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Analyses of unified congestion measures for interrupted traffic flow on urban roads

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Abstract: To study the congestion of interrupted flow on urban roads, a comprehensive evaluation method is proposed. First, based on the results of correlation analysis between different parameters of interrupted flow, the traffic parameters of interrupted traffic flow are divided into two categories: the basic parameters and the operation parameters. Polynomial regression is used to formulize the nonlinear relationships between the basic parameters and the operation parameters. Then, the congestion model incorporating both operational and volume characteristics of traffic flow is proposed. The inputs of the model are the basic parameters, while the output is a dimensionless index value between 0 and 1. Finally, the proposed methods are compared with existing evaluation measures of congestion. Results show that the proposed indices can capture the variation of both the basic parameters and the operation parameters, which is more balanced compared with the existing evaluation measures.

Key words: interrupted flow; correlation analysis; polynomial regression; comprehensive congestion model

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Traffic congestion in China is a serious concern to transportation engineers due to its uncontrolled growth with economic loss, additional delay and air pollution. As the mitigation of traffic congestion is a priority goal of the government, there is an increasing need to have a realistic understanding of traffic congestion and its rational quantification technique.

Traditionally, the growing of traffic congestion was considered as the result of the growth of vehicular traffic volume, shortfall of roadway capacity, etc. Accordingly, congestion mitigation measures have emphasized the reduction of traffic volume and the increase of roadway capacity. Therefore, high-traffic volume and less roadway capacity, etc. are the causes of congestion; delay, additional fuel consumption and increasing traffic density, etc. are the results of congestion[1].

With growing concerns about traffic congestion, efforts are made to reveal the severity of this problem in a quantitative manner. However, it is found that either the operational characteristics (such as speed, delay, travel time, density, etc.) or the volume characteristics (such as traffic volume, volume to capacity ratio, traffic volume per lane, etc.) are used independently and singularly to quantify congestion on urban roads[2-4].

Maitra et al. [5] proposed a balanced measure of congestion combining speed and flow, which embodies the operational characteristic and the volume characteristic, respectively. In this congestion model, congestion is quantified as the area under the speed-flow envelope between the free flow point and the operating point. However, for traffic flow on urban roads, the increase of traffic volume is not the only reason of the reduction of vehicular speed[6-7]. The vehicle stops at an intersection also significantly affects the travel speed of this intersection's adjacent roads. In addition, speed is not the only operational characteristic of traffic flow on urban roads. Delay, queue length, stop rate or other traffic parameters are often used to characterize the degree of congestion. Therefore, it is necessary to make further investigation of the congestion nature of interrupted flow on urban roads.

To further investigate the traffic congestion of interrupted flow on urban roads, field data collection is conducted. Then, the correlation features of traffic parameters are studied, and the traffic parameters of interrupted traffic flow are divided into two categories: the basic parameters and the operation parameters. Through nonlinear fitting of parameters of different categories, a comprehensive evaluation method for the quantification of the congestion of urban roads is presented, and the feasibility of this method is demonstrated.

1 Field Data Collection and Analysis

1.1 Data collection

Using the traffic parameters to study the nature of traffic congestion can be dated back to the 1950s. A series of congestion quantification indicators have been established. These indicators can be classified into three categories: the indicators based on HCM; the indicators based on the queuing theory and the indicators based on

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travel time[8]. The fundamental parameters involved in different categories are different, as shown in Tab. 1. These fundamental parameters are also the most common and critical parameters in congestion analysis [9]. All of these fundamental parameters including v/c, stop rate, delay, travel speed and queue length are selected to be analyzed in this study.

Tab. 1 Fundamental parameters involved in congestion quantification indicators

Category of indicators	v/c	Queue length	Delay	Travel speed	Stop rate
Indicators based on HCM	✓		✓	✓	
Indicators based on queuing theory		✓			✓
Indicators based on travel time			✓	✓	

Note: ✓ represents parameters involved in certain category.

To study the traffic status of urban roads and intersections, field data collection is conducted at the north approach of an intersection located on Jiangdong road in Nanjing. The north approach of this intersection is an eight-lane divided road with four through lanes. The circle length of the signaled intersection is 160 s, and the green time for the through vehicles of the north approach is 60 s. The traffic capacity of the through lanes of the north approach is 1 900 pcu/h. The length of the adjacent north road is 270 m.

A video camera was set up in the field for recording traffic data. A total of 30 h of video tapes were recorded. The recorded video tapes were later reviewed in the laboratory for obtaining traffic data. By reviewing video tapes, over 300 groups of intersection delay, maximum queue length, v/c (volume to capacity ratio), stop rate data of the north approach every 5 min were collected, as well as the travel speed data of the adjacent north road.

1.2 Data analysis

1.2.1 Correlation analysis of parameters

In order to analyze the relationships between different traffic parameters of the interrupted flow, the pairwise correlation analysis is conducted to study the correlation relationship of the collected parameters. The correlation coefficient values R of every two parameters are obtained. The P-value (significant value) of the correlation coefficient is calculated. All these values are shown in Tab. 2. $|R| < 0.3$ means that two parameters are slightly correlated; $0.3 \leqslant |R| < 0.7$ means that two parameters are moderately correlated, and $|R| \geqslant 0.7$ means that two parameters are highly correlated. The value of P illustrates whether R is significant. $P < 0.01$ means that its corresponding R is highly significant; $0.01 < P < 0.05$ means that its corresponding R is significant, and $P \geqslant 0.05$ means that its corresponding R is not significant.

The values of correlation coefficients of different parameter pairs are different. The value of the correlation coefficient between v/c and stop rate is -0.089, which means that v/c and stop rate are slightly correlated. The values of the correlation coefficients of v/c and intersection delay, v/c and travel speed, stop rate and maximum queue length are 0.392, -0.325, 0.506, respectively, which means that they are moderately correlated. The values of other correlation coefficients are greater than 0.7, which means that they are highly correlated.

Most P-values shown in Tab. 2 are 0.00, which means that their corresponding correlation coefficients are highly significant. The P-value of the correlation coefficient of v/c and stop rate is 0.177, which means that it is not significant. So it can be concluded that all the parameters are highly or moderately correlated, except for v/c and stop rate which are not correlated to each other. If v/c changes, stop rate does not change with it, vice versa.

Tab. 2 Results of correlation analysis of interrupted traffic flow

Results of correlation analysis		v/c	Stop rate	Travel speed	Intersection delay	Maximum queue length
v/c	R	1	−0.089	−0.325	0.392	0.802
	P		0.177	0	0	0
Stop rate	R	−0.089	1	−0.766	0.773	0.506
	P	0.177		0	0	0
Travel speed	R	−0.325	−0.766	1	−0.895	−0.739
	P	0	0		0	0
Intersection delay	R	0.392	0.773	−0.895	1	0.804
	P	0	0	0		0
Maximum queue length	R	0.802	0.506	−0.739	0.804	1
	P	0	0	0	0	

Generally speaking, two conclusions can be drawn from the correlation analysis. 1) Travel speed, intersection delay and maximum queue length have similar correlation characteristics. For the three parameters, each of them is significantly correlated to one another, and each of them is highly correlated to v/c or stop rate. 2) v/c and stop rate have similar correlation characteristics. These two parameters are not correlated to each other, but each of them is highly or moderately correlated to travel speed, intersection delay and maximum queue length.

1.2.2 Nonlinear fitting of parameters

It can be concluded from the correlation analysis of parameters that when traffic flow is unsaturated, stop rate has similar correlation characteristics to v/c (which is a typical representation of the volume characteristic). So stop rate and v/c are put together as one category in this study, classified as the basic parameters, which is expressed as x_i. x_1 means v/c, and x_2 means stop rate. Travel speed, intersection delay, and maximum queue length are traditionally classified as the operational characteristics. They have similar characteristics in correlation analysis. These three parameters are put together as the other category in this paper, classified as the operational parameters, which is expressed as y_j. y_1 means travel speed, y_2 means intersection delay, and y_3 means maximum queue length.

Tab. 3 Fitting results of polynomial regression

Method	Fitting result
Two-dimensional polynomial regression	$y_1 = 38.98 - 21.48x_1 + 5.03x_2 + 27.62x_1^2 - 18.20x_2^2 - 66.63x_1x_2 - 29.67x_1^3 + 14.22x_2^3 + 66.06x_1^2x_2 - 6.48x_1x_2^2$, $R^2 = 0.887$
	$y_2 = 6.39 - 5.88x_1 + 72.25x_2 + 40.36x_1^2 - 87.56x_2^2 - 9.73x_1x_2 - 66.61x_1^3 + 60.92x_2^3 + 88.35x_1^2x_2 - 4.7x_1x_2^2$, $R^2 = 0.954$
	$y_3 = 0.14 - 0.35x_1 - 1.12x_2 - 0.50x_1^2 + 1.34x_2^2 + 24.89x_1x_2 + 0.58x_1^3 - 0.38x_2^3 - 0.96x_1^2x_2 - 2.30x_1x_2^2$, $R^2 = 0.999$
One-dimensional polynomial regression	$y_1 = 31.30 - 31.79x_1 + 26.51x_1^2 - 17.45x_1^3$, $R^2 = 0.430$; $y_1 = 33.59 - 14.08x_2 - 29.73x_2^2 + 28.56x_2^3$, $R^2 = 0.415$
	$y_2 = 52.5 - 103.14x_1 + 198.43x_1^2 - 84.64x_1^3$, $R^2 = 0.270$; $y_2 = 15.80 + 7.37x_2 + 74.75x_2^2 - 42.25x_2^3$, $R^2 = 0.630$
	$y_3 = 2.81 + 2.16x_1 + 8.81x_1^2 + 3.44x_1^3$, $R^2 = 0.677$; $y_3 = 2.14 - 8.96x_2 + 46.73x_2^2 - 33.25x_2^3$, $R^2 = 0.313$

To analyze the relationships between the basic parameters and the operational parameters, polynomial regression is introduced in this paper. The nonlinear regression model of SPSS 19.0 is adopted. The results of the one-dimensional polynomial regression and the two-dimensional polynomial regression are shown in Tab. 3.

The two-dimensional polynomial fitting models bring a higher degree of fitting of regression compared with the one-dimensional polynomial fitting models, and the operational parameters change with the variations of both v/c and stop rate. It can be seen from Tab. 3 that the coefficients of determination of the two-dimensional polynomial fitting models are 0.887, 0.941, 0.999, which correspond to travel speed, intersection delay, maximum queue length, respectively. Taking v/c as the independent variable, the coefficients of determination R^2 of the one-dimensional polynomial fitting models are 0.430, 0.270, 0.667, which correspond to travel speed, intersection delay, and maximum queue length, respectively. Taking stop rate as the independent variable, the coefficients of determination R^2 of the one-dimensional polynomial fitting models are 0.415, 0.630, 0.313, which correspond to travel speed, intersection delay, and maximum queue length, respectively.

Setting stop rate as a fixed value, the fitted polynomials of two variables can be regarded as the polynomials of one variable whose operational parameters change with the variation of v/c. These polynomials of one variable can be described as the operational parameters-v/c curves. For different levels of stop rate, there are different operational parameters-v/c curves correspondingly. To verify the validity of the fitting results of the two-dimensional polynomials models, the stop rate is separately fixed at 0.8 and 0.3. The operational parameter-v/c curves of different operational parameters are given in Fig. 1. The scattered points (which represent field data) of different stop rates (0.8 and 0.3) are also shown in Fig. 1. It can be concluded from the comparisons of the curves and the scattered points that all these of the two-dimensional polynomial models fit well with the field data.

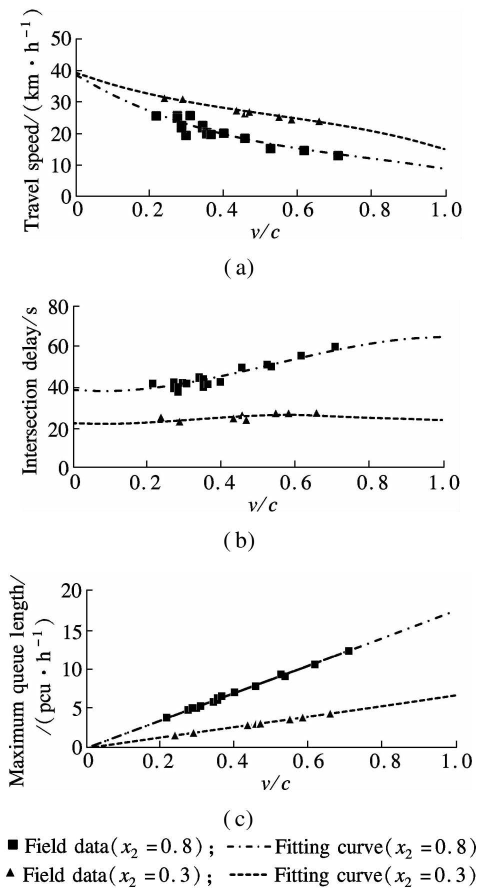

Fig. 1 Comparisons between field data and fitting curves. (a) Travel speed; (b) Intersection delay; (c) Maximum queue length

2 Comprehensive Congestion Models of Interrupted Flow

2.1 Conceptualization

Considering that a comprehensive measure of congestion should embody both operational characteristics and volume characteristics[5], v/c (belongs to volume characteristics) and one operational parameter (belongs to operational characteristics) are put together as the basic unit of congestion analysis. The basic units can be expressed as $Y_j = \{x_1, y_j\}$, $j = 1, 2, 3$. The congestion index corresponding to basic units Y_j is $C_j (j = 1, 2, 3)$. C_1 represents the congestion index based on travel speed, and C_2 represents the congestion index based on intersection delay. C_3 represents the congestion index based on the maximum queue length. Congestion indices can be calculated as

$$C_j = f_j(Y_j) = f_j(x_1, y_j) = f_j[x_1, g_j(x_1, x_2)] \quad (1)$$

where $C_j = f_j(Y_j)$ is the congestion calculation equation; $y_j = g_j(x_1, x_2)$ is the two-dimensional polynomial regression equation, which is derived from the nonlinear fitting of parameters.

When the basic parameters (x_1^t, x_2^t) are obtained from data collection, the corresponding operational parameters can be calculated according to the two-dimensional polynomial regression equation $y_j^t = g_j(x_1^t, x_2^t)$, and the corresponding congestion indices C_1^t, C_2^t, C_3^t can be calculated consequently.

2.2 Modeling congestion

According to the traffic congestion model proposed by Maitra et al. [5], traffic congestion can be expressed as the additional operational burden derived from the increase of v/c. Congestion indices can be obtained by referring to the operational parameter-v/c curves described in section 1.2.2.

Take the index based on travel speed as an example for illustration. Different values of stop rate correspond to different travel speed-v/c curves, as shown in Fig. 2. When the stop rate is 1, the relationship between travel speed and v/c can be described as curve AB. When the stop rate is 0, the relationship between travel speed and v/c can be described as curve DC. When the value of stop rate is smaller than 1 and greater than 0 $(0 < x_2 < 1)$, the relationship between travel speed and v/c can be described as a curve between curve AB and curve DC.

For the obtained basic parameter (x_1^t, x_2^t), according to

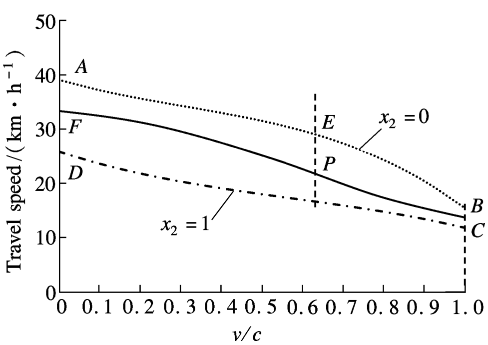

Fig. 2 Travel speed-v/c curves

the stop rate x_2^t, there is a certain travel speed-v/c curve corresponding to it. Suppose that it is the solid curve in Fig. 2. The additional loss of travel speed can be expressed as the area between curve AB and curve FP, and CG_1^t (the congestion index based on travel speed) can be expressed as

$$C_1^t = f_1^t[{}^t_1, g_1(x_1^t, x_2^t)] = \frac{S_{ABCD}}{S_{AFPE}} = \frac{\int_0^{x_1^t}[g_1(x_1, 0) - g_1(x_1, x_2^t)]d_{x_1}}{\int_0^1[g_1(x_1, 0) - g_1(x_1, 1)]d_{x_1}} =$$
$$-0.37x_1^t x_2^t + 1.35x_1^t(x_2^t)^2 - 1.05x_1^t(x_2^t)^3 + 2.47(x_1^t)^2x_2^t - 0.23(x_1^t)^2(x_2^t)^2 - 8.54(x_1^t)^3x_2^t \quad (2)$$

Similarly, C_2^t and C_3^t change with the variations of v/c and stop rate, and then the traffic congestion can be expressed as the increase of intersection delay and maximum queue length.

3 Example Application

In order to demonstrate the feasibility of the comprehensive congestion evaluation method proposed in this paper, comparative analysis between the proposed method and the existing methods for the level of service evaluation is conducted. First, 4 h of field data collection is conducted. 48 groups of data including v/c, stop rate, travel speed, intersection delay and maximum queue length are collected. Secondly, based on the method proposed in this paper, the values of congestion indices C_1, C_2, C_3 of each group of data are calculated. Thirdly, the existing level of service measures based on travel speed (refers to HCM), intersection delay (refers to HCM), and maximum queue length (refers to Ref. [10]), respectively, are calculated. The HCM divides traffic conditions into six levels of service, which are represented by A to F, respectively. In Ref. [10], the traffic conditions are divided into five levels of service, which are represented by 1 to 5, respectively. Finally, the scatter plots of the 48 groups of data are made, as shown in Fig. 3.

It is interesting to note that generally the proposed congestion indices and existing measures show the same trend. Higher levels of service correspond to higher value of congestion indices. While the proposed congestion indices show differences even within the same level of service class.

To further analyze the differences of the congestion indices at the same level of service class, the 11 groups of traffic parameters at the HCM level of service D are selected, as shown in Tab. 4. It can be seen from Tab. 4 that due to the differences in stop rate, data groups with the same v/c correspond to different values of travel speed. Using either v/c (which represents volume characteristic) or travel

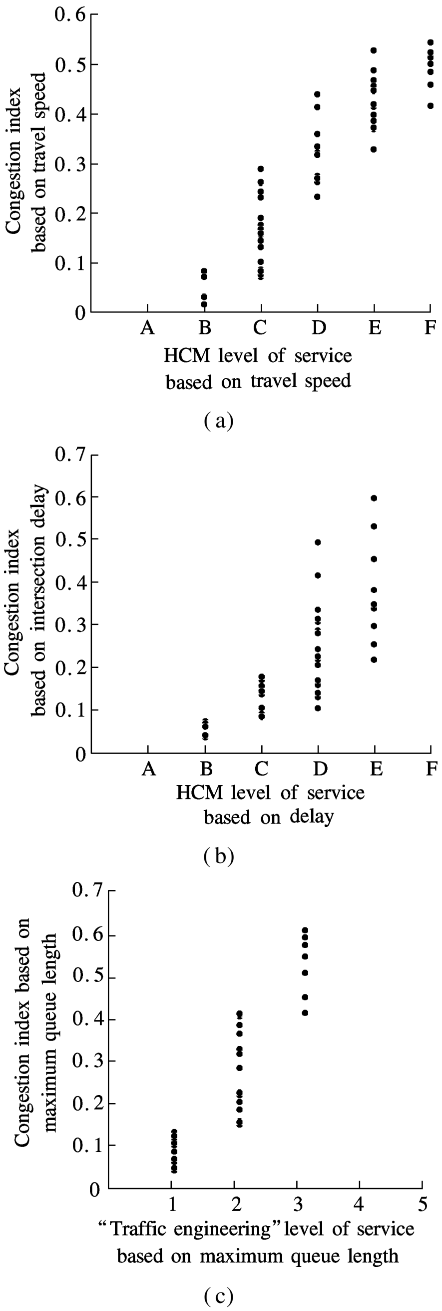

Fig. 3 Scatter plots of proposed methods and existing methods. (a) Congestion evaluation method based on travel speed; (b) Congestion evaluation method based on intersection delay; (c) Congestion evaluation method based on maximum queue length

Tab. 4 Illustration of selected data groups

Group of data	v/c	Stop rate	Travel speed	HCM level of service	Congestion index based on travel speed
1	0.55	0.71	18.3	D	0.32
2	0.55	0.58	17.3	D	0.27
3	0.56	0.55	19.5	D	0.26
4	0.56	0.67	18.4	D	0.32
5	0.57	0.56	17.3	D	0.27
6	0.57	0.48	18.6	D	0.23
7	0.60	0.65	16.6	D	0.33
8	0.65	0.48	18.3	D	0.28
9	0.76	0.67	16.4	D	0.44
10	0.77	0.61	16.8	D	0.41
11	0.77	0.53	16.5	D	0.36

speed (which represents an operational characteristic) cannot capture the real status of the conditions.

Comparing the first two groups of data, they have the same value of v/c, while the travel speed values of these two groups are different. So it is not appropriate to only adopt v/c to represent the status of these two conditions. In this case, the congestion index proposed in this paper can represent the situation in which v/c is low but high stop rate causes low travel speed. The 1st and 8th groups of the data have the same value of travel speed, while the values of v/c are different. So it is not appropriate to only adopt travel speed to represent the status of these two conditions. In this case, the congestion index proposed in this paper can represent the situation in which travel speed is high but high value of v/c decreases the freedom of travelling.

4 Conclusion

The traffic parameters of interrupted flow in China can be divided into different categories. In this paper, the collected parameters can be divided into two categories: the basic parameters and the operational parameters. Every operational parameter can be well fitted by the corresponding two-dimensional polynomial regression model of basic parameters, which means that both v/c and stop rate (not v/c only) are the causes of the traffic status' variations of interrupted flow on urban roads in China.

Based on the two-dimensional polynomial regression model of the operational parameters and basic parameters, the comprehensive congestion measures combining operating characteristics and volume characteristics can be deduced. Example application shows that the congestion evaluation method proposed in this paper has the same trend with the existing methods for level of service evaluation. Higher levels of service correspond to higher values of congestion indices. Moreover, because the proposed indices in this paper combine both volume characteristics and operational characteristics, they can provide a more detailed indication of the congestion status than the existing methods.

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城市道路间断交通流综合拥挤指标分析

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摘要: 为了研究城市道路间断交通流的交通拥堵特性,提出了一种综合评价方法. 首先,采用相关分析的方法研究了调查所得的间断交通流参数之间的关系,并将交通流参数分为基础参数和运行参数 2 类,进而采用多项式回归的方法拟合了运行参数与基础参数的非线性关系. 然后,提出了一个综合考虑运行特性和流量特性的综合拥挤模型,该模型以基础参数为输入,0 ~ 1 之间的无量纲拥挤度值为输出. 最后,通过实例分析,对提出的综合评价方法和现有拥挤评价方法进行了对比. 结果表明,相比现有评价方法,所提出的评价指标能够同时表征运行参数和基础参数的变化对交通拥挤的影响,能够更加均衡地评价交通拥堵.

关键词: 间断流;相关分析;多项式回归;综合拥挤模型

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