The Traffic Circle for Thee

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Abstract

Being recognized of their benefits in comparison with traditional intersections, the use of traffic circles around the world has increased rapidly during the past years. In this paper, we analyzed and compared unsignaled and signaled flow control method under different circumstances, concluded with a series of recommendations for how to control traffic flow better.

At the beginning investigation of unsignaled method, two classical models were established to calculate the entry capacity and delay time respectively about the traffic circles with different characteristic such as lanes, entries and vehicles. Then we formulate the problem as a mathematical programming model by overall con- sideration of capacity and service level, and we employ genetic algorithm to solve it. Conclusions from simulation results show that unsignaled method is causing bottlenecks in some cases.

Then we analyze the capacity and delay time of two common signaled methods, namely “each phase for entrance” and “multi-approach going combined with circulating road contro”. We calculated the capacity and optimal signal circle by saturation flow rate method, and estimate average delay of each phase for entrance method based on classical delay model in HCM2000.Associated capacity with level of service, we developed optimization model to estimate least average delay time and the corresponding optimal signal circle.

Finally, we compared unsignaled method with a common signaled method (each phase for entrance method) with actual data using our models, and Illustrate the practicability of our models.

Contents

1 Introduction

1.1 Background

A traffic circle[1] is an intersection with a circular shape (usually a central island). The first traffic circle was first built by a French architect on 1877 and the use of traffic circle has increased rapidly around the world during the last few decades due to their advantages in comparison with traditional controlled intersections . There are many types of traffic circles, from large ones with many lanes in the circle (such as at the Arc de Triomphe in Paris, see in Figure 1) to small ones with one or two lanes in the circle (seen in Figure 2).

It was found that traffic circles have their advantages and disadvantages as following (Taekratok, 1998):

1. **Advantages**
   - **Less traffic conflict.**
   - **Safety.** Design elements of traffic circles and the traffic rules cause drivers to reduce their speeds.
   - **Efficient traffic flow.** It was found that traffic circle is usually more efficiency than the common crossing.
   - **Money saved.** When no signal equipment to install or maintain, plus savings in electricity use.
   - **Community benifits.** Traffic calming and enhanced aesthetics by landscaping.
2. **Disadvantages**
   - **Space required.** Traffic circle often occupies a great space and lead to a waste of space.
   - **Difficulties with maneuvering.** It is difficult to maneuver, especially in roundabouts that have several lanes and during heavy traffic times.
   - **Confusing.** Drivers may be confusing if the traffic circle is too complicated, such as the famous magic traffic circle in Swindon[2].

[1] In this paper, traffic circles are also refered to as “roundabout” or “totaries”
[2] seen in en.wikipedia.org/wiki/File:Swindon_Magic_Roundabout_eng.svg

Figure 1. A traffic circle with many lanes and thirteen entries. From www.k-state.edu/roundabouts/

Figure 2. A traffic circle with two lanes and four entries. From adamjcopeland.com/tag/scotland/

1.2 Restatement of the Problem

Different traffic circles have different control methods, here are three common methods:

- **No signal lights.** These traffic circles usually position a stop sign or a yield sign on every incoming road that gives priority to traffic already in the circle.
- **With signal lights.** These traffic circles position signal lights on crossings to control the traffic flow, and the traffic lights can also position in the circle.
- **Mixed methods.**

Everyone want to pass the traffic circle as soon as possible, therefore it is important to implement proper control method in different traffic circles. There are too many factors which affect the satisfaction of control method, such as delay time, capacity, justice, etc. We seek to balance these effects, along with the delay time associated to level of service, in order to provide enough capacity as far as possible.

1.3 Survey of Previous Research

There are a series of theories of capacity and delay models for roundabouts in several countries, and most models fall into four groups(Elba, 2000):

- **Deterministic Theories.** These theories are earlier ideas about traffic circles, they described the problem as a deterministic system by some assumptions. Deterministic ideas are not commonly used because traffic circles system is always a stochastic system.
- **Statistical Theories.** The statistical approach is based on studying a pre-existing stock of roundabouts data, consequently more reliance is placed on other theories in countries with a few of roundabouts because of lack of historic data. The statistical theories measure operational and geometric variables from a sample of roundabouts to determine the relationships between them, and then to use these relationships as predictors. The statistical approach to roundabout capacity is widely used in the United Kingdom.
- **Probabilistic Theories.** Gap-acceptance was mainly applied to non-roundabout intersections before, but has been applied to traffic circles recently. Gap-acceptance theory assumes that the vehicles in the traffic circle are the major flow (they can pass the conflict area freely without delay); while vehicles at the entries are minor flow (they can enter the circle only when the gap in front of them are greater than the critical value. The theory defines the traffic capacity of the traffic circle by the maximum flow that can enter the circle from entries.
- **Simulation Models.** Simulation methods is a new approach to model traffic streams. They can simulate entry capacity, delay efficiently with the availability of powerful computers.

Above theories mainly focus on analysis of capacity and delay of traffic circles with no signal lights, yet how to control the flow efficiently under different circumstances is still a difficult problem to be studied.

2 General Assumptions

We make the following assumption when attacking the problem:

- All drivers are required to obey the traffic rules.

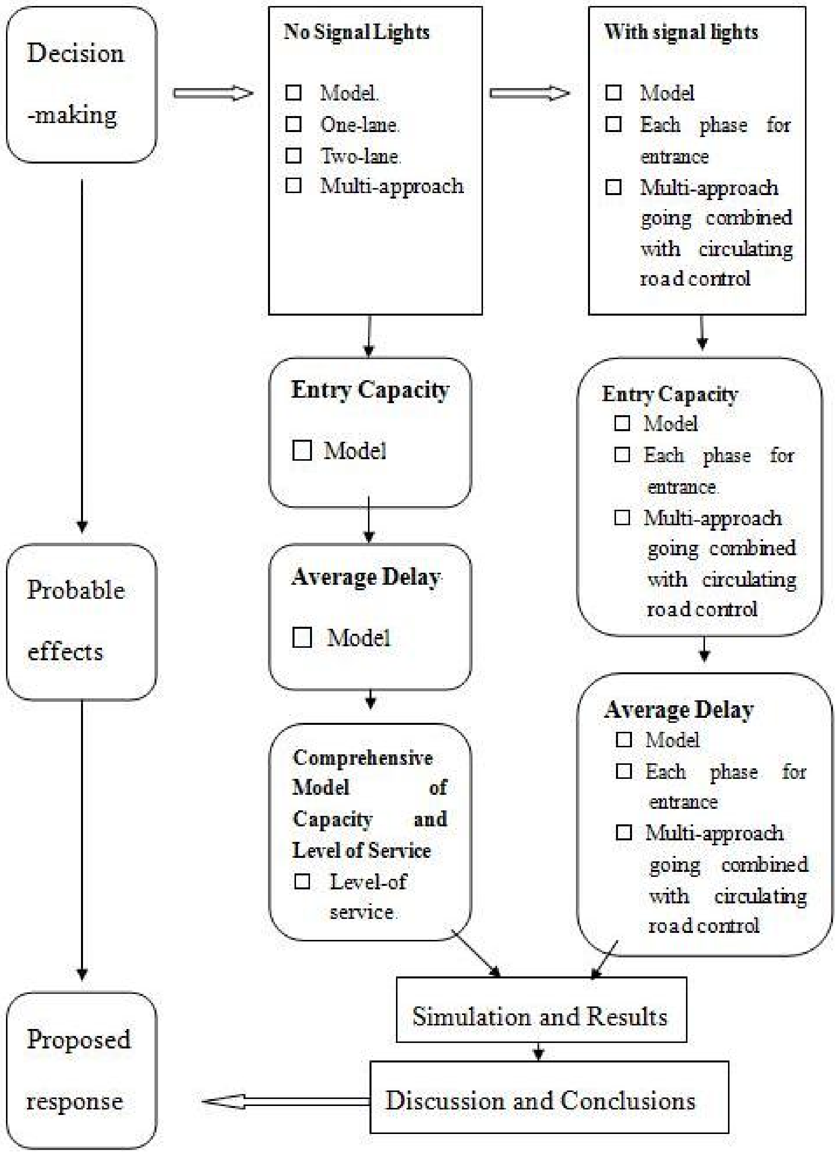

Figure 3. Model Overview

- Pedestrians and bicyclists are not taken into account.
- All vehicles circulate around the central island in the counterclockwise direction.
- There is just one type vehicle.

3 Unsignaled Flow Control Method

3.1 Motivation

We begin with the analysis of capacity, efficiency, delay time of traffic circles without signal lights. Actually there are no signal lights at many small traffic circles, consequently it is important to know more about unsignaled flow control method.

3.2 Entry Capacity Model

The capacity of a traffic circle is influenced by its geometry through the critical gap parameters(Elba, 2000). Troutbeck calculate the follow-up time and the ratio of the critical gap-acceptance to the follow-up time at single-lane entries in 1989, and Zou Bo (2007) propose a general equation about entry capacity with multiple lanes:

$$C = \Lambda \prod_i \frac{q_i a_i}{\lambda_i} \frac{e^{-\sum\limits_i \lambda_i T_i} e^{\sum\limits_j \lambda_j \Delta}}{1 - e^{-\sum\limits_m \lambda_m T_{0m}}} \tag{1}$$

where

- C is entry capacity.
- a_i is proportion of free(not bunched) vehicles on the i^{th} lane in the circulating stream.
- Δ is the minimum headway between entry vehicles.
- q_i is the flow of vehicles on the i^{th} lane in the circulating stream.
- $Q = \sum\limits_i q_i$, is the total traffic flow in the circulating stream.

- λ_i is parameter that depends on a_i and circulating flow,defined as follows:
$$\lambda_i = \frac{q_i a_i}{(1 - q\Delta)}$$

- $\Lambda = \sum_i \lambda_i$

- T_i is critical gap acceptance on the i^{th} lane between entering vehicles.

- T_{0m} is follow-on headway on the i^{th} lane between entering vehicles.

We can calculate capacity of entry lanes using equation (1) under different circumstances, however equation (1) is hard to calculate because the model is too complicated. Haight (1963) indicated that a is approximately equal to $1 - \Delta q$ because it does not affect entry capacity serious, thus we can get that $\lambda = q$, consequently equation (1) can be approximately simplified as equation (2):

$$C = Q \prod_i (1 - q_i \Delta) \frac{e^{-QT} \ e^{Q\Delta}}{1 - e^{-QT_0}} \tag{2}$$

From equation 2, it was found that the entry capacity C is determined by $\prod_i (1 - q_i \Delta)$ if the total traffic capacity is fixed. Therefore the entry capacity is dependent on the mathematic optimization problem as follows:

$$\begin{aligned} &\max \ f = \prod_i (1 - q_i \Delta) \\ &\text{s.t.} \ \sum_i q_i = Q \end{aligned} \tag{3}$$

Now we analyze the influence to entry capacity of vehicles flow distribution on different lanes. Generally, most of traffic circles have two lanes, then $Q = q_1 + q_2$, from equation (1-3), we can get the following equation:

$$C = Q(1 - q_1 \Delta)(1 - (Q - q_1)\Delta) \frac{e^{-QT} \ e^{Q\Delta}}{1 - e^{-QT_0}} \tag{4}$$

Based on above theory, we use the graph in Figure 4 to simulate the change of entry capacity under different cases ($\Delta = 2s, T = 5s, T_0 = 2s$) as an example. Figure 4 shows that the entry capacity with two lanes is always great than that with one lane, but the values are very closed when vehicle flow is less than 1500 veh/h. In addition, vehicles flow distribution on different lanes just make a tiny difference of the entry capacity (when total traffic is not too heavy).

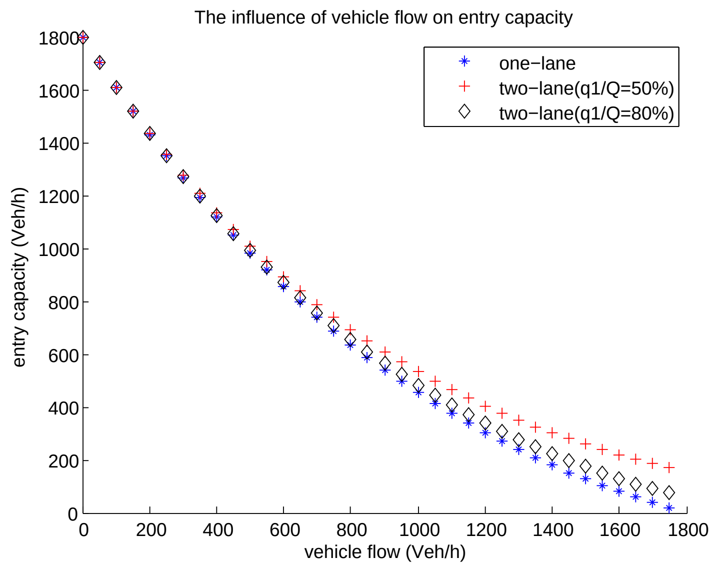

Figure 4. The influence of vehicle flow on entry capacity.

3.3 Average Delay Model

Average delay is another factor to measure efficiency in a traffic circle, Harders (1968) proposed an approximate but simple and powerful equation to estimate the average delay:

$$d = \frac{1 - e^{-(QT - pt_f)}}{c - p} \tag{5}$$

where

- d is average delay time.
- Q is traffic flow in the circulating stream (veh/s).
- T is critical gap acceptance between entering vehicles.
- p is traffic flow on an entry lane (veh/s).
- t_f is follow up time.
- c is entry capacity.

To demonstrate the change in delay time traffic flow under different entry capacity, we plot Figure 5 in Matlab ($p = 800$ veh/h).

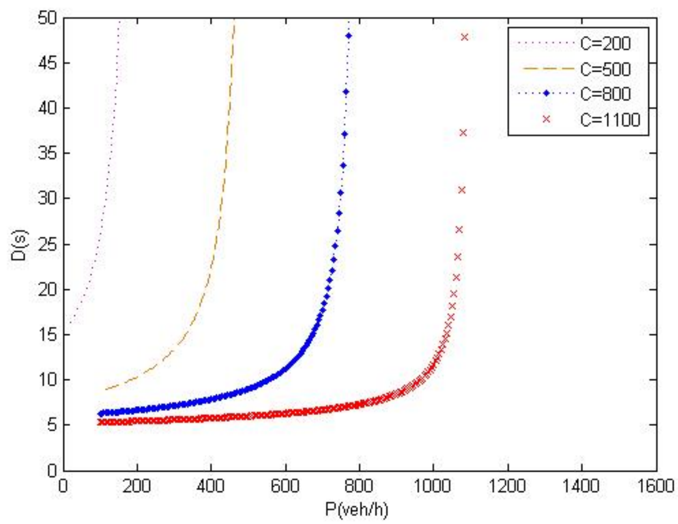

Figure 5. Relations between delay and flow under different capacity

3.4 Comprehensive Model of Capacity and Level of Service

Now we will develop a model to study the entry capacity of multi-entry traffic circle under different levels of service.

Figure 6 shows a traffic circle with n entries, s traffic flowand there are n areas around the central island, the i^{th} area is close to the i^{th} entry in counterclockwise direction.

Definitions.

- n is the number of entries.
- Q_i is traffic flow in i^{th} area.
- C_i is capacity of i^{th} entry.
- D_i is average delay of i^{th} entry.

- P_{ij} is vehicles flows from i^{th} entry to j^{th} exit.
- P_i is $\sum_{j=1}^{n} P_{ij}$, it present traffic flow of i^{th} entry.

C_i is mainly affected by Q_i, as shown in Figure 7.

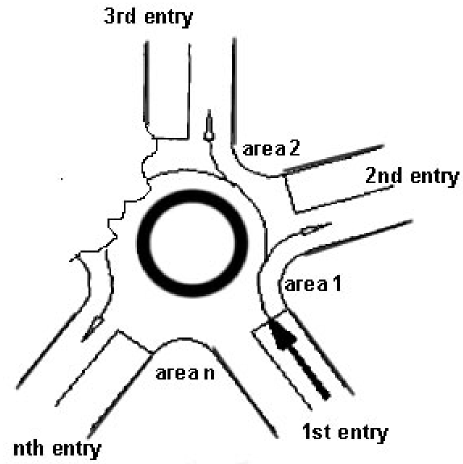

Figure 6. A traffic circle with multiple-entry

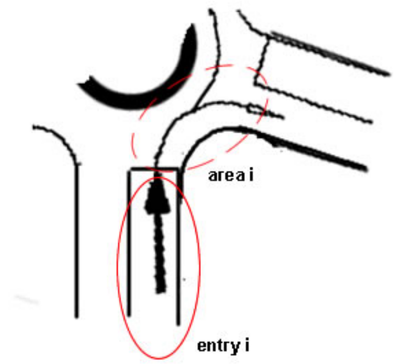

Figure 7. Area i and entry i

From equation (2) in Section 3.2, we have

$$C_i = Q_i \prod_k (1 - q_k \Delta) \frac{e^{-Q_i T} \; e^{Q_i \Delta}}{1 - e^{-Q_i T_0}} \tag{6}$$

From equation (5) in Section 3.3, we have

$$D_i = \frac{1 - e^{-(Q_i T - P_i t_f)}}{C_i - P_i} \tag{7}$$

Q_i is determined by matrix P, for example, if there are four entries in a traffic circle, we have

$$\begin{aligned} Q_1 \quad = \quad & P_{22} + \\ & P_{32} + P_{33} + \\ & P_{42} + P_{43} + P_{44} + \\ & P_{11} + P_{12} + P_{13} + P_{14} \end{aligned} \tag{8}$$

We derive a general equation as follows:

$$Q_i = \sum_{j=1}^{m} \sum_{k=i+1}^{i+j} P_{\bmod(i+j-1,m)+1,\quad \bmod(k-1,m)+1} \tag{9}$$

Level-of service

The transportation LOS system uses letters A through F, with A being best and F being worst. LOS A is the best, described as conditions where traffic flows at or above the posted speed limit and all motorists have complete mobility between lanes. The standard in the USA is shown in Table 1.

Table 1. level-of-service for signalized and unsignalized intersection in the USA

LOS	Signalized Intersection	Unsignalized Intersection
A	$\leq$ 10s	$\leq$ 10s
B	10-20 s	10-15 s
C	20-35 s	15-25 s
D	35-55 s	25-35 s
E	55-80 s	35-50 s
F	$\geq$80s	$\geq$50s

D_{level}(level can be letters A-F) is defined to represent the maximum allowed delay time of the level-of-service, we can get it from table 1. For instance, $D_A = 10$ and $D_F = \infty$ at signalized intersection.

From equation (6, 7, 9), we can get the entry capacity of multi-entry traffic circle under different levels of service through optimization problem in equation (10).

$$\begin{aligned} &\max \sum_i \sum_j P_{ij} \\ &\text{s.t.} \begin{cases} P_{ij} & \geqslant \ 0 \\ \sum\limits_{j=1}^{m} P_{ij} & \leqslant \ C_i \qquad i = 1,2,\cdots,m \\ D_i & \leqslant \ D_{level} \qquad \imath = 1,2,\cdots,m, \text{level=A-F} \end{cases} \end{aligned} \tag{10}$$

3.5 Simulation and Results

3.5.1 Genetic Algorithm

The optimization problem in equation (10) is very difficult to solve, because it is dependent on the complicated equation (6, 7, 9). Consequently, we use genetic algorithm (one of common heuristic algorithm) to solve it.

Genetic algorithms are implemented as a computer simulation in which a population of abstract representations (called chromosomes or the genotype of the genome) of candidate solutions (called individuals, creatures, or phenotypes) to an optimization problem evolves toward better solutions. This algorithm employs the biological techniques of mutation and crossover to seek out locally optimal solutions.

3.5.2 Results

Considering the common numbers of entries, we simulate the entry capacity of traffic circle with 3, 4 and 5 entries under different levels of service, respectively($\Delta = 2s, T = 5s, T_0 = 2s, t_f = 2, lanes = 2$, and $q_1/Q = 80\%$). The results come from genetic algorithm simulation in 10 times and is averaged (Figure 8).

Figure 8 shows the trend of entry capacity with the change of LOS (level of service) and the number of entries. It is obviously that the better LOS leads to less entry capacity, and the more entries leads to more entry capacity.

3.5.3 Discussion

We find that our model matches our general assumptions, and more importantly, that our results match our expectations. Namely, worth pointing out are the facts that the entry capacity is reducing with respect to the growing level of service, and we can know which level of service of a traffic circle with the actually data of matrix P (detailed traffic flow). And it must be clear that some parameters like T, t_f, Δ, etc. in our model is dependent on the actual situations, consequently we should be care and prudent when dealing with them.

The benefits of this rather model are open and flexible, we can adjust parameters to adapt practical situation, for instance, if there is extra limitation of road conditions, we can set extra constraints of parameter P_i or C_i. The obvious weak-

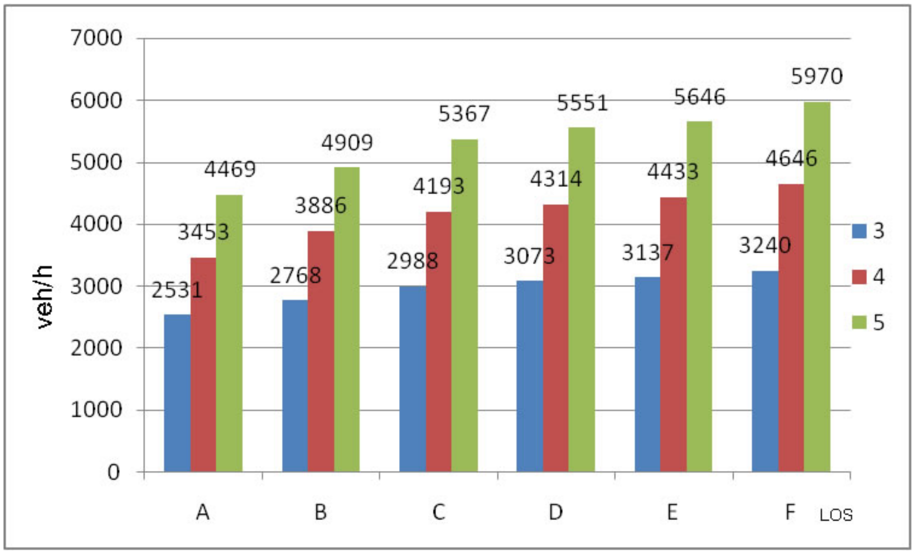

Figure 8. Capacity under A-F level of service and 3-5 entries

ness here is that it is difficult to solve the optimization problem as shown in equation 10 because the variables are too many and the relationships among them are complicated.

We can draw a conclusion from simulation results that unsignaled method is causing bottlenecks when traffic is heavy, or requiring high level of service, etc. consequently we must find other methods to tackle these problems.

4 Signaled Flow Control Method

4.1 Motivation

In view of unsignaled method's limitations, we may seek another method to control flow in traffic circle. Signaled method is a typical way to control flow deal with , especially in peak times.

In order to control vehicle flow better in traffic circle by signaled method, we should analyze the influence to capacity and service-level by setting traffic lights. The most common traffic circle is cross type around the world, and we begin our research by studying it.

Two common signaled methods of crossing roundabout are each phase for entrance and multi-approach going combined with circulating road control, respectively.

4.2 Entry Capacity Model

4.2.1 Each phase for entrance

It is set up a phase for every entry, left-turn and go-through vehicles at the same entry share the same phase, it light green one by one entry, obviously it is the same with control method in common crossing Zhao Jing (2008).

Each phase for entrance method implements clockwise rule to light green, this will reduce loss of time phase to the greatest extent, phase-sequence is shown in Figure 9, it belongs to four-phase signal control.

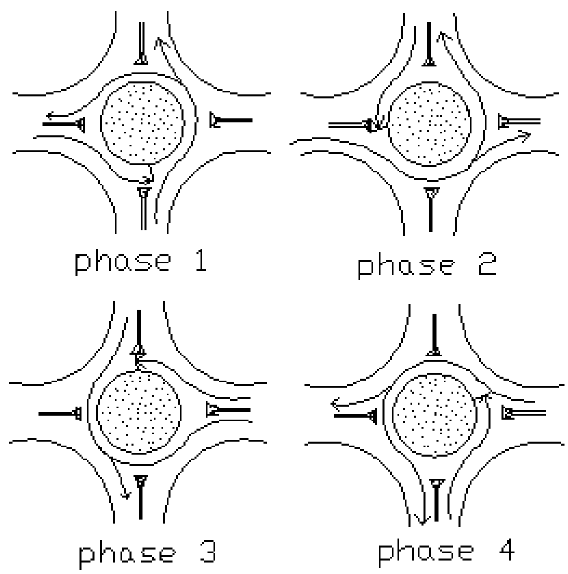

Figure 9. Phase sequences of Each phase for entrance

The effective green time is assigned by saturation equalization theories

$$g_{ei} = \frac{Y_i}{Y}(R - L) \tag{11}$$

where,

- R is signal-cycle length.
- g_{ei} is effective green time using phase i.
- Y_i is the maximum value of the ratios of approach flow rates to saturation flow rates using phase i.
- Y is $\sum_i Y_i$.
- L is lost time.

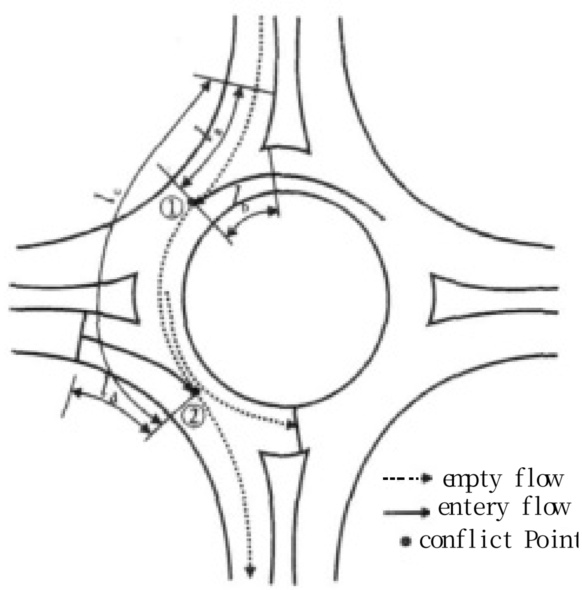

Figure 10. Parameters of space distance

As shown in Figure 13, l_a is the distance from the first stop line to conflict point ①, l_b is the distance from the second stop line to conflict point ①, l_c is the distance from the first stop line to conflict point ②, l_d is the distance from the fist stop line in next phase to conflict point ②.

The lost time L_1 occurs nearby conflict point ①,

$$L_i = \frac{l_a}{v_1} - \frac{l_b}{v_2} \tag{12}$$

where

- v_1 is velocity of entry.
- v_2 is velocity of empty.
- L_i is the lost time of i^{th} phase.
- $L = \sum_i L_i$

4.2.2 Multi-approach going combined with circulating road control

Yang Xiaoguang (2004) proposed a new method of traffic-signal control to solve the traffic problem by eliminating the conflict points and weaving sections at a roundabout with different traffic-flow rates on each approach, which normally appear in the real world.

A second stop line is set exclusively for the left-turn traffic on the circulatory roadway. It is beside the first stop line on the approach. Traffic signals are installed before each stop line and the signal-phase sequences are designed (Figure 11). Equations are derived to compute the signal timing considering the limited queue on the circulatory roadway.

$$g'_{ei} = \frac{Y'_i}{Y'}(R' - L') \tag{13}$$

The meaning of parameters in equation (13) is the same with equation (11).

From above analysis,we get the formula for computing lost time in equation (14, 15):

$$L_{gi} = \frac{l_c}{v_2} - \frac{l_d}{v_1} \tag{14}$$

And $L_g = \sum_i L_{gi}$, represents the go-through vehicles' lost time.

$$L_{li} = \left(\frac{l_a}{v_1} - \frac{l_b}{v_2}\right) + \left(\frac{l_c}{v_2} - \frac{l_d}{v_1}\right) \tag{15}$$

And $L_l = \sum_i L_{li}$, represents the left-turn vehicles' lost time.

Calculating traffic capacity based on saturation flow rate method, a formula for computing capacity is given (Council, 2000) in equation (16) with $CAP_i =$ capacity

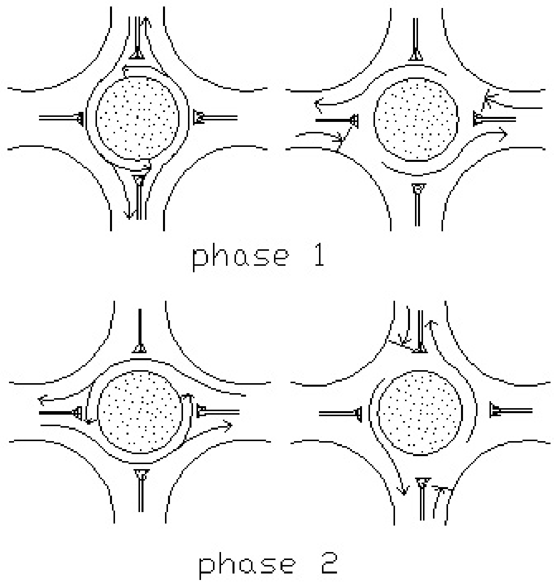

Figure 11. Phase sequences of Multi-approach going combined wit circulating road control

of the i^{th} entry:

$$CAP_i = S \cdot \frac{g_{ei}}{R} \tag{16}$$

We use the graph in Figure 12 to demonstrate the change in capacity with circle length,

4.3 Average Delay Model

4.3.1 Each phase for entrance

Average delay is a standard parameter used to measure the performance of an intersection, the formula for computing average delay of each phase for entrance circle is given as follows (HCM 2000): .

$$D = \frac{0.5 \times R \times (1 - g/R)^2}{1 - \left(\min(1, X) g/R\right)} + 900 \times T \times \left((X-1) + \sqrt{(X-1)^2 + \frac{8kIX}{cT}}\right) \tag{17}$$

where

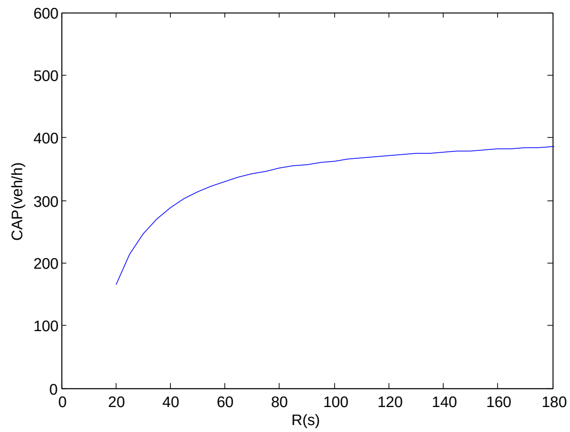

Figure 12. Capacity and circle length

- R is cycle length in seconds.
- g is effective green time in seconds.
- X is degree of saturation (v/c)
- T is duration of analysis period hours, 0.25 for generally .
- k is incremental delay factor, 0.5 for pre-timed signals.
- I is upstream filtering/meeting adjustment factor, 1 for isolated intersection.
- c is capacity in vehicles per hour.

Put the general value of T, k, i into equation (17), then we have

$$D = \frac{0.5 \times R \times (1 - g/R)^2}{1 - \big(\min(1,X) g/R\big)} + 225\Big((X-1) + \sqrt{(X-1)^2 + \frac{16X}{c}}\Big) \qquad (18)$$

To demonstrate better the change in delay with saturation and cycle length, we plot over Figure 13 and Figure 14 based on above equations. From the two graphs, we can know the relationship of them ntuitively.

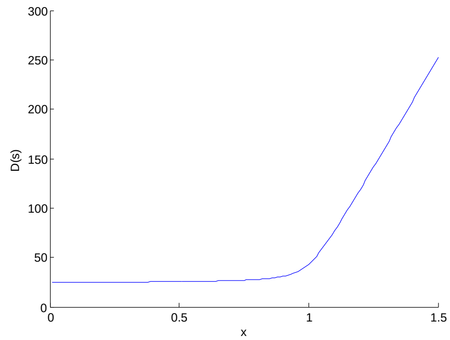

Figure 13. Delay and saturation

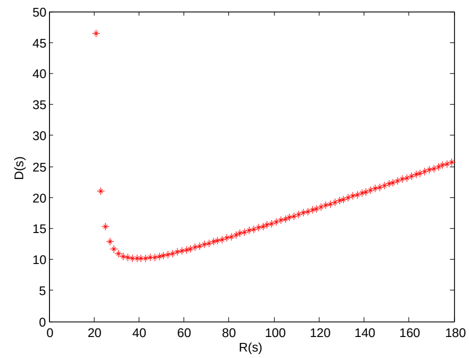

Figure 14. Delay and cycle length

4.3.2 Multi-approach going combined with circulating road control

Go-through traffic

Equation (18) is also suit to go-through vehicles because they only go by the signal light one time just as they go through common crossings. Consequently, we have

$$d_s = \frac{0.5 \times R \times (1-g/R)^2}{1-\left(\min(1,X)g/R\right)} + 225\left((X-1)+\sqrt{(X-1)^2+\frac{16X}{c}}\right) \tag{19}$$

Left-turn traffic

Left-turn vehicles go by the signal light twice, therefore the delay is contributed by two parts, the first stop line delay and the second stop line delay. And the first stop line delay is equal to the go-through vehicles, the second stop line delay d_L is given by (Yang Xiaoguang, 2008) as following equation (20-24)

$$d_L = d_1 + d_2 \tag{20}$$

where $d_1 = d_s$, and

$$d_2 = \begin{cases} 0 & g+I-T \leqslant 0 \\ \int_0^{\frac{S_1 S_2}{S_2 - S_1}(g+I-T)} (t_2 - t_1)dQ/qC & g+I-T < \frac{S_2(g+I-T)}{S_2-S_1} \leqslant \frac{qr}{S_1-q} \\ \int_0^{\frac{qS_2}{S_2-q}(g+I-T+r)} (t_2 - t_1)dQ/qC & \frac{qr}{S_1-q} < \frac{S_2(g+I-T)+qr}{S_2-q} \leqslant g \\ \int_0^{qC} (t_2 - t_1)dQ/qC & \frac{S_2(g+I-T)+qr}{S_2-q} > g \end{cases} \tag{21}$$

As shown in equation (21), d_2 is dependent on four respective function:

- **case 1**: Left-turn vehicles meet green light when they arrived the second stop line.
- **case 2**: Left-turn vehicles achieve dissipation equilibrium pointwhen entry saturation flow rate is S.(Figure 15)
- **case 3**:Left-turn vehicles achieve dissipation equilibrium point when arrival rate is q.(Figure 16)
- **case 4**:Left-turn vehicles achieve dissipation equilibrium point when arrival rate is 0.(Figure 17)

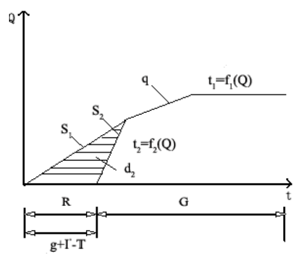

Figure 15. Case 2

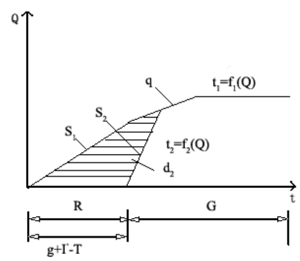

Figure 16. Case 3

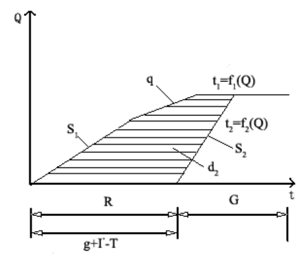

Figure 17. Case 4

$$t_1 = f_1(Q) = \begin{cases} \frac{Q}{S_1} & 0 \leqslant Q \leqslant \frac{S_1 qr}{S_1 - q} \\ \frac{Q}{q} - r & \frac{S_1 qr}{S_1 - q} < Q \leqslant qC \end{cases} \tag{22}$$

$$t_2 = f_2(Q) = g + I - T + Q/S_2 \tag{23}$$

where t_1 and t_2 is vehicles' reach function and leave function.

The average delay is the weighted average of d_{ij}, as shown in equation (24)

$$d = \frac{\sum\limits_{i=1}^{n}\sum\limits_{j=1}^{m} d_{ij} q_{ij}}{\sum\limits_{i=1}^{n}\sum\limits_{j=1}^{m} q_{ij}} \tag{24}$$

If we need to analyze the delay time of each phase for entrance, we just need to associate equation with (18), and if we want to analyze the delay time of multi-approach going combined with circulating road control, we just need to associate equation with (20).

5 Choose the Better Control Method

Through above analysis, we can draw a conclusion that only if we know the matrix P (traffic flow data , defined in Section 3.4), we can calculate the service level under different control methods. And a traffic engineer can easily know the traffic flow data through research, than he can choose proper control method using our models.

Now we compare the capacity and service level under unsignaled method and signaled method. Here is a actual traffic flow data in one roundabout with four entries.

Table 2. Traffic flow data (matrix P)

	East	North	West	South
East	0	134	128	78
North	96	0	92	272
West	88	126	0	174
South	311	99	175	0

Through simulation using our models (some parameters come form (HCM 2000), the code in Appendix), we get Table 3 . In table 3, P_i is entry flow of i^{th}

Table 3. Results

			Unsignaled Flow Control		Each phase for entrance		
	P_i	Q_i	C_i	LOS	g	X	LOS
East	340	740	730	7(A)	10	0.58	10(A)
North	460	841	635	14(A)	11	0.72	10(A)
West	388	834	641	11(A)	11	0.51	9(A)
South	585	895	588	812(E)	10	0.9	12(A)
				D=221			R=33 D=10.2

entry, Q_i is traffic flow in i^{th} area, C_i is the entry capacity of i^{th} entry, LOS is level-of-service, g is green light time, X is saturation rete. From Table 3, we know that unsignaled flow control method is very bad (average delay is 221s, and the South road is extremely crowed), so the traffic engineer should not choice this method in this case, however each phase for entrance method is much better (average delay is 10.2s).

6 Discussion and Conclusions

6.1 Technical Summary

In this paper, we analyzed and compared unsignaled and signaled flow control method under different circumstances in order to control the traffic flow more efficiency, our advice and method of control flow are as follows:

- The capacity and service level is obviously affected by control method, and different control methods may lead to big difference even when traffic circles have the same characteristic. Consequently, we should be prudent to choose control method.
- Unsignaled method can be chosen when traffic flow is small, but it does not suit the turnpike road in large and medium-sized cities because this method is causing bottlenecks when the traffic is heavey.
- Although signaled control method is more complicated than unsignaled method, yet it may cause high efficiency to the traffic system when the Signal Timing is proper.

6.2 Strengths and Weaknesses

1. **Strengths**
   - Our models are flexible and practical .
   - Genetic Algorithm explores our optimization problem conveniently.
   - Accounts for most of major factors involved in traffic circles.
2. **Weaknesses**
   - Does not account for pedestrians and bicycles.
   - Our optimization problem is hard to solve by common algorithms.
   - Does not account for different types of hevicles.

6.3 Future Work

- Take into consideration the effects of pedestrians and bicycles on the capacity and level of service of traffic circles.

- Develop new powerful method to control traffic flow.
- Take into consideration the effects of different types of vehicle.

7 Appendix

```
function QQ=Roundabout2(sol)

m=4;
Lev=6;
tm=2;
t=5;
t0=2;
LD=[10 15 25 35 50 Inf];
T=[1,1]*t;
T0=[1,1]*t0;
qq=[0.8,0.2];
tf=2;

PP=zeros(m,m);
Q=zeros(1,m);
C=zeros(1,m);
D=zeros(1,m);

for i=1:m
    k=(i-1)*m;
    PP(i,:)=sol(k+1:k+m);
end

for i=1:m
    PP(i,i)=0;
end

Q=[];
for i=1:m
    for j=1:m
        for k=i+1:i+j
            r=mod(i+j-1,m)+1;
            s=mod(k-1,m)+1;
            Q(i)=Q(i)+PP(r,s);
        end
    end
end

C=[];
for i=1:m
```

```
    q=qq*Q(i)/3600;%
    a=1-q*tm;
    x=q.*a./(1-q*tm);
    X=sum(x);
    C(i)=X*prod(q.*a./x)*exp(-sum(x.*T))*exp(sum(x.*tm))/(1-exp
        (-sum(x.*T0)));
end


flag=1;

if(flag~=0)
for i=1:m
    for j=1:m
        if (PP(i,j)<0)
        flag=0;
        end
    end
end
end

if(flag~=0)
for i=1:m
   if (sum(PP(i,:)/3600)>C(i))
   flag=0;
   end
end
end

if(flag~=0)
for i=1:m
    pp=sum(PP(i,:)/3600);
    D(i)=(1-exp(-(Q(i)*t/3600-pp*tf)))/(C(i)-pp)+tf;
    if (D(i)>=LD(Lev))
    flag=0;
    %D(i)
    end
end
end

if (flag==1)
QQ=-sum(Q);
else
QQ=0;
end

PP=[0 134 128 78
   96 0 92 272 ;
   88 126 0 174 ;
```

```
    311  99  175  0  ;];

yi=zeros(1,4);
v=zeros(1,4);
for i=1:m
        r=mod([i,i+1],m)+1
        yi(i)=max(PP(i,r))/sum(PP(i,r))
end

y=yi/sum(yi);
for i=1:m
        r=mod([i,i+1],m)+1
        v(i)=sum(PP(i,r))
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function DD=Roundabout4(sol)

L=12;
R=33;
%for R=33:0.1:41;
s=2400;
m=4;
y =[ 0.1907    0.2787       0.2477       0.2829];
v=[262,364,262,410;];
gi=y*(R-L);
G=zeros(1,m);
ds=zeros(1,m);
for i=1:m
G(i)=sum(gi(mod([i+3,i+4],m)+1));
end

for i=1:m
g=G(i);
c=s*g/R;
x=v(i)/c
a=min([x,1]);
ds(i)=0.5*R*(1-g/R)^2./(1 - x*a.*g/R)+900*0.25.*(x-1+sqrt((x-1)
    .^2+4*x./(0.25*c)));

end
DD=sum(ds.*v)./sum(v);
%plot(R,DD,'r*')
%axis([0 180 0 50]);
%hold on
%end

ds
```

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