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An Improved Mixed Distribution Model of Time Headway for Urban Roads Based on a New Traffic State Classification Method

HONGWEI LI[1], YUNYUE ZHOU[2], YINGYING XING[3], CHUNQIN ZHANG[4], AND XIAOLI ZHANG[1]

[1]College of Civil and Transportation Engineering, Hohai University, Nanjing 210098, China
[2]Zhuji Logistics Management Information Center, Zhuji Bureau of Traffic and Transportation, Shaoxing 311800, China
[3]College of Transportation Engineering, Tongji University, Shanghai 200092, China
[4]School of Civil Engineering and Architecture, Zhejiang Sci-Tech University, Hangzhou 310018, China

Corresponding author: Yingying Xing (yingying199004@tongji.edu.cn)

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ABSTRACT The Mixed distribution model of time headway plays an important role in Intelligent Transportation System. A more accurate improved model based on a new traffic state classification method and correlation coefficient method was established in this study. Upon analyzing traffic data from three unban roads in Nanjing, China from December 8, 2017 to April 24, 2018 in clear days free of fogs and haze, it was found that 1) the improved model dwarfs the other models, for it boasts higher goodness-of-fit and it represents the only one to successfully pass the Chi-square test. 2) the improved model shows better performance in application because the relative errors between the field traffic rate and calculated traffic rate obtained from the improved model are the smallest. 3) the goodness-of-fit of the improved model is affected by traffic state, and the fitting precision of the improved model under four states is the best. Thus, it is hard to tell performance of which model established under two states or three-state model is better. 4) correlation coefficients between time headway and the absolute value of relative speed make the improved Mixed model more fitted and precise. The improved model proposed in this study is a more accurate time headway distribution model.

INDEX TERMS Urban roads, time headway, speed, traffic state, correlation coefficient.

I. INTRODUCTION

Time headway is a fundamental measure in both traffic flow theory and transportation applications [1]. It is usually defined as the time between two successive vehicles as they pass the same common feature (e.g., front/rear bump) of both vehicles [2]. The observed headways are not constant due to several reasons, such as inaccurate perceptions / actions of drivers and heterogeneity in vehicle performance [2]. Therefore, various distribution models have been proposed to describe the probability of a particular value or value range of time headway [2].

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Time headway distributions are often called mesoscopic models for containing abundant information of car-following behavior, and they act as a bridge that links microscopic and macroscopic traffic flow models [3]. The introduction of headway distribution models has made it easy to describe uncertainty in traffic flow [2]. For example, traffic rate can be predicted based on the relationship between traffic rate and time headway by using time headway distribution according to probability theory [4], [5]. Based on traffic rate, traffic managers can smooth traffic stream, reduce traffic congestion, design traffic signal timing, and evaluate passenger satisfaction [5]–[8].

The distribution model of time headway was first proposed by Adams who successfully fitted the time headway distribution with a negative exponential distribution [9].

Noteworthy, the improvement of the model is closely related to the evolution of traffic state. In the early development of transportation, vehicles were sparse on the ground, and the traffic operated in a smooth fashion. Several single distribution models of the time headway have been proposed for free flow, such as Shifted negative exponential distribution, Lognormal distribution, Erlang distribution, Poisson distribution, and Weibull distribution models [10]–[12]. As the number of vehicles mushroomed, bumper-to-bumper traffic has been becoming a norm in some crowded cities. In order to adapt to multiple traffic states, Cowan first proposed a Mixed distribution model of time headway (Mixed model). This model fits the distribution models of time headway for free flow and car-following condition, respectively. Then, the two fitted models were combined due to distribution coefficient confirmed by traffic flow rate under free flow state [13]. From then on, several time headway distribution models have been established based on Mixed distribution model. For example, Tao used expectation maximization to calibrate distribution coefficients of the model [14]. Wang built an improved M3 distribution model to describe the time headway distribution of free flow, strong car-following condition and weak car-following condition [15]. Branston found that the fit of Mixed distribution model was not good in the presence of more overtaking behaviors on the roads [16]. Therefore, he proposed several single lane distribution models based on queuing theory under free flow and car-following condition, which is more suitable for roads with overtaking behavior. Moreover, scholars also improved the Mixed distribution model by dividing car-following condition into overtaking state and no overtaking state using minimum car-following interval to suit for the roads with overtaking behavior [17]. As traffic flow is divided into free flow, congestion and jam, some scholars have established the time headway distribution model under three traffic states [18], [19].

Above mentioned studies indicate that, time headway distribution models are established based on traffic state. In general, traffic flow is mainly divided into three states based on three-phase theory, and four states [20] or six states by using clustering algorithm [21]. These traffic state classification methods, whether three-phase theory or clustering algorithm, classify traffic state in terms of macroscopic traffic flow, ignoring the information of microscopic traffic flow. Wang considered that it is better to use both macroscopic and microscopic traffic flow theory in practice [22]. Moreover, the new distribution models have been usually verified by comparing Chi-square tests with the classical models, but rarely verified via the practical application. Furthermore, researchers focus on obtaining more accurate distribution models, but the factors affecting the accuracy of the models are seldom analyzed.

The main objective of this study is to propose a more accurate time headway distribution model based on a new traffic state classification method combining both the macroscopic traffic flow information and microscopic traffic flow information. The accuracy of the model was verified not only by Chi-square test, but also through application. The generality of models was tested, too. Furthermore, the influence of factors on the accuracy of the model, such as traffic state and the model's coefficient determination methods, were also discussed.

The present thesis is composed of six parts. The main issues associated with each discussed part are listed as follows: Section 2 describes the collection and processing of the field data, and presents the analysis indicating which parameters are more useful in classifying traffic flow state. Section 3 introduces the classification of traffic states based on speed, headway, and relative speed. Section 4 expounds upon the processes of the improved model. Section 5 validates the goodness of fit, application performance, and generality of the improved models and presents the analysis of the influencing factors on the fitting precision of the improved model. Section 6 presents the conclusion, in which the goodness-of-fit, application performance and the influence on the accuracy of the model are discussed.

II. DATA COLLECTION AND REDUCTION

A. SITES DESCRIPTION

The survey sections of the urban roads were selected as follows:

(*a*) The road sections should meet the requirements of visual distance and visual field.

(*b*) There is no special incident on the sections, such as road constructions or traffic accidents.

(*c*) There is no curb parking and bus station on the sections.

(*d*) The road conditions should be flat and straight.

(*e*) The distance from upstream intersection to the survey site should be between 50 and 100 m [23].

The locations and attributes of survey sections are shown in Fig. 1 and Table 1, respectively. The traffic data were collected using a video recording. The middle segment is far from the intersection and the traffic flow in this area is more stable than in other areas; therefore, the video recording was made on the middle part of survey sections' roadside. Li concluded that traffic flow changed from the off-peak (6:50 AM) to the peak (8:10 AM) on weekdays after analyzing 24-hours traffic data of arterial roads and secondary trunk roads in Nanjing [24]. Therefore, the survey period was 6:50 AM – 8:10 AM on weekdays from December 8, 2017 to April 24, 2018 in normal day weather without fog and haze. The survey days, traffic rate, and speed are shown in Table 2.

B. DATA PROCESSING

The data are preprocessed as follows:

1) TIME HEADWAY

The time headway which equals 0 s should be eliminated for manual error. The time headway more than 25 s should also be eliminated because the frequency of the data is almost zero [25].

FIGURE 1. Locations of survey sections.

TABLE 1. Attributes of survey sections.

Indexes	Hanzhongmen Street	Hanzhong Road	Beijing West Road
Road hierarchy	Secondary Trunk Road	Arterial Road	Arterial Road
Number of lanes	4	4	6
Lane width (m)	3.75	3.75	3.75
Speed limit (km/h)	40	60	50
Separation facilities	Yes	Yes	Yes

TABLE 2. Traffic rate and speed of survey sections.

Parameters		Hanzhongmen Street	Hanzhong Road	Beijing West Road
Traffic rate (pcu)	S[a]	14400	17789	18492
	M[b]	246	457	369
	H[c]	842	654	639
	Mean	1193	1417	1462
Speed (km/h)	Min	2.7	2.57	2.34
	Max	68.4	60	51
	Mean	13.4	14.85	14.53

[a] S is the passenger car; [b] M is the middle-sized vehicle; [c] H is the heavy vehicle.

2) OVERTAKING

Overtaking behavior accounted for 0.070%, 0.056%, and 0.061% in the total number of behaviors in Hanzhongmen Street, Hanzhong Road, and Beijing West Road, respectively. Therefore, in this study, overtaking behaviors were not considered when establishing distribution model of time headway.

3) STATISTICAL INTERVAL

The stability of traffic flow is an essential factor for analyzing traffic state. It could be expressed by the standard deviation of traffic parameters in a certain statistical interval. If the standard deviation of traffic parameters is smaller than 5 km/h, the traffic flow will be stable. The minimum time interval recommended by the Highway Capacity Manual is 5 min [1]. Yeung *et al.* [26] and Dong *et al.* [27] selected 1 min and 2min as the statistical interval of highway traffic flow data, respectively. In this study, the statistical intervals of 1 min, 2 min, …, and 10 min were selected by using the standard deviation of traffic rate and speed.

Fig. 2 exhibits the standard deviation of traffic rate and speed in different statistical intervals. Following results can be obtained from the figure:

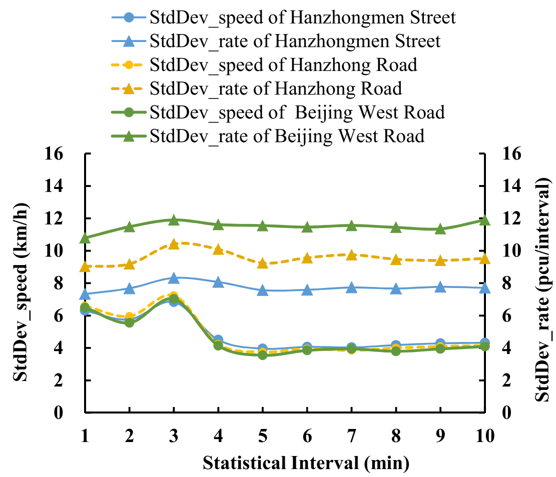

FIGURE 2. Standard deviation of flow rate and speed in different statistical intervals.

(a) In each interval, the standard deviation of traffic rate at each interval is greater than 5 pcu/interval.

(b) In 1, 2, 3 min intervals, the standard deviation of speed is greater than 5 km/h. When the interval is more than 4 min, the standard deviation of speed is smaller than 5 km/h.

It can thus be concluded that speed is more suitable for traffic states analysis than traffic rate. This conclusion is consistent with the result that speed is the most critical parameter of traffic flow [28].

III. TRAFFIC STATE CLASSIFICATION METHOD

A. PARAMETER SELECTION

Many parameters including macroscopic parameters and microscopic parameters have been applied to classify traffic state in previous studies.

1) MACROSCOPIC INDICATORS

Traffic rate, speed and density are widely used in classifying traffic states [29]–[32]. As a single variable, traffic rate is insufficient to exactly specify traffic state since a certain value of flow may correspond to two distinct density and speed values in two completely different flow states, i.e., congested and un-congested. That explains why density was introduced for the fundamental diagram of traffic rate vs. density [31] to sort out traffic states. However, it has been demonstrated that density may not properly indicate congestion because congestion is not likely to increase proportionally to the increase of density [33], [34]. Some researchers concluded that speed works well in classifying traffic congestion [35]. For example, Chen claimed that the time headway decreases with the increase in speed, and the time headway conforms to shifted lognormal distribution in each speed range [36].

2) MICROSCOPIC INDICATORS

Time headway is one of the most important parameters in traffic flow theory because it reflects the uncertainty of drivers' car-following maneuvers and clearly describes the stochastic feature of traffic flow, which cannot be observed by macroscopic parameters [37]. Time headway is a bridge to link macroscopic traffic flow and microscopic traffic flow because the fundamental diagram implicitly depends on the time headway [2]. Besides, it has also been proven that the time headway is speed-dependent when traffic flow is congested [38].

Very few studies combined the macroscopic indicator and the microscopic indicator to classify the traffic state. In this study, speed and time headway were used to define traffic states.

B. K-MEANS CLUSTERING

Clustering algorithms have been widely applied to discover homogeneous and heterogeneous characteristics of traffic flow [39], [40]. Some researchers found that K-means clustering is more suitable for classifying traffic state than Fuzzy clustering, clustering large-scale application, 2 and 3 nearest neighbor algorithm, and artificial neural network [41], [42]. Compared to a simple histogram, K-means clustering is able to determine an optimal cluster number according to clustering principle and obtain a more precise threshold. Therefore, K-means clustering was utilized to classify traffic state based on speed.

The validity of clustering is measured by Calinski–Harabasz (CH) criterion because it is a common method to determine the optimal number of clusters in terms of distance among them. When clustering, the data within the same cluster should be as close as possible, and the data between the different clusters should be as far away as possible. The larger the value of CH, the better the clustering effect [43]. CH is obtained by using Formula (1) as follows:

$$\mathrm{CH}(k) = \frac{tr(B_k)}{tr(W_k)} \frac{l-k}{k-1} \tag{1}$$

where l corresponds to samples in training set; k is the number of clusters; B_k is the covariance matrix between clusters; W_k is the covariance matrix of the data within the cluster; and tr is the trace of the matrix.

C. RELATIVE SPEED ABSOLUTE VALUE METHOD

Under car-following condition, the driver of the following vehicle should pay more attention to the speed change of the leading vehicle due to the limitation from the leading vehicle, compared to free flow. Therefore, the car-following condition is determined based on significant changes in speed of vehicles. There are two common methods to classify car-following condition.

1) The first is expected speed method. If the speed of leading vehicle is lower than the expected speed of the following vehicle, traffic state is under car-following condition [44]. The method is not maneuverable because it is difficult to obtain the expected speed of each vehicle [45].

2) The other is relative speed absolute value method, which determines car-following condition by using the curve of time headway and the absolute value of relative speed between leading vehicle and following vehicle on the same lanes [46]. The curve describes the following two trends: the relative speed absolute value increases approximately in a straight line with the increase of time headway, and the absolute value of relative speed floats horizontally with the increase of time headway. Further, the time headway corresponding to the inflection point where the curve changes from oblique line to horizontal fluctuation is regarded as the demarcation point between car-following condition and free flow. One is the car-following state while the other is free flow. The effectiveness of the method was proved by using the measured data of two expressways. In this study the relative speed absolute value method was utilized to classify car-following condition and free flow.

The process of this method is illustrated as follows,

Step 1: Initialize relative speed by using Formula (2)

$$\Delta v = \frac{v_{leading\,vehicle} - v_{following\,vehicle}}{3.6} \tag{2}$$

where Δv is the relative speed, m/s; $v_{\mathrm{leadingvehicle}}$ is the speed of the leading vehicle, km/h; and $v_{\mathrm{followingvehicle}}$ is the speed of the following vehicle, km/h.

Step 2: Draw the curve of time headway and absolute value of relative speed.

Step 3: Make the value of time headway of the point where the curve changes from oblique line to horizontal fluctuation as the threshold value for car-following condition and free flow.

D. CASE STUDY

K-means clustering was utilized to classify the traffic state by using speed. Before clustering, the number of traffic state was assigned as 2 to 6 because traffic flow is usually divided into these numbers [20], [21]. Fig. 3 shows the curves of CH values and cluster number, revealing that when K is 3, the CHs on three roads have maximums values. Therefore, traffic flow is divided into three states: discrete state, steady state, and blocked state, as presented in Table 3. The explanations of the states are shown below,

a) Discrete state. In discrete state, vehicles were sparse and running freely. The traffic volume is small and speed is fast. The traffic flow is free flow.

b) Steady state. In steady state, speed has decreased compared to the speed in discrete state. Vehicles in this state are affected. Some vehicles' speeds are slightly lower than the minimum speed of the free flow because the vehicles

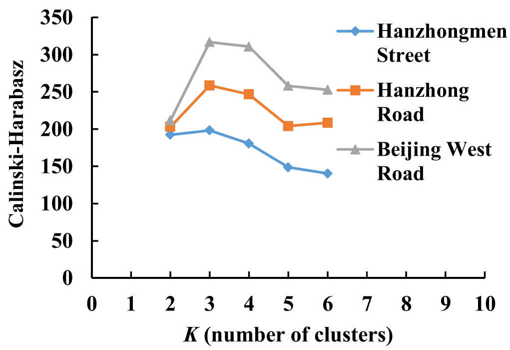

FIGURE 3. The relationship between the values of CHs and the numbers of clusters.

TABLE 3. Classification of traffic states by speed.

Sections	Traffic states		
	discrete	steady	blocked
Hanzhongmen Street	v[a] >21.21	13.03 < v <21.21	v<13.03
Hanzhong Road	v>21.88	14.78 < v <21.88	v<14.78
Beijing West Road	v>23.34	14.82 < v <23.34	v<14.82

[a] v is speed, km/h.

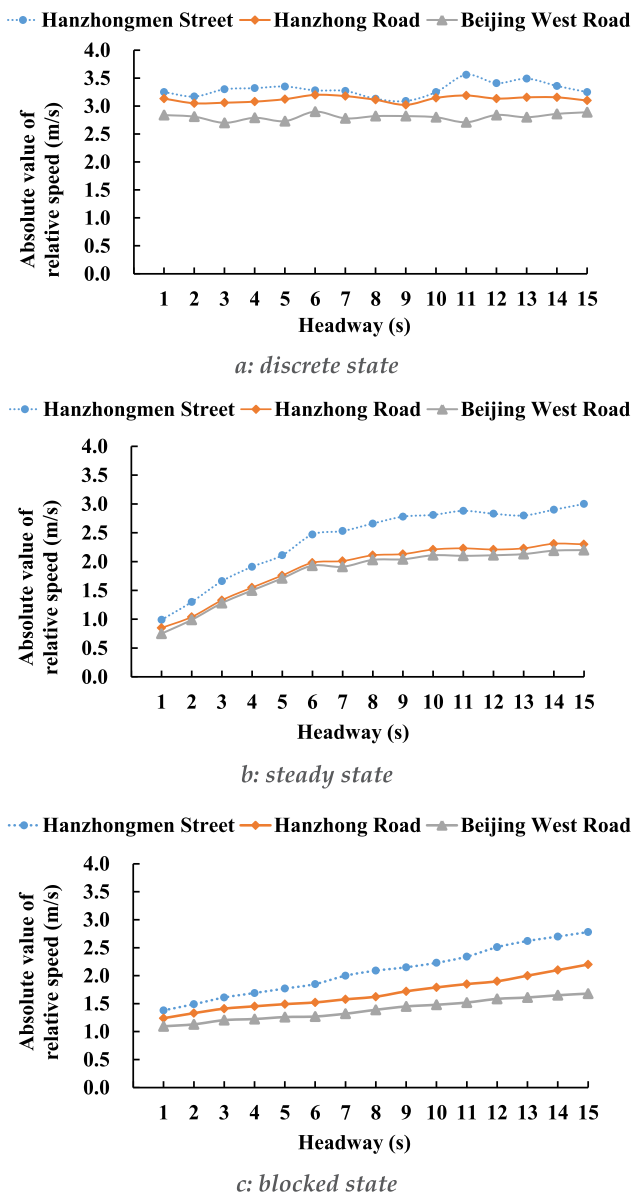

FIGURE 4. Curves of time headway and absolute value of relative speed under three traffic states.

affected only by the signal lights. Some vehicles' speeds are significantly lower than the speed of free flow because the vehicle is affected by the interaction between the vehicles

c) Blocked state. In blocked state, the density increases and the speed decreases. The vehicle is heavily influenced by the vehicle in front. Traffic jams often occur.

The curves between time headway and absolute value of relative speed under different traffic states are shown in Fig. 4. The absolute value of relative speed indicates the average relative speed with corresponding headway. In Fig 4c, for Hanzhongmen Street, the value of the point corresponding to 1s is the arithmetic average of the absolute value of relative speed with all 1s. The values of the other h are calculated the same way. The difference of time between two consecutive vehicles crossing the same section shown on the video recordings is the time headway. Fig. 4 illustrates the following observation:

(*a*) The trend of the curves of time headway and absolute value of relative speed is similar in three sections under the same traffic state.

(*b*) There is almost no trend change in the curves under discrete state and blocked state. Under steady state, the curve shows two trends.

(c) When the time headway is less than 6 s, the absolute value of relative speed is positively correlated with the time headway, and the traffic flow is car-following condition. Absolute value of relative speed fluctuates as time headway increases, and the traffic flow is free flow.

(*d*) Under discrete state, the absolute value of relative speed on Hanzhongmen Street is similar to that on Hanzhong Road due to the same number of lanes. Under steady state, the absolute value of relative speed on Hanzhong Road is similar Beijing West Road due to the same road hierarchy. Under blocked state, the absolute value of relative speed on Hanzhong Road is almost halfway between those on Hanzhongmen Street and Beijing West Road. The main factors leading to this phenomenon may be speed limit and the number of lanes. Finally, traffic flow can be divided into four states: discrete free flow, steady free flow, steady car-following condition, and blocked car-following condition as shown in Table 4.

The explanations of the states are shown below,

a) Random free flow. Random free flow is the same as the discrete state.

TABLE 4. Classification of traffic conditions speed.

Sections	Indicators	Traffic states			
		I [a]	II [b]	III [c]	IV [d]
Hanzhongmen Street	Speed (km/h)	≥21.21	[13.03, 21.21)	[13.03, 21.21)	<13.03
	Headway (s)		h>6	h≤6	
Hanzhong Road	Speed (km/h)	≥21.88	[14.78, 21.88)	[14.78, 21.88)	<14.78
	Headway (s)		h>6	h≤6	
Beijing West Road	Speed (km/h)	≥23.34	[14.82, 23.34)	[14.82, 23.34)	<14.82
	Headway (s)		h>6	h≤6	

[a] I represents Random free flow; [b] II represents Steady free flow; [c] III represents Steady car-following flow; [d] IV represents Block car-following flow.

b) Steady free flow. In steady free flow, the vehicles' speeds are slightly lower than the speed of free flow because the vehicles affected only by the signal lights, not the interaction between the vehicles. The traffic flow is also free flow.

c) Steady car-following flow. In steady car-following flow, the flow rate and speed decrease as the density increases. The vehicle is affected by the vehicle in front.

d) Block car-following flow. Block car-following flow is the same as the blocked state.

IV. IMPROVED MIXED TIME HEADWAY MODEL

A. A MIXED DISTRIBUTION MODEL

The Mixed model is suitable for traffic flow divided into free flow and car-following condition. The establishment of the model includes two steps. First, the time headway distribution models for each traffic state are fitted. Second, all fitting time headway distribution models are combined using distribution coefficient which is confirmed by the proportion of traffic rate under the free flow. The Mixed model is shown in Formula (3).

$$f(t) = \begin{cases} \alpha\lambda \exp\{-\lambda(t-\tau)\}, & t \geq \tau \\ 0, & t < \tau \end{cases} \tag{3}$$

B. IMPROVED MODEL

To improve the feasibility and effectiveness of the model, the new model should suit all types of traffic states, and the distribution coefficients should be determined by using the correlation coefficient which is calculated by using headway and speed.

The traffic state is divided into four classes, thus the improved model can be expressed as Formula (4).

$$f_{mix}(t) = \begin{cases} w_1 f_1(t) + w_2 f_2(t) + (1-w_1-w_2) f_4(t) & \text{if } t < t_{\text{threshold value}} \\ w_3 f_1(t) + w_4 f_3(t) + (1-w_3-w_4) f_4(t) & \text{else} \end{cases} \tag{4}$$

where $f_{mix}(t)$ is the improved Mixed distribution model of time headway; t is time headway, s; $t_{\text{threshold value}}$ classifies free flow and car-following condition using time headway, s; and f_1, f_2, f_3, and f_4 are the single distribution model of time headway under the random free flow, steady car-following, steady free flow, block car-following respectively. w_1 and w_2 are the distribution coefficients under random free flow and steady car-following, when $t < t_{\text{threshod value}}$; w_3 and w_4 are the distribution coefficients under random free flow and steady free flow, when $t \geq t_{\text{threshod value}}$, respectively.

The common single models used fitting time headway distribution including Negative exponential distribution, Log-normal distribution, Erlang distribution, Poisson distribution, Weibull distribution, Shifted exponential distribution, Shifted log-normal distribution, Shifted Erlang, Shifted negative exponential, Shifted lognormal model etc. [14], [15], [38]. Therefore, the above mentioned models are applied to fit for each traffic state. The R^2 is used to test the fitting effect. When R^2 is greater than 0.9, it indicates a perfect fitting effect. When the value of R^2 is closer to 1, better fitting effect is obtained [47]. The model with the best fitting effect under the same traffic state is selected as the single distribution model of time headway under that traffic state.

The correlation coefficients of the improved model are calculated by using time headway and absolute value of relative speed. w_i is calculated by using Formula (5).

$$w_i = \sum_{|\Delta v|=1}^{m} r_{(t,|\Delta v|)} \Big/ \sum_{t=1}^{n} \sum_{|\Delta v|=1}^{m} r_{(t,|\Delta v|)} \tag{5}$$

where $r_{(t,|\Delta v|)}$ is the correlation coefficients between time headway and absolute value of relative speed under a certain traffic state; m is the number of absolute values of relative speed under a certain traffic state; and n is the number of time headway under a certain traffic state.

The correlation coefficient can be calculated using Formula (6).

$$r = \frac{Cov\,(t, |\Delta v|)}{\sqrt{D\,(t) \cdot D\,(|\Delta v|)}} \tag{6}$$

where $D(t)$ and $D(|\Delta v|)$ are the variance of time headway and absolute value of absolute value, respectively; and $Cov(t, |\Delta v|)$ is the covariance of the time headway and absolute value of relative speed.

C. C CASE STUDY

The model with the maximum R^2 under a certain traffic state is selected as the single time headway distribution model under that traffic state, as shown in Tables 5 – 7. In these Tables, the R^2 of each model is greater than 0.9, indicating that the model has a good fitting effect. Therefore, the model illustrated in the Tables can be used to establish the improved model. According to Formulas (3) –(6), the improved time headway distribution models on three roads are shown as

TABLE 5. Information of the improved model of hanzhongmen street.

State	Indicators	Content
I	Model type	Shifted negative exponential model
	R^2	0.92
	Model	$f^1{}_1(t)=0.13\exp[-0.13(t-0.89)]$
II	Model type	Shifted negative exponential model
	R^2	0.98
	Model	$f^1{}_2(t)=0.21\exp[-0.21(t-0.29)]$
III	Model type	Shifted Erlang model
	R^2	0.90
	Model	$f^1{}_3(t)=[0.44^2(t-0.45)/1]\exp[-0.44(t-0.45)]$
IV	Model type	Shifted Erlang model
	R^2	0.92
	Model	$f^1{}_4(t)=[0.52^2(t-0.41)/1]\exp[-0.52(t-0.41)]$

TABLE 6. Information of the improved model of hanzhon road.

State	Indicators	Content
I	Model type	Shifted negative exponential model
	R^2	0.94
	Model	$f^2{}_1(t)=0.28\exp[-0.28\ (t-0.71)]$
II	Model type	Shifted negative exponential model
	R^2	0.96
	Model	$f^2{}_2(t)=0.44\exp[-0.44\ (t-0.04)]$
III	Model type	Shifted Erlang model
	R^2	0.92
	Model	$f^3{}_3(t)=[0.50^2(t-0.64)/1]\exp[-0.50\ (t-0.64)]$
IV	Model type	Shifted Erlang model
	R^2	0.91
	Model	$f^2{}_4(t)=[1.45^3(t-0.53)^2/2]\exp[-1.45(t-0.53)]$

Formulas (7), (8), and (9), respectively.

$$f_{mix} = \begin{cases} 0.232f_1^1(t) + 0.325f_2^1(t) + 0.462f_4^1(t) & \text{if } h < 6s \\ 0.341f_1^1(t) + 0.356f_3^1(t) + 0.303f_4^1(t) & \text{else} \end{cases} \tag{7}$$

$$f_{mix} = \begin{cases} 0.243f_1^2(t) + 0.356f_2^2(t) + 0.401f_4^2(t) & \text{if } h < 6s \\ 0.333f_1^2(t) + 0.345f_3^2(t) + 0.322f_4^2(t) & \text{else} \end{cases} \tag{8}$$

$$f_{mix} = \begin{cases} 0.213f_1^3(t) + 0.325f_2^3(t) + 0.462f_4^3(t) & \text{if } t < 6s \\ 0.323f_1^3(t) + 0.336f_3^3(t) + 0.341f_4^3(t) & \text{else} \end{cases} \tag{9}$$

V. RESULTS AND DISCUSSION

A. VALIDITY

The accuracy of the improved model is verified by comparing the chi-square value, application performance of different models. The compared models include the original model and other classical models. Therefore, the Mixed distribution model, which is the original model of the improved model, and the classical models that are used in the process of establishing the improved model, are utilized for comparative analysis to verify the accuracy of the improved model.

TABLE 7. Information of the improved model of Beijing west road.

State	Indicators	Content
I	Model type	Shifted negative exponential model
	R^2	0.92
	Model	$f^3{}_1(t)=0.23\exp[-0.23(t-0.86)]$
II	Model type	Shifted negative exponential model
	R^2	0.94
	Model	$f^3{}_2(t)=0.32\exp[-0.31(t-1.32)]$
III	Model type	Shifted Erlang model
	R^2	0.91
	Model	$f^2{}_3(t)=[1.24^3(t-0.25)^2/2]\exp[-1.24(t-0.25)]$
IV	Model type	Shifted Erlang model
	R^2	0.90
	Model	$f^3{}_4(t)=[0.84^3(t-0.32)^2/2]\exp[-0.84(t-0.32)]$

1) CHI-SQUARE TEST

Chi-square tests and K-S tests are commonly used to test goodness-of-fit. K-S test is appropriate for continuous variables and Chi-square test is suitable for classified variables. Time headway used in this study is a classified variable. Therefore, Chi-square test was used to verify the improved model.

The χ^2 is the statistic under a hypothesis distribution. C is critical value of χ^2 and can be obtained from Chi-square table. When $\chi^2 < C$, it can be deduced that the statistical samples obey the hypothesis distribution [48]. If χ^2 from several distribution functions is smaller than C, the hypothetic distribution with the smallest χ^2 fits the best. In this study, the value of C is 22.362 with 95% confidence.

Chi-square test results of the distribution models of time headway are summarized in Table 8. Only the improved model passed the Chi-square test for three roads and exhibited the best fitting effect.

TABLE 8. Chi-square test results.

Methods	Sections		
	Hanzhong men Street	Hanzhong Road	Beijing West Road
Improved model	**19.83**[a]	**20.95**	**20.33**
Mixed distribution model	27.35	39.56	48.47
Shifted lognormal	25.01	54.36	48.21
Shifted negative exponential	26.33	31.07	27.83
Shifted Erlang	**22.12**	33.41	25.43
Shifted log-normal distribution	**20.18**	62.36	22.81
Poisson distribution	35.50	61.03	53.54
Weibull distribution	**19.56**	30.28	41.17
Gaussian distribution	60.07	36.34	60.77
Erlang distribution	32.93	58.60	36.55
Lognormal distribution	61.21	63.01	**21.64**
Negative exponential distribution	23.25	**22.27**	26.45

[a] The text in the bold font represent the corresponding statistical samples obey the hypothesis distribution.

2) TRAFFIC RATE TEST

The most common application of the distribution models of time headway is to forecast traffic rate. In this section, the application performance of the improved model is verified by comparing the relative errors between the field data of traffic rate and the calculated value obtained from the improved model and the compared models. The traffic rate can be calculated by using Formula (10).

$$Q_{\text{Calculated traffic rate}} = \sum_{h=1}^{25} \frac{3600}{h} \cdot f\,(t) \qquad (10)$$

where $Q_{\text{Calculatedtrafficrate}}$ is the calculated traffic rate, pcu/h; t is time headway, s; $f\,(t)$ is frequency when the time headway is t.

Relative errors of traffic rate between field data and calculated values are presented in Table 9. Table 9 summarizes that, in three roads, only the relative errors calculated by using the improved model are all smaller than those of other models. Therefore, in terms of application performance, the improved model is the best than the compared models.

B. GENERALITY TEST

In order to testify the generality of the Mixed model, Zhanjiang Road, Zhongshan North Road and Shanghai Road were selected, which are similar to Hanzhongmen Street, Hanzhong Road and Beijing West Road respectively. The attributes of the survey sections are shown in Table 10. The survey period was 6:50 AM – 8:10 AM on November 20, 21, and 27, 2020 without fog and haze. We also collected traffic data on Hanzhongmen Street, Hanzhong Road and Beijing West Road from December 1 to 3, 2020 free of fog and haze in the same period. The traffic rate and speed of all the roads are shown in Table 11.

The time headway frequency distributions of all the roads are shown as Fig 5. The absolute value of the absolute error of time headway frequency between the actual data and the fitted value obtained by the Mixed model is illustrated as Fig 6, respectively.

In Fig 5., "Fitted" is the time headway frequency distribution obtained by the Mixed model; "Actual" is actual distribution obtained by actual data which used to establish the Mixed model; "Same road" is the distribution obtained by actual data of the same road on other day; and "similar road" is the distribution obtained by actual data of similar road.

It can be learned that the trends of the time headway frequency distribution curves between the same road and similar road are similar. The models works best when applied to the same road, followed by the similar roads. The fitting effect is acceptable because the time headway frequency distributions of the similar road and the same road differ little from the time headway frequency distribution obtained by the models.

In Fig 6., "Fitted" is the absolute value of the absolute error of time headway frequency obtained by Mixed model; "same road" is the error obtained by actual data of the same road on other day; and "similar road" is the error obtained by actual data of similar road.

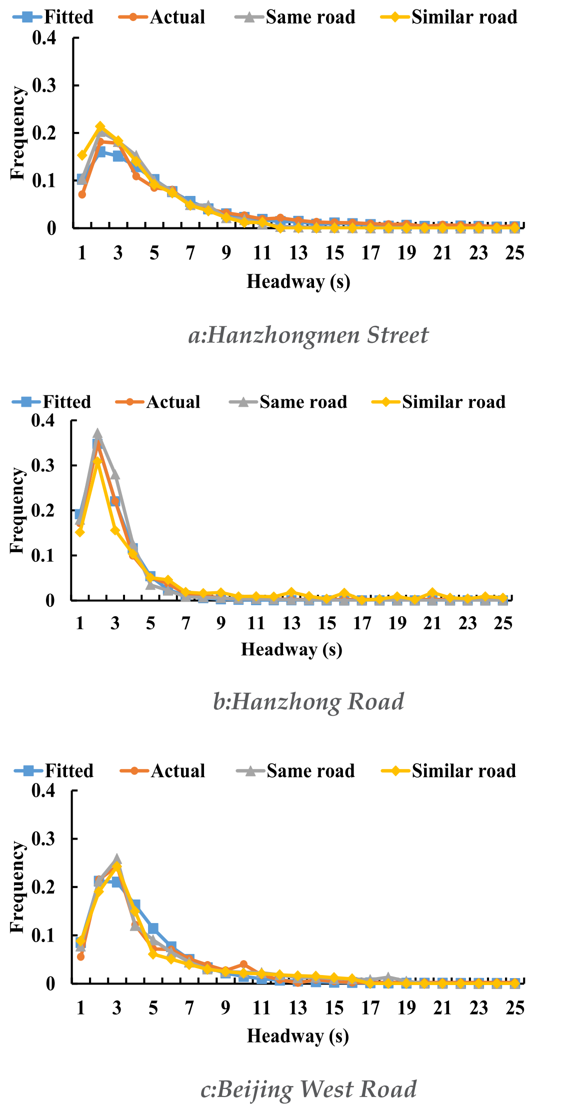

FIGURE 5. **The frequency of time headway obtained by Mixed models and actual data.**

Following conclusions can be drawn from Fig. 6:

The absolute value of the absolute error of time headway frequency of same roads and similar roads increase slightly. In general, the increase of similar roads is greater than the increase of the same roads. The errors are acceptable because none of them exceed 0.07.

Hence, the Mixed models are used for roads with similar attributes and the same roads on different days.

C. ANALYSIS OF INFLUENCING FACTORS

The model used in this paper was improved with reference to traffic state and distribution coefficients. Therefore, the effects of traffic state and distribution coefficients determination method on the improved model about fitting precision are analyzed in this section.

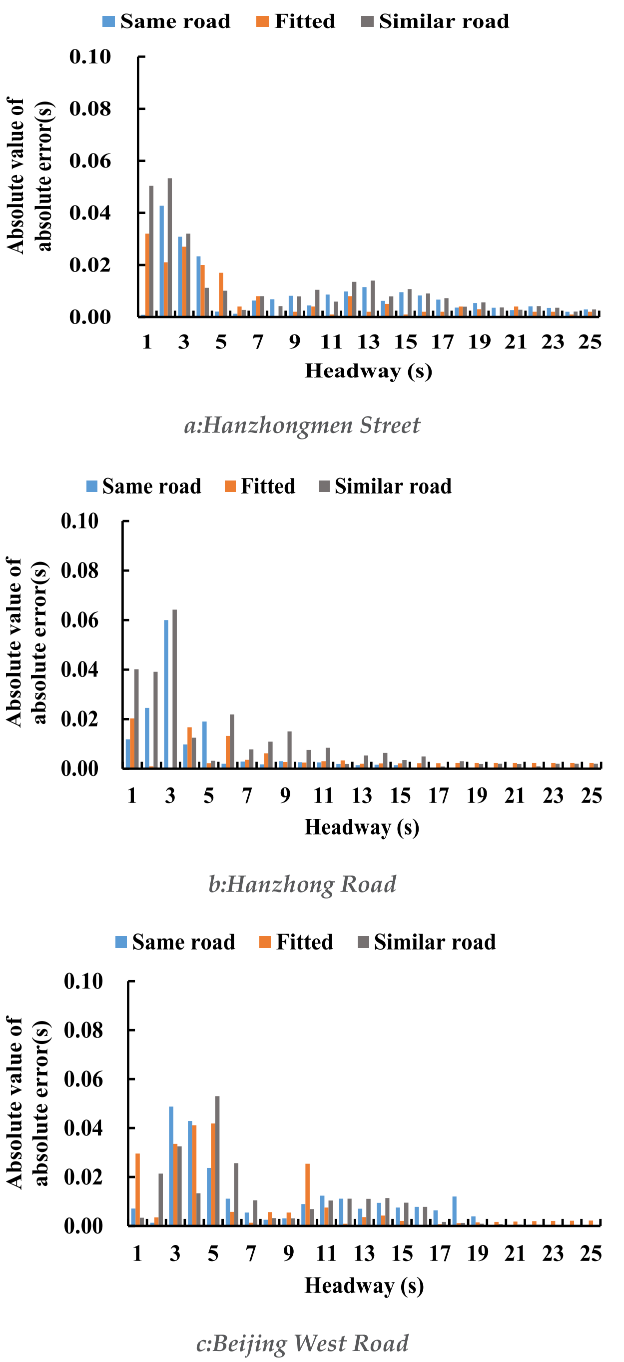

FIGURE 6. The absolute value of absolute error of time headway frequency between actual data and fitted value obtained by Mixed model.

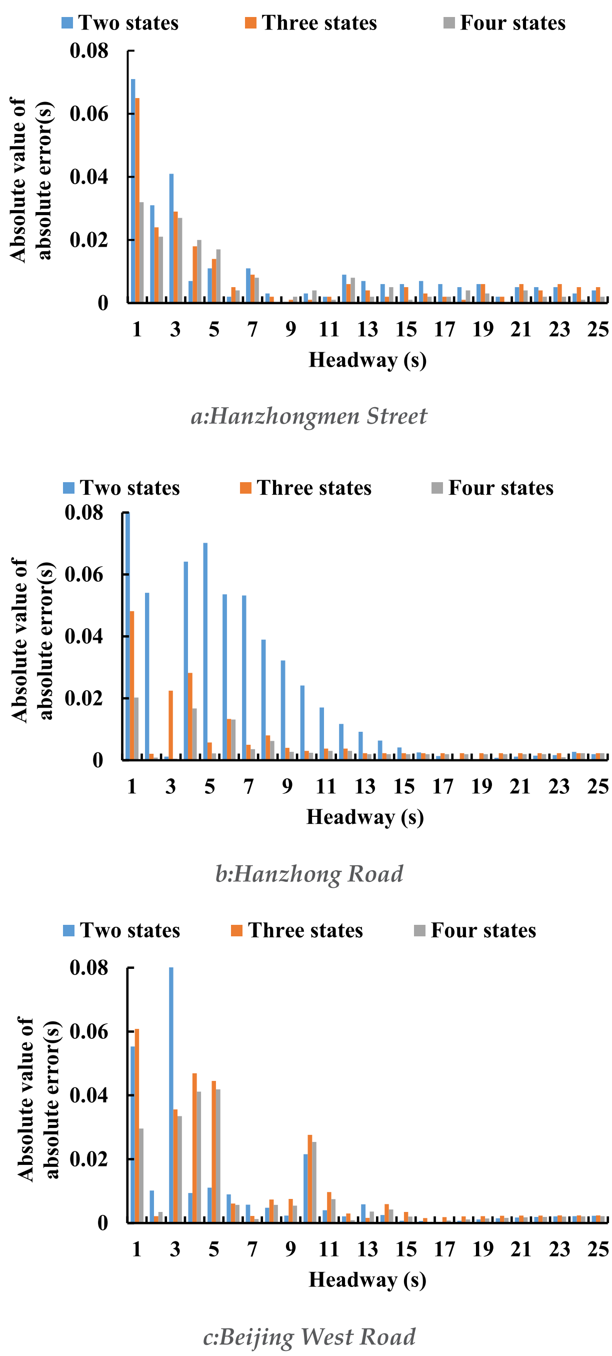

FIGURE 7. Absolute value of absolute errors of the models under different traffic states.

1) EFFECT OF TRAFFIC STATE

The bar graph of absolute value of absolute errors of field data of time headway and fitted value of time headway, which was obtained by the improved models established under two states, three states, and four states are shown in Fig. 7. Following results can be deduced from Fig. 7:

1) For Hanzhongmen Street, the absolute values of absolute error between the field data and the fitted data calculated by using the model under four states are the smallest, except at 4, 5, 6, and 12 s. From 3 s to 6 s, the model under two states performs the best in goodness-of- fit. At 12 s, the best goodness-of-fit of the model is generated under three states. The goodness-of-fit of the models from high to low is produced under four states, two states and three states.

2) For Hanzhong Road, the absolute values of absolute error under four states are almost always the smallest from 1s to 25 s. From 1s to 15 s, the absolute values of absolute error

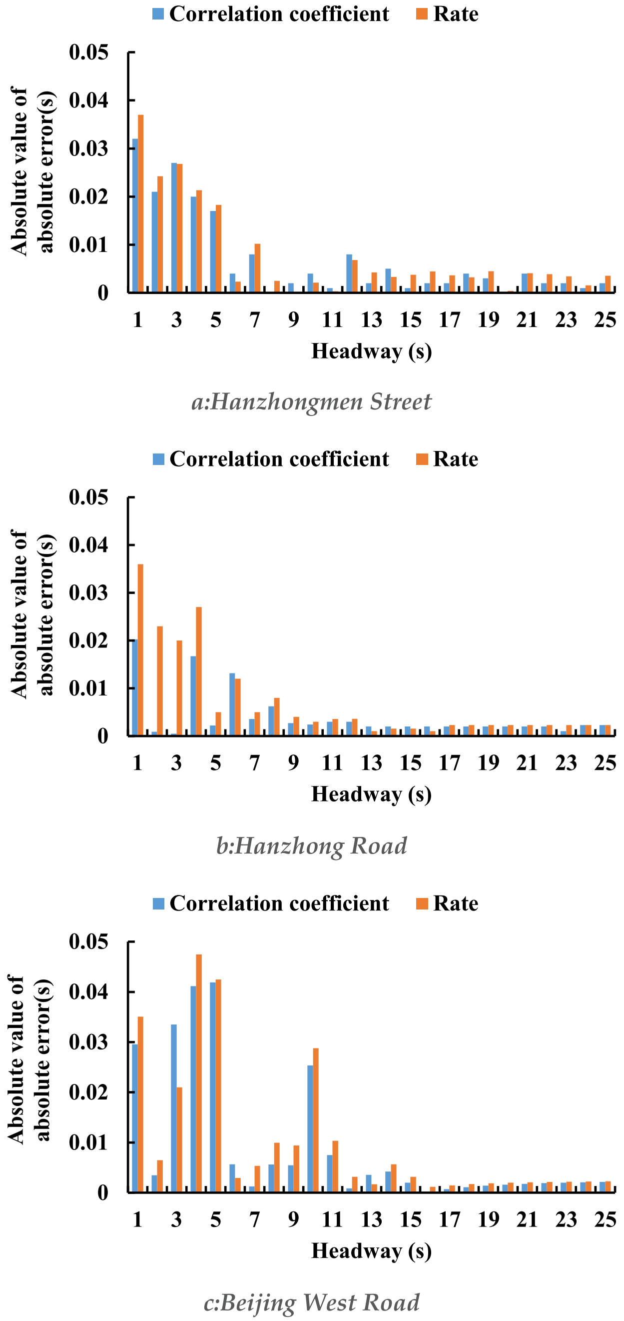

FIGURE 8. Absolute value of absolute errors of model based on correlation coefficient and proportion of traffic rate.

TABLE 9. Relative error of traffic rate between field data and calculated value.

Methods	Indexes	Sections: Hanzhongmen Street	Sections: Hanzhong Road	Sections: Beijing West Road
Improved model	Calculated rate(pcu/h)	1204	1479	1516
	Relative error (%)	**−0.92**	**−4.37**	**−3.69**
Mixed distribution model	Calculated rate(pcu/h)	1050	1065	1075
	Relative Error (%)	11.99	28.24	26.47
Shifted lognormal	Calculated rate(pcu/h)	1158	1045	1130
	Relative Error (%)	2.93	26.25	22.71
Shifted negative exponential	Calculated rate(pcu/h)	1248	1530	1380
	Relative Error (%)	−43.61	−7.97	5.61
Shifted Erlang	Calculated rate(pcu/h)	1219	1572	1312
	Relative Error (%)	−2.18	−10.94	10.26
Shifted log-normal distribution	Calculated rate(pcu/h)	1221	1589	1438
	Relative Error (%)	−2.32	−12.13	8.89
Poisson distribution	Calculated rate(pcu/h)	1007	1311	1219
	Relative Error (%)	15.62	7.49	16.63
Weibull distribution	Calculated rate(pcu/h)	1237	1491	1228
	Relative Error (%)	−3.70	−5.23	15.98
Gaussian distribution	Calculated rate(pcu/h)	1319	1410	1196
	Relative Error (%)	−10.56	11.48	18.21
Erlang distribution	Calculated rate(pcu/h)	1235	1430	1155
Lognormal distribution	Relative Error (%)	−3.50	−4.04	21.01
Negative exponential distribution	Calculated rate(pcu/h)	1046	1259	1207
	Relative Error (%)	12.36	11.14	17.42

between the field data and fitted value calculated by using the model under two states are always the largest. The goodness-of-fit of the models is divided, ranging from high to low, into four states, three states and two states. The models' goodness-of-fit is set up under different states.

3) For Beijing West Road, except at 4, 5, 9, 11, 14, 15, 17, 20, 21, and 24 s, the best goodness-of-fit of the model is established under four states at other time headway. At 4, 5, 9, 11, 14, 15, 17, 20, 21, and 24 s, the absolute values of absolute error under two states are almost the smallest. The performance of the model established under four states is slightly better than that under two states, and much better than that under three states. The reason for small difference of performance of the models set under four states and two states is due to provincial government' stricter traffic control which is located along this road.

Therefore, goodness-of-fit of the model established under four states is the best. When the traffic control is strict, the performance of the model established under two states is much better than that under three states. In other cases, it is difficult, if not impossible to determine which performances of the models established under two states or three-state model is better.

TABLE 10. Attributes of survey sections.

Indexes	Zhanjiang Road	Zhongshan North Road	Shanghai Road
Road hierarchy	Secondary Trunk Road	Arterial Road	Arterial Road
Number of lanes	4	4	6
Lane width (m)	3.75	3.75	3.75
Speed limit (km/h)	40	60	50
Separation facilities	Yes	Yes	Yes

TABLE 11. Traffic rate and speed of survey sections.

Sections	Traffic rate (pcu)				Speed(km/h)		
	S	M	H	Mean	Min	Max	Mean
Hanzhongmen Street	1287	22	75	1385	2.71	52.36	13.47
Hanzhong Road	1176	30	43	1250	2.56	59.83	14.86
Beijing West Road	1442	29	50	1521	2.35	54.12	14.54
Zhanjiang Road	1258	21	74	1353	2.73	48.55	13.49
Zhongshan North Road	1427	37	52	1516	2.49	61.65	14.88
Shanghai Road	1412	28	49	1489	2.41	53.48	14.59

2) EFFECT OF DISTRIBUTION COEFFICIENT

In order to analyze the effect of distribution coefficient methods on the fitting precision of the model, the bar graph of absolute value of absolute errors of field data and fitted value based on correlation coefficient and the proportion of traffic rate were obtained as shown in Fig. 8. Following conclusions can be drawn from Fig. 8:

1) For Hanzhongmen Street, the absolute values of absolute errors between the field data and the fitted data calculated by using the model based on the correlation coefficient are smaller, except at 6, 9, 10, 11, 12, and 14 s.

2) For Hanzhong Road, the absolute values of absolute errors are also smaller, except at 3, 6, and 13 s. From 1 s to 5 s, the performance of the model is far better than that of the model based on the proportion of traffic rate.

3) For Beijing West Road, except at 3, 6 and 13 s, the better performance of the model is established based on the correlation coefficient.

As a result, goodness-of-fit of the model established based on the correlation coefficient is the best.

VI. CONCLUSION

This study proposed an accurate distribution model of time headway for urban roads and analyzed the effect of traffic state and distribution coefficient methods on the model. The Mixed models are used for roads with similar attributes and the same roads on different days. After traffic flow was divided into four states by combing the K-means clustering and the relative speed absolute value method, an improved Mixed distribution mode of time headway under four traffic states based on the correlation coefficient between time headway and absolute value of relative speed was established.

The goodness-of-fit and application performance of the improved Mixed model were validated by Chi-square tests and traffic rate test.

Only the model proposed in this study satisfied Chi-square test compared to the Mixed distribution model, and other classical time headway distribution models. And the relative errors between the field traffic rate and calculated traffic rate obtained by using the improved model were found to be the smallest.

The effect of distribution coefficient methods on the model was analyzed. The goodness-of-fit of the model established under four states was found to be the best. Under strict flow control, the performance of the model set in the two states was much better than that of the model established in the three states. In other cases, it could not be deduced performance of which model built under the two-state or three-state model is better. The correlation coefficient between time headway and absolute value of relative speed is more effective than the method of proportion of traffic rate.

The improved headway distribution model combining the information of both macroscopic traffic flow and microscopic traffic flow provides expressiveness of uncertainties in traffic flows for diversified applications. It may be possible to derive more accurate headway related traffic flow models and algorithms. This study may be beneficial to traffic rate estimation, traffic control and traffic safety.

Due to the limitation of the data acquisition equipment in terms of time precision, the time headways used in this paper are expressed as integers. We will use the time headway with decimals in future researches.

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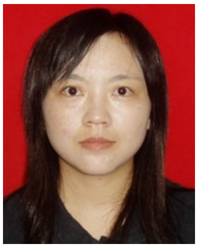
HONGWEI LI received the B.S. degree in traffic information engineering and control from Jilin University, Changchun, China, in 2009, and the Ph.D. degree in transportation engineering from Southeast University, Nanjing, China, in 2014. Since November 2014, she has been working with the College of Civil and Transportation Engineering, Hohai University, China. Her research interests include traffic flow theory and urban traffic management.

YUNYUE ZHOU received the B.S. degree in transportation engineering from Hohai University, Nanjing, China, in 2020. She joined Zhuji Bureau of Traffic and Transportation, Shaoxing, China, in July 2020. Her research interests include traffic flow theory and urban traffic management.

YINGYING XING received the B.S. degree in transportation engineering from Southwest Jiaotong University, Chengdu, China, in 2011, and the Ph.D. degree in civil engineering from Shanghai Jiao Tong University, Shanghai, China, in 2017. She currently holds a postdoctoral position with the College of Transportation Engineering, Tongji University, Shanghai. Her research interests include urban mobilities and urban spatial-temporal travel patterns by using large-scale traffic data.

CHUNQIN ZHANG received the B.S. degree in traffic information engineering and control from Jilin University, Changchun, China, in 2011, and the Ph.D. degree in management science and engineering form Shanghai Jiao Tong University, Shanghai, China, in 2015. She joined the School of Civil Engineering and Architecture, Zhejiang Sci-Tech University, Hangzhou, China, in December 2015. Her research interests include urban traffic management, travel behavior, and transportation economy and policy.



XIAOLI ZHANG received the Ph.D. degree in transportation engineering from Southeast University, Nanjing, China, in 2011. She is currently working with the College of Civil and Transportation Engineering, Hohai University, China. Her research interests include travel behavior dynamics and optimization of connected transportation systems.