Association of Signal-Controlled Method at Roundabout and Delay

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Abstract—**The uncontrolled roundabout is only applicable to smaller vehicle flows. With increasing of roundabout flows, series of problems have occurred in respect of traffic jams and accidents. Arrangement of signal control will help to improve delay and safety at roundabout while differences exist between condition of adaptability and traffic efficiency under different signal controlling methods. It is on the basis of "The Secondary Control Theory on Left-turn at Circular Road" that this text is aimed at mainly introducing the three different control methods of "Control of Orderly Discharge Clockwise at Single Entrance Lanes", "Control of Orderly Discharge Clockwise at Single Entrance Lanes +Sub-traffic Flow Interweaving", and "Control of Synergistic Discharge at Multi Entrance Lanes". Everything is done in consideration of roundabout with different amount of entrance lanes and based on the control theory of traffic signal and the optimization method. In this foundation, by applying methods of numeric calculation and experimental traffic engineering, we analyze the influence law on the average delay of vehicles caused by the signal cycle of time-space strategic parameters and radius of central island. The research result will help to improve the theoretical system concerning signal-controlled circus road and will also provide technical support to the reconstruction of uncontrolled circus road and to the mode selection of signal control for circus road, which is of important application value in practice.**

Index Terms—**signal-controlled roundabout, signal-controlled method, average delay, adaptability**

I. INTRODUCTION

Uncontrolled circular road features in less conflict points, non-necessity of stopping and simpler way of management. The increasing demand for roundabout traffic have brought forth series of problems at uncontrolled circular road in respect of traffic jam, rising of accident rate, growth of vehicle delay and saturation growth. Signalizing at roundabout has greatly improved the traffic capability and reliability of roundabout as well as has made the travel delay relatively stable while differences exist between condition of adaptability and traffic efficiency under different signal controlling methods. Hence, influences on average delay vary accordingly. It is quite necessary to make a study on the adaptability for various methods when searching for the optimization method to effectively lower the average delay.

II. RESEARCH REVIEW

It is divided into two directions of unsignal-controlled roundabout and controlled roundabout in the related domestic research. For the research of unsignal-controlled roundabout, it mainly involves the study of traffic characteristics and its applicable conditions, capacity, delay, safety and geometrical design, etc. in which, for most cases, the capacity and delay of roundabout entrance under different conditions of entrance and loop is calculated by using gap-acceptance model[1][2][3][4]. For foreign researchers, they tend to connect safety with geometrical design of roundabout which is made under guidance of safety requirements for vehicle and pedestrians[5][6][7]. In the countries of the States, Australia and Britain, numbers of national regulations have been issued concerning roundabout design, which have laid a foundation for the study of space related optimal design of signal-controlled roundabout and evaluation of traffic efficiency.

The study on signal-controlled roundabout started at a later time and according to designing guidance for roundabout in the States and Australia, it qualitatively regulates that signal control could be implemented for certain entrances if necessary, stressing that it should be used with great care and should not be used for purpose of a long-term solution to traffic jam. Baranowski[8] made a study on the signal control method for roundabout

Manuscript received Dec. 1, 2010; revised Apr. 5, 2011; accepted Apr. 12, 2011..
Project number: 50708080

doi:10.4304/jsw.7.2.346-351

pedestrians, exploring condition and safety of arranging signal for roundabout pedestrians. Akçelik made a study on the limit control of capacity at entrance of roundabout[9]. We study the relevant research in our country in 1998, which was initially raised by researchers from engineering department of Tongji University[10][11]. They established basic principle and approach for left-turn with two-stop control at roundabout and gave it a good study in the way of traffic law, signal timing method, applicable condition, optimization control method and efficiency evaluation. Mr. Ao Guchang[12] put forward signal control method for roundabout under condition without of straight flow.

Researches from home and abroad focus on the field of non-signal controlled roundabout, with less time in the study of signal-controlled roundabout. It needs further research in terms of capacity of signal-controlled roundabout, condition of geometric topology, demand for mixed traffic flow and adaptability of signal control at roundabout.

III. Introduction to Signal Control Method at Roundabout[13]

A. *Control of In-turn Discharge Clockwise at Signal-entrance Path*

In this control method, each entrance lane discharge In-turn of clockwise, see Fig. 1

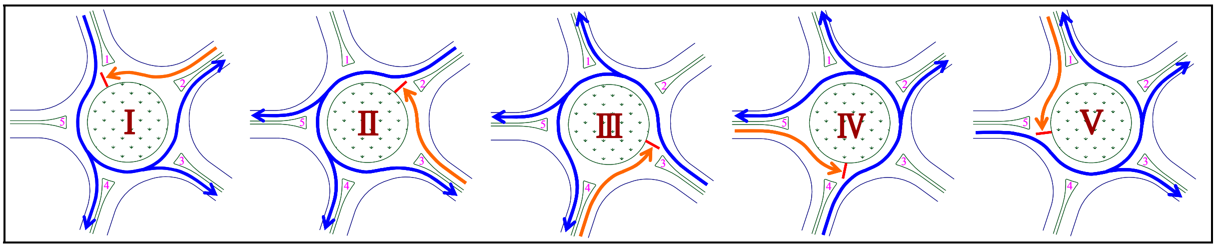

Figure 1. Phase sequence of control of in-turn discharge clockwise at signal-entrance path

This control method could be converted into a one-way closed intersection group (Fig. 2). To take the five-fork intersection as a example, it could be regarded as an intersection group made of five intersections of A, B, C, D and E. To select datum point of coordination control, to set the Max delay as optimization target and to choose signal period, phase difference and queuing length as constraint condition, the optimization of other parameters will be carried out.

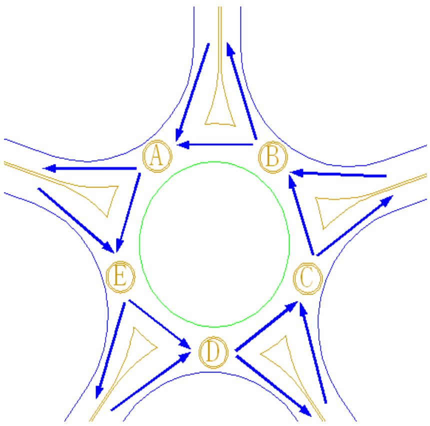

Figure 2. Schematic diagram for one-way closed intersection group of signal controlled intersections

B. *Control of In-turn Discharge Clockwise at Signal-entrance Path + Interlace of Minor Flow*

With consideration of order and efficiency of multi-fork roundabout, on the basis of Control of In-turn Discharge Clockwise at Signal-entrance Path, the interlace of secondary traffic flow is introduced (Fig. 3), i.e. to treat a main flow and several secondary flows which have least conflicts between each other as the same phase.

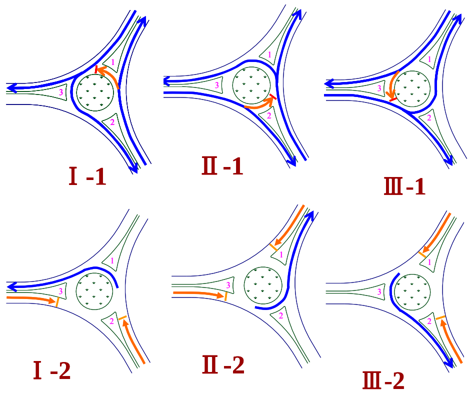

Figure 3. Schematic diagram for three-fork roundabout

C. *Association Roundabout Control at Multi--entrance Path*

Three phases are usually designed for three-fork roundabout and twice is released within one period at each entrance (Fig. 4). Two phases are usually designed for four-fork roundabout (Fig. 5). Twice is released within one period at each entrance of five-fork roundabout, and release is made clockwise at entrance lane (Fig. 6). Three phases are arranged at for six-fork roundabout and release is made clockwise at entrance lane (Fig. 7).

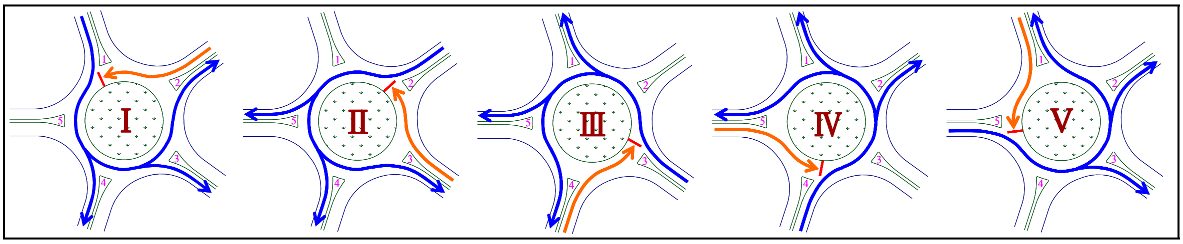

Figure 4. Schematic diagram for Control of In-turn Discharge Clockwise at Signal-entrance Path + the Interlace Phase of Minor Flow

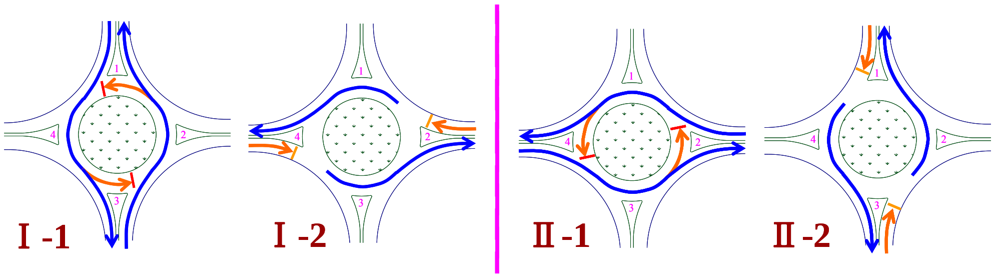

Figure 5. Schematic diagram for four-fork roundabout

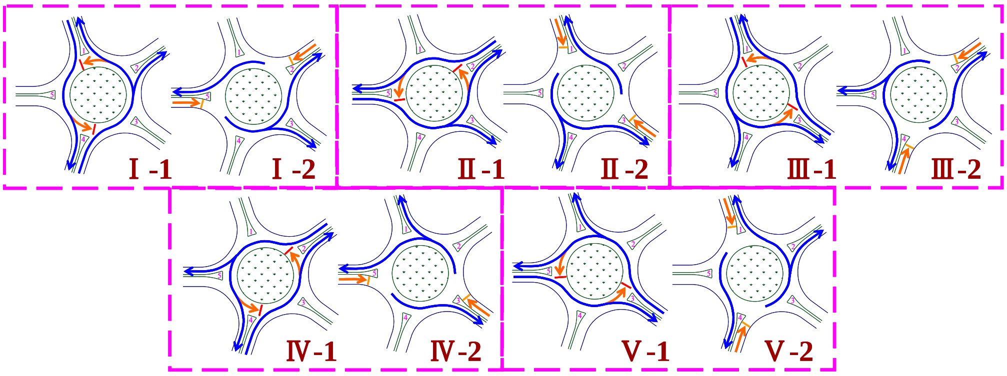

Figure 6. Schematic diagram for five-fork roundabout

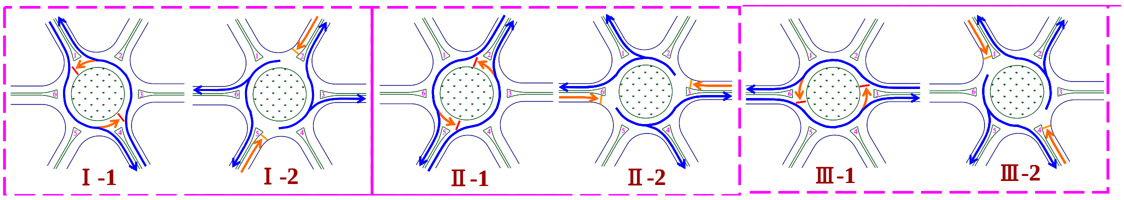

Figure 7. Schematic diagram for six-fork roundabout

Associated Roundabout Control at Multi-entrance Path includes, in two ways, the coordination of entrance signal and loop signal, and then the coordination with loop signal. The optimization model of timing parameters is established under concept of equisaturation, but the space constraint of loop parking should be realized. When flow ratio between different entrance lanes in the same phase is unbalanced, or queuing vehicles inside the loop go beyond conflict point (or stop line), which influences the normal traffics, it is suggested to take coordination measures of delayed start-up, early disconnection or start-up and late disconnection for green signals of conflict flows.

IV. Calculation Method for Average Delay of Signal-Controlled Roundabout

Traffic retention time due to signal control by colored lights at circular road is defined as delay of signal control. Delay of signal-controlled circular road could be classified into delay of straight forward vehicles at entrance stop line (i.e. the first stop line), delay of left-turn vehicles at entrance stop line and delay of left-turn vehicles at stop line of circular road (i.e. the second stop line).

A. *Delay of straight forward vehicles at signal-controlled roundabout*

Straight forward vehicles at signal-controlled circular road is only controlled by the first stop line and its travel characteristics are quite similar with those at regular crossings, with calculation method[10 for delay of stop line at regular crossings borrowed for reference. Model of average delay for single straight forward vehicle at No i entrance is as following:

$$\bar{d}_{iS} \approx \begin{cases} \dfrac{x_S^{\ 2}}{2q_{iS}(1-x_S)} + \dfrac{Q_{0S}}{s_{poS}} & x_S < 1 \\ 0.5r + \dfrac{Q_{0S}}{s_{poS}} & x_S \geq 1 \end{cases}$$

In which, $Q_{os}$is the number(pcu) of detained flows for straight forward vehicles at the initial moment *T* of research time section. S_{poS} is the utmost dispersal number(pcu/s) of straight forward vehicles inside the cycle. *r* is the duration(s) of red phase light for straight forward and left-turn vehicles at the first stop line. x_{iS} isthe saturation of straight forward flow at No *i.* entrance. q_{iS} is the arrival rate (*pcu/s*) of straight forward vehicles at No *i.* entrance.

B. *Delay of the first stop line for left-turn vehicles at signal-controlled roundabout*

Left-turn vehicles at signal-controlled circular road have the similar situation in travel characteristics at regular crossings when passing through the first stop line. We take calculation method to measure the stop line delay at crossings for reference when calculating delay of left-turn vehicles right before the first stop line. The model for average delay $\bar{d}_{iL}^{a}$ of single vehicle for left-turn vehicles at the first stop line of No i. entrance is as following [14]:

$$\bar{d}_{iL}^{a} \approx \begin{cases} \dfrac{x_L^{\ 2}}{2q_L(1-x_{iL})} + \dfrac{Q_{0L}}{s_{poL}} & x_{iL} < 1 \\ 0.5r + \dfrac{Q_{0L}}{s_{poL}} & x_{iL} \geq 1 \end{cases}$$

In which, Q_{oL} is the number(pcu) of detained left-turn vehicles at the first stop line at the initial moment T of research time section. S_{poL} is the utmost dispersal number(pcu/s) of left-turn vehicles at the first stop line inside the cycle. x_{iL} is the saturation of left-turn flow at No *i.* entrance. q_{iL} is the arrival rate(pcu/s)of left-turn vehicles at No I entrance.

C. *Delay of the second stop line for left-turn vehicles at signal-controlled roundabout*

Delay of the second stop line at circular road should be put into consideration in respect of capacity constraints of roundabout. Meantime, movement track of vehicles is relatively fixed and vehicles arriving at the second stop line have strong regularities without obvious discrete phenomenon. In this sense, we choose “Method of Gather-disperse Waves” to calculate vehicle delay [14] at the second stop line of circular road. Average delay $\bar{d}_{iL}^{a}$ of single vehicle for left-turn vehicles at the second stop line of No i entrance is as following:

$$\bar{d}_{iL}^{b} = \frac{D_{iL}^{b} \cdot n_{ih}}{q_{iL} \cdot C}$$

$$D_L^b = \begin{cases} \left[q_L \cdot f \cdot \dfrac{1-\lambda_L^a}{1-y} + \dfrac{f \cdot e^k}{2C \cdot (1-x_L^a)} \right] \cdot \dfrac{C \cdot d_1}{n_{ih}} + \dfrac{\theta \cdot d_1^{\ 2}}{2} - \dfrac{d_1}{2} & x_L^a < 1 \text{且} C > \dfrac{d_h - I_2 \cdot v_0}{v_0 \cdot \lambda_L^a} + L \\ \dfrac{g_{eL}^a \cdot S_L \cdot d_1}{n_{ih}} + \dfrac{\theta \cdot d_1^{\ 2}}{2} - \dfrac{d_1}{2} & x_L^a \geq 1 \text{且} C > \dfrac{d_h - I_2 \cdot v_0}{v_0 \cdot \lambda_L^a} + L \\ 0 & C \leq \dfrac{d_h - I_2 \cdot v_0}{v_0 \cdot \lambda_L^a} + L \end{cases}$$

$$\theta = \frac{S_L \cdot q_L}{(S_L - q_L) \cdot n_{ih}} ; d_h = \alpha \cdot (R + 0.5w) + d_{h1} ; d_1 = g_{eL}^a + I_2 - t_{h1}$$

In which, D_{iL}^{b} is the total delay(s) for vehicles on the same lane of the second stop line at No. i entrance within one cycle. n_{ih} is the total number of roundabout used for left-turn vehicles at No. *i* entrance. *f* is the correction factor for vehicles without complete stopping, 0.9 is usually taken. *C* is the cycle(s) of signal control at circular road. x_{iL}^{a} is the saturation of left-turn vehicles at the first stop line. g_{eiL}^{a} is the effective green time(s) for left-turn vehicles at the first stop line. S_L is the saturation flow(pcu/s) of left-turn vehicles. d_1 is the delay(s) of the first left-turn vehicle. I_2 is the interval(s) between left-turn green light at the first stop line and the green light at the second stop line. $t_{h1}$is the travel time(s) for the first left-turn vehicle moving from the first stop line to the second stop line. *L* is the total loss of time(s) within one single cycle. d_h is the distance(m) for the left-turn vehicle moving from the first stop line to the second stop line. d_{h1} is the distance(m) for the first vehicle at the first stop line moving to the conflict point. α is the central angle (radian) formed by the triangles of weaving point, central point of the second stop line and island center. *w* is the width(m) of roundabout. *R* is the island radius(m) and $v_0$is the design speed of roundabout(m/s).

D. *Average delay at signal-controlled roundabout*

Average delay of single vehicles at signal-controlled circular road is referred to the average delay of all vehicles passing through roundabout per unit time (usually for an hour). i.e.:

$$\bar{d} = \frac{D}{\sum_i 3600 \cdot (q_{iS} + q_{iL})}$$

$$D = \sum_i 3600 \cdot (\bar{d}_{iS} \cdot q_{iS} + \bar{d}_{iL}^{a} \cdot q_{iL} + \bar{d}_{iL}^{b} \cdot q_{iL})$$

In which, *D* is the total vehicle delay(s) at unit time (one hour) at signal-controlled circular road.

V. RELEVANCE BETWEEN FACTORS OF TIME & SPACE AND AVERAGE DELAY

In addition to regular road and traffic conditions, major factors influencing average delay of vehicles at signal-controlled circular road also includes number of circular road, central island radius of roundabout, signal cycle and green intervals, etc. This text focuses on analyzing relevance between central island radius, signal cycle and average delay of vehicles. Starting from the physical meaning of parameters, we presume that the circular road belongs to the type of orthogonal crossing and the number of entrance lanes, the number of circular road and the number of exit lanes match. The saturation flow for straight forward lanes of entrances is 1650pcu/h and saturation flow for left-turn lanes is 1550pcu/h, which are symmetrically matching.

A. *Analysis on average delay for control method of synergistic discharge at multi entrance lane*

1) Relevance Between Average Delay and Signal Cycle: On the basis of above calculation method via using VISSIM simulation results for model modification, we obtain variety laws of average delay of left-turn and straight forward vehicles with the changes of signal cycle under the control method for synergistic discharging at multi entrance lane of circular road. Refer to Fig.8

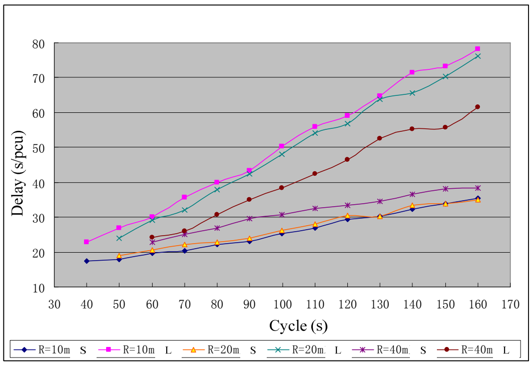

Figure 8. elevance between average delay of vehicles and signal cycle

- The average delay of left-turn and straight forward vehicles grows with the increasing of signal cycle under the synergistic control of discharging at multi entrance lane of roundabout.
- Rate of increase for average delay of left-turn vehicles will be greater with increase of signal cycle while rate of increase for average delay of straight forward vehicles changes little.
- Under condition of the same signal cycle, the bigger the central island radius is, the smaller the average delay of left-turn vehicles will be and the bigger the average delay of straight forward vehicles will be at the same time.

2) Relevance between average delay and radius of central island of roundabout: On the basis of above calculation method via using VISSIM simulation results for model modification, we obtain variety laws of average delay of left-turn and straight forward vehicles with the changes of central island radius under the control method for synergistic discharging at multi entrance lane of circular road. Refer to Fig.9.

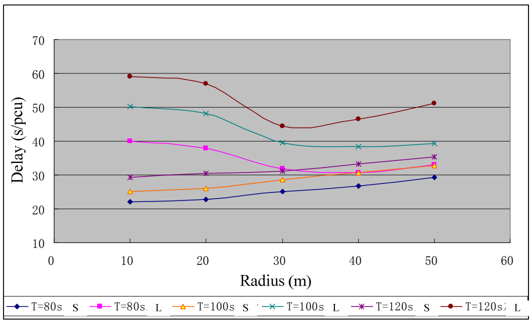

Figure 9. Relevance between average delay of vehicles and radius of central island

- Average delay of left-turn vehicles gets smaller at first and then bigger little by little with increasing of central island radius under the control method for synergistic discharging at multi entrance lane of circular road.
- Average delay of straight forward vehicles is relatively less influenced by central island radius but slightly increased with growth of the radius.

B. *Analysis on average delay under control method of orderly discharge clockwise at single entrance lane*

On the basis of above calculation method via using VISSIM simulation results for model modification, we obtain variety laws for average delay of left-turn and straight forward vehicles with the changes of signal cycle under control of orderly clockwise discharging at single entrance lane of circular road, with conditions of 10m, 20m and 40m in central island radius. Refer to Fig.10.

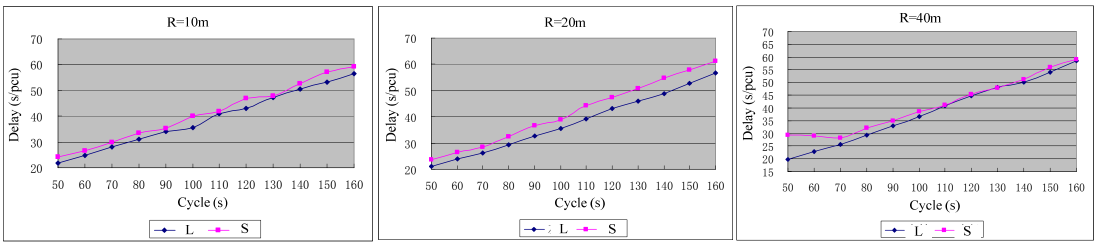

Figure 10. Relevance between average delay of vehicle and signal cycle (R=10m/20m/40m)

It could be found that:

- Average delay of left-turn and straight forward vehicles develops in an approximately linear growth trend under control of orderly clockwise discharging at single entrance lane of circular road.
- The radius size of central island influences little on the average delay of left-turn and straight forward vehicles.

VI. CONCLUSIONS

Arrangement of signal control at roundabout will greatly help to increase the traffic capacity and safety and there lies difference for applicable conditions and traffic efficiency under different methods. This research puts forward three control methods concerning auto vehicles at signal-controlled circular road, establishes stop rate models for the first stop line at entrance lane of signal-controlled crossings and the second stop line of roundabout and analyzes the influence laws on the average delay of vehicles at signal-controlled crossings caused by the signal cycle of time & space parameters and radius of central island under the two different modes of method of synergistic roundabout control discharged at multi entrance lanes and control method of orderly discharge clockwise at single entrance lane.

Researches show that the major determining factors for average delay of vehicles at signal-controlled circular road is signal cycle, revealing positive correlation between average delay of vehicles and cycle. With precondition of the same signal cycle, average delays for left-turn flows and straight forward flows are quite close with each other in terms of control method of orderly discharge clockwise at single entrance lane while average delay of straight forward flows is smaller than that of left-turn flows under synergistic roundabout control discharged at multi entrance lanes. The bigger the cycle is, the larger the difference will be between the two. From this sense, roundabout with a relatively bigger straight forward flows mostly adopts control method of synergistic discharge at multi entrance lane to effectively reduce the average delay of vehicles. Meanwhile, average delay of vehicles under control method of orderly discharge clockwise at single entrance lane will not be influenced by central island radius of roundabout and average delay of vehicles under synergistic roundabout control discharged at multi entrance lanes has non-monotonic relation to the radius of central island. When the radius of central island is over 30 meters, the increased radius will lead to the rise of average delay. The research result has provided us with quantitative basis in theory when choosing signal control method of roundabout.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (Project No.50708080) and the Specialized Research Fund for the Doctoral Program of Higher Education (SRFDP).

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