

Influence of Stretching-Segment Storage Length on Urban Traffic Flow in Signalized Intersection

Weiwei Guo, Wuhong Wang*

*School of Mechanical Engineering, Beijing Institute of Technology
Beijing 100081, China*

Geert Wets

*Transportation Research Institute, Hasselt University,
Wetenschapspark 5 bus 6, 3590 Diepenbeek, Belgium*

Dianhai Wang

*College of Civil Engineering and Architecture, Zhejiang University
Hangzhou 310058, China*

Yan Mao

*School of Mechanical Engineering, Beijing Institute of Technology
Beijing 100081, China*

Xiaobei Jiang^{1,2}

1Department of Transportation Engineering, Beijing Institute of Technology, Beijing 100081, China

2Lehrstuhl für Ergonomie, Technische Universität München, München 85747, Germany

Hongwei Guo

*School of Mechanical Engineering, Beijing Institute of Technology
Beijing 100081, China*

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Abstract

Intelligent traffic control is influenced by Stretching-segment design, parameters optimization of traffic control have to consider saturation flow rate in approach. Many intersections with different stretching-segment design forms are selected to study on saturation flow rate at peak rush hour and ordinary time hour, the characteristic of saturation flow rate in green time is analyzed. Based on the real traffic situation, the influence of the length of stretching-segment storage to straight-cross flow rate was explored in this study. The data showed that the duration and stability of saturation flow rate were highly influenced by the length of stretching-segment storage. A probabilistic computing model was proposed, which analyzed the effect of the length of stretching-segment to the flow rate and described the impact of vehicles in the upstream. Finally, the attenuate regulation of the straight-cross flow rate in green phase is developed by the analysis of vehicle's blocking.

Keywords: Stretching-segment, Intelligent Traffic control, Parameter optimization, Saturation flow rate, Probabilistic computing

* Corresponding author: wangwuhong@bit.edu.cn

1 Introduction

During the channelizing design process of the intersection, Broadening the approach appropriately to increase the number of lanes Intersection to is an effective way to improve traffic capacity. The design of Stretching-Segment can directly affect the traffic flow rate of approach. Experts in China and abroad have launched a long-term research about this. Clayton (1941) first proposed the motion characteristics of the traffic flow through the intersection stop line during the single lane saturation release process¹, then experts Wardrop、Webster² and Cobbe etc. Continue to use and developed the Clayton model. About the calculation of saturation flow, Since the 1950s till now, has formed a number of empirical formula, including Webster and Cobbe methods, Akcelik method³, Kimber method⁴, the cumulative curve method⁵ and HCM method⁶ and so on. These methods together show the two features of the saturation flow rate: (1) the maximum flow rate in flow rate; (2) can persist for some time. However, in subsequent theory and practice, scholars have increasingly found that the saturation flow rate is actually unworthy of the title, only appear under the ideal traffic state, This was reflected by the "stability" of the saturation flow rate does not really stable, Affected by a variety of factors' interference, saturation flow rate tend to last a short time after the apparent attenuation, or showing volatility, for this reason, scholars from various countries conducted a series of related research. Michalopoulos (1978) studied the estimates question of Left-turning saturated flow rate in both Signal intersection and no signal intersection⁷. Soegondo (1983) thought that saturation flow is the maximum traffic volume of approach during the green and yellow light period and limited to the through traffic flow and left-turning traffic flow⁸. Khosla (2006) studied the running effect of saturated flow rate under a longer green time at an approach Intersection of Texas⁹. Wang (2010) studied the Left-turning saturated flow rate model by considering left-turning operation characteristic and the impact on the traffic flow¹⁰.

In summary, during the research process of the saturation flow rate, Defining and measuring method of the saturation flow rate should be considered preferential on preliminary stage, then gradually consider the influence of other factors: Lane width, traffic driving direction, vehicle types, loss of time etc., Saturation flow

rate is defined as a maximum flow rate which can persist for some time, besides, some scholars believe that the saturation flow rate is not stable and consistent but has certain volatility, Especially the long green light will lead to a decline in saturation flow rate^{11,12}. Although the saturation flow rate is not stable and consistent in practice has been noticed, the research about saturated flow rate steady continuous rule, fluctuation and decline reason is not enough, the study of channelizing design effect on saturation flow rate is more rare, And because the through traffic flow is usually the main traffic flow at approaches, therefore the main research target of the current paper is: the design of Stretching-Segment effect on through traffic flow rate.

2 basic design philosophy of Stretching-Segment

The broaden of the intersection Import-way consists of Stretching-transition section and Stretching-Segment, Stretching-transition section is part of transition between the Connecting-road and Stretching-segment. The Stretching-Segment is used to compress and storage vehicles that arrive during the Red-light, the compressed Line-up vehicles during the Green-light was released efficiently^{13,14}, which improve the traffic efficiency during the Green-light, then improve the traffic capacity of the intersection.

The design of Import-way of the signal-intersection includes the horizontal-design and vertical-design, the horizontal-design is mainly determine the number and attributes of import-way, the study about the influence of horizontal of Stretching-segment to the flow-rate is more mature; the vertical-design is mainly design the length of import-way^{15,16}. How to design the length of Stretching-Segment and Stretching-transition section, it has developed a more sophisticated algorithm at home and abroad, the relevant standards and norms studied by United States, Japan and China, has the same design ideas basically, just the specific parameters differ according to national traffic characteristics. Nevertheless, due to the limitations of the road space, random fluctuations of traffic flow, characteristics of different drivers, it is still difficult to completely avoid the adverse effects of the shortage of Stretching-Segment storage length to traffic flow rate.

3 Data Collection

Based on the real traffic situation, the traffic survey which contains the flow rates under different stretching-segments needs to be done for this research. Therefore, the data of 4 intersections in Beijing were observed in peak hours, such as the Xizhaosi Street – Guangming Road intersection, the Zhongguancun Street – Zhichun Road intersection, East Huayuan Road – Longxiang Road intersection and the Guanganmen Inner Street – Baiguang Road intersection.

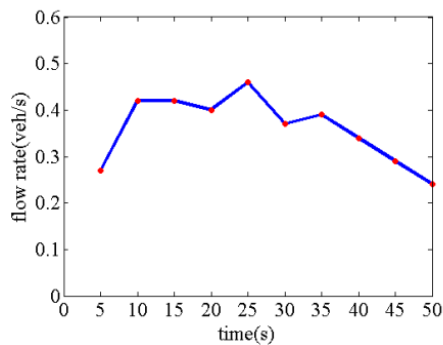


Fig.1 Without Stretching-segment

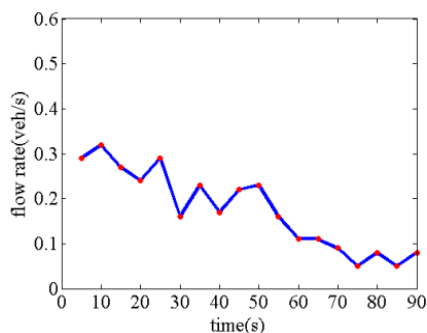


Fig.2 With a 35m Stretching-segment

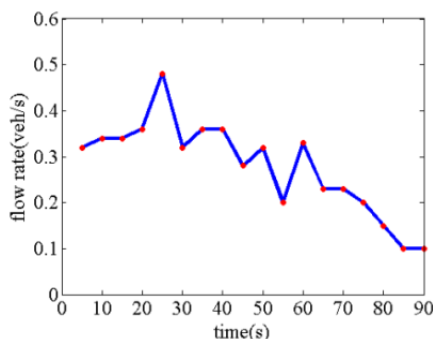


Fig.3 With a 50m Stretching-segment

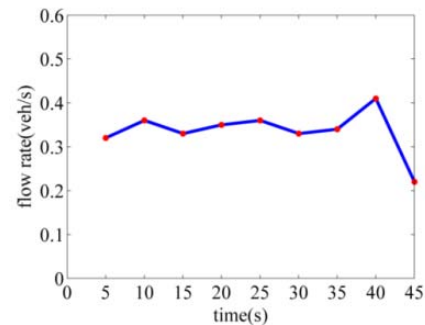


Fig.4 With a 130m Stretching-segment

From those flow rate data under different stretching-segments, it is easy to find that all of the flow rates approached saturation flow rates in 10s and were more stable with the increasing length of the stretching-segments. However, the flow rates became waved in the end of the green phase. The main reason is that vehicles will disturb each other when entering the stretching-segment under the condition that the stretching-segment storage is not enough, the vehicle queue overflows and vehicles complete crossing. That is to say, the efficiency of vehicles crossing in the intersection is decreased.

4 Methodology

As shown in Fig.5, the straight-cross vehicle is mainly disturbed by the left-turn vehicle. When the left-turn vehicle queue overflows, the straight-cross vehicle will be disturbed¹⁷. So, the number of vehicles completed straight-crossing task will decrease and traffic accident will even happen in the upstream of the stretching-segment.

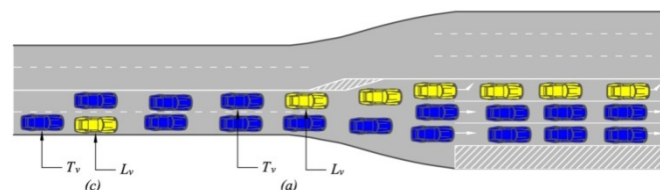


Fig.5 Illustration of the approach

4.1 Important Assumptions

In order to analyze the process that straight-cross vehicle is disturbed by the left-turn vehicle and the flow rate of straight-cross vehicles, some important assumptions

are defined as follows.

- (a) The entrance of the intersection is shown in Figure 2.2.4;
- (b) The number of arrival vehicles fits the Poisson Distribution;
- (c) The effect of the right-turn vehicles should be ignored;
- (d) The straight-cross and left-turn vehicle rates are the same in $Lane_1$ and $Lane_2$, and they have the same input.

Where,

n_v —the number of straight-cross and left-turn vehicles in recorded time, *veh*;

n_{vT} —the number of straight-cross vehicles in recorded time, *veh*;

n_{vL} —the number of left-turn vehicles in recorded time, *veh*;

n_{lane} —the number of vehicle lanes in recorded segment;

n_{laneT} —the number of straight-cross vehicle lanes in the stretching-segment;

n_{laneL} —the number of left-turn vehicle lanes in the stretching-segment;

n_{av} —the maximum number of vehicles which is possible in a vehicle lane of the stretching-segment, *veh*;

n_{avTL} —the total number of straight-cross and left-turn vehicles which is possible in the stretching-segment, *veh*;

n_{avT} —the total number of straight-cross vehicles which is possible in the stretching-segment, *veh*;

n_{avL} —the total number of left-turn vehicles which is possible in the stretching-segment, *veh*;

ρ_T —the straight-cross vehicle rate;

ρ_L —the left-turn vehicle rate, $\rho_L = 1 - \rho_T$;

$P_L(x)$ —the probability that x vehicles enter the intersection;

P_{JL} —the blocking probability of straight-cross vehicles caused by left-turn vehicles.

4.2 Blocking Probability

The straight-cross and left-turn vehicles are all fitted with the Binominal Distribution, where the number of vehicles entered the intersection is n_v , the probability of vehicles which choose straight-crossing is ρ_T and the probability of vehicles which choose left-turning is ρ_L ($\rho_T = 1 - \rho_L$).

The regularity of distribution of left-turn vehicles can

be formulated by Equation (1).

$$P_L(n_{vL}) = C_{n_v}^{n_{vL}} \rho_L^{n_{vL}} (1 - \rho_L)^{n_v - n_{vL}} \quad (1)$$

for $n_{vL} = 0, 1, 2, \dots, n_v$

n_{avL} is the number of left-turn vehicles which is possible in the stretching-segment and P_{JL} represents the blocking probability of straight-cross vehicles caused by left-turn vehicles. When $n_{vL} > n_{avL}$, the left-turn vehicles overflow and disturb the straight-cross vehicles, P_{JL} could be formulated by Equation (2).

$$P_{JL} = \sum_{n_{vL}=n_{avL}+1}^{n_v} P_L(n_{vL}) \quad (2)$$

The numerical analysis method was used to analyze the performance of Equation (1) and (2). A set of curves can be achieved when $n_v \in (1 \sim 40)$, $n_{av} = 5$, $\rho_L \in (0.1 \sim 0.9)$, as see in Figure 6. The curve from right to left followed by $n_v \in (1 \sim 40)$. When n_v is less and the stretching-segment is larger than the traffic demand, P_{JL} is slowly increased with the growth of ρ_L . While n_v becomes larger, P_{JL} is highly increased and the inflection point of $P_{JL} = 1$ moves forward. When $n_v = 40$ and $\rho_L = 0.3$, P_{JL} is almost equal to 1. The regularity of distribution of the blocking probability of straight-cross vehicles caused by left-turn vehicles under different number of arrival vehicles is shown in Figure 6, which indicates that the larger the traffic demand than the traffic supply the higher the blocking probability is.

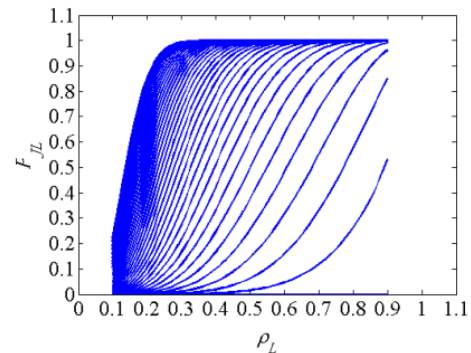


Fig.6 Left-turn vehicle was disturbed by the straight-cross Vehicle, $n_v \in (1 \sim 40)$

4.3 Blocking condition

The blocking probability distribution of straight-cross vehicles caused by left-turn vehicles was analyzed. However, as shown in Figure 5, when the left-turn vehicles overflow, there is still a lane for

straight-cross vehicle to cross. So, it is necessary to analyze the expectation of straight-cross vehicles when the left-turn vehicles overflow, because of the different blocking degrees under different flow rate.

The number of left-turn vehicles in $Lane_1$ can be calculated by Equation (3).

$$n_{vLJ} = n_{vL} - n_{avL} \quad (3)$$

The position j_1 of the i_1 th left-turn vehicle in the queue can be defined by Equation (4), where the O_{QLJ} represents the position matrix of the overflowed left-turn vehicles.

$$\begin{aligned} O_{QLJ}(i_1) &= j_1, i_1 = 1, 2, \dots, n_{vLJ}, \\ j_1 &= n_{av} + 1, n_{av} + 2, \dots, n_{av} + n_{vLJ} + \frac{n_{vT} - n_{avT}}{2} \end{aligned} \quad (4)$$

If the order of the overflowed vehicles are only considered and the $j_1 = n_{av} + 1$ can be simplified to be $j_1 = 1$, the Equation (4) can be described as the Equation (5).

$$\begin{aligned} O_{QLJ}(i_1) &= j_1, \\ i_1 &= 1, 2, \dots, n_{vLJ}, \\ j_1 &= 1, 2, \dots, n_{vLJ} + \frac{n_{vT} - n_{avT}}{2} \end{aligned} \quad (5)$$

If the array O_{AL} is the arrival order of the left-turn vehicles and j_2 is the order of the i_2 th left-turn vehicle, the Equation (6) can be acquired.

$$\begin{aligned} O_{AL}(i_2) &= j_2, \\ i_2 &= 1, 2, \dots, n_{vLJ}, \\ j_2 &= 1, 2, \dots, n_v \end{aligned} \quad (6)$$

As every overflowed left-turn vehicle can only effect the straight-cross vehicle in the upstream of the vehicle queue, the position of the first overflowed vehicle will determin the total number of the blocked straight-cross vehicles and the affections by other overflowed left-turn vehicles are all contained within the first overflowed vehicle's impact.

The Equation (7) can be obtained when the arrival order of the vehicles in the reserved left-turn vehicle lane fits certain conditions.

$$O_{AL}(i_2) \leq n_{avT} + 2 + i_2 - 1 \text{ for } 1 \leq i_2 \leq n_{avL} \quad (7)$$

Let $F_0(i_2)$ to expression below,

$$F_0(i_2) = n_{avT} + 2 + i_2 - 1 \text{ for } 1 \leq i_2 \leq n_{avL} \quad (8) \text{ Equation}$$

(9) indicates the probability when the position of the first overflowed left-turn vehicle $O_{QLJ}(1)$ is equal to j_1 , $j > 1$.

$$\begin{aligned} P_{OQLJ}(O_{QLJ}(1) = 1) &= C_{(F_0(n_{avL}))}^{n_{avL}} \rho_L^{n_{avL}} (1 - \rho_L)^{F_0(n_{avL}) - n_{avL}} \\ C_2^1 \rho_L C_{n_v - F_0(n_{avL}) - 1}^{n_{vL} - n_{avL} - 1} \rho_L^{n_{vL} - n_{avL} - 1} (1 - \rho_L)^{n_v - F_0(n_{avL}) - 1 - (n_{vL} - n_{avL} - 1)} \end{aligned} \quad (9)$$

Equation (10) describes the probability of the first overflowed left-turn vehicle when $O_{QLJ}(1)$ is equal to j_1 and $j > 1$.

$$\begin{aligned} P_{OQLJ}(O_{QLJ}(1) = j_1) &= C_{(F_0(n_{avL}))}^{n_{avL}} \rho_L^{n_{avL}} (1 - \rho_L)^{F_0(n_{avL}) - n_{avL}} \\ (1 - \rho_L)^{2(j-1)-1} C_2^1 \rho_L C_{n_v - (2(j-1)-1) - F_0(n_{avL}) - 1}^{n_{vL} - n_{avL} - 1} \rho_L^{n_{vL} - n_{avL} - 1} \\ (1 - \rho_L)^{n_v - (2(j-1)-1) - F_0(n_{avL}) - 1 - (n_{vL} - n_{avL} - 1)} \end{aligned} \quad (10)$$

According to the principle of conditional probability, when the flow and the rate of the different vehicle rate is given, the probability of the position of the first vehicle $O_{QLJ}(1)$ is equal to j_1 can be calculated by Equation (11).

$$P_{if}(AL|BL) = \frac{P_{if}(AL \cdot BL)}{P_{if}(BL)} = \frac{P_{OQLJ}(O_{QLJ}(1) = j_1)}{P_L(n_{vL})} \quad (11)$$

As a result, the probability model of the queue position order of the left overflow first vehicle was obtained. Fig. 5 shows the example of the approach, setting parameters $n_v = 50$, $n_{vL} = 10$, $n_{av} = 5$, can be get the variation regular of $P_{if}(AL|BL)$ with the the queue position order, as shown in Fig. 7.

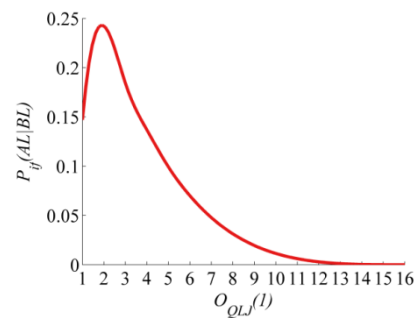


Fig.7 $P_{if}(AL|BL)$ regularity of distribution, $n_v = 50$

The probability of the queue position order of the left overflow first vehicle decreases as the increasing the

queue position order, then the left overflow first vehicle more queues at the first location, also straight vehicle is possibly blocked. The expected number of blocked straight vehicle is the product accumulator by the number of blocked straight vehicle and the probability of the order queue position of the first left overflow vehicle, the expected number of blocked straight vehicle can express by equation (12).

$$E(n_{vT_j}) = \sum_{j_1=1}^{j_1=O_{vT_j_max}} P_{ij}(AL|BL)n_{vT}'(j_1) \quad (12)$$

5 Conclusion

The design of stretching-segment have a significant effect on the efficiency of vehicles' crossing at intersections in green phase. Based on the real traffic situation, the influence of the length of stretching-segment storage to straight-cross flow rate was explored in this study. The data showed that the duration and stability of saturation flow rate were highly influenced by the length of stretching-segment storage. A quantitative model which analyzed the effect of the length of stretching-segment to the flow rate and described the impact of vehicles in the upstream was proposed. Finally, the attenuate regulation of the straight-cross flow rate in green phase is developed by the analysis of vehicle's blocking.

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