Hindawi
Mathematical Problems in Engineering
Volume 2017, Article ID 3723575, 8 pages
https://doi.org/10.1155/2017/3723575

Research Article

Variability of Green Time to Discharge a Specified Number of Queued Vehicles at a Signalized Intersection

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Received 6 January 2017; Revised 15 February 2017; Accepted 6 March 2017; Published 22 March 2017

Academic Editor: Tomasz Kapitaniak

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The aim of this paper is to study the headway distribution of queued vehicles (less than 16 vehicles) at signalized intersections. Existing studies usually take the average statistics of headway at any queuing place. When different percentile points of statistical data are assigned to headway, the passing rate (the rate of all queued vehicles passing the stop line) under the ideal signal timing scheme varies. When selecting the mean value, the passing rate of a queue of fewer than 16 vehicles is no more than 65%. When selecting 75% as the percentile, the passing rate is up to 94%. The queue length also decides the assigned percentile of headway to ensure the passing rate reaches a certain level. The value assignation of headway directly affects lane capacity and start-up loss time. This paper provides a new perspective on parameter calibration and will make the signal timing algorithm method more effective.

1. Introduction

The signal control method is one of the most universal and effective intersection control methods. Rational signal control can not only improve the order and efficiency of traffic flow but also provide an effective method to guarantee traffic safety. An effective signal timing scheme is at the core of signal control but is difficult to realize. Many institutions and scholars have conducted research on the signal timing scheme, including a few that have been widely implemented, such as TRANSYT in Britain, Webster, ARRB in Australia, Highway Capacity Manual [1] in America, the stop line method, and the conflict point method in China. As described by Crabtree [2], TRANSYT tries to optimize static signal timing through traffic simulation, but the discharge rule of queued vehicles affects the results of simulation. ARRB, an extension of Webster, is an algorithm based on the traffic saturation flow determined by lanes and environment. Webster, ARRB, and HCM all consider traffic volume, lane capacity, and queue delay as the main parameters. The stop line method and the conflict point method are both based on highway capacity but differ in computing; the stop line method computes the capacity for each lane based on headway, while the conflict point method introduces a few conflict points that influence highway capacity. Thus, calibrating the discharge rule of queued vehicles, lane capacity, and start-up loss time in conventional signal timing algorithms decides the calculation's precision.

Traffic Engineering, by Professor Wang [3], has always been one of the books referred to for China's traffic engineering. In it, Wang [3] mentions that lane capacity can be calculated by means of (1), and the widely accepted HCM [1] clearly states that the start-up loss time can be calculated by (2) as follows:

$$C_s = \frac{3600}{T_c}\left(\frac{t_g - t_0}{t_a} + 1\right)\varphi \tag{1}$$

$$l_i = \sum_{i=1}^{n} t_i, \tag{2}$$

where

C_s is lane capacity (vehicle/h);

T_c is signal cycle (s);

t_g is green time of corresponding phase (s);

t_0 is time of the first vehicle passing through the stop line after light turning green (s), which can be 2.3 seconds when no statistic is available;

t_a is the average time for vehicles to pass through the stop line;

φ is reduction coefficient, which can be 0.9;

l_i is start-up loss time (s);

t_i is lost time for ith vehicle in queue (s);

n—queue length.

Both calculations on lane capacity and start-up loss time rely on the discharge headway of queued vehicles. Therefore, the more accurate the research on discharge headway distribution, the more helpful it would be for building a reasonable signal timing scheme.

As defined in HCM [1], headway is the time between successive vehicles as they pass a point on a lane or roadway, measured from the same point on each vehicle. It is an important parameter in microscopic traffic analysis because it directly reflects the traffic flow state, drivers' behavioral characteristics, lane capacity, and service level of road sections or intersections. It is the most basic parameter used to calculate lane capacity, optimize signal timing, and construct a car-following model. But traditional traffic theory focuses on modeling that uses constant saturation flow rate and converts the displayed green time into an effective green time using start loss and end gain time parameters associated with the saturation flow rate (Rouphail 1776) [4–7].

As early as 1947, Greenshields et al. [8] discovered that vehicles with different queuing positions have different headway characteristics in movement at traffic lights: from the first vehicle waiting in line, the headway gradually reduces until the fourth or the fifth vehicle, where the headway reaches a comparatively stable value. The conclusions reached in the research are important for the HCM in analyzing the saturated headway and traffic capacity at traffic lights. Akçelik [5] described saturation flow rate as the average queue departure flow rate during the saturated part of green period excluding the vehicles departing during the first 10 seconds. HCM [1] believes the headway of queued vehicles is constant after the fourth vehicle and the saturated headway can be calculated using the average value of headways after the fourth vehicle. Sadoun [9] discovered that the influence of queuing positions on the average headway at a signalized intersection is obvious and that, generally, vehicles between the fourth and the sixth positions accelerate fully, and the headway reaches a steady state. Through analyzing the survey data of signalized intersections of a Virginia highway, Denney Jr. et al. [10] discovered that headway decreases toward the back of the queuing line, but this feature is not obvious in the central and interior through lanes. He et al. [11] also found that when the light turns green, the headway is influenced by the queuing position: the lead vehicles have a larger headway of up to 3.85 seconds, while the reaction time lapses in the trailing vehicles, and this rule no longer applies. Shao et al. [12] explored the headway of the through lane vehicles at signalized intersections of Beijing and found that logarithmic normal distribution can be used to match the headway distribution of queued vehicles at the intersection. The headway of the first vehicle is lower than that of the vehicles in the next two positions. They suggest that the measure of saturated headway in each signal cycle should start from the sixth vehicle passing though the traffic light.

Akçelik and Besley [13] described the exponential queue discharge flow and speed relationships, which present a new realm of possibilities for more realistic traffic modeling instead of simpler modeling based on the use of constant saturation flow assumptions used to date. Recent data analysis from Hawaii, USA (2002, 2005), Long Island, New York (2005, 2007), and Taiwan (2009) determines that the headway of queued vehicles trends toward constant decrease once the traffic light turns green while, at the same time, the through capacity trends toward constant increase.

The studies on the headway of queued vehicles at a signalized intersection so far include the following:

(1) The headway of queued vehicles is affected by the queuing position.

(2) The first vehicle waiting in the line is unique in comparison with the others in that its headway is either higher or lower.

(3) Headway reaches a constant value from vehicles between the fourth and the sixth vehicles.

(4) Headway is also affected by other factors, such as vehicle types, diversion, and road conditions.

(5) Headway of vehicles in different positions can be expressed by a concrete value in specific lanes.

By summarizing the existing research results, it has been found that most studies on headway distribution are based on measured data, and measured data usually uses average values as the headway of vehicles at different queuing positions. It is a reasonable method when using statistics. However, headway is a key parameter in deciding signal timing schemes; the headway value and reasonable signal timing are closely related. Thus, it is necessary to test the feasibility of using average values as the headway from the effectiveness (the passing rate of the queue) of signal timing. This paper has carried out research based on this reasoning.

The organization of the rest of the paper is as follows. The second section summarizes the field study and data statistics. The data is divided into two groups: the experimental group and the validation group. The third section analyzes the characteristics of headway distribution using the data obtained from the experimental group. The fourth section discusses the relation between headway, queue length, and queue passing rate. Validated group data is used to test the results of this study in the fifth section. The final section presents the conclusion and recommendations for future study.

2. Data Sources

One intersection in Nanjing, China, was selected to collect data. The two roads that cross at the intersection are Xinglong

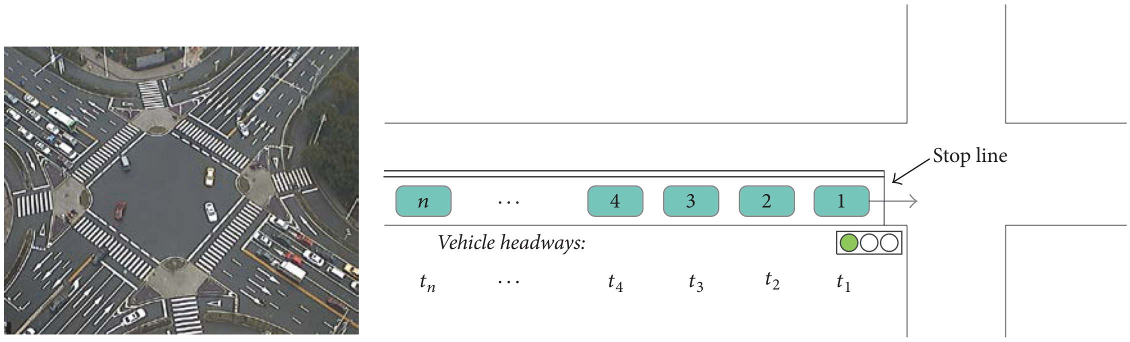

Figure 1: Collection site and headways at the intersection.

Street and Jiangdong Road, both arterial roads. The detailed channelization of the intersection is shown in Figure 1. There are three through lanes, one left-turn lane, and one right-turn lane in each approach. The intersection is located in the prosperous area of the city with high traffic volumes where signal control is adopted. The timing scheme in morning peak hours contains four phases, and the cycle time is 134 seconds.

The field study focused on through traffic on the eastbound approach during morning peak (7:30–8:30 a.m.) and evening peak (17:00–19:00 p.m.) times on weekdays. Video cameras were used to record the real traffic conditions around the intersection. With the help of video-editing software, all recorded videos were processed manually. More importantly, to improve the accuracy of data collection, discharge headways were defined before counting. For the first vehicle of a queue, the discharge headway was the elapsed time between the start of a green light and the time when the vehicle's front bumper passed the stop line. For the remaining vehicles in the queue, including all the vehicles that join the queue during the green, the discharge headways were the elapsed time between the points when two successive vehicles' front bumpers passed the same stop line. Considering the weak role in specifying headway distribution, queues with fewer than five vehicles were excluded. However, queues with weaving vehicles and queues influenced by pedestrians, drivers' distractions, or other reasons were under survey, as they mirror driving behavior.

The data collected was divided into two groups, these being the experiment group (EG) and the validation group (VG). The EG was used to analyze the rule the headway distribution obeyed and the rule's characteristics. It consists of 500 groups of headway, each group containing discharge headways of all vehicles in queue. The VG was used to verify the research results of this study and consists of 420 groups of headway. The rule the headway distribution obeyed is named the distribution rule. The queue lengths of the 920 groups of data were not all the same. Regarding the EG, there were 461 groups of data with queue lengths of no less than 10 vehicles, while 182 groups of data had lengths of no less than 15 vehicles. There were 100 groups of data where the length was more than 15. As it is inaccurate to calculate the distribution rule when the data amount for queuing position is too small, the analysis does not take any queuing positions after the 15th vehicle into consideration. Whether the distribution rule of queues longer than 15 vehicles should contribute to the research conclusion of this article must be discussed in other research studies where more data will be collected. The standard deviations in the statistical data at the different positions of the two groups show a low dispersion degree.

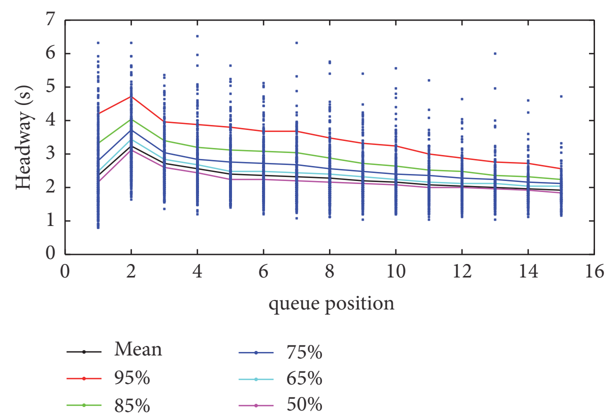

Figure 2: Headway distributions across vehicle positions.

3. Headway Distribution Characteristics Analysis

3.1. Headway Distribution Obeys Logarithmic Functions. In the experiment group, each queuing position (from 1 to 15) has a large amount of collected headways no less than 185, but the premise of analyzing headway distribution is that the headway for each queuing position should have an exact value. The method of selecting reasonable headway values for each queuing position will be discussed in the next section. In order to ensure the effectiveness and scientific correctness when analyzing the headway distribution in this section, the average value, 95th percentile, 85th percentile, 75th percentile, 65th percentile, and 50th percentile of statistical data were, respectively, selected as the headway of each queuing position in order to conduct the analysis. The headway value of each queuing position at different percentiles is shown in Figure 2.

The paper employs the least square method to find the best function to match the headway data and uses the integrity of index R^2 to reflect the matching degree of the placing function and statistical data. The value range of R^2 is $[0, 1]$, and the closer the value of R^2 is to 1, the better the fitting degree is. The exponential function, linear function, logarithmic function, quadratic polynomial, and power functions were used to match the data, and the matching GFI (goodness of fit index) obtained from various functions are collected.

Matching results shows that R^2 value in the fitting function of the headway with a queuing line fewer than 16 vehicles is usually low. The headway distribution diagram in Figure 2 shows that when choosing the headway at any percentile, the headway of the first vehicle is notably inconsistent with the headway distribution rule regarding other queuing positions. Usually, one would expect the first vehicle to have higher discharge headway as the first driver has to go through the full perception-reaction sequence and then accelerate through the intersection. However, in this research, all the headway percentiles and average data for the second vehicle is greater than the first one. There are two possible reasons for this phenomenon. First, the lead vehicle's headway is mainly affected by the driver's response to the green light, while the headway of subsequent line positions is mainly affected by the vehicle ahead. Signal lamp countdown, which can help drivers reduce perception-reaction time, is widely used in China, as with the studied intersection in this research. The first vehicle's headway is reduced with the help of signal lamp countdown. Second, while other vehicles must keep a safe distance from the vehicle ahead, the first vehicle stopped can be quite close to the stop line, which means the headway of the first vehicle is 0. For these reasons, function fitting on the headways, except that of the first vehicle, was carried out, and the result was shown in Table 1. It was found that the GFI of the fitting function when eliminating the first car was greatly improved.

By comparing the value of R^2 in various functions, it is seen that the value of R^2 in the logarithmic function is the highest under any percentile of the headway data, of which the lowest value of R^2 is 0.9227. This means that the fitting degree between the logarithmic function and headway is really high. Assuming the headway subjects to the logarithmic function, a chi-square test was applied to verify the assumption through MATLAB programming. The result shows h is 0, which means the assumption cannot be rejected. Thus, logarithmic functions ought to be used to reflect the headway distribution rule. In short, the headway distribution rule can be expressed by means of the equation below.

$$y_x = f(x) = A \ln(x) + B, \quad (3)$$

where

y_x is the headway at the queuing position of x;

x is the queuing position of vehicles and $x > 1$;

A and B are the function coefficient;

x is an integer larger than 1.

Table 2 shows that coefficients A and B are affected by headway percentile. Thus, the distribution rule differs under different percentiles. Through graphing the coefficients versus percentile (see Figure 3), there is clearly some sort of nonlinear relationship between them. It should be possible to develop a single equation in which coefficients A and B are functions of the percentile. The exponential function, linear function, logarithmic function, quadratic polynomial, and power functions were used to establish the relationship. Using the least square method and chi-square test, quadratic polynomial was found to best reflect the relationships. The integrity of index R^2 is 0.999 and 0.996, and chi-square test parameter h is 0 for both, which mean coefficients A and B are subject to quadratic polynomial. So coefficients A and B can be expressed by means of the equation below.

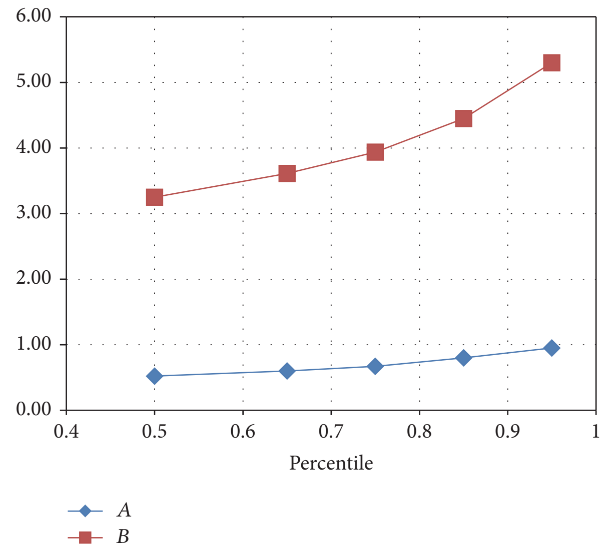

Figure 3: Relationship between the coefficients and percentile.

$$\begin{aligned} y_A &= f_A(p) = 1.62p^2 - 1.41p + 0.82 \\ y_B &= f_B(p) = 8.63p^2 - 8.10p + 5.16, \end{aligned} \quad (4)$$

where

y_A is the value of coefficient A;

Y_B is the value of coefficient B;

p is headway selecting percentile.

3.2. Headway Selection Affects the Service Level of Signal Control. The research as discussed above proves that the headway of the vehicles waiting at positions other than the first obey the logarithmic distribution. If the headway distribution rule of the lane can be expressed by means of (3), the theoretic green time T_G that should be allocated to that lane can be calculated by using the equation below when there are vehicles waiting to pass the traffic light. It is not the general method for timing signals in practice or theory, but all theories on signal timing schemes are based on fixed capacity for each lane, which implies the headway is also a fixed one. In essence, all methods try to give a reasonable green time to meet the headway requirement for all queued vehicles.

Table 1: R^2 value in the fitting function of the headway data (excluding the first vehicle).

Percentile	Exponential function	Linear function	Logarithmic function	Quadratic polynomial	Power function
95th Per.	0.965	0.9417	0.9431	0.9493	0.9192
85th Per.	0.9515	0.9094	0.9651	0.9445	0.9600
75th Per.	0.897	0.8334	0.9443	0.9066	0.9351
65th Per.	0.8608	0.7972	0.9356	0.9044	0.9232
50th Per.	0.8347	0.7709	0.9227	0.8877	0.9132
Mean	0.8913	0.8326	0.9548	0.9202	0.9451

Table 2: Headway distribution in different percentiles.

Percentiles	R^2 (for the whole queue)	R^2 (exclude the first vehicle)	Logarithmical forms (exclude the first vehicle)
Mean	0.8273	0.9431	$y = -0.56 * \ln(x) + 3.43$
95th Per.	0.7683	0.9651	$y = -0.95 * \ln(x) + 5.30$
85th Per.	0.6556	0.9443	$y = -0.80 * \ln(x) + 4.45$
75th Per.	0.5747	0.9356	$y = -0.67 * \ln(x) + 3.94$
65th Per.	0.4858	0.9227	$y = -0.60 * \ln(x) + 3.61$
50th Per.	0.5804	0.9548	$y = -0.52 * \ln(x) + 3.25$

Equation (5) provides one way of calculating the theoretic green time T_G while other conditions related to signal timing are simplified.

$$T_G = y_1 + \sum_{x=2}^{n} y_x = y_1 + \sum_{x=2}^{n} f(x), \quad (5)$$

where

T_G is the green time that should be allocated to the lane in theory;

y_1 is the headway of the first vehicle waiting in the line;

n is the queue length of the lane.

The rate of queued vehicles passing the stop line within one green light is named the passing rate, which is closely related to the green time T_G. The longer the theoretic green time T_G is, the greater the passing rate of the queued vehicles is, but the loss time of the green light might be longer as well. The shorter the theoretical green time T_G is, the smaller the passing rate of the queued vehicles is, meaning there is a higher possibility of residual queue. Therefore, reasonable signal timing should reduce the green time T_G as far as possible, on the condition that there is a high passing rate for queued vehicles.

The green time T_A spent when passing the stop line in different queue lengths can be acquired, according to the statistics: $T_G \geq T_A$ means the queued vehicles can pass the green light in theoretic time, while $T_G < T_A$ means the queued vehicles need a residual queue to pass the stop line. In other words, some vehicles need to wait for the green light no less than twice. We used the experiment group's data to measure the green time spent by vehicles in different queue lengths when passing the stop line and calculated the possibility of $T_G \geq T_A$ of different queue lengths. The result is shown in Figure 4.

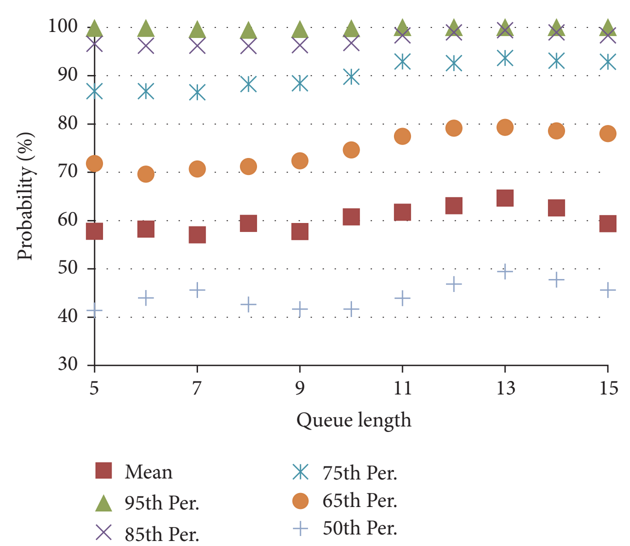

Figure 4: The probability of $T_G \geq T_A$ at different percentiles in different queue lengths.

Figure 4 shows that if the length ranges from 5 to 15 vehicles, the maximum passing rates in each queue length when choosing the 95th, 85th, 75th, 65th, and 50th percentiles of the statistical data as the headway are, respectively, 100%, 99.43%, 93.68%, 79.31%, and 49.43%. When choosing the average value as the headway, the maximum passing rate is 64.66%. Thus, it is obvious that the headway value greatly influences the passing rate of the queued vehicles—the higher the percentile, the higher the passing rate of the queued vehicles. Figure 4 also reflects that, at the same percentile of headway,

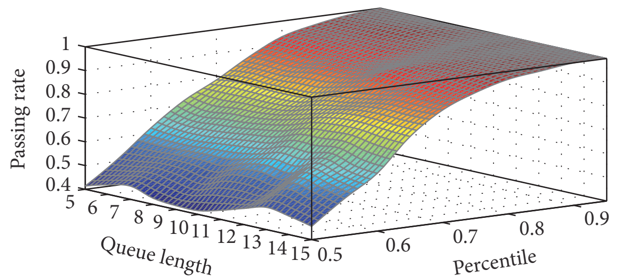

FIGURE 5: The parameter-relation diagram among passing rate, queue length, and headway percentile selection.

the passing rate of different queue lengths vary. To summarize, the passing rate, as the key indicator of the intersection's service level, is directly decided by the headway value.

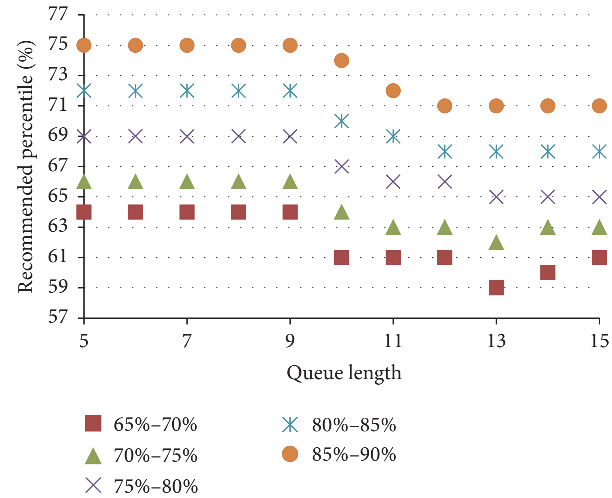

FIGURE 6: Recommended percentile for headway selection.

4. Headway Selection Analysis

The analysis above shows that the passing rate of the queued vehicles at the intersection is directly affected by queue length and headway value. In order to further discuss the method of choosing a reasonable headway for intersection signal control, the study used the 500 groups of data in EG to analyze the relationship between the passing rate (P), queue length (N), and the percentile (Q) of the headway. The parameter-relation diagram is shown in Figure 5.

Figure 5 shows that the relationship between the passing rate, queue length, and headway selection percentile obeys the binary function, which can be expressed in (6) with percentile Q as the dependent variable. This means that if the length N can be predicted accurately, the value percentile Q has a 1 : 1 correspondence to the passing rate P.

$$Q = f(P, N). \tag{6}$$

Substantial data was collected for this study, but it is still not enough to build accurate relationships between passing rate, queue length, and headway percentile selection. There are some irregular variations in Figure 5, so equations (or series of equations) that can indicate a relationship were not stated formally here. It can only be finished when enough data is collected.

In order to provide more efficient guidance in designing the signal timing scheme, the study undertook further research on the headway selection under the given queue length and service level. In engineering applications, 5% is usually taken as the step size to divide the service levels. The study divides the service level into six ranges, including 60–65%, 65–70%, 70–75%, 75–80%, 80–85%, and 85–90%. Service levels less than 60% and higher than 90% were not taken into account because they have fewer application values. Through the equations set below, it can be concluded that if the queue with N vehicles wants to meet with the passing rate range $[P_a, P_b]$, theoretically, the headway percentile Q_0 should be adopted, which is accurate to the integer. The result is shown in Figure 6.

$$\begin{aligned} Q_a &= f(P_a, N) \\ Q_b &= f(P_b, N) \\ P_b &= P_a + 5\% \\ Q_0 &= \mathrm{INT}\left[\frac{Q_a + Q_b}{2}\right], \end{aligned} \tag{7}$$

where

P_a, P_b denote the service level (passing rate) range;

$P_a \in (60\%, 65\%, 70\%, 75\%, 80\%, 85\%)$;

Q_a, Q_b are percentiles for headway selection when the service level is P_a, P_b;

N is queue length, $N \in [5, 15]$;

Q_0 is percentile for headway selection when the passing rate is $[P_a, P_b]$.

As seen in Figure 6, the percentile for headway selection can be smaller when the queue length is longer under the same service level. When comparing the average percentile value (last row), the percentile for headway selection shows a large variation in order to meet with different service levels. In order to keep the passing rate within [85–90%], the average percentile value is 73%, while the average percentile value is only 62% to keep the passing rate within [65–70%]. This implies that, during practical applications, the percentile value for headway selection should be analyzed according to the needs of the service level, rather than choosing the average value as the percentile.

5. Implementation Discussion

The VG data contain 420 groups of headway. Different percentiles (with average values of 95%, 85%, 75%, 65%, and

Table 3: Verification results on headway distribution in different percentiles.

Percentiles	R^2 (for the whole queue)	R^2 (exclude the first vehicle)	Logarithmical forms (exclude the first vehicle)
Mean	0.7970	0.9734	$y = -0.64 * \ln(x) + 3.64$
95th Per.	0.9638	0.9688	$y = -1.03 * \ln(x) + 5.66$
85th Per.	0.8790	0.9525	$y = -0.84 * \ln(x) + 4.65$
75th Per.	0.8575	0.9419	$y = -0.72 * \ln(x) + 4.10$
65th Per.	0.8311	0.9610	$y = -0.67 * \ln(x) + 3.80$
50th Per.	0.7490	0.9608	$y = -0.62 * \ln(x) + 3.47$

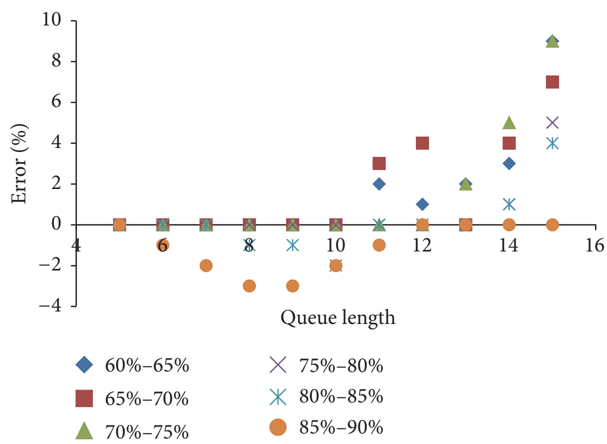

Figure 7: Verification results on recommendation for headway selection.

50%) for the headway selection of the VG data were chosen to carry out the logarithmic function fitting. The results are shown in Table 3. Using the least square method and chi-square test, and the verified result is consistent with the conclusions of the paper. The headway of the first vehicle has a poor fitting with regard to the subsequent queued vehicles; thus the headway of the first vehicle should be considered by itself. The headway distribution of the vehicles, excluding the first one, conforms to the logarithmic function, and coefficients A and B conform to quadratic polynomial.

$$y_A = f_A(p) = 2.36p^2 - 2.54p + 1.31$$
$$y_B = f_B(p) = 11.09p^2 - 11.42p + 6.44. \quad (8)$$

The suggested percentiles for headway selection under the different service levels for each queue length are shown in Figure 6. According to this, the 420 groups of data in VG are used to verify the passing rate of each queue length under the suggested value, and the results thereof are shown in Figure 7.

Using the VG data, the passing rates of the queue with lengths ranging from 5 to 15 vehicles are calculated, according to the suggested percentile value in Figure 6. Among the 66 calculated passing rates, 41 rates are in the range of the theoretical passing rate. They thus conform to the demanded passing rate. Twenty rates have errors within 5% of the theoretical passing rate, and five rates have errors that range between 5% and 10%. The errors between the actual and theoretical passing rates are also less than 10%.

The five passing rates with errors ranging between 5% and 10% occurred in the queue with 15 vehicles. The valid headway is 165 groups of that queue length. The main reason for such errors is possibly the small sample size. The total number of samples of the EG (500) and VG (420) is also small and the main reason for the 0 to 5% error range in 20 of the results.

The verification conclusions all show the validity of the research regarding the headway distribution rule of queued vehicles waiting behind the stop line at signalized intersections.

6. Summary and Discussion

The main purpose of the research was to analyze the headway distribution rule regarding queued vehicles (less than 16 vehicles) waiting behind the stop line at signalized intersections and to make sure of the distribution characteristics. It also aimed to find the correct means of determining reasonable headway distribution, thereby offering accurate parameters for the design of signal timing schemes at intersections. The field and case studies were both located at a common intersection in Nanjing, and data from 920 queues was collected. Five hundred groups of data collected were used to explore the headway distribution characteristics, while the other 420 groups were used to verify the research's conclusions.

Many studies choose average statistics as the headway value for each queuing position. This study not only calculated the average value but also extracted the various percentiles of each queuing position, including 95%, 85%, 75%, 65%, and 50%. By using the least square method and chi-square test to fit headway distribution, headway distribution conforms to logarithmic distribution no matter whether the average value or headway value at any quintile is used. The fitting degree is higher without the headway of the first vehicle while R^2 is no less than 0.92. It can also be concluded that the queue length N, the percentile Q for headway selection, and the passing rate P obey the binary function. According to the above analysis, selecting different headway percentiles for queuing vehicles with fixed queue length would result in very different passing rates. When analyzing intersections using methods such as the HCM, the suggested percentiles for headway selection can be acquired from the parameter-relation diagram when the queue length needed meets with a desired passing rate. Four hundred groups of data in VG were used to verify the conclusions and prove the effectiveness of the research results.

It is evident that the 920 groups of headway data collected during the research are too small. Though the study provides feasible and practical research methods for headway distribution by analyzing the experimental data, it is still not accurate enough to reflect the headway distribution of the researched lane under different conditions, such as different percentages of large vehicles and queue length more than 16 vehicles. What is more, the headway distribution rule may be different according to different lanes. This is not considered in this research but will be taken into account in the subsequent study.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work is sponsored by two National Natural Science Foundations of China. The fund numbers are no. 51178108 and no. 51208100, respectively. It is also supported by the Fundamental Research Funds for the Central Universities (KYLX15_0152) and the Scientific Research Foundation of Graduate School of Southeast University.

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