Continuous Flow Control Method for Straight Forward Vehicles at Cross Intersections Under Vehicle-Road Coordination

Chenyu Yang*, Jingan Wu, Qiucheng Chen, Yixuan Wang

School of Transportation and Logistics Engineering, Wuhan University of Technology, Wuhan Hubei 430063, China

*1964181059@qq.com

Abstract. At intersections, the interaction of different directions of traffic is frequent, and the conflict between straight vehicles is particularly serious, and the formation of continuous flow at intersections has become an urgent problem to be solved. Therefore, this paper proposes a continuous flow regulation method for straight traffic at intersections under vehicle-road coordination. Based on the roadside equipment RSU and vehicle following behavior, design a kind of intersection straight vehicle first to the current, alternate pass rules. At the same time, based on the dynamics model and vehicle passing rules, the virtual cycle concept is introduced instead of the original signal, and the vehicle speed and distance are regulated in front of the vehicle inlet channel to construct the vehicle continuous flow regulation model. Through the simulation of the original intersection signal phase and the method in this paper, the effectiveness of the continuous flow regulation method is verified. The simulation results show that the use of continuous flow regulation method can improve the intersection capacity, while reducing the vehicle delay by 50% to 70%, the effect is significant. The effectiveness of the continuous flow regulation method for straight vehicles is verified.

Keywords: intersections; straight through traffic; vehicle-road coordination; continuous flow; regulation methods.

1 Introduction

As an important node of urban road network, planar intersection affects the smooth operation of urban road traffic. Traditional traffic signal control methods are limited by traffic perception and control capabilities, and intersection control has to stagnate in low-speed, intermittent mode [1]. Although models such as RHODES [2,3] and SCOOT [4] have attempted to improve the inefficient traffic conditions at intersections by adjusting the traffic signals, most of these methods cannot dynamically adapt to real-time traffic. It not only wastes the time and energy consumption of traveling individuals, but also reduces the traffic efficiency and service level of the whole transportation system [5]. Therefore, intersections now need new traffic management models to

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regulate to achieve traffic safety and efficiency. With the gradual improvement of autonomous driving technology, Connected and Autonomous Vehicle (CAV) provides new ideas for cooperative control of vehicles at intersections. The characteristics of vehicle-road cooperative signal interaction and the controllability of CAV can predict the driving conflict point in advance to realize the high-speed and continuous traffic pattern at intersections.

Existing studies have explored the issues of signal timing optimization, right-of-way allocation and vehicle trajectory control optimization at intersections under the traffic environment of network-connected automated vehicles, mainly through mathematical analysis of performance indicators such as delays [6,7], accessibility [8], service level and fuel consumption [9]. Some scholars have also proposed intersection control decision-making mechanisms to develop better control decision-making schemes based on the specific environment of intersections [10,11]. Based on this, this paper proposes a new intersection continuous flow control method for straight vehicles based on vehicle-road coordination. Based on urban primary and secondary road intersections, the traffic signal is considered to be canceled, and the first-come-first-served principle is adopted to control the time of vehicles arriving at the intersection's public area by regulating vehicle speed and vehicle spacing. At the same time, combined with the preset rules of access to make vehicles in the public area of the intersection without stopping to pass, to improve the safety and efficiency of vehicles through the intersection.

2 Problem Description

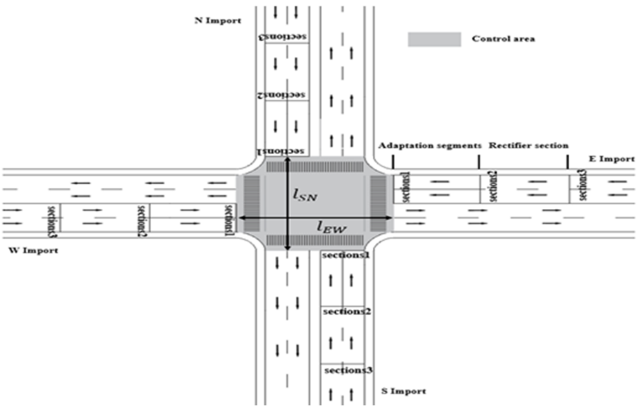

Fig. 1. Schematic illustration of the regulation scenario for a straight cross intersection

Most of the existing intersections are divided into straight, left turn and right turn direction, the main traffic for the amount of straight traffic, through the study of cross intersection straight direction of the traffic conflict can mention the intersection capacity. Therefore, the main research object of this paper is to solve the problem of intermittent passage of straight vehicles through the intersection, the main theme of this paper is to break through the traditional signal control management mode, to realize that the straight vehicles can pass through the intersection at a high speed and continuously, and to put forward the method of continuous passage of straight vehicles at the intersection based on the Internet of Things.

In this paper, the research object for the left turn and right turn traffic flow is low and did not set up the left turn and right turn direction of the intersection, refined as a cross intersection of four directions including straight and right turn direction vehicles, which the right turn vehicles exist in the right turn lane. Combined with the intersection road side equipment RSU (Road Side Unit) senses the real-time state information of vehicles within the intersection, thus dividing the intersection into a control area, rectification section, and an adaptation section to control the speed and position of vehicles. The cross-intersection control scenario is shown in Figure 1.

3 A Continuous Flow Regulation Method for Straight Intersections Based on Vehicle-Road Coordination

3.1 Operational Logic of the Straight-Line Continuous Flow Regulation Method

In order to satisfy the continuous passage of straight vehicles at this intersection, the operating rules for straight vehicles passing through the control area are as follows: north-south (or east-west) inlet-direction straight vehicles pass through the conflict area first, and then east-west (or north-south) inlet-direction straight vehicles pass through the conflict area by utilizing the headway gaps between north-south (or east-west) inlet-direction vehicles, and so on iteratively, with north-south inlet-direction and east-west inlet-direction vehicles passing through the intersection in turn. Conflict area. The specific regulation process relies on control sections 1, 2, and 3 for vehicle speed and spacing, and obtains the traveling speed and vehicle position of the vehicles traveling straight ahead in the roadway section before entering the intersection at the control section 3; for the vehicles reaching the control section 3, according to the preset desired regulation speed and minimum regulation headway spacing, the headway spacing of the control vehicle and the vehicle in front in the same lane is adjusted to the minimum headway spacing before the vehicle arrives at the control section 2 regulating headway distance, and adjusting the traveling speed of the control vehicle to the preset desired regulating speed based on acceleration and deceleration. The vehicle control mode of each entrance road is shown in Figure 2.

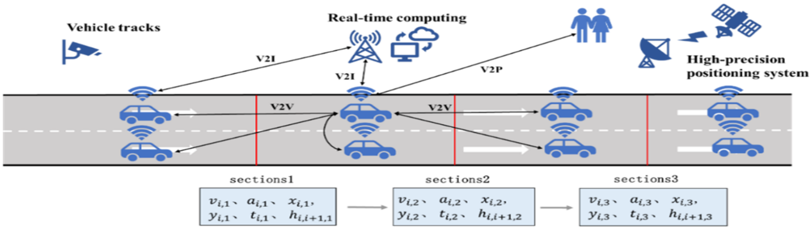

Fig. 2. Schematic of section control

3.2 Intersection Inlet Lane Vehicle Speed Control Setting

The preset desired regulation speed described in the regulation method refers to the speed in the case of maximum capacity obtained based on the basic road capacity calculation model, and the desired regulation speed of the east-west and north-south inlet road in the inlet and outlet directions isV_{EW},V_{SN}, and is not greater than the maximum traveling speed at the intersection V_{max}, i.e., $V_{EW} \leq V_{max}$ and $V_{SN} \leq V_{max}$.

$$\mathrm{C} = \frac{3600V}{h}$$

Format: C is the theoretical capacity of the vehicle, the unit is veh/h; h is the headway spacing, the unit is m; V is the traveling speed, the unit is m / s.

3.3 The Time of Each Inlet Straight Vehicle through the Control Area

This paper considers a symmetrical shaped intersection, so only the time for straight vehicles to pass through the control area is divided into the time for straight vehicles to pass through the control area in the east-west and north-south inlet directions t_{EW}, t_{SN}, according to the different desired regulation speeds preset in the east-west and north-south directions.

$$t_{EW} = max\left\{\frac{L_{EW}+L_i}{V_{EW}} + \Delta t\right\};\ \ t_{SN} = max\left\{\frac{L_{SN}+L_i}{V_{SN}} + \Delta t\right\}$$

Format: L_{EW} is the distance between control section 1 in the east-west inlet direction in m; L_{SN} is the distance between control section 1 in the north-south inlet direction in m; L_i is the body length of the i vehicle in the east-west inlet direction that simultaneously enters the control area in a straight line in m; and Δt is the reservation error for the time of a vehicle passing through the control area in s.

3.4 Pre-Setting of Desired Headway Spacing for Vehicles Traveling Straight ahead at each Inlet Lane

According to the overall rules of the road, it is set that the vehicles in the north-south import direction arrive at the beginning of the import control section, and the vehicles in the east-west import direction arrive at the end of the exit control section as a cycle T. At the same time, according to the road safety regulations, the headway between the same lanes should satisfy the minimum stopping time distance requirement. Because when the main road and the secondary road road level is different, the main road import direction and the secondary road import direction to calculate the minimum stopping time distance is not the same. To ensure safety, t_{safe} should take the larger value of the two. The specific formula is as follows.

$$T = t_{EW} + t_{SN}$$

$$t_{Safe} = max\left\{\frac{\frac{V_{EW}t}{3.6} + \frac{V_{EW}^{2}}{254\varphi} + S_0}{V_{EW}}, \frac{\frac{V_{SN}t}{3.6} + \frac{V_{SN}^{2}}{254\varphi} + S_0}{V_{SN}}\right\}$$

Format: t is the driver's reaction time, generally taken as 2.0s; φ is the longitudinal friction resistance coefficient between the road surface and the tires; S_0 is the safety distance.

According to the intersection straight continuous flow regulation method operation logic, the vehicle through the intersection according to the virtual cycle, in order to prevent unexpected situations to ensure the safety of vehicles, the headway between vehicles should not be less than the shortest cycle time T, while the headway between vehicles should not be less than the headway to ensure the safety of inter-vehicle stopping distance corresponding to the headway. Then the minimum headway distance between neighboring vehicles in the same lane shall be taken as the maximum of the two.

$$t_{\mathrm{h}} = max\{T, t_{Safe}\}$$

3.5 Determination Method of Desired Headway for Straight Vehicles

Since t_{h} is determined by the maximum value of T and t_{Safe}, it is divided into two cases: ① When $T \geq t_{Safe}$, the expected headway of the straight vehicle is T, and its spatial and temporal schematic of passing through the intersection control area is shown in Fig. 3. ② When $t_{Safe} \geq T$, for safety considerations, each cycle time is also t_{Safe}. then the same cycle of the east-west inlet direction straight vehicles and the north-south inlet direction straight vehicles can pass through the control area by utilizing the T time, but after the complete passage of the control area there still exists the length of the control area for the length of the (t_{Safe}–T) time period is empty. In order to ensure the safety of vehicle traveling, the length of ((t_{Safe}–T) time period is divided into the east-west inlet direction straight vehicles through the control area of time t_{EW} and north-south inlet direction straight vehicles through the control area of time t_{SN}. thus describing the east-west, north-south inlet direction straight vehicles occupy the control area of the time t_{EW}, t_{SN}.

$$T_{EW} = \begin{cases} t_{EW} & t_h = T \\ t_{EW} + \frac{t_{Safe-T}}{2} & t_h = t_{Safe} \end{cases}; \quad T_{SN} = \begin{cases} t_{SN} & t_h = T \\ t_{SN} + \frac{t_{Safe-T}}{2} & t_h = t_{Safe} \end{cases}$$

In particular, when $t_{Safe} \geq T$, i.e., when t_h takes t_{Safe}, the degree of conflict in the control area between straight vehicles entering the control area at the same time from different directions in the same cycle is smaller with respect to $t_{Safe} \leq T$ as shown in Fig. 4.

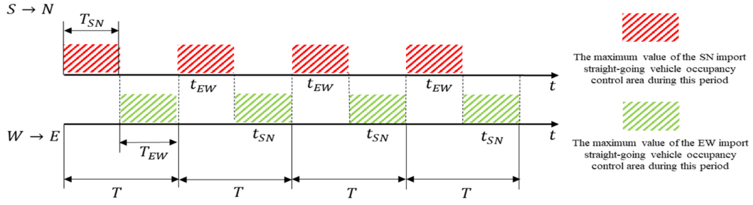

Fig. 3. Distribution of the time of occupancy of the public area by vehicles traveling straight through the intersection at $t_h = T$

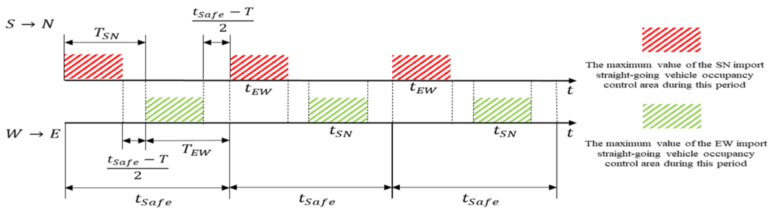

Fig. 4. Distribution of the time of occupancy of the public area by straight vehicles at the intersection for $t_h = t_{Safe}$

3.6 Rectifier Section, Adaptation Section Length Determination

Rectification Section Length Determination.
The fairing section is to accurately regulate the speed of vehicles before they enter the intersection within the roadway. The initial speeds of the vehicles are different, and it is necessary to combine the control system on the roadside to issue control commands to achieve the desired control speed and the minimum control headway by reasonably adding or subtracting the vehicle speed within the fairing section, so as to ensure that the subsequent control is carried out. The length of the fairing section is the distance between the control section 3 and the control section 2 in the regulation scene, and its length is determined according to the initial speed and the desired regulation speed of the vehicle.

$$L_R^{EW} = \frac{V_{EW}^2 - V_{min}^2}{2a}; L_R^{SN} = \frac{V_{SN}^2 - V_{min}^2}{2a}$$

Format: L_R^{EW} is the length of the rectification section in the east-west direction, in m; L_R^{SN} is the length of the rectification section in the north-south direction, in m; V_{min} is the initial possible minimum speed of the vehicle, in m/s; a is the given acceleration, generally a range value [-5, 5].

Adaptation Section Length Determination.
Adaptation section is to adjust the vehicle after it passes through the rectification section to reach the desired regulation speed. Ensure that the vehicle in the adaptation section to maintain the desired regulatory speed traveling. The length of the adaptation

section is the distance between the control section 2 and the control section 1 in the regulation scenario, the specific formula is as follows.

$$L_A^{EW} = nV_{EW}T_n; \quad L_A^{SN} = nV_{SN}T_n$$

Format: L_A^{EW} is the length of the adaptation section in the east-west direction, unit m; L_A^{SN} is the length of the adaptation section in the north-south direction, unit m; n is the adaptation coefficient, $n = 1, 2, 3 \ldots$.

4 Simulation Verification and Analysis

4.1 Intersection-Related Status Quo

In this paper, the simulation scenarios and data are taken from the 2019 Wuhan Youyi Avenue and Industrial Road intersection straight lane, east-west and north-south direction are two-way four-lane intersection, and the east-west direction is a major road, its east-west saturated traffic flow is set to 1650 pcu/h, and the north-south direction is a secondary road, its saturated traffic flow is set to 900 pcu/h. The flow rate and signal timing are shown in Table 1 below. The phase signal timing of this intersection is shown in Figure 5 below.

Table 1. Intersection flow and signal period related parameters

	flow rate (pcu/h)	phase	Signal period (s)	Green light duration (s)
East-west direction	1650	← →	60	40
North-South direction	900	↓↑	60	27

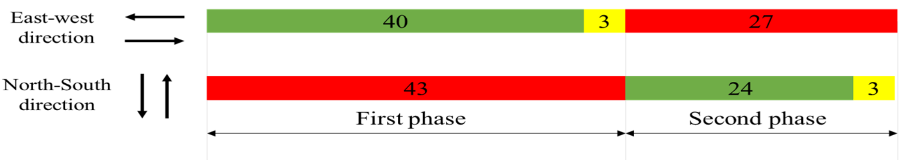

Fig. 5. Illustration of phase signal timing

4.2 Vissim Simulation

Through Vissim simulation software for two-way four-lane straight cross intersection traffic simulation analysis, firstly, the data of intersection traffic flow and signal timing obtained from the investigation are inputted into the software, and then the traffic control module and traffic flow module are set up. The simulation running time is set to 600s, while avoiding the intersection area without vehicles when vehicles just appear, the data collection time starts at 100s, and the data collection time outputs the results every 250s, The simulation is shown in Figure 6. The method of vehicle travel time and node detection is used to derive the queue length and vehicle delay of each inlet lane of the intersection, and the simulation status quo data are shown in Table 2.

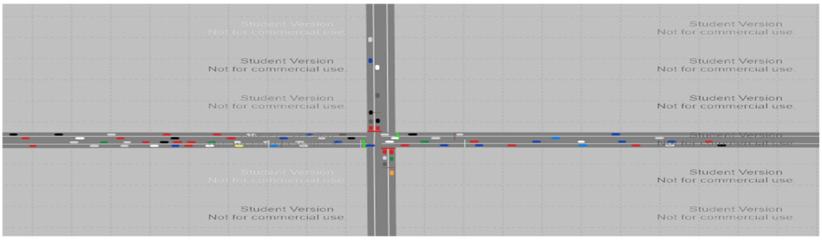

Fig. 6. Schematic simulation of the current state of the intersection

Table 2. Simulation queue length and delay data

Direction	W-E	E-W	N-S	S-N
Queue length/m	24.88	15.59	16.37	15.00
Bicycle delays/s	14.05	10.6	20.26	19.43
Average delays/s			15.12	

From the simulation of the intersection status quo, it can be seen that the queue lengths of the main road in the east-west inlet approach, especially in the west inlet direction, are longer compared to the north-south direction. Meanwhile, due to the difference in road class, the east-west direction accounts for 57% of the total signal cycle in terms of the green time allocation of the signal phases, and the delay of vehicles on its lanes is less than that of the north-south secondary road by 5-10 s. However, in terms of the overall delay of the intersection, the average single-vehicle delay of the whole intersection is 15.12 s. In accordance with the evaluation of the level of service of the intersection, the level of service of the intersection is B, while there is a level of service of C in the local area.

4.3 Simulation of Continuous Flow Regulation Method for Straight Intersection

The continuous flow regulation method proposed in this paper for straight intersections is applied to this intersection to simulate and validate it, and the rule construction of the above model is accomplished by adjusting the parameters of vehicle composition, vehicle arrival distribution, and vehicle desired speed distribution in each inlet lane. The Windemann74 model provided in the driving behavior model of Vissim is mainly used, but due to the model parameters in Vissim are set according to the default parameters, and the driver's driving state are all in the ideal state, less affected by the lane width, pedestrians, non-motorized and other factors. Therefore, the corrective parameters are based on the following Table 3.

Table 3. Reference values of corrected parameters

Model parameters	Windemann74		
	ax	bxadd	bxmult
Default value	2.0	2.0	3.0
Recommended values	2.5	2.0	3.5

According to Table 3, the parameters of Vissim driving behavior model are adjusted, and the deceleration zone and the desired speed decision point are set to regulate the speed of vehicles through the intersection, and the speed of the east-west main road is set to be 60km/h, and the speed of the north-south secondary road is set to be 40km/h. After the parameters have been set, the simulation is carried out. The results are analyzed with the intersection signal timing simulation data. Comparison results are shown in Figure 7.

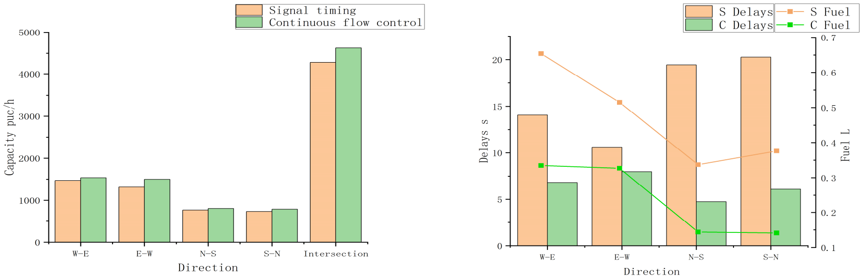

Fig. 7. Traffic capacity and Delay analysis

As shown in Figure 7, it can be concluded that the continuous flow traffic method proposed in this paper utilizes the occupancy time of the intersection better than the original intersection signal timing regulation, and the capacity of each of its inlet lanes is improved compared to that of the original letter control, and the capacity of the entire intersection is improved by 7.9%. At the same time, the method for the elimination of intersection signals as a target departure, according to the simulation results, it can be seen that the use of the method to eliminate the original intersection queue length and the number of stops, at the same time, this thesis regulation method to reduce the delay time of each inlet vehicle, especially for the north-south direction to reduce the delay of the best effect, year-on-year reduction of 69% and 75%, the intersection level of service up to A level. At the same time, due to solving the intersection parking problem, the fuel consumption of vehicles in each inlet lane is generally reduced.

5 Conclusions

This paper focuses on proposing a new continuous flow method applicable to straight vehicles, which is verified by comparing and contrasting the continuous flow method for straight intersections with signalized control and straight intersections under vehicle-road coordination in a straight intersection scenario, and the following main conclusions are drawn through Vissim simulation:

(1) The method utilizes speed and distance regulation on the data before the vehicles enter the intersection, and the conclusion shows that the continuous flow regulation method for straight ahead vehicles at intersections under improved vehicle-lane coordination has significant advantages in improving traffic efficiency, reducing delays, and lowering energy consumption.

(2) Through the data comparison, the continuous flow regulation and control method of straight vehicles improves the efficiency of vehicles and the level of road traffic service, and the most important thing is to cancel the control of the signal light, which can achieve the vehicle without stopping through the intersection, and can alleviate the traffic congestion at the intersection.

Although the continuous flow control method for straight vehicles at intersections under vehicle-road coordination shows significant advantages in improving traffic efficiency and reducing energy consumption, the method may face technical and economic challenges in the implementation process. Meanwhile, the actual road environment is complex, and the current method only regulates the straight forward intersections, and the traffic flow in the left-turn and right-turn directions has not been considered.

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