2014

A STUDY OF DYNAMIC RIGHT-TURN SIGNAL CONTROL STRATEGY AT MIXED TRAFFIC FLOW INTERSECTIONS

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Traffic in the Cities
Original Scientific Paper
Submitted: Aug. 18, 2013
Approved: Nov. 11, 2014

A STUDY OF DYNAMIC RIGHT-TURN SIGNAL CONTROL STRATEGY AT MIXED TRAFFIC FLOW INTERSECTIONS

ABSTRACT

Traffic conflicts among right-turn vehicles (RTVs), non-motorized vehicles (NMVs) and pedestrians were examined for urban signalized intersections with exclusive right-turn lane. This study proposed an approach to dynamically calculate the duration of the prohibited right-turn for vehicles by using a measure called the Degree of Clustered Conflict (DCC). The process of DCC control includes: 1) quantitative calculation of DCC value in the conflict area; 2) establishing the general cost model that combines the delay and conflict indicators; and 3) applying the DCC-control time model to control RTV in real time. Based on these, the paper presented a general approach of detailed dynamic on-line signal control process of RTV. Finally, the RTV control process was programmed based on VISSIM simulation to evaluate the control effectiveness. The results showed that the general cost (weighted summation of delay and conflict) of the RTV control decreases rapidly compared with non-control, fixed control and full control (drop of 58%, 35% and 42% under small flow conditions and 70%, 59% and 17% in the large flow conditions, respectively). The method not only improved the operation efficiency, but also reduced the potential safety risks among traffic participants when vehicles turn right at intersections.

KEY WORDS

right-turn vehicles; signal control; traffic conflict; delay; non-motorized vehicles;

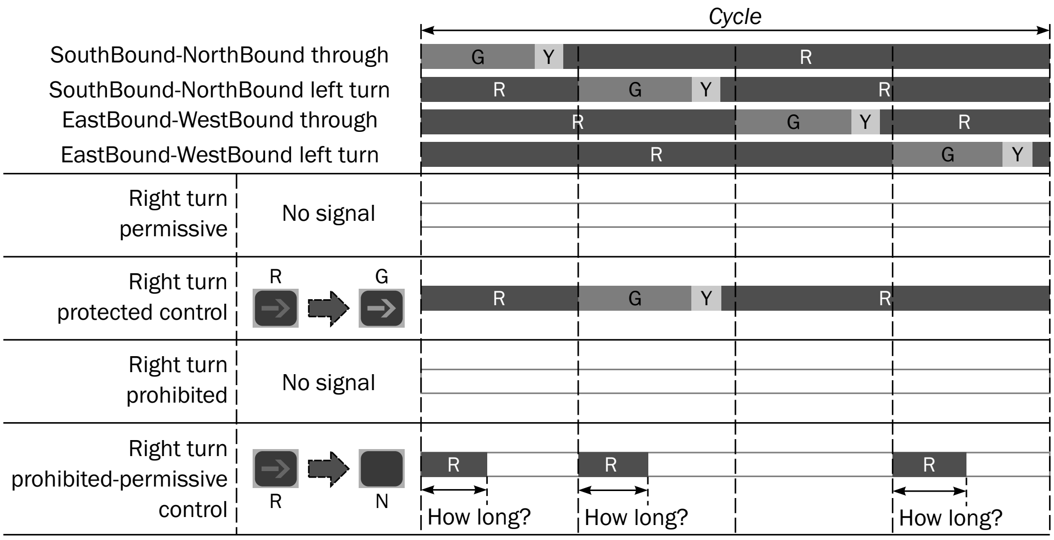
1. INTRODUCTION

Signal control is one of the key means to improve the operational safety and efficiency at intersections. At present, there are more concerns for through and left-turn traffic flows in making control plans. It is a common thought in China that right-turn vehicles (RTVs) from each direction can cross the intersection in any phase by giving way to other traffic flows.

The current Road Traffic Security Act of China states that RTVs should slow down when passing a crosswalk and should yield priority when a pedestrian is crossing a crosswalk. However, according to the survey results of reference (1), the actual proportion of RTVs yielding initiatively to pedestrians is merely about 22%, while its average speed is up to 15 km/h. Just as Huang (2) pointed out that none of the passive treatments other than signal control can ensure that RTVs slow down and yield to pedestrians during the red light.

On the other hand, even if RTV yields to pedestrians, there are still large numbers of non-motorized vehicles (NMVs, e.g. bicycles, motorbikes or scooters) and bidirectional pedestrians (BPs) on its trajectory. This results inevitably in a serious conflict with them no matter whether RTV decelerates or not. Moreover, improper RTV yielding also causes huge safety problems at signalized intersections (3).

Table 1 - Different RTV control modes in China (e.g. Eastbound right-turn)



Note: R = Red light, G = Green light, Y = Yellow light, N = No signal

Currently, as *Table 1* shows, the right-turn signal control in China generally has three modes: right-turn permissive phase, right-turn protected phase and right-turn prohibited/permissive phase. Most of the intersections adopt the first one, which means RTVs are out of control at any time. Our research, however, has focused on the controlled RTVs by adding a period of red arrow light at the beginning of certain right-turn phase in which the RTVs conflict seriously with the counterpart of NMVs and Pedestrians. In those situations which are called prohibited-permissive phases, the vehicles are prohibited to turn right in the red arrow light period, while they can turn right when the red arrow light is off. The key of the protected-permissive phase is to determine the length of the red arrow light duration.

In the remainder of this paper, firstly an overview of the research on RTV control is given. Section 3 introduces the proposed degree of clustered conflict (DCC) model which we will use for dynamic control of RTVs. A detailed control methodology based on flow-DCC model is presented in Section 4, which consists mainly of two parts: the determination of the basic control time and its extension time. Section 5 studies four cases in simulation platform and then their results are discussed. Finally, Section 6 presents the conclusions.

2. RESEARCH REVIEW

In the U.S. the pedestrian signal is 3-5 seconds earlier than RTV signal to expose pedestrians of the first group to the conflict area, which is called LPI (leading pedestrian interval) approach. Otherwise, when both RTVs and pedestrians are in large numbers, RTVs are prohibited with red light (4). Similarly, the German current rules set pedestrian signals 1-2 seconds earlier to indicate the pedestrian's priority when encountering the RTVs (5). Since the demands of pedestrians (and NMVs as well) for crossing the intersection are relatively low in Europe and America, and often RTVs are required to stop to give way (i.e. yield) for pedestrians, many studies focus on the right turn on red (RTOR) (6-9). For example, Yi studies the safety of RTOR in the U.S. and comes to the conclusion that it does not lead to an increase in the number of crashes by reviewing the existing studies and collecting the current RTOR practices (9).

In Australia, the field study of 129 intersections where a right-turn phase had been installed was carried out. In terms of safety, the sample covered three types of changes considered in that study: no control to partially controlled right-turn phase, no control to fully controlled right-turn phase and partially to fully controlled right-turn phase. And the study found that the installation of the partially controlled right-turn phase had no apparent safety benefits. The change from no control to fully controlled right-turn phases showed a 45% reduction in all types of casualty accidents. And the effect of partial to full right-turn control was not statistically significant (10).

Since RTV problems are more serious in China, many studies have been done. Based on the analysis of the conflict type of RTV, Liu et al. use simulation methods to reach the conclusion that the average delay of RTVs increases with the increase of NMV and pedestrians under the similar safety level, and take the jumping point of the relationship curve as the threshold for right-turn control (11). Su et al. consider the conflict between RTVs and NMV/BP, and using conflicting probability model as one of the conditions in the right-turn signal control (12). Considering bicycles and pedestrians as a group, Yu et al. propose a signal control strategy in which RTVs are prohibited for a period of time when the through-phase is released. For this, six phases are used to conduct the right-turn signal control and the sum of velocity is used as an indicator to optimize the signal control (13); however, the calculation approach of the prohibition time has not been provided.

Through the above review, it can be found that the western studies mainly focus on RTVs with pedestrian traffic, and few pay attention to NMVs combined with pedestrians in certain areas (14). The parameter calculation of right turning and a detailed process for RTV signal control are very few. In conclusion, problems and challenges still exist in the current studies:

(1) Since RTV will conflict with both NMV and BP in one right-turn process, it should consider these two kinds of conflict simultaneously, thus the delay and potential safety risk caused by these two kinds of conflict also needs to be considered;

(2) When a vehicle turns right, it needs to pass though NMV flow and BP flow. Thus, the spatial-temporal relationship between the conflicting parts should be taken into account to correct the control (i.e. red light) time;

(3) In the process of assessing the control effect, not only the efficiency index (e.g. delay) but also the safety issue (e.g. conflict) require to be considered in the right-turn control;

(4) Since the volumes of RTV, NMV and BP are different cycle by cycle, the control time for RTV should also change (i.e. the real-time or actuated control need to be studied).

Aiming at problems above, according to the traffic flow characteristics of RTVs, NMVs and BPs, this paper proposes a dynamic control approach of right-turn signal based on DCC. For signalized intersections with exclusive right-turn lane, through the real-time prediction of the NMV and pedestrian arrival flow in the current period, the basic RTV control time (also known as prohibition time) can be determined. Then the curves of DCC-control time are used to dynamically extend the basic prohibition time. Moreover, the risk of RTVs crossing the conflict area is detected and estimated, and the general cost (Combining the delay and conflict among RTV, NMV and BP) is used to evaluate the control effectiveness.

3. ESTABLISHMENT OF DCC MODEL

As shown in *Figure 1*, through analyzing the crossing process of NMV and pedestrian during green light, 2 stages can be summarized under the large flow condition: in the first stage, NMVs and pedestrians enter the intersection in the clustered form; in the second stage, they are in random individual form.

When NMV and pedestrian flows are large, it is easy to form a cluster exposed in the conflict region at the intersection. They directly block the RTV and not only have conflicts with RTVs, but also cause mutual

Figure 1 - The process of NMVs/pedestrians entering the intersection

yielding delay. Thus, in this paper we define the degree of clustered conflict, that is, the traffic individual number (i.e. NMVs and BPs that the RTVs encountered) in the conflict area delimited by two traffic flows and their conflict degree as well. According to the different conflict objects it can be classified into DCC of NMV and DCC of pedestrians.

Theoretically speaking, the red arrow light time (i.e. the prohibited time) of RTV is determined by the current DCC of the conflict traffic in the flow direction: right-turn traffic flows can pass through by yielding when the conflicted traffic is sparse; otherwise, vehicles in the right-turn direction need to wait until it becomes sparse. However, the exact degree of conflict density is the lack of quantitative research in literature. The intuitive understanding of RTV control is: in large cluster, RTVs are controlled to stop in order to guarantee the safety of most NMVs and pedestrians, whilst in small cluster it cancels the control to ensure the benefits for the RTVs, aiming at reaching a balance between efficiency and safety.

As the definition of DCC indicates, the establishing of the DCC model involves the following two parts: a) the definition of the conflict area and its DCC value; and b) the assessment model of yielding delay and safety risk when RTVs cross different values of DCC, for which the general cost (GC) is used for evaluation.

3.1 Defining the conflict area

As the definition of DCC, the conflict area should be defined in advance. Combined with the crossing space of the traffic participants (i.e. RTV, NMV and pedestrian), the conflict area is the space surrounded by traffic individuals' tracks from different directions in the right-turn regions. For example, when the eastbound RTVs want to turn right, they will firstly encounter the straight movement of NMV on the right side to form a conflict area in front of the NMV stop line, and then meet the BP on the crosswalk to form the second conflict area before entering the objective road, as seen in *Figure 2*.

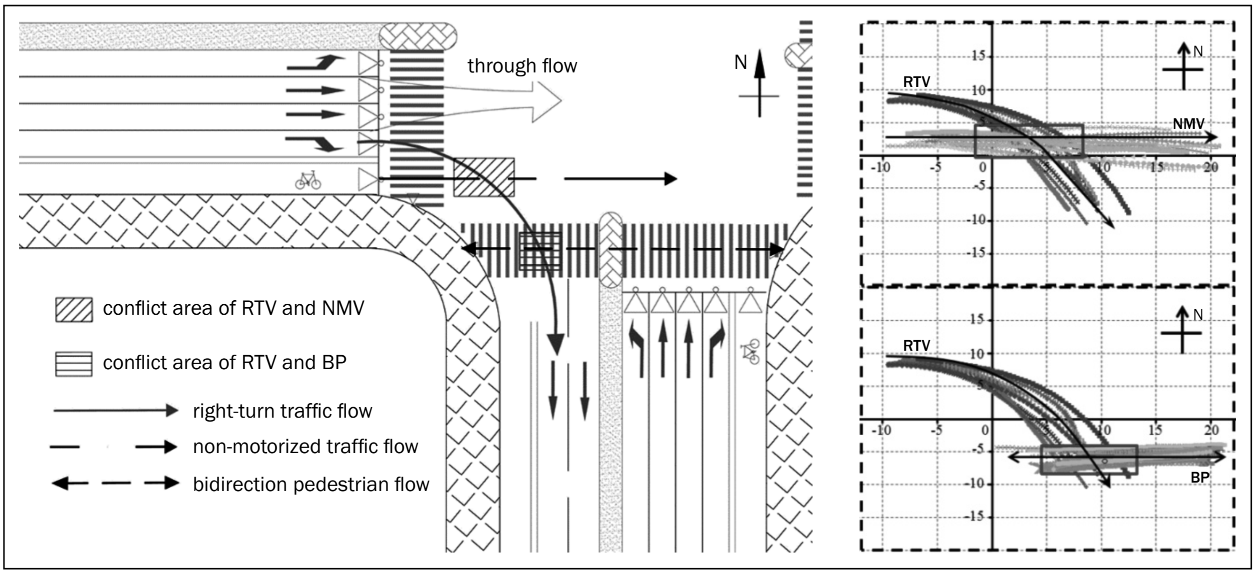


Figure 2 - The scheme of RTV-related conflict areas

The trajectories of RTV, NMV and pedestrian shown in *Figure 2* are all ideal. To get the actual conflict area, the actual turning radical and the dynamic trajectory in the right-turn region of the intersection should be analyzed, and the trajectories of NMV and pedestrians are also irregular lines when avoiding conflicts. Before this paper, a lot of field surveys had been done and the readers can refer to (15) for detailed knowledge. We have determined the actual conflict area by extracting video tracks of these conflicting parties, as seen in the rectangles in the right part of *Figure 2*.

3.2 Converting delay and conflict to general cost

Since the DCC indicates the degree of both delay and conflict when RTVs pass through the conflict area, general cost (GC) is used to evaluate the two sides which could not be compared originally. According to the per capita income, the conversion relationship between conflict and traffic accident, and the compensation standard of road traffic accidents rank issued by the Ministry of public security of China, RTV signal control delay, yielding delay as well as conflict among the three parts are united as general cost. At the intersection with traditional RTV permissive control, the process of vehicles turning right causes fees including total delay cost of mutual yielding among RTV, NMV and BP, and total conflict cost generated between RTV and NMV/BP. While after implementing right-turn prohibited signal control (RTPSC), the GC in a certain period of red light time is mainly the RTV delay due to RTPSC, as well as yielding delay cost and conflict cost after the RTPSC is removed, and calculating this part of cost is similar to the permissive signal control. The detailed process is discussed in the following sections respectively.

1. Delay converted to costs

Delay caused by signal control can be measured with reference to HCM 2010 (16). The yielding delay can be detected in real time, plus the signal control delay to obtain the total delay time and then convert into cost. The conversion relationship between delay time and cost are expressed in equation (1).

$$f_d = b \times d \times \frac{C_d}{365 \times 24 \times 3600} \tag{1}$$

where, f_d is delay cost (yuan); b is passenger load factor; d is delay time (s); C_d is per capita income (yuan).

2. Conflicts converted to costs

Assuming RTV does not encounter a conflict during RTPSC, after removal of control, RTV will encounter NMV and then BP (or first BP and then NMV depending on the specific phase). Because of the diversity of conflict object, conflict angle and conflict serious degree, to add the different conflicts directly would not reflect the real quantitative safety in the process of RTV operation. Thus, they need to be converted into cost via Equation (2).

$$f_c = \frac{a \sum_{n=1}^{N} f(n)}{M} \tag{2}$$

where, f_c is conflict cost (yuan); a is conversion factor between conflict and accident; $f(n)$ is accidents cost (yuan); M and N are the total number of conflicts and accidents, respectively. The conversion factors value between conflict and accident can refer to (17, 18). Thus, the GC can be calculated using Equation (3):

$$f_{GC} = f_d + f_c \tag{3}$$

From the above model the GC can be expressed as: using the decrease of the conflict cost and the yielding delay cost to counterbalance the increase of the RTPSC delay costs. So whether and how long it needs to control RTV depends on whether or not the controlled GC exceeds the uncontrolled GC, or under what duration of the control time the GC can reach a minimum. Through large quantities of field video observation and simulating calibration, the minimum GC that varies with different traffic flows can be acquired.

4. RTV CONTROL METHODOLOGY BASED ON FLOW – DCC MODEL

The determination of control time consists of two parts: firstly determining the basic prohibition control time (Section 4.1) through the predicted RTV, NMV and BP flow in the current cycle before implementing the RTV control; then during the signal control processing, prolonging the control time dynamically (Section 4.2) based on the DCC value of NMV and BP. If the actual required control time is larger than the basic calculated control time in the current cycle, it should prolong the unit of control time; if not, the RTPSC still runs a basic control time, and the reduced control time due to the decrease of flow will be reflected in the next cycle.

4.1 Determining the basic prohibition time PT_0

The basic prohibition time PT_0 is determined by comparing the maximum GC of NMV and BP with different volumes under different control time. In addition, since the design and channelization of intersections are different, some revising processes are then needed when the control plan is put into field.

4.1.1 Flow-control time model

It is very difficult to get conflicts and delays between RTVs and NMVs/BPs under various right-turn volumes, and it will surely cost a lot of manpower and resources to perform in practical projects. As the first step of the research, this study uses a calibrated microsimulation model to obtain the GC curves under different volume combinations. *Figure 3* demonstrates conflict numbers and delay time in these different scenarios with changing NMV volume (*Figure 3*a) and BP volume (*Figure* 3b) scales, respectively (note that RTV volume of 800 puc/h stays unchanged). According to the conversion relationship between conflict/delay and cost, the conflict cost per unit and delay cost per unit can be obtained. Then add the two to get the GC curves per unit as shown in *Figure 3*.

The curves in *Figure 3* show that changing the RTV prohibition time in simulation cause the corresponding changes of GC with different NMV and BP flows. The curve with scattered dots illustrates the minimum GC in different scenarios, which reflects the initial control time. Using the same method, we can get

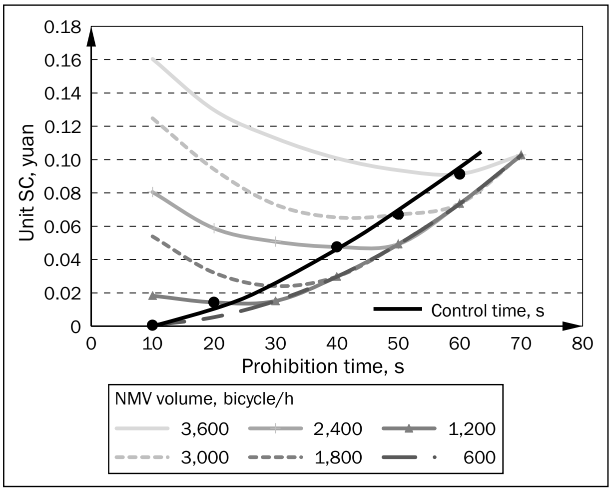


Figure 3a - NMV's GC at different volumes with changing control time

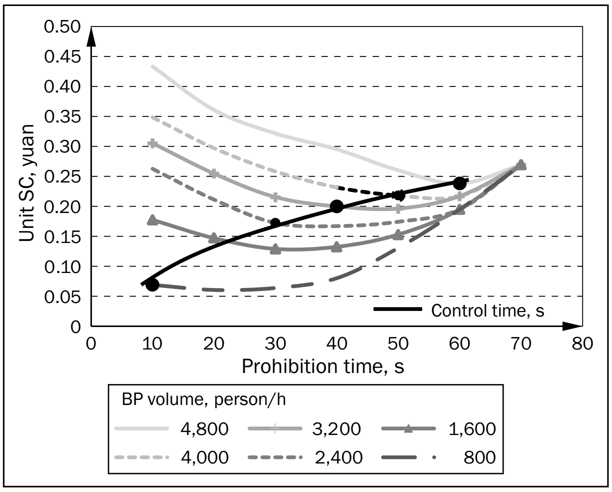


Figure 3b - BP's GC at different volumes with changing control time

the initial flow-control timetable under different RTV flows. And by looking at the flow-control timetable in the actual control, the basic right-turn control time t_b^b with regard to NMV and t_b^p tbp to Pedestrian can be determined.

4.1.2 Revise the basic control time

When the vehicle turns right, it needs to pass through the conflict area with NMV and with BP. Thus, the spatial-temporal relationship between the conflict parts needs to be considered as a factor to rectify the prohibited control (i.e. red arrow light) time.

Assuming the time that RTV gets to and crosses the NMV conflict area are t_1 and t_w respectively, then getting to and crossing the BP conflict area are t_2 and t_w' respectively. NMV cluster arriving at the conflict area needs time t_b, and the near-side and far-side pedestrian cluster need time t_n and t_f respectively to reach the conflict area. The spatial-temporal relationship of these values can be seen in *Figure 4*.

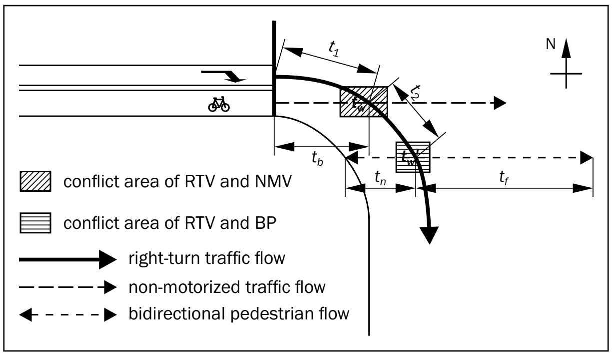


Figure 4 - The spatial-temporal relationship between RTV and its conflicting traffic

According to *Figure 4*, the time that RTV encounters NMV t_{d1}, and encounters BP t_{d2} can be expressed as:

$$t_{d1} = t_1 - t_b \tag{4}$$

$$t_{d2} = t_1 + t_w + t_2 - t_f \tag{5}$$

Henceforth, the initial control time plus the revision time comprise the final basic prohibition time PT_0, which can be presented by a uniform formula:

$$PT_0 = \max\{(t_b^b + t_{d1}),(t_b^p + t_{d2})\} \tag{6}$$

4.2 Determining the extension time

Since the arrival of RTV, NMV and BP varies cycle by cycle, the DCC is proposed in this paper to dynamically adjust the basic control time more accurately.

We still use simulation method to obtain the DCC variation when crossing the conflict area within a certain cycle as an example case shown in *Figure 5*, when NMV flow is in the range of 200 to 2,000 pcu/h and BP flow is from 400 to 4,000 persons/h (including but not limited to these ranges). *Figure 5* depicts an example of the NMV-DCC and BP-DCC changing with time under the exact flow scenario with RTV 800 pcu/h, NMV 600 pcu/h and BP 800 person/h (400 person/h for each direction). Almost all the flow in the tested scenarios has such characteristics that the DCC decreases rapidly after the peak and finally stabilizes at a low value. We can always find such a point that can be regarded as "stop to continuing decrease", which we call the critical DCC.

Despite the fact that different flows require different times (i.e., the length *dx* in *Figure 5*) to reach the critical value, all of the DCC change of NMV and BP will eventually stabilize below the threshold $C_{b0} = 0.1$ bicycle/m^2 and $C_{p0} = 0.5$ person/m^2 in large numbers of simulation under different volume scenarios. Therefore, these two thresholds are used to determine whether to prolong the prohibition time or not after the basic control time is ended, which means we should determine:

$$C_b > C_{b0} \tag{7}$$

$$C_p > C_{p0} \tag{8}$$

Here, C_b and C_p are the detected DCC value of NMV and BP respectively. If either of the Equation (7) and (8) is satisfied then the control time prolongs unit time Δt (usually $\Delta t = 1$ s) until C_b and C_p are below the thresholds.

4.3 RTV dynamic control process

To sum up the sections discussed above, we adopt GC as the index in the different flow – DCC scenarios. For any exclusive right-turn lane at an intersection, the flowchart of RTV signal control with six steps can be seen in *Figure 6*a. Here, some brief interpretations for each step are offered below:

Step1: Manoeuvre the weighted average of RTV flow $Q_c(T_i)$, NMV flow $Q_b(T_i)$ and BP flow $Q_p(T_i)$ with the past several cycles (e.g. $Q_T = 1/2Q_{T-1} + 1/3Q_{T-2} + 1/6Q_{T-3}$) to obtain the anticipated arrival traffic flow of the three in this cycle;

Step2: Calculate the NMV control time t_b^b and the BP control time t_b^p in accordance with the minimum GC; and then revise it to get

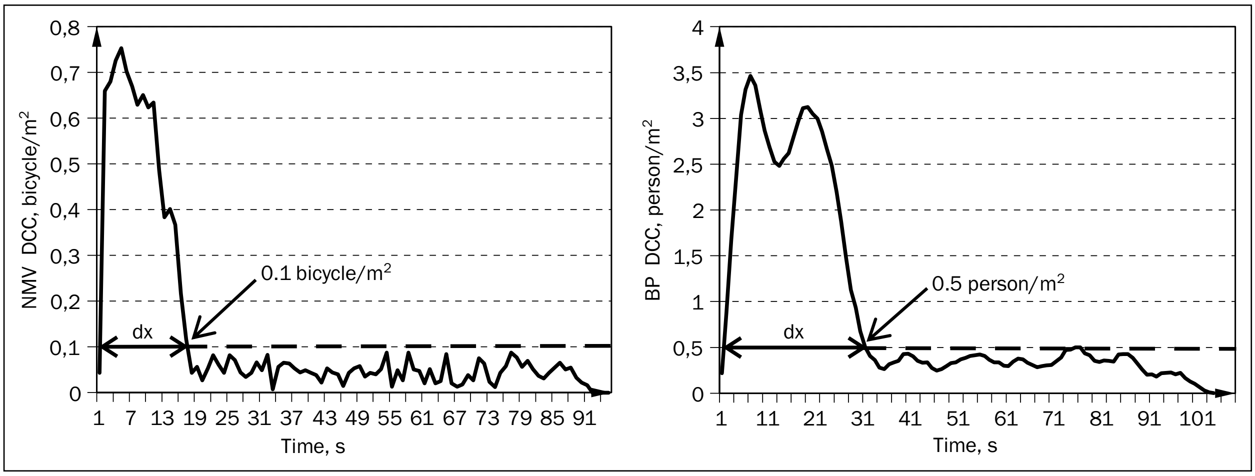


Figure 5 - An example of DCC curves of NMV/BP dynamical change with time

the time to the conflict area (t_{d1} and t_{d2}) based on the spatial-temporal relationship between RTV and the conflicting traffic to obtain the basic prohibition time $PT_0 = \max\{(t_b^b + t_{d1}),(t_b^p + t_{d2})\}$;

Step3: Implement the RTV prohibited signal control. After the basic prohibition time, the system actuates the real-time detection C_b of the NMV-DCC and C_p of the BP-DCC in the current conflict area;

Step4: Compare the detected C_b and C_p with the critical value C_{b0} and C_{p0} to determine whether there is need to prolong the basic

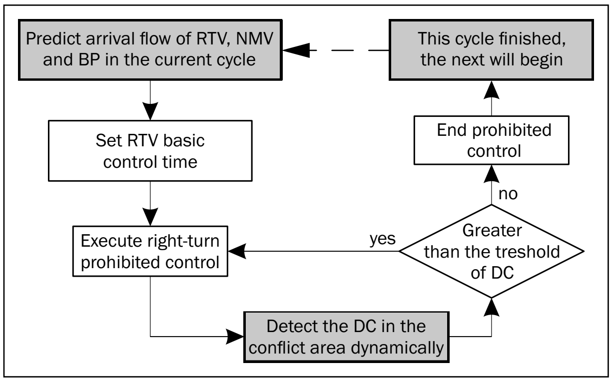


Figure 6a - The flowchart of RTV signal control

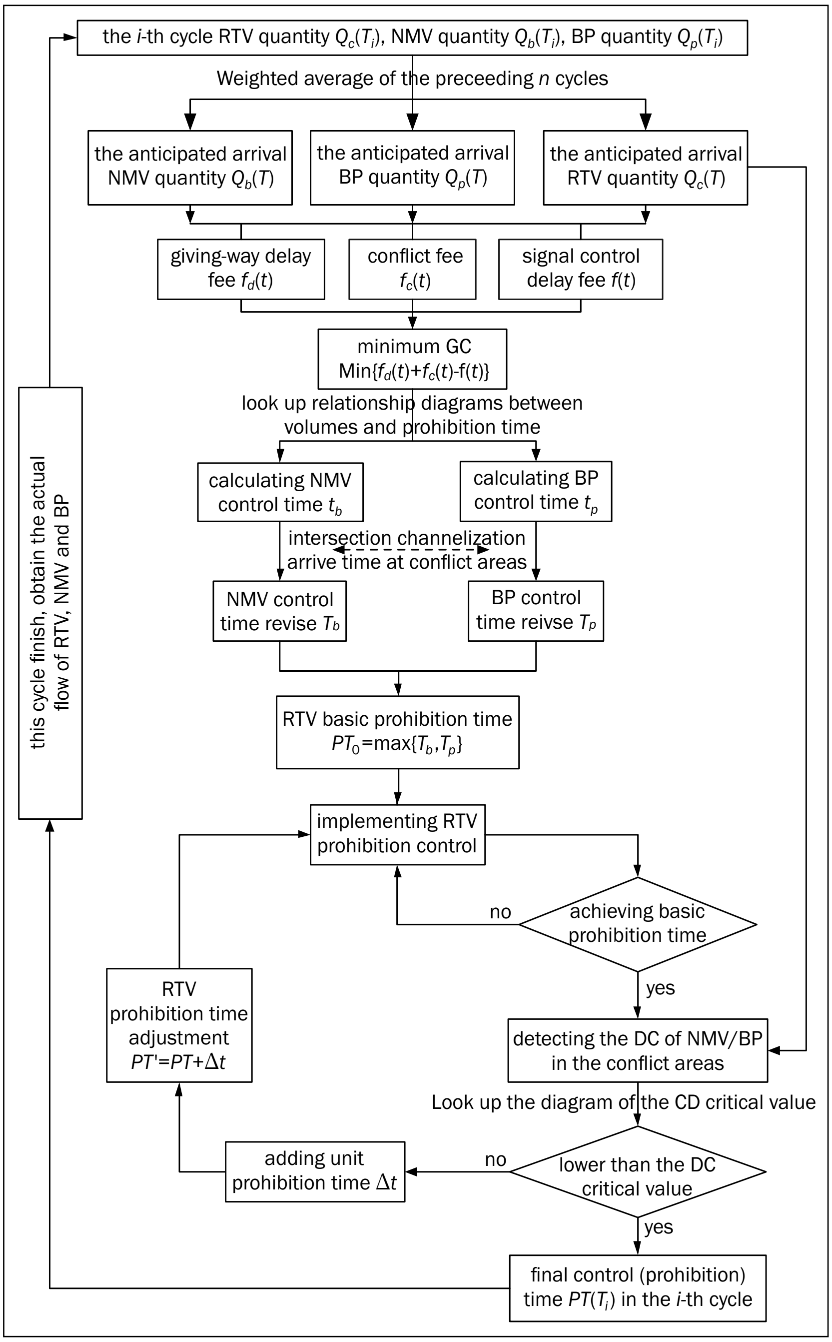
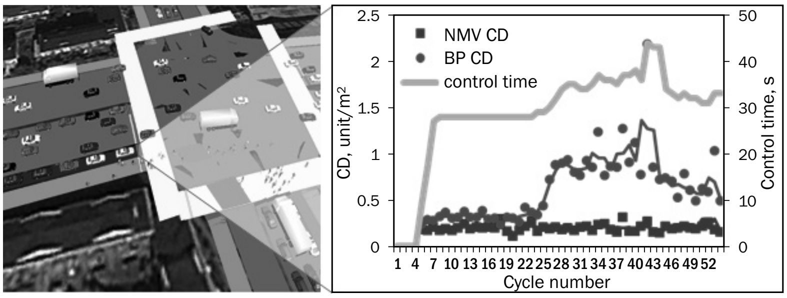


Figure 6b - The detailed RTV signal control flowchart



a. Calibrated simulation model   b. Response of RTV control time to Flow-DCC

Figure 7 - The real-time response of dynamic control time in the simulation case

control time. If either of the Equations (7) and (8) is satisfied then prolong Δt, and return to *step3* until both Equations (7) and (8) do not hold any more. In order to fully balance the interests of all parties, *step4* considers RTV delay caused by control time, and DCC is also converted into cost so as to determine and fine-adjust the prolonging of the prohibition time;

Step5: Remove the prohibition control. The final actual red arrow light time is the RTV prohibition time with the min GC in this cycle.

The details of the above steps are shown in *Figure* 6b.

5. CASE STUDIES

The Caoyang Rd-Wuning Rd (non-control of RTV) intersection in Shanghai is selected as the reference case. The VISSIM simulation model is built after field surveys. To ensure the reliability of the simulation results, 376 sets of valid data including conflict and delay of RTV, NMV and BP trajectories under different RTV volume, as well as the channelization and signal plan of the intersection and the peak-hour flow, etc. are used to calibrate the simulation model (19). The input flow error is within 5% and the conflict and delay error are less than 12%. The exclusive right-turn lane in east-bound road (dark grey road in *Figure 7*a) is chosen, and the simulation model and dynamic control time are shown in *Figure 7*.

We use the external program via COM interface of VISSIM to detect the flow in every direction and DCC in all conflict areas, then the DCC is calculated and the RTPSC control plan is sent back into the simulation model. *Figure 7*b represents the dynamic change of average DCC and control time in one cycle in correspondence with varying input flow of RTV, NMV and BP.

5.1 Scenarios designed for comparison

In order to evaluate the signal control of RTV, we design other three comparison cases. Among these, case1 is non-signal control (i.e. permissive control) which is mostly used in China and also is the field case that we had investigated as well as studied; case2 is RTV fix control with a period of prohibition time (empirically, 10 s are taken as such a period); case3 is an extreme case of full prohibited control without any RTV passing through in this phase; and case4 represents the optimized signal control responding to the calculation of flow and DCC. The evaluation objects are the RTV flow and its conflicting NMV/BP flow in the east-bound and GC including conflict cost and delay cost are used as evaluation indices.

For each case, volumes are changed under simulation experiments. To make it clearer, we take the small and large volume situations as examples to demonstrate the result. In the small volume situation, NMV and BP volumes are 400 bicycle/h and 800 person/h respectively; in the large volume situation, NMV and BP volume are 1,800 bicycle/h and 2,000 person/h, respectively. The RTV flow is set for 800 pcu/h in the two scenarios, and the simulation experiments are conducted with five random seeds then averaging the results to minimize random errors.

5.2 Results analysis

In accordance with the four cases set above, GC under different control cases can be obtained in *Figure 8*. Here, the optimized control time is about 29 s and 47 s in the small and large volume situations, respectively. Note that full control time in these cases is 60 s.

Among these four simulation control cases, the GC in case4 is lesser than all the other three cases. In the small scenario, compared with non-control (case1), fixed control (case2) and full control (case3), the GC of optimized control (case4) drops by 58%, 35% and 42%, respectively, and the larger the volumes the more obvious is the advantage of case4 (GCs drop 70%, 59% and 17%, respectively in the large flow situation). Additionally, the results also reflect that cost caused by conflict has a larger influence on the GC (the lower part in *Figure 8*), which reminds of the principle of safety first.

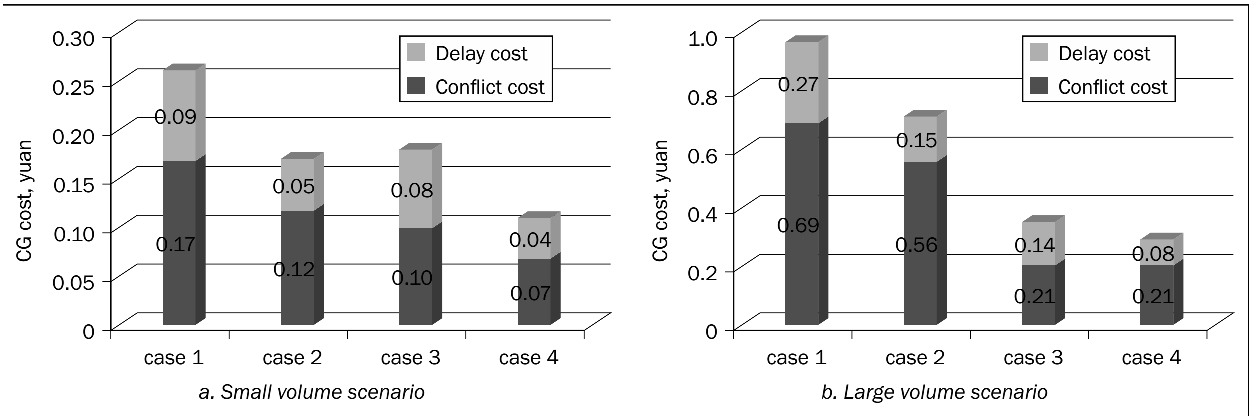


Figure 8 Experiments of GC comparison under different control cases

6. CONCLUSION

This paper takes the spatial-temporal relationship between RTV and NMV/BP and their potential conflicts as basic considerations to propose the concept of DCC, and thus establishes flow-DCC model to dynamically control the RTV flow. Combining with VISSIM simulation platform, the RTV on-line control is built according to real-time detected data. Finally, a case study is tested to verify the feasibility and effectiveness of the model. Some main conclusions are then reached:

(1) The idea of DCC control is similar to the actuated control. Through the off-line spatial-temporal trajectories and traffic flow analysis, the basic RTV control time can be determined under different flow situations. Then the curves of DCC control time can be used for dynamic extension;

(2) The GC index in this paper takes not only traffic delay caused by conflict in each direction, but also the potential safety risks into consideration, which comprehensively describes the RTV control problem;

(3) Compared with non-control, fixed control and full control, the GC of optimized control drops by 58%, 35% and 42%, respectively, and the larger the volumes the more obvious advantages can be reached;

(4) The method can be not only off-line calibrated to execute fixed control of RTV, but also online detected through video cameras and loop detectors to implement inductive real-time control of RTV flow. We are developing the video detection tools to analyse the DCC automatically.

ACKNOWLEDGEMENTS

The authors would like to thank the Natural Science Foundation of China (51238008, 51422812), and the Fundamental Research Funds for the Central Universities for supporting this research.

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摘要

混合交通流交叉口右转专用车道动态信号控制

针对城市典型四相位交叉口右转专用车道无控制机动车流与非机动车、行人的冲突问题，提出了基于集聚度的右转专用车道信号控制模型。该控制模型包括三个模块：1）冲突区域集聚度计算、考虑冲突延误和潜在事故风险的综合费用模型、以及右转车流与非机动车以及行人的动态时间-集聚度模型。最后利用VISSIM微观仿真模型，实现了上述集聚度控制模型策略，并进行了仿真评价。结果表明：与无信号控制和右转机动车固定时间控制相比，基于集聚度的控制策略，右转机动车、直行非机动车和行人的综合费用在右转车流量大时分别下降了58%、35%和42%；而在较小流量时，亦分别下降70%， 59%和17%。基于集聚度的信号控制方法不仅改善了交叉口的运行效率，同时使得交通流冲突数大为减少。

关键词

右转车辆;信号控制; 交通冲突; 延误; 非机动化交通流

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