Modeling level-of-safety for bus stops in China

Zhirui Ye, Chao Wang, Yongbo Yu, Xiaomeng Shi, and Wei Wang

Abstract

Objective: Safety performance at bus stops is generally evaluated by using historical traffic crash data or traffic conflict data. However, in China, it is quite difficult to obtain such data mainly due to the lack of traffic data management and organizational issues. In light of this, the primary objective of this study is to develop a quantitative approach to evaluate bus stop safety performance.

Methods: The concept of level-of-safety for bus stops is introduced and corresponding models are proposed to quantify safety levels, which consider conflict points, traffic factors, geometric characteristics, traffic signs and markings, pavement conditions, and lighting conditions. Principal component analysis and k-means clustering methods were used to model and quantify safety levels for bus stops.

Results: A case study was conducted to show the applicability of the proposed model with data collected from 46 samples for the 7 most common types of bus stops in China, using 32 of the samples for modeling and 14 samples for illustration. Based on the case study, 6 levels of safety for bus stops were defined. Finally, a linear regression analysis between safety levels and the number of traffic conflicts showed that they had a strong relationship ($R^2$ value of 0.908).

Conclusions: The results indicated that the method was well validated and could be practically used for the analysis and evaluation of bus stop safety in China. The proposed model was relatively easy to implement without the requirement of traffic crash data and/or traffic conflict data. In addition, with the proposed method, it was feasible to evaluate countermeasures to improve bus stop safety (e.g., exclusive bus lanes).

Introduction

Studies have shown that public transportation is a safer form of transport compared to other traffic modes (Chimba et al. 2010). Interest in improving bus safety is not as great as improving safety for other types of vehicles (Cafiso et al. 2013a; Kelvin et al. 2014). Nonetheless, bus safety plays an important role in public transportation services. Wahlberg (2004) studied the characteristics of bus accidents in the Swedish town of Uppsala and found that 26.4% of crashes occurred at bus stops. In China, about 28.2% of total bus crashes in urban areas occurred at bus stops (Nan 2007). These facts indicate that bus stops are the locations with significant safety concerns, and there is a strong demand to have a practical and feasible way of evaluating safety performance of bus stops, especially in China.

Bus safety performance is generally evaluated by using historical traffic crash data or traffic conflict data. Consequently, it involves the following 2 categories of evaluation methods: (1) statistical analysis of traffic crash data and (2) traffic conflict analysis. The first category uses several methods such as descriptive statistics (Zegeer et al. 1994), crash severity (Truong et al. 2011), and regression analysis (Strathman et al. 2010). In recent studies, instead of descriptive statistics, severity indices were used for analysis and ranking the unsafe bus stops (Pulugurtha and Vanapalli 2008). Because absolute counts of crashes may not truly indicate safety problems, crash rates per unit exposure or crash rates based on severity would be more useful (Truong et al. 2011). In addition, several regression analysis methods, mostly dominated by negative binominal and Poisson models (Chimba et al. 2010), have been applied in bus crash modeling. The second category is traffic conflict analysis (van der Horst et al. 2014). It uses the assumption that the number of traffic conflicts is directly related to traffic crash frequency. Compared to crash data analysis, traffic conflict analysis can be carried out within a relatively short period without observing traffic crashes for years. However, the shortcoming of the method is that subjective biases from observer(s) could be introduced into the analysis (Lu et al. 2008).

Although a variety of methods have been developed to evaluate bus stop safety, the random characteristics of traffic crashes may not necessarily reflect the safety performance of a specific bus stop. Brenac and Clabanx (2005) reported that approximately 60% of accidents in which buses were indirectly involved were not considered in the statistical analysis. The random characteristics of crashes may result in significant biases in evaluating bus safety performance (Ma et al. 2010). Most important, traffic crash data around bus stops have not been well monitored and maintained in China. The traffic conflict analysis method is a relatively time-consuming and expensive manual...
process, especially for a project with budget constraints. In addition, there are a variety of bus stop designs that influence safety level. Consequently, it is essential to develop a safety evaluation method that can be practically used in the evaluation of bus stop safety performance. The method should not rely on traffic crash data and/or traffic conflict data but considers site characteristics and traffic situation, including traffic conflict points (Luo and Wen 2007), traffic conditions (Cafiso et al. 2013b; Vasudevan et al. 2007), geometric characteristics (Milton 1998; Shankar et al. 1995), traffic signs and markings (Houten et al. 2001), pavement conditions (Yang 2007), and lighting conditions (Bullough et al. 2013; Kelvin et al. 2014). In light of this, a concept of level-of-safety at bus stops is introduced and a model is developed to quantify safety levels.

The remaining sections of the article are organized as follows. The following 2 sections describe the data collection and methods to validate the proposed methodology. Finally, the findings and conclusions are provided in the last section.

**Data collection**

Based on right-of-way, bus lanes at bus stops can be divided into 3 categories: grade-separated bus lanes, at-grade bus lanes, and shared lanes (KFH Group 2013). In general, the more exclusive—that is, the less interaction that a transit vehicle has with other traffic—the safer bus operation can be achieved. In terms of the form, bus stops can be classified into 2 categories: on-line and off-line. Many public transportation agencies prefer off-line stops to reduce the potential for rear-end collisions between the stopped buses and other vehicles (KFH Group 2013). Moreover, based on the location of the cross section, bus stops can be divided into 2 categories of median and curbside. According to the above classifications, 7 types of bus stop designs are most commonly observed in China.

Type 1: The at-grade bus lanes are separated from motor vehicle lanes by traffic markings. Bus stops are on-line and set on the curbside.

Type 2: There is no exclusive bus lane. Bus stops are on-line and set on the curbside.

Type 3: The at-grade bus lanes are separated from motor vehicle lanes by traffic markings. Bus stops are off-line (bay-style) and set on the curbside.

Type 4: There is no exclusive bus lane. Bus stops are off-line (bay-style) and set on the curbside.

Type 5: The grade-separated bus lanes are separated from motor vehicle lanes by separation strips. Bus stops are on-line and set in the median of the cross section.

Type 6: The at-grade bus lanes are separated from motor vehicle lanes by traffic markings. Bus stops are on-line and set in the median of the cross section.

Type 7: There is no exclusive bus lane. Bus stops are on-line and set on the curbside. Buses pull over to the curbside and occupy bicycle lanes to dwell.

In this study, data were collected at 23 bus stops both in peak and nonpeak periods for these 7 different types of bus stops in China. The duration of data collection for each bus stop include 4 h for peak (2 h for morning peak and 2 h for evening peak) and 4 h for nonpeak. The 23 bus stops (i.e., 46 samples) were separated into 2 parts: the first part included 16 stops (32 samples) and was used for modeling; the second part included 7 stops (14 samples) for illustration. The site and traffic flow characteristics of these bus stops are shown in Table 1.

**Methods**

Many factors can affect bus stop safety, including subjective factors and objective factors. Subjective factors mainly involve human factors (e.g., driving behavior), which are difficult to quantify.
measure and quantify in real-world applications. Consequently, objective factors are taken into account for the modeling of level-of-safety in this study.

**Basic model based on major factors and traffic factors**

Traffic conflict was found to be a leading factor affecting road safety, and the number of conflict points had a positive relationship with the number of crashes (Howard 2001). In light of this, we apply the number of conflict points, type of conflict points, and severity of conflict points to evaluate bus safety at stops. Based on the classification method for traffic conflicts and the method to calculate the number of conflict points for highway intersections (Lu et al. 2008), equations for calculating the number of crashes (Howard 2001). In light of this, safety, and then the number of conflict points had a positive relationship with the number of crashes. Consequently, safety and the number of conflict points have a positive relationship with the number of crashes. In this study, the basic model is developed as follows:

\[
DD_m = \eta_{m} \sum_i NCP_i \times SCP_i, \tag{1}
\]

where \(NCP_i\) is the number of conflict points for type \(i\); \(SCP_i\) represents the severity of conflict points for type \(i\); \(\eta_m\) is the traffic influence coefficient between motor vehicles and is expressed as follows:

\[
\eta_m = 1 + \frac{V}{C}. \tag{2}
\]

Currently, several urban roads in China do not have dedicated lanes for non-motor vehicles. In addition, a number of cyclists do not obey traffic regulations and ride bikes in bus lanes or motor vehicle lanes. In light of this, the basic model for traffic conflict points between motor vehicles and non-motor vehicles includes traffic conflict points, traffic conflict type (\(j = \) stopped, arriving, or departing), and percentage of non-motor vehicle traffic violation time. The degree of danger (\(DD_{m,n}\)) between motor vehicles and non-motor vehicles is determined by the following equation:

\[
DD_{m,n} = \eta_{m,n} \sum_j NCP_j \times SCP_j, \tag{3}
\]

where \(NCP_j\) is the number of conflict points for type \(j\); \(SCP_j\) represents the severity of conflict points for type \(j\); \(\eta_{m,n}\) is the traffic influence coefficient between motor vehicles and non-motor vehicles and can be expressed as follows:

\[
\eta_{m,n} = 1 + NMP_{m,n}, \tag{4}
\]

where \(NMP_{m,n}\) is the percentage of non-motor vehicle traffic violation time.

Similarly, bus passengers also have unsafe behaviors at bus stops, such as waiting in bus lanes or motor vehicle lanes and jay-walking. Thus, the factor of percentage of passenger traffic violation time should be considered. The degree of danger (\(DD_{n,p}\)) between non-motor vehicles and passengers is determined by the following equation:

\[
DD_{n,p} = \eta_{n,p} \sum_k NCP_k \times SCP_k, \tag{5}
\]

where \(k = \) boarding or alighting passengers; \(NCP_k\) is the number of conflict points for type \(k\); \(SCP_k\) represents the severity of conflict points for type \(k\); \(\eta_{n,p}\) is the traffic influence coefficient between non-motor vehicles and passengers and can be shown as follows:

\[
\eta_{n,p} = 1 + PP_{n,p}, \tag{6}
\]

where \(PP_{n,p}\) is the percentage of passenger traffic violation time.

The basic model is developed by linearly combining \(DD_{m,m}\), \(DD_{m,n}\), and \(DD_{n,p}\), which are not equal to 0. It should be noted, in some cases (such as exclusive bus lane and non-motor vehicle lane), that there is no conflict point between motor vehicles and non-motor vehicles or non-motor vehicles and passengers in theory. However, in practice, passengers and cyclists may not obey traffic regulations and perform unsafe behaviors. Hence, the basic model is developed as follows:

\[
DD = \begin{cases} \sigma_{m,m} \times \eta_{m,n} \times \eta_{n,p} \times \sum_i NCP_i \times SCP_i, & DD_{m,m} = 0 \\ \sigma_{m,m} \times DD_{m,n} + \sigma_{m,n} \times DD_{m,n} + \sigma_{n,p} \times DD_{n,p}, & DD_{m,n} = 0 \end{cases} \tag{7}
\]

where \(DD\) represents degree of danger, and \(\sigma_{m,m}, \sigma_{m,n}, \sigma_{n,p}\) are the weights for \(DD_{m,m}, DD_{m,n}\), and \(DD_{n,p}\), respectively.

In this study, expert surveys and focus group discussion methods (Lu et al. 2008) are used to determine the weights and severity of conflict points. In this study, 3 groups of survey participants were involved: (1) transportation engineers and research scholars; (2) traffic managers in the relevant areas; and (3) road users (e.g., passengers and cyclists). From the results of the expert survey and focus group discussion, statistical analysis (analytic hierarchy process) was conducted to obtain the weight and severity of conflict points, as shown in Table 2.

### Adjusted model for level-of-safety

In addition to conflict points and traffic conditions, many research studies have indicated that other adjustment factors

| Category of conflict point | Weight | Type of conflict point | Severity |
|---------------------------|--------|------------------------|----------|
| Conflict points between motor vehicles | 0.30 | Diverging | 1.0 |
| Conflict points between motor vehicles and non-motor vehicles | 0.39 | Merging | 1.5 |
| Conflict points between passengers and non-motor vehicles | 0.31 | Crossing | 2.5 |
| Conflict points between bus stops and non-motor vehicles and boarding/alighting passengers | 0.20 | Stopped buses | 2.0 |
| Conflict points between passengers and non-motor vehicles | 0.35 | Arriving/departing buses | 3.0 |
| Conflict points between motor vehicles | 0.40 | Non-motor vehicles and boarding/alighting passengers | 5.0 |
have impacts on traffic safety performance (Roess et al. 2011). These factors include geometric characteristics, traffic signs and markings, pavement conditions, and lighting conditions. Each adjustment factor consists of several subfactors. Geometric characteristics include vertical slope (the slope with respect to the horizon), sight distance (the length of roadway ahead visible to the road users), lane width (typical lane widths range from 3 to 3.6 m), cross slope (the slope of a roadway perpendicular to the centerline), lane configuration (whether or not the bus lanes are separated from motor vehicle lanes), channelization (involving the form of bus stops; i.e., on-line or off-line), and shoulder width. Traffic signs and markings involve selection (including type, size, shape, and color), installation (including location, height, width, and way of setting signs and markings), visibility (whether or not traffic signs and markings are blocked by an obstacle, such as trees and billboards), message (including amount of information and clarity), and integrity (whether or not signs and markings are damaged or missing). Pavement conditions include pavement roughness (whether or not surface deterioration exists, such as ruts, crocodile cracks, and potholes); pavement friction coefficient (skid resistance); and pavement drainage (whether or not standing water is present). Lighting conditions involve selection (including type, size, and shape), installation (including location, height, and way of installing lights), and brightness and uniformity of illumination.

In order to reduce the dimensionality of the transformed data (i.e., the types of subfactors), a principal component analysis is utilized to identify the significant subfactors. It is mathematically defined as an orthogonal linear transformation that transforms the data to a new coordinate system. The greatest variance by some projection of the data comes to lie on the first coordinate (called the first principal component), the second greatest variance on the second coordinate, and so on (Jolliffe 2002). Due to space limitations, a detailed procedure of the method is furnished in Appendix C (see online supplement). According to the results of principal component analysis, the subfactors for all of the adjustment factors are summarized as geometric characteristics (sight distance, lane configuration, channelization, and road slope); traffic signs and markings (visibility, installation, and message); pavement conditions (skid resistance and pavement roughness); and lighting conditions (installation and condition).

The selected subfactors are included in the adjusted model for level-of-safety through linear combination:

\[
AF_r = 1 + \frac{100 - \sum q \sigma_{rq} S_{rq}}{100},
\]

where \( AF_r \) is the \( r \)th adjustment factor; \( \sigma_{rq} \) represents the weight for the \( q \)th subfactor of \( r \)th adjustment factor; and \( S_{rq} \) is the safety score of the \( q \)th subfactor of \( r \)th adjustment factor and can be obtained by field survey. Due to space limitations, the evaluation criterion and scoring standard are not presented; interested readers may refer to Pan (2008) for more details.

The model for adjustment factors is developed by linearly combining the impacts of these adjustment factors:

\[
AF = \sum_r \psi_r AF_r,
\]

where \( AF \) is the total adjustment factor and \( \psi_r \) is the weight for the \( r \)th adjustment factor.

Practically, most weights for adjustment factors and corresponding subfactors cannot be objectively measured. Field surveys and subjective rating are a feasible way to obtain the weights. Similar to the way of determining the weights for \( DD_{m,n} \), \( DD_{m,n} \), and \( DD_{p,s} \), the weights (\( \psi_r \) and \( \sigma_{rq} \)) are also determined by using expert surveys and focus group discussion methods. The 50 respondents are asked to fill out survey forms and provide a rating of the importance for each adjustment factor and corresponding subfactor. The weights are listed in Table 3.

The adjusted model for level-of-safety at a specific bus stop is given in the following equation:

\[
ADD = DD \times AF,
\]

where \( ADD \) is the adjusted degree of danger. \( ADD \) represents the level-of-safety for bus stops.

**Definition of level-of-safety at bus stops**

In order to define the level-of-safety at bus stops, \( DD \), \( AF \), and \( ADD \) are analyzed by \( k \)-means clustering method. \( k \)-Means clustering is a method of vector quantization and is popular for cluster analysis in data mining. It aims to partition \( n \) observations into \( k \) clusters in which each observation belongs to the cluster with nearest mean, serving as a prototype of the cluster. The number of clusters, \( k \), may be either specified in advance or determined as part of the clustering procedure (Johnson and Wichern 2007).

Given a set of observations \((x_1, x_2, \ldots, x_n)\), where each observation is a \( d \)-dimensional real vector (in this study, \( d \) is equal to 3, namely, \( DD \), \( AF \), and \( ADD \)), \( k \)-means clustering aims to partition the \( n \) observations into \( k \) sets \( S = \{S_1, S_2, \ldots, S_k\} \) to minimize the within-cluster sum of squares. In other words, its objective is to find

\[
\arg\min_S \sum_{i=1}^{k} \sum_{x \in S_i} \|x - \mu_i\|^2,
\]

where \( \mu_i \) is the mean of the sample \( S_i \).

Given an initial set of \( k \) means \( m_1^{(1)}, \ldots, m_k^{(1)} \), the algorithm process is composed of the following 3 steps:

Step 1: Partition the items into \( k \) initial clusters.

**Table 3. Adjustment factors and corresponding weights.**

| Adjustment factor                  | Weight | Subfactor                  | Weight |
|-----------------------------------|--------|----------------------------|--------|
| Geometric characteristics         | 0.30   | Road slope                 | 0.17   |
|                                   |        | Sight distance             | 0.35   |
|                                   |        | Lane configuration          | 0.25   |
|                                   |        | Channelization             | 0.23   |
| Traffic signs and markings        | 0.22   | Sign and marking visibility| 0.42   |
|                                   |        | Sign and marking installation| 0.34  |
|                                   |        | Sign and marking message   | 0.24   |
| Pavement conditions               | 0.23   | Pavement roughness         | 0.44   |
|                                   |        | Skid resistance             | 0.56   |
|                                   |        | Light installation          | 0.60   |
| Lighting conditions               | 0.25   | Light condition             | 0.40   |


Step 2: Proceed through the list of items, assigning an item to the cluster whose centroid (mean) is nearest. Distance is usually computed using the squared Euclidean distance; assign each item to the cluster whose centroid (mean) is nearest. Distance is usually defined as

$$d(x_i, x_j) = \left\| x_i - x_j \right\|^2$$

where each $x_i$ is assigned to exactly one $S^{(t)}$, even if it could be assigned to 2 or more. Recalculate the centroid for the cluster receiving the new item and for the cluster losing the item.

$$m_i^{(t+1)} = \frac{1}{|S_i^{(t)}|} \sum_{x_j \in S_i^{(t)}} x_j > m_i^{(t+1)} = \frac{1}{|S_i^{(t)}|} \sum_{x_j \in S_i^{(t)}} x_j$$

Step 3: Repeat step 2 until no more reassignments take place.

Results

In order to evaluate the performance of this method, it was applied to 7 bus stops both in peak and nonpeak periods (14 samples) for 7 types of bus stops. The calculated results are shown in Table 4. In terms of DD and ADD, the non-peak period had relatively good performance compared to the peak period, especially at bus stops on Shengzhou Road and Zhongshan Road North, with 19.41 and 23.98% reductions, respectively.

According to the results from statistical software, the 14 observations were sorted into 6 clusters in which each observation belonged to the cluster with the nearest mean. Each level was obtained by using the equally spaced value range, based on the ADD value. When the interval length was equal to 12, ADD values within the same cluster fell into the same interval. Consequently, the safety performance of a bus stop could be quantified into 6 levels—A to F. Level A represented the best level of safety and level F represented the worst level: level A = 0 to 12; level B = 12 to 24; level C = 24 to 36; level D = 36 to 48; level E = 48 to 60; and level F = 60 to $\infty$.

In order to validate the proposed model, a linear regression analysis was performed to find the correlation between ADD and the number of traffic conflicts. The $R^2$ value (0.908) showed that they had a strong relationship. In addition, the ADD value and total number of conflicts from the bus stops were converted to level-of-safety (based on grade definition as stated). The results further indicated the model was well validated and could be used in practical applications.
This study proposed a method to quantify bus stop safety in China. The concept of level-of-safety for bus stops was introduced and corresponding models were proposed to quantify safety levels, which considered conflict points, traffic factors, geometric characteristics, traffic signs and markings, pavement conditions, and lighting conditions.

A case study was conducted to show the applicability of the proposed model with data collected from 46 samples for the 7 most common types of bus stops in China, with 32 of the samples used for modeling and 14 samples for illustration. Principal component analysis and k-means clustering were used to model and quantify safety levels for bus stops. Based on the case study, 6 levels of safety for bus stops in China were defined. In order to validate the proposed method, a linear regression analysis was performed to find the correlation between safety levels and the number of traffic conflicts. It showed that they had a strong relationship ($R^2$ value of 0.908). The results indicated that the method was well validated and could be practically used for the analysis and evaluation of bus stop safety.

The proposed model is relatively easy to implement without the requirement of traffic crash data and/or traffic conflict data. In addition, the method can be applied to different types of bus stops. Finally, with the proposed method, it is feasible to evaluate countermeasures to improve bus stop safety (e.g., exclusive bus lanes).

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