which remain red (that is, the time of each light which remain green) changes, the number of vehicles entering the traffic circle does not vary significantly (since the difference of the maximal one and the minimal one is about 0.62%). While when the number of the incoming road is 8, if the same event happens, the number of vehicles entering the traffic circle varies apparently (since the difference of the maximal one and the minimal one is about 2.94%).

Accordingly, we get the kind of conclusion that as the number of the incoming road increases, the importance of the time of the traffic light which remains red is also increasing. That mean, when the number of the incoming road is small (such as 3, 4), it is not that essential to determine the time of the traffic light which remain red, since it does not change the result significantly. While when the number of the incoming road is large (such as 8, 9), there is a great necessity to determine the time.

In the Comparison Section, since traffic circle with more incoming road is not very common, so according to the data we can get, we use our model to the condition that the traffic have 4 incoming road. However, from the conclusion above, we can figure that if we use our model to the condition that the traffic have more (which means 8 or 9) incoming road, we can believe that the result should be even better than the Comparison Section stated before.

Secondly, we will discuss how the incoming flow influences m

In order to realize more clearly how the flow coming to the traffic circle influence the final choice, here we mainly refer to the number of lights we choose to use., we suppose that the half of the incoming road have the same flow coming to the traffic circle, and the other half have also the same one whose main goal is to simplify the calculation. Then according to what we have known, we can get the figure of how the flow coming to the traffic circle change the number of lights when the number of the incoming road is 4 and 8 respectively as follow:

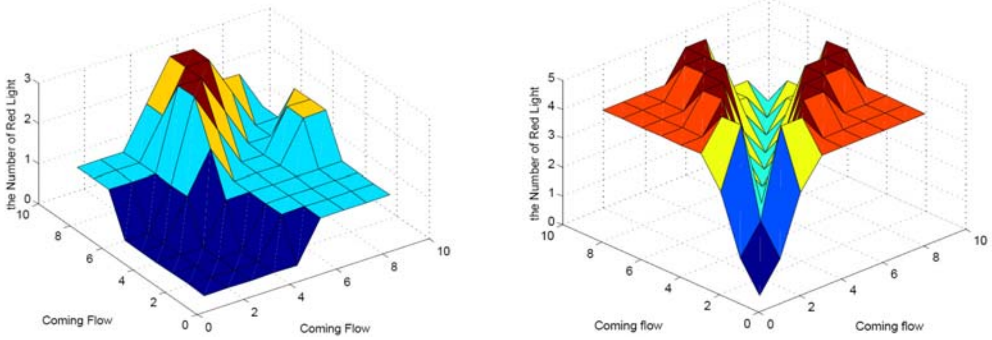

Figure 4: How incoming flow Influence m

From the figure, we can know that no matter when the number of the incoming road is 4 or 8, the number of lights both vary significantly. Therefore, the flow coming to the traffic circle is an important element in order to decide which one among the light, the stop sign and the yield sign we should position on every incoming road. That is, using our model to work with specific examples, it is necessity to know the concrete flow coming to the traffic circle as precise as possible.

3.2 Revised model: multi-lane traffic circle

Traffic circle with only one lane often used in county road or the traffic flow is small intersection. However, for the big cities, the single-lane traffic circle can't bear the large traffic flow. So the multi-lane traffic circle is more popular in cities. Now we want to improve the model based on the model we have constructed above in order to make it can be applied to the traffic circle with many lanes.

3.2.1 Model description

Suppose the traffic circle have k lanes. (Here we suppose that 1 represent the outer lane and k represent the most inside lane) For every lane, using the former model and the data about every lane, we could calculate its expectation of the number of the inserting vehicles (for short, we call it E_i). Considering the possibility that the vehicle which want to insert into the traffic circle cannot insert into the inside lane even if the inside lane have a large E_j , when the $E_i(i<j)$ of the outside lane is too small. Therefore we choose k parameters, which are $a_1, a_2, \cdots, a_k$ in order to denote the efficiency of inserting vehicles for every lane. Obviously,

$$a_1 < a_2 < \cdots < a_k$$

since the efficiency of inserting vehicles of the inside lane is the lowest. This is consistent with our common sense. Then the total E of all the lanes can be calculated by the formula that

$$E = \sum_{i=1}^{k} E_i$$

Consequently, using E , we can equivalently use the model constructed above to solve the problem about the traffic circle with many lanes. Then it can get great help from the basic model. However, the introduction of the efficiency of inserting vehicles for every lane (a_i) is just simply reflect the problem.

3.2.3 Remark

After our revise, the model can roughly deal with the situation which has the large traffic circle. In the model, our main idea is equivalence. However, the introduction of the efficiency of inserting vehicles for every lane (a_i) is just simply reflect the problem. How to determine the value of a_i still needs further discussion.

4 Conclusions and Future work

Traffic circle is a complicated system, and so many factors could affect it. But in the high-speed world, we must pay more attention to the traffic circle. This is because the design of traffic circle enabled high-speed merging and weaving of vehicles. On the other hand, we couldn't neglect the terrible experience in history. So, it asks us to try to give a better design for the complicated system.

We focus on the design of control method. After the series deep discussion, we develop a model for the small traffic circle to control the traffic flow in, around, and out a circle. In the model we give the criterion for the choice of controlling method. And give an algorithm to determine the best time which the light should remain green. Then, the stochastic simulation for the specific example interprets the effectiveness and the Rationality. From the sensitivity analysis of the model, we could see that the incoming flow is an important factor to the control method. Further, we could know that the time of red light is also an important factor to the entry capacity. And, the influence isn't significant for the small traffic circles, but it is significant for the large traffic circles.

However, for the large traffic circles we just carry on a roughly discussion. It could descript the main situation on the traffic circle. But, to the large traffic circle we can't neglect the confliction of exchange lanes. It is a considerable complicated problem and need further more work on it.

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