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Construction and Simulation of Rear-End Conflicts Recognition Model Based on Improved TTC Algorithm

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ABSTRACT In order to identify the rear-end conflicts in the freeway work zone. The traditional traffic conflict measure time to collision (TTC) can only identify the conflict risk in the situation that the speed of the following vehicle is higher than the leading vehicle. In addition, TTC is not applied to identify the potential conflict in the process of car-following due to the special road section environment of the freeway work zone. To address these limitations, time to collision in the work zone (WTTC) is proposed based on TTC. Considering the influence of the limit speed of the freeway work zone, a rear-end conflicts identification model is built based on WTTC and the deceleration rate threshold value. Then, the correlation coefficient between road risk (RR) and conflict risk (CR) is used to determine the optimal threshold of WTTC. Finally, the one-way closed work zone on Hefei Ring Expressway is selected to evaluate the identify accuracy of WTTC. The results show that compared with TTC, the accuracy of the recognition model has increased by 30% based on WTTC, which can capture more potential rear-end conflicts in the freeway work zone. Therefore, the proposed model can evaluate collision risks in the freeway work zone, and further improve the safety level of the road section.

INDEX TERMS Freeway, rear-end conflicts, surrogate measure, TTC, work zone.

I. INTRODUCTION

The freeway management departments need to carry out various maintenance and construction work on the road regularly for the safe and efficient mobility of traffic in the freeway work zone. As the occupation of road resources by freeway maintenance operations, the number of lanes and the traffic capacity decrease, which leads to traffic congestion. At the same time, the difficulty of driving operations in the work zone is also greatly increased, drivers need to experience complex driving conditions such as vehicle merging, diverging, lane changing, and car following, which will easily cause crashes.

In previous studies (e.g. Wang *et al.* [1], Rouphail *et al.* [2]), vehicle rear-end conflicts are the most common type of traffic conflict in the freeway work zone. It refers to the collision between the leading vehicle's tail and the following vehicle's head, mainly caused by the short distance between the vehicles, poor braking performance of vehicle, and slow reaction of driver *et al*. Since the mutual restraint between the vehicles, when the traffic volume is unsaturated, 50 percent of the vehicles on the freeway work zone is in the car-following state. Compared with the ordinary section, the proportion of vehicles in the car-following state increases significantly, so the risk of rear-end collision is obviously improved (e.g. Khattak *et al.* [3], Li *et al.* [4]). In addition, when the vehicle is in the process of car-following, the driver's view of the following vehicle is obscured, so that the road information in front cannot be obtained in time. As the speed in the freeway is relatively fast, the rear-end collision easily occurred if the vehicle in front suddenly brakes on the section. Therefore, it is necessary to study the rear-end conflicts in the freeway work zone and calibrate the accuracy of the identification model, which is conducive to improving the traffic capacity and ensuring safety in the work zone.

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II. LITERATURE REVIEW

In the previous research, scholars always used historical crashes data that includes crash frequency and severity information to evaluate traffic safety levels (Harb *et al.* [5], Kim *et al.* [6], Meng *et al.* [7], Qi *et al.* [8]). However, the freeway work zone area has the characteristics of short duration, complicated road environment, and the crash events are rare and random. The data collection is difficult and time consuming. The quality and reliability of the collected data are poor. Hence, recent research has focused on the safety analysis method using non-crashes data statistics to evaluate the safety of freeway work zone areas. One of the most promising alternatives is to use traffic conflict technology that quantifies the potential of crash risks. Tian *et al.* [9] proposed a traffic conflict model for freeway work zone based on the hydrodynamic theory, and first applied traffic conflict technology to the freeway work zone activity area. Meng and Weng [10] used the deceleration to avoid the crash (DRAC) and established a rear-end crash risk model at work zone activity area and merging area. Wu *et al.* [11] used the vehicle speed and merging angles as the main characterization parameters of traffic conflict, and employed the surrogate measure time to collision (TTC) to develop the risk calculation model in the merging areas of the freeway work zone. Gao *et al.* [12] used two surrogate safety measures, TTC and DRAC, to study the rear-end conflict in the work zone based on the trajectory data of vehicles. Li *et al.* [13] proposed a relationship model among TTC, vehicle deceleration rate and driver characteristics, and revised a conflict risk threshold for collisions in various regions of freeway based on the driver characteristics. Zheng *et al.* [14] used the conflict rate as the evaluating measure, combining with the extreme value theory, then established the work zone traffic conflict risk measurement model. In the above study, researchers have used various surrogate measures to replace the traditional historical accident data method and carried out research on the safety of the freeway work zone, which all have made effective results.

Traffic conflict technology is one of the surrogate safety methods. Under the observable conditions, that two or more road users are close to each other at the same time and space, if one of them takes abnormal traffic behavior, such as changing direction, changing speed, sudden parking *et al*., unless the other side also takes an emergency measure accordingly, it is prone to the collision between the two vehicles. This phenomenon is called traffic conflict. The selection of traffic conflict measurement indicators is a key problem in the application of traffic conflict technology. The commonly used indicators for traffic conflict identification are TTC, DRAC, and PET (Post-encroachment time) *et al*., which are also called surrogate safety measures (Kuang and Qu [15]). However, these measures are universal and have low recognition accuracy for complex road sections. So Kuang and Qu [15] summarized the shortcomings of existing measures. One of the shortcomings is that when the leading vehicle speed is greater than or equal to the speed of the following vehicle, even if the distance between two vehicles is small, this situation is always considered to have no potential traffic conflict. However, when the vehicle enters the section of the freeway work zone, the speed limit signs will interfere with the vehicles. Then the leading vehicle starts to decelerate following the speed limit value, if the original distance between the two vehicles is short, there is a greater probability of collision. Mostly, these measures are not suitable for this condition. Kuang *et al*. [16] proposed a new surrogate safety measure ACI (Aggregated Crash Index). This index reflects the accommodability of freeway traffic state to a traffic disturbance. The result shows that this new index ACI performs better than traditional crash surrogate measures. It is difficult to calculate ACI as it needs to consider the driver's reaction time and the braking ability of various vehicles. Given this problem, Xie *et al*. [17] proposed a new measure based on the concept of TTC, similar to ACI, impose a disturbance on the leading vehicle and capture the risk of car-following scenarios when the speed of the following vehicle is not higher than the leading vehicle. In their research, the disturbance they applied to the vehicle is random, which causes the leading vehicle to stop. But it is very dangerous to park on the freeway, this situation should be avoided. At the same time, the disturbance from the work zone is speed limit signs rather than random. As an important part of urban traffic safety research, Traffic conflicts generally include conflicts between vehicles in the same direction and in different directions. Traffic signals [18] are often used to resolve conflicts between traffic flows in different directions. For collisions of vehicles in the same direction, TTC is usually used to describe the risk of collision. Therefore, the purpose of this study is to propose an alternative measure that is more suitable for the identification of rear-end conflicts in the freeway work zone. This measure is improved based on the TTC algorithm, considering the impact of speed limit value on the vehicles in the freeway work zone. On the one hand, the measure can improve the shortcomings of traditional measures, on the other hand, it can consider the special environment of the work zone. And we obtained the measured time to collision in the work zone (WTTC) which is able to identify the potential conflict and evaluate the road risks more accurately in the freeway work zone.

III. METHODOLOGY

A. TIME TO COLLISION

Time to collision (TTC) is one of the most widely used surrogate safety measures for the purposes of traffic and vehicle safety. TTC is defined as the time remaining to avoid an accident, from the time the driver takes an action to the point where the accident occurs (Hyden and Linderholm [19]). It responds sensitively according to changes in the current position and speed, and it is possible to predict whether a collision occurs at a specific point in time when the speed and direction of a subject vehicle do not change. TTC can be calculated only when the following vehicle is faster than a leading vehicle. Nevertheless, TTC is the most frequently used surrogate safety measure because it is easy for users to understand. Mathematically, it is given by:

$$TTC_i = \frac{X_{i-1}(t) - X_i(t) - l_{i-1}}{\dot{X}_i(t) - \dot{X}_{i-1}(t)} \quad \dot{X}_i(t) > \dot{X}_{i-1}(t) \tag{1}$$

where $X_i(t)$ is the initial vehicle position of the following vehicle, $X_{i-1}(t)$ is the initial vehicle position of the leading vehicle, l_{i-1} is the length of the leading vehicle, $\dot{X}_i(t)$ is the initial speed of the following vehicle, $\dot{X}_{i-1}(t)$ is the initial speed of the leading vehicle.

Since the observation vehicles are in motion, the distance between the two vehicles is difficult to measure. Therefore, the headway is generally used to calculate the time to collision [10] and the corresponding transformation of Eq. (1) is carried out, which can be denoted as:

$$TTC_i = \frac{\dot{X}_i(t) \cdot H - l_{i-1}}{\dot{X}_i(t) - \dot{X}_{i-1}(t)}, \quad \dot{X}_i(t) > \dot{X}_{i-1}(t) \tag{2}$$

where H is the headway between two vehicles.

B. TIME TO COLLISION IN THE WORK ZONE

Traditional surrogate safety measure TTC is only employed under the conditions that the leading vehicle is slower than the following vehicle, and the distance between the two vehicles is short. However, if there is a disturbance from the freeway work zone to the leading vehicle when the speed of the leading vehicle is slightly larger than that of the following vehicle, but two vehicles are very closed, the potential conflict risk could not be recognized. Considering the interference of the speed limit measures in the work zone area, this study proposes a new measure WTTC based on TTC. WTTC could capture the risks of the rear-end conflicts even the following vehicle speed is less than leading vehicle speed. Assume the scenario that the vehicle enters the speed limit section of the freeway work zone area at t_0 moment, if the driving speed of the leading vehicle is greater than the speed limit value, a certain braking speed is required to decelerate. At this time, if the following vehicle keeps initial speed and continues to move, there is a certain risk of conflict between two vehicles. The duration from the start of the deceleration of the leading vehicle to the collision is defined as WTTC. Since the warning zone and the upstream transition zone of the operation section are the areas with a high risk of rear-end collision (Meng *et al*. [20]), this study put them as the main research objects. Figure 1 illustrates the rear-end collision caused by vehicle motion during the deceleration of the leading vehicle. The relationship between the two vehicles is described by Eq. (3).

$$D_0 + D_1 = D_2 + l_1 \tag{3}$$

where t_0 is the moment when the leading car enters the speed limit section of the work zone area and starts braking, D_0 is the distance between the leading vehicle and following vehicle at time step t_0, D_1 is the distance traveled from the moment of t_0 to the time of collision, D_2 is the distance

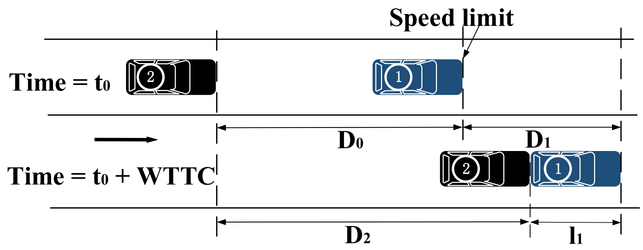


FIGURE 1. Rear-end collision.

traveled from the moment of t_0 to the time of collision, l_1 is the length of the leading vehicle.

Depend on the motion state of the leading vehicle, there are two possible types of rear-end collision. The first collision type is when the rear-end collision occurs, the leading car speed is higher than the speed limit value. The second collision type is when the rear-end collision occurs, the leading has reached the speed limit value. To investigate whether the speed of leading vehicle runs at speed limit value when the collision occurs. We calculated the deceleration rate of the leading vehicle at the point the collision happened just after the leading vehicle speed had reduced to the speed limit value. In this case, the distance traveled by the leading vehicle is given by Eq. (4).

$$D_1 = \frac{v_1^2 - v_s^2}{2A} \tag{4}$$

The time it took for the leading vehicle to decelerate to the speed limit value is given by Eq. (5).

$$T_1 = \frac{v_1 - v_s}{A} \tag{5}$$

The distance traveled by the following vehicle during the braking time of leading vehicle is given by Eq. (6).

$$D_2 = v_2 T_1 = v_2 \frac{v_1 - v_s}{A} \tag{6}$$

where v_1 is the initial speed of the leading vehicle at time t_0, v_s is the speed limit value of the work zone area, A is the deceleration rate of the leading vehicle that causes the collision to occur exactly when the leading vehicle speed equals to the speed limit value, v_2 is the initial speed of the following vehicle at time t_0.

Substituting Eqs. (4)-(6) into Eq. (3), we can get:

$$A = \frac{2v_2(v_1 - v_s) - v_1^2 + v_s^2}{2(D_0 - l_1)} \tag{7}$$

Based on the critical value of the deceleration rate of the leading vehicle, the rear-end collision outcomes can be divided into the following two types:

$$\text{Collision outcome 1: } a_1 \leq A = \frac{2v_2(v_1 - v_s) - v_1^2 + v_s^2}{2(D_0 - l_1)}$$

Collision outcome 1 represents the scenario when the following vehicle collides with its leading vehicle, the speed of the leading vehicle has not decelerated to the speed limit value. The distances traveled by the leading vehicle and the following vehicle in this scenario are given by Eqs. (8) and (9):

$$D_1 = v_1 t_1 - \frac{1}{2} a_1 t_1^2 \tag{8}$$

$$D_2 = v_2 t_1 \tag{9}$$

where t_1 is the time of collision in the work zone, a_1 is the deceleration rate of the leading vehicle.

By substituting Eqs. (8) and (9) into Eq. (3), we can get:

$$WTTC = \frac{\sqrt{2a_1(D_0 - l_1) + (v_2 - v_1)^2} - (v_2 - v_1)}{a_1}$$

Collision outcome 2: $a_1 > A$

$$= \frac{2v_2(v_1 - v_s) - v_1^2 + v_s^2}{2(D_0 - l_1)} \tag{10}$$

Collision outcome 2 represents the scenario when the following vehicle collides with its leading vehicle, the speed of the leading vehicle has decelerated to the speed limit value. The distances traveled by the leading vehicle and the following vehicle in this scenario are given by Eqs. (11) and (12):

$$D_1 = \frac{v_1^2 - v_s^2}{2a_1} + (t_1 - \frac{v_1 - v_s}{a_1})v_s \tag{11}$$

$$D_2 = v_2 t_1 \tag{12}$$

By substituting Eqs. (11) and (12) into Eq. (3), we can get:

$$WTTC = \frac{(v_1 - v_s)^2 + 2a_1(D_0 - l_1)}{2a_1(v_2 - v_s)} \tag{13}$$

Eq. (14) summarizes the calculation results of WTTC for the two above scenarios:

$$WTTC = \begin{cases} \dfrac{\sqrt{2a_1(D_0 - l_1) + (v_2 - v_1)^2} - (v_2 - v_1)}{a_1}, \\ \quad a_1 \leqslant \dfrac{2v_2(v_1 - v_s) - v_1^2 + v_s^2}{2(D_0 - l_1)} \\ \dfrac{(v_1 - v_s)^2 + 2a_1(D_0 - l_1)}{2a_1(v_2 - v_s)}, \\ \quad a_1 > \dfrac{2v_2(v_1 - v_s) - v_1^2 + v_s^2}{2(D_0 - l_1)} \end{cases} \tag{14}$$

IV. THRESHOLD DETERMINATION

A. DATA COLLECTION

To evaluate the WTTC, a large amount of experimental data is required to collect, including accurate data such as vehicle position, vehicle speed, and crashes counts. Therefore, the high-definition camera and manual record method were combined to collect the data of the rear-end collision in the Hefei Ring Freeway work zone. Heifei Ring Freeway took a one-way closed construction method at the 31km from Nanjing to Hefei. According to Safety Work Rules for Highway Maintenance (JTG H30-2015), the layout of the maintenance work area is divided into warning zone, upstream transition zone, buffer zone, work zone, and downstream transition zone [21], as shown in Figure 2. The road section is a two-way 8-lane asphalt concrete expressway with a designed speed of 120km/h, a lane width of 3.75m, a speed limit of 80km/h in the maintenance work area, and traffic management measures such as warning signs and speed limit signs are set.

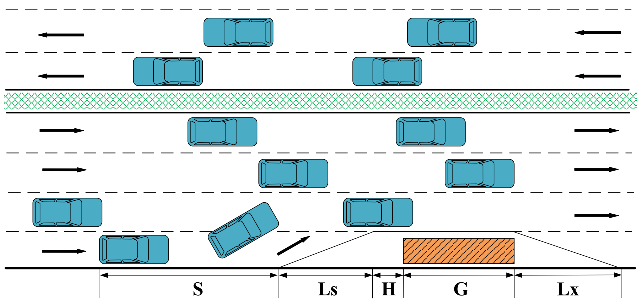


FIGURE 2. Hefei ring expressway one-way closed work zone.

The data was collected during daylight hours, and in similar weather conditions, it was sunny. It contains basic traffic parameters such as traffic volume, vehicle type, and vehicle speed. Besides, the parameters of the headway, conflict distance, the initial speed of conflict vehicles, and the severity of collision are also obtained. The data acquisition equipment includes a high-definition camera, WM-JD2.0 handheld multi-functional traffic survey instrument and WM-LDS 3.0 portable laser survey system, as shown in Figure 3. To ensure the quality and reliability of the collected data, professional video editing tools were also used to analyze the transport live video.

FIGURE 3. Data acquisition equipment WM-LDS3.0 portable laser survey system.

B. CALIBRATION OF MODEL PARAMETERS

1) v_1, v_2 AND D_0

v_1 and v_2 are the traffic speed of the leading vehicle and following vehicle passing through the collection point recorded by the traffic survey. D_0 is the distance from the leading

TABLE 1. Optimal threshold.

Measure	Threshold	Pearson's correlation coefficient	P-value
WTTC	2s	0.45	0.00002
TTC	2.3s	0.42	0.00000

vehicle to the following vehicle calculated by the headway, which recorded by the traffic survey.

2) l_1

l_1 is the length of the leading vehicle. This paper only studies the rear-end collision between cars, which selected is 4.75m.

3) v_S

In this study, the speed limit value of the Hefei Ring expressway selected is 80km/h.

4) a_1

Due to the speed limit of the maintenance work area, there is a random deceleration rate in the leading vehicle. We assumed that the deceleration rate of the leading vehicle follows a shifted gamma distribution (17.315, 0.127, 0.657), which is calibrated by Kuang *et al.* [16] by analyzing the normal deceleration rate taken due to the lane-changing maneuver on freeways using the Next Generation Simulation (NGSIM) data (FHWA 2005).

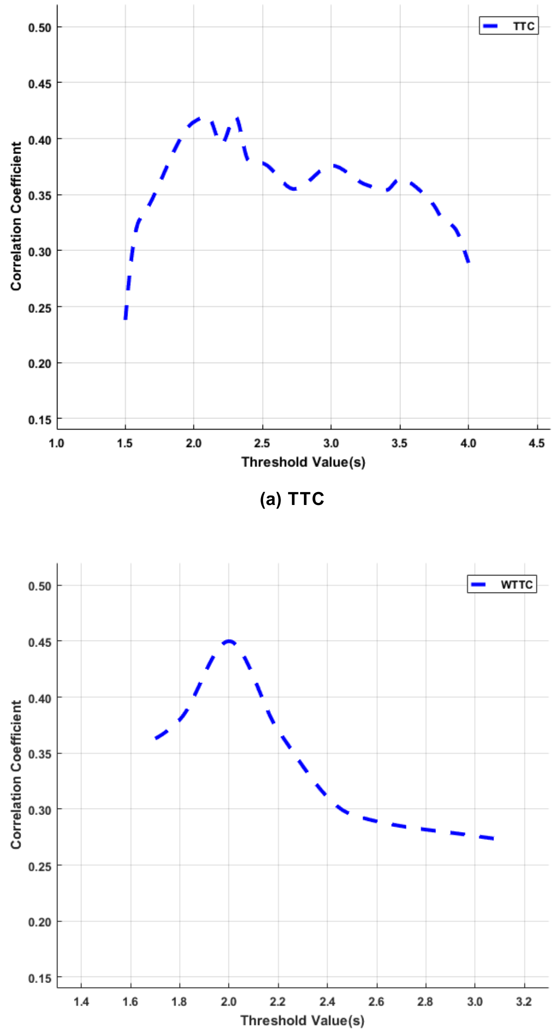
C. DETERMINATION OF CONFLICT THRESHOLD

Similar to the approach of identifying conflict with TTC, it is necessary to determine the appropriate threshold of the WTTC to better identify the rear-end collision in the freeway work zone. When the WTTC is lower than the threshold, a serious conflict between the vehicle pairs is occurred, which means collision. According to the Eq. (14), WTTC is related to the speed and relative distance of the two vehicles, the deceleration rate of the leading vehicle and the speed limit value in the work zone. In this case, car-following scenarios with the initial speed of the following vehicle less than or equal to the initial speed of the leading vehicle could still yield risks rather than always regarded as safe by measures TTC. To better define the optimal threshold of WTTC, this study calculated the Road Risk (RR) and Conflict Risk (CR) in the freeway work zone [17]. It is worth to mention that RR and CR are continuous variables, ranging from 0 to 1, and thus has better flexibility to quantify road risks.

The Road Risk is defined in Eq. (15).

$$RR = \frac{CollisionCounts/ObservationHours}{HourVolume} \tag{15}$$

where *CollisionCounts* is the number of collisions in observation hours, *ObservationHours* is the number of investigated hours, *HourVolume* is the traffic volume (vehicles/h) in observation hours.



(a) TTC

(b) WTTC

FIGURE 4. Correlation coefficient using different threshold values.

The Conflict Risk is defined in Eq. (16).

$$CR = \frac{N(WTTC < wttc)}{N} \tag{16}$$

where N is the number of conflict samples collected within hours, *wttc* is the threshold value of WTTC.

For each possible threshold value of TTC and WTTC, the Pearson Correlation Coefficient (Pearson [22]) was tested between Road Risk and Conflict Risk, as shown in Figure 4. The Pearson correlation coefficient is a measure of the linear dependence between two random variables, which is the most widely used measure of relationship. This coefficient is calculated utilizing the following Eq. (17).

$$r_{xy} = \frac{\sum (x_i - \bar{x}) \sum (y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2} \sqrt{\sum (y_i - \bar{y})^2}} \tag{17}$$

TABLE 2. Crash counts and conflict counts.

Number	Time interval (min)	Speed limit value 80km/h			Speed limit value 60km/h		
		Crash counts	Conflict counts		Crash counts	Conflict counts	
			WTTC	TTC		WTTC	TTC
1	60	15	13	7	6	4	1
2	60	10	9	4	12	10	6
3	60	8	4	2	27	22	17
4	60	2	1	0	29	25	21
5	60	1	0	0	25	20	12
6	60	1	0	0	13	15	8
7	60	4	1	1	20	17	14
8	60	7	6	4	5	4	2
9	60	3	1	0	3	1	0
10	60	2	1	0	2	1	0
11	60	16	8	6	9	9	5
12	60	5	5	3	11	8	2

where $\bar{x} = \frac{1}{n}\sum_{i=1}^{N} x_i$ denotes the mean of x, $\bar{y} = \frac{1}{n}\sum_{i=1}^{N} y_i$ denotes the mean of y. The coefficient ranges from -1 to 1.

When the correlation coefficient $0.4 \leqslant r < 0.7$, there is a significant linear correlation between RR and CR. Looking at each subplot separately, the optimal thresholds to achieve the highest correlation coefficients are 2.3s for TTC and 2s for WTTC. This threshold of TTC is consistent with previous results obtained by Li *et al.* [13]. It proves the validity of using this method. When choosing the optimal threshold of WTTC and TTC, the p-value of the Pearson's correlation coefficient was calculated. As shown in Table 1, all p-values are less than 0.05, which indicates a statistically significant correlation between the road risk calculated by actual statistical crashes data and the road risk calculated by conflict identification measures. It is found that when the WTTC threshold is 2s, the highest correlation coefficient between road risk and conflict risk is 0.45.

V. VALIDATION

To better verify the effectiveness of the rear-end conflicts identification model using WTTC, 12 sets of valid observation fragments (the statistical interval of each fragment is 60 minutes, and a total observation time is 12 hours) were selected to evaluate the accuracy of the WTTC rear-end conflicts identification model. The specific data is reported in Table 2.

Combine the number of crash counts observed with the conflict counts identified by the WTTC model, the accuracy and relative error was computed, as shown in Figure 5.

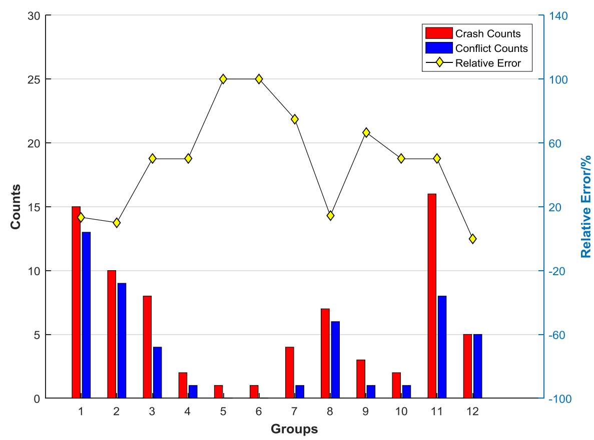


FIGURE 5. Validation of WTTC model.

The approximation degree between the actual value and identify value was obtained based on the Root Mean Square Error (RMSE) test and Mean Error(ME) test (Meng and Weng [10], Benekohal [23], Bham and Benekohal [24]).

The RMSE and ME are described as follows:

$$RMSE(X, h) = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(h(x_i) - y_i)^2} \tag{18}$$

$$ME(X, h) = \frac{1}{m}\sum_{i=1}^{m}(h(x_i) - y_i) \tag{19}$$

TABLE 3. Comparison of error tests.

Speed limit	Measure	Accuracy	RMSE (%)	ME (%)
80km/h	TTC	24.28%	4.8045	-3.9167
	WTTC	51.73%	2.9296	-2.0833
60km/h	TTC	41.28%	6.9162	-6.1667
	WTTC	77.84%	2.9155	-2.1667

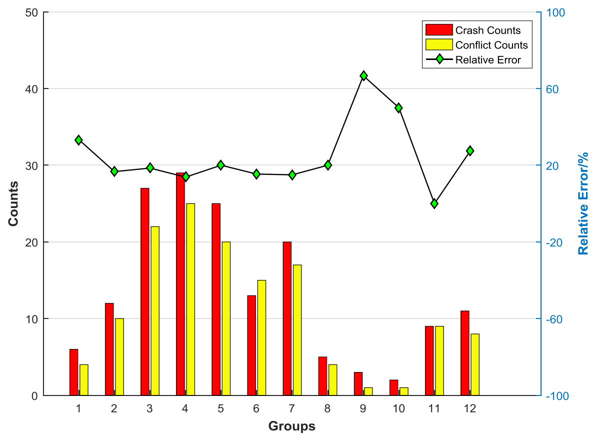


FIGURE 6. Validation of WTTC model with different limit speed.

where m represents the number of observation groups, $h(x_i)$ represents the conflict counts based on the WTTC or TTC, y_i represents the crash counts observed.

Table 3 shows the accuracy rate of the rear-end conflicts identification model based on WTTC is 51.73%, which is clearly higher than the accuracy rate of TTC by 24.28%. Besides, the results of the error tests on each group data are aggregated in Table 3. As can be seen in the table, both models have low identification counts. Relatively speaking, the RMSE of the WTTC model is less than TTC, which suggests that its identification results are closer to the actual values.

In the rear-end conflicts identification model using WTTC, the influence of the speed limit value of the freeway work zone on the vehicle was mainly considered. Therefore, we continued to use the micro-traffic simulation tool VISSIM (Cunto and Saccomanno [25], Huang *et al.* [26], Wang and Stamatiadis [27]) to simulate the traffic of investigated section on the Hefei Ring Expressway. To observe the impact of various speed limit values on rear-end collision in the freeway work zone, we integrated the collected data, set the traffic parameters related to the road section, and adjusted the speed limit value of the road section to 60km/h. In the VISSIM model, 12 sets of valid observation samples were also obtained, and the identification conflict counts of WTTC and TTC were calculated. The results are shown in Table 2.

Combine the number of crash counts observed with the conflict counts identified by the WTTC model, the accuracy

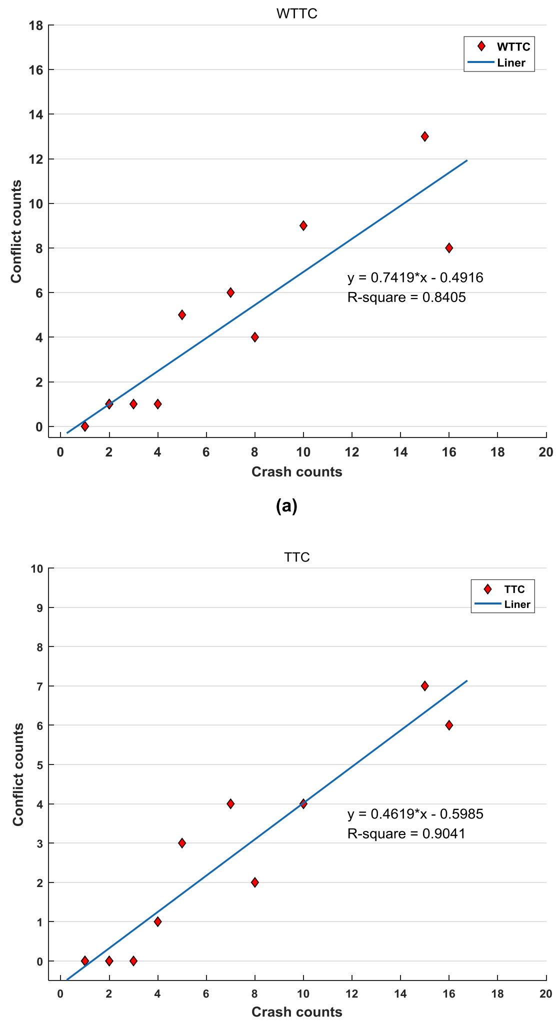


FIGURE 7. The relationship between crash data and identification counts.

and relative error was computed, as shown in Figure 6. The approximation degree between the actual value and identification value was obtained based on the Root Mean Square Error (RMSE) test and Mean Error (ME) test.

As shown in Table 3, when the speed limit value is 60km/h, the accuracy rate of the rear-end conflicts identification model is 77.84%, and the accuracy rate of TTC is 41.28%. The WTTC model has a smaller RMSE value and closer to the crash counts, which is consistent with the conclusions above.

The validation of the rear-end conflicts model based on WTTC has been further studied in this paper. Figure 7 shows the linear relationships between crash counts and conflict counts represented by WWTC and TTC. The R-square value is the determinant coefficient, which means how well the conflict counts fit the crash counts in a linear model. The closer R-square value is to 1, indicates better performance of the surrogate measure on identifying crash in a linear relationship. As can be seen in the Figure 7, when the speed limit value is 80km/h, the R square of TTC (0.9041) is higher than that of WTTC (0.8405), suggested that although the

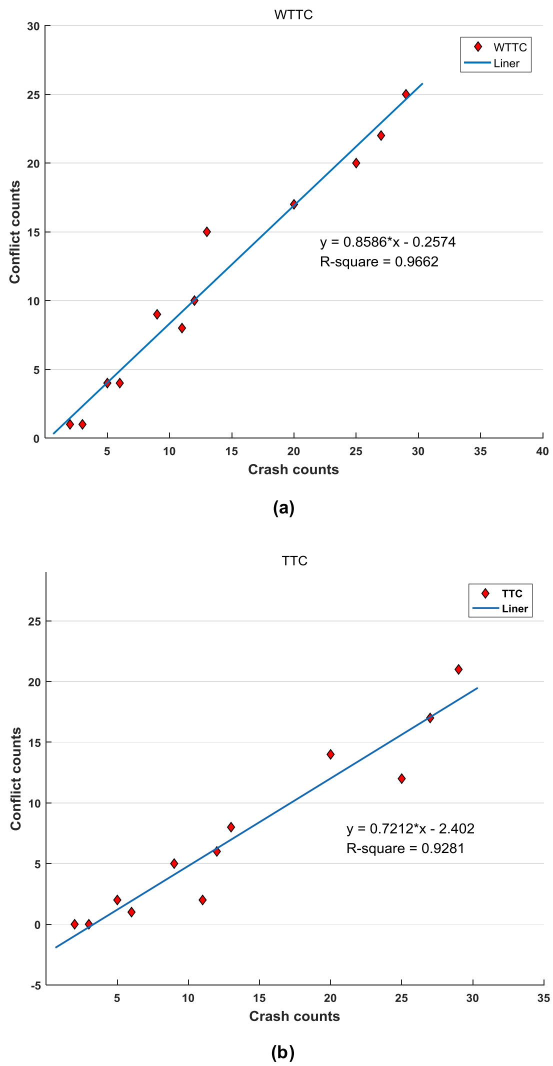


FIGURE 8. The relationship between crash data and identification counts with different speed limit.

identification value of WTTC model is higher than TTC, the fitting effect of TTC model and actual observation value is better. According to Figure 8, when the speed limit in freeway work zone changes to 60 km/h, the R-square value of TTC (0.9281) is less than that of WTTC (0.9662). It can be concluded that, on the whole, the identification value of the TTC model is closer and more stable to the actual observation value in the linear relationship. The WTTC performs better in the linear fitting when the difference between the speed distribution and the speed limit value in the freeway work zone, that the number of conflicts identified is higher.

VI. CONCLUSION AND RECOMMENDATIONS

This paper aims to construct and validate the rear-end conflicts identification model in the warning zone and upstream transition zone of the freeway work zone area. Combine the special road condition of the freeway work zone, a new surrogate safety measure WTTC based on the TTC algorithm was proposed, and the rear-end identification model based on WTTC was established. Optimal threshold values for measures WTTC and TTC were determined by maximizing the correlation coefficient between the road risk value and conflict risk value. Results show that conflict risks captured by WTTC could achieve the highest level of correlation with crash counts data compared with TTC. Also, the effectiveness of the rear-end conflicts identification model was validated by the error test method between actual observation crash counts and identification conflict counts.

The result shows that the new surrogate safety measure WTTC could detect risks in the various car-following scenarios, even when the following vehicle speed is less than the leading vehicle speed. In contrast to TTC, the recognition accuracy of rear-end conflicts identification model based on the WTTC has improved by 30%, which is more suitable for the freeway work zone and performs well in identifying crash frequencies. At the same time, this study found that the smaller the speed limit set value by sections with the same traffic parameters in the work zone, the higher traffic conflict risks WTTC could identify, and accordingly, the conflict counts increased. Therefore, if the difference between the speed limit value and the speed distribution in the freeway work zone is too large, the possibility of accidents will increase. It is suggested to take hierarchical speed limit measures to avoid the rear-end crashes caused by the sudden deceleration of leading vehicles.

Although the feasibility of the proposed surrogate safety measure has been demonstrated, further research should be conducted to fully implement this methodology. The differential effects of traffic parameters on this measure need to be regarded to ensure more accurate and reliable identification of risk situations. The characteristics of speed limits value should be taken into consideration cause their changes will have a significant impact on the conflict model identification results. Additionally, more analyses of the vehicle types are required. The WTTC was validated only using the rear-end collision data from cars in this study. Different vehicle types have different vehicle length and deceleration rates, so the proposed WTTC maybe reflect different identification results.

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