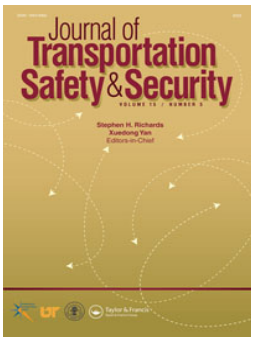


Journal of Transportation Safety & Security

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/utss20

Traffic safety analysis at interchange exits using the surrogate measure of aggressive driving behavior and speed variation

Ying Yao, Xiaohua Zhao, Jia Li, Jianming Ma & Yunlong Zhang

To cite this article: Ying Yao, Xiaohua Zhao, Jia Li, Jianming Ma & Yunlong Zhang (2023) Traffic safety analysis at interchange exits using the surrogate measure of aggressive driving behavior and speed variation, Journal of Transportation Safety & Security, 15:5, 515-540, DOI: 10.1080/19439962.2022.2098439

To link to this article: https://doi.org/10.1080/19439962.2022.2098439

JOURNAL OF TRANSPORTATION SAFETY & SECURITY
2023, VOL. 15, NO. 5, 515–540
https://doi.org/10.1080/19439962.2022.2098439

Traffic safety analysis at interchange exits using the surrogate measure of aggressive driving behavior and speed variation

Ying Yao[a], Xiaohua Zhao[a], Jia Li[a], Jianming Ma[b], and Yunlong Zhang[c]

[a]Beijing University of Technology, Beijing, China; [b]Texas DOT, Austin, TX, USA; [c]Texas A&M University College Station, College Station, TX, USA

ABSTRACT

Because of heavy traffic on urban expressways, the exits of expressway interchanges have become accident-prone sites. This study explores the impacts of various traffic control devices and road conditions on road safety at interchange exits based on driving behavior data from navigation software. The traffic order index (TOI) based on driving behavior and speed variation is used to evaluate road safety. The general safety characteristics and partitioned safety characteristics of interchange exit sections for different traffic control devices and under different road conditions were described, and a structural equation model (SEM) was constructed to observe the influences of the traffic control devices, road conditions, congestion degree, and time on road safety. The results show that traffic control devices (the number of warning signs, number of advance exit signs and complexity of diagrammatic guide signs) and road conditions (the number of lanes and merging conflicts within 500 m) have significant influences on the road safety of interchange exits. Road conditions have the greatest impact on the safety of interchange exits, followed by the congestion index, traffic control devices, and time. The results could help traffic management departments reconstruct or rehabilitate traffic control devices and enable reasonable road planning at interchange exits. The safety evaluation method for traffic control devices and road conditions based on driving behavior data collected from navigation software could be further used on other roads.

KEYWORDS

Traffic safety; road conditions; traffic control devices; interchange; driving behavior; surrogate indicator; structural equation modeling

1. Introduction

Rapid economic development has been accompanied by many road traffic problems. Frequent traffic accidents caused by urban traffic jams and traffic disorders are serious problems affecting urban development. According to the statistics from the Ministry of Transport (Traffic Accident Lawyers, 2017), China's annual traffic fatality toll in 2017 ranked second in the world, accounting for 80% of the total accidental deaths in China.

CONTACT Jia Li lijia18@bjut.edu.cn Beijing University of Technology, Beijing, China.

According to the Global Status Report on Road Safety 2018 issued by the WHO (World Health Organization, 2015), nearly 1.35 million people lose their lives annually on roads worldwide, and road traffic injuries are the leading cause of death of people aged 5-29 years. Therefore, to improve road safety, it is very important to explore the factors affecting road risk and propose improvement strategies.

Urban expressway interchanges connect two intersecting expressways or connect expressways with general roads, which are key passageways for traffic flow conversion. The safety of expressways is greatly affected by interchanges (Chuan, Chaoyang, Qiaojun, & Yongfeng, 2011). A large proportion of traffic accidents on expressways occur at interchange entrances and exits (Wu, Meng, & Song, 2021). Road infrastructure is strongly linked to fatal and serious injury causation in road collisions, and research has shown that improvements to road infrastructure are critical for improving overall road safety (Jeon, Kim, Moon, & Park, 2021; Llopis-Castelló, Findley, & García, 2021; Turner, Breen, & Howard, 2015). Many studies have evaluated the safety of interchange traffic control devices and road conditions based on accident data. Chen, Liu, Lu, and Behzadi (2009) evaluated the impacts of the number and arrangement of lanes on freeway exit ramps on the safety performance of freeway diverge areas based on crash data at 343 freeway segments in the state of Florida and found that the ramp and freeway annual average daily traffic (AADT), posted speed limit on the freeway, deceleration lane length, right shoulder width, and type of exit ramp significantly affected the safety performance of freeway diverge areas. Kim, Kim, and Park (2011) conducted a study on the S-ramps of trumpet interchanges in South Korea based on traffic accident data, and the results show that the accident probability increased with the increase in traffic flow, while increasing the ramp radius is helpful to reduce accidents. Persaud and Lyon (2006) described the development of new safety performance functions for interchanges, ramps and ramp terminals for Ontario freeways using negative binomial regression modeling that relates the collision frequency to traffic volumes and basic entity characteristics.

At the same time, there are also studies on the safety evaluation of interchange traffic control devices and road conditions based on driving behavior data. Upchurch, Fisher, and Waraich (2005) used a driving simulator to evaluate the effect of setting guide signs at the exits of highway interchanges to revise the related specifications of the manual on uniform traffic control devices for streets and highways (MUTCD). Fitzpatrick, Chrysler, Nelson, and Iragavarapu (2013) compared the influences of different types of interchange exit guide signs on driving behavior by using a desktop driving simulation experiment to provide theoretical guidance for the optimization of the setting of interchange exit guide signs. Zhao, Huang, and

Rong (2015) analyzed the influences of interchange guide signs on vehicle speed in three kinds of interchange ramps of an urban expressway by driving simulator experiments. The results indicated that under the effects of different levels of complex alignments of ramps, interchange diagrammatic guide signs combined with three advance guide signs had different influences on speed indicators in three kinds of interchange ramps. Ding, Zhao, Rong, and Ma (2015) used a driving simulator to study the effects of transverse speed reduction markings and longitudinal speed reduction markings on driving behavior at interchange exit sections. Bared, Granda, and Zineddin (2007) proved that a driving simulator is a valuable tool for evaluating the novel diverging diamond interchange design. The impact of road alignment at a diverging diamond interchange on safety was assessed by a 74-person simulated driving experiment. Farah, van Beinum, and Daamen (2017) collected trajectory data on free-moving vehicles based on stabilized video images taken from a camera mounted underneath a helicopter. The findings showed that speeds were affected by several road geometric characteristics of curves, driver expectancy, design consistency, and percentage of trucks in traffic.

However, limitations still exist in the safety evaluations of interchange traffic control devices and road facilities in previous studies. First, research on safety evaluations based on accident data is widely used for traffic control devices and road condition evaluation. Since an accident is a low-probability event, it is difficult to describe in detail the causes of road risk and the temporal and spatial variations in road risk. Second, safety evaluation research on interchange traffic control devices and road conditions based on driving behavior data mostly employ driving simulations, and comparative studies are carried out by implementing different guide signs or road alignments. The evaluation results consider the impacts of traffic control devices and road conditions on the driver's operation of the vehicle and the driver's physiological condition. Due to the small sample size of a driving simulator study, individual differences of the experimenters may affect the accuracy of the conclusions. Therefore, driving behavior evaluation results based on large samples are more universal.

Driving behavior data are a surrogate for accident data, which could detail the impact of facilities on road safety under different temporal and spatial conditions. Navigation software can collect map data, sign information and location data, and GPS data is collected from over one hundred million users every day. The GPS data could be converted into driving behavior data through calculations, possibly providing more representative safety evaluation results in terms of interchange traffic control devices and road facilities that ignore individual differences. Big data based on navigation enable more detailed and accurate safety assessments of interchange traffic control devices and road facilities.

Many studies have been conducted on the safety assessment of individual driving behaviors, such as the "100-car study", Strategic Highway Research Program 2. However, these studies only considered the safety improvement of individual drivers. This study proposes an innovative method for safety evaluation of road conditions and traffic control devices based on aggregate driving behavior data to explore the influence of external conditions on road safety.

The objective of this study was to explore the impacts of various traffic control devices and road conditions on road safety at interchange exit based on aggregate driving behavior data. All data were gathered from navigation software users in Beijing. By matching various types of data and observing their characteristics, a database is built of a road before five interchange exits. The general safety characteristics and partitioned safety characteristics of the interchange exit sections for different traffic control devices and under different road conditions were described, and a structural equation model (SEM) was constructed to observe the influences of the traffic control devices, road conditions, congestion degree, and time on road safety. The analysis results are based on a large amount of driving behavior data, which comprehensively and specifically express the influences of different traffic control devices and road conditions on road safety. This study provides the basis for traffic management departments to reconstruct or rehabilitate traffic control devices and enable the reasonable planning of roads at interchange exits.

The remainder of this paper is organized as follows: methodology and data are introduced first, followed by results and discussions, concluding remarks, and future research directions.

2. Methodology

2.1. Data sources

All data of this research come from the most commonly used navigation software program in China, AutoNavi. According to the statistics of the China Internet Annual Report 2017, the number of active monthly users of the software reached 325.79 million, which ranks AutoNavi at the top of the map navigation software category (QuestMobile, 2019). The data are used to study the relationships among traffic control devices, road conditions and safety.

According to the objective of this research, the driving behavior data required by the safety evaluation method is not small sample data but rather the aggregate driving behavior data when a large number of drivers pass the interchange exit. In this study, more than 46,000 driving behavior events involving more than 30,000 people occurred at the interchange exit. This large sample of event data can reflect the safety level at the interchange exit. Five interchanges are used as an example to evaluate the safety impact of road conditions and traffic control devices. This method can also be applied to the safety of facilities on a larger scale, which can help traffic management departments improve road conditions and traffic control devices.

2.2. Driving behavior data

Six kinds of driving behavior data were collected by users' mobile phones and uploaded to the company's cloud server, including sharp acceleration, sharp deceleration, sharp merge into the left lane, sharp merge into the right lane, sharp left turn, and sharp right turn. The driving behavior data include the event type of the driving behavior, the coordinates of the event, the occurrence time of the event, and the road ID where the event occurred. Driving behavior is a form of event triggering, and every aggressive driving behavior is recorded when it occurs. Events are recorded with accuracy to the second.

The following describes the collection and definition of these six indicators.

Data access: Sensors on the user's mobile phone are used to collect acceleration and angular velocity data; GPS is used to collect speed and angle data.

Acquisition method: The sensor detects whether the driving user has any of the six driving behaviors; GPS is used to supplement the identification of the behavior when a sensor is not available such as in certain low-end mobile phones.

Sharp acceleration and deceleration: If the linear acceleration is higher than a certain threshold, sharp acceleration or deceleration is recognized and recorded when the mobile phone is in a fixed position.

Sharp merges into another lane and sharp turns: In the case of a mobile phone staying in a certain (fixed) position, the centripetal force of the original historical turn is judged. If the detection angle is larger than a certain threshold, the turn is identified as either a sharp merge into another lane or a sharp turn. Sharp merges into another lane and sharp turns include sharp merges into the left lane, sharp merges into the right lane, sharp left turns, and sharp right turns.

2.3. Map data

The map data include the road number, road length, road grade, number of lanes, lane width, speed limit, road type and other information on each road in the region. The indicators used in this study are road ID, number of lanes, and types and locations of warning signs.

2.4. Congestion data

The congestion data include time, average speed (km/h), congestion index (CI) and road ID. All congestion data are collected every 2 minutes on all roads for the study duration.

The CI is calculated by comparing the current average road speed to the free-flow road speed (Federal Highway Administration, n.d); the calculation method is shown in Equation (1).

$$\mathrm{CI} = \frac{\text{Free–flow speed}}{\text{Average road speed}} \tag{1}$$

2.5. User proportion data

The user proportion data come from the number of navigation software users. The number of users passing through each road per hour was counted. Because of the need to demystify the data of user numbers, user proportion data were obtained by using the number of users on each road per hour for all days divided by the total users for all days. The user proportion data are used to calculate the frequencies of driving behavior events (relative). This research only compares the relative risks to get the best solution for the road conditions and traffic control devices. The user proportion data include the time (hour interval), user proportion of the road, and road ID.

2.6. Traffic order index (TOI)

Some assessment methods of road safety are based on driving behavior, and they play an important role in traffic safety management. These methods allow for the safety assessment of traffic control devices and road conditions based on large samples. Yao et al. (2019) proposed a traffic order index (TOI) for evaluating the order of traffic on urban roads, and the index can reflect traffic safety risks. The method of road risk assessment provides a basis for further exploring the causes of risks and proposing solutions to improve road safety.

The TOI describes the degree of orderly movement of vehicles (Yao et al., 2019). The index is proposed based on aggressive driving behavior and speed variation data of urban roads by using the Order of Preference by Similarity to Ideal Solution (TOPSIS) method. In fact, TOI is calculated by the weighted sum of two parts of data, one is the behavioral risk calculated by the frequency of all types of aggressive driving behavior, and the other is the traffic flow risk reflected by the speed variation. The specific calculation method is referred to (Yao et al., 2019).

TOI is a surrogate indicator of accidents that reflects road safety risks. "Order" is an index reflecting the order or disorder degree of the road. The lower the TOI value is, the more aggressive driving behaviors on the road and the greater fluctuation of traffic flow speed in the time period, which means higher traffic safety risks. On the contrary, high order indicates less aggressive behaviors and lower speed fluctuation of traffic flow. The specific calculation method of TOI could be expressed as Equation (2):

$$TOI_i = w_{db} \cdot S_{dbi} + w_{CSV} \cdot S_{CSVi} \tag{2}$$

where $i = 1,2,3,\dots,m$, S_{db} is the score of driving behavior, S_{CSV} is the score of speed variation, w_{db} and w_{csv} is the weight of S_{db} and S_{db} calculated by using the mean-squared deviation weighted method.

This order index is also related to but different from a safety measure. A safety measure is often based on the outcomes of crashes, but an order index is based more on the conditions conducive to crashes but not on crash outcomes. TOI is a surrogate indicator of accidents that reflects road safety risks. The lower the TOI value is, the more aggressive driving behaviors on the road and the greater fluctuation of traffic flow speed in the time period, which means higher traffic safety risks. Based on the TOI, the risk distribution of urban roads could be obtained. Figure 1 shows an example of a TOI heat map of an area from the North Third Ring Road to the North Fifth Ring Road of Beijing. The darker the color, the less orderly and safe the road.

Grade of Road Safety: To rate the road safety, three TOI grades are distinguished by using K-means clustering (Kanungo et al., 2002), namely,

- Risky road, TOI ϵ [0,0.378), represents the road with higher risk which have more aggressive behavior and greater speed fluctuations
- General road, TOI ϵ [0.378,0.405), represents the road with the general level of risk
- Safe road, TOI ϵ [0.405,+∞), represents the road with the lower risk which have fewer aggressive behaviors and smaller speed fluctuations, are less likely to occur risky events.

Figure 1. TOI heat map of 9:00-10:00 (peak time) on Oct. 12, 2017 (Yao et al., 2019).

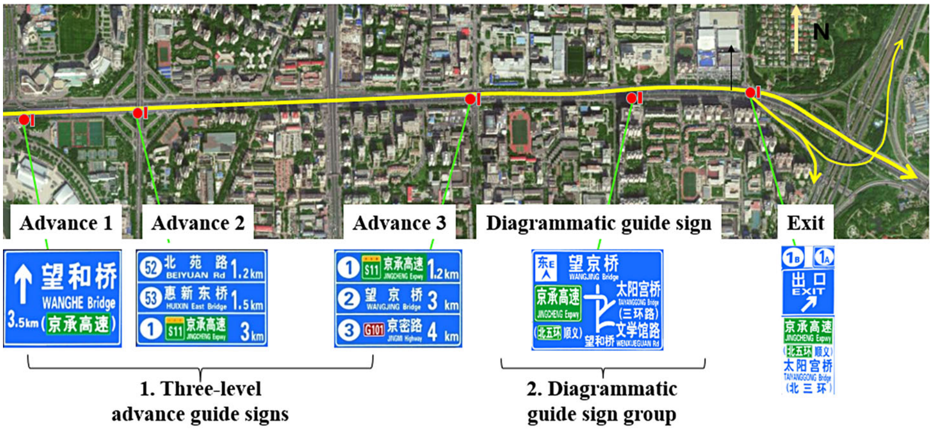
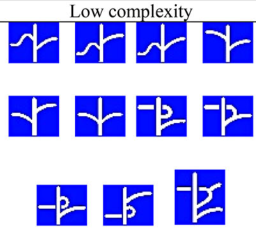
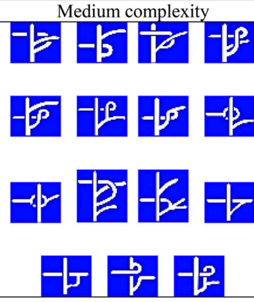
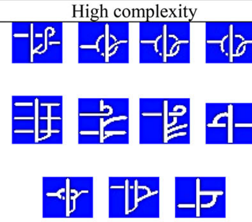


Figure 2. Advance exit signs in one direction of Wanghe interchange.

Table 1. The complexity category of the diagrammatic guide sign.

Low complexity	Medium complexity	High complexity
		

2.7. Traffic control devices and road conditions

The range from 500 m before the exit to the exit of the interchange is the main scope of this study (Zhao et al., 2015). The general arrangements of Beijing expressway interchanges are shown in Figure 2. Before drivers approach an interchange exit, they first see advance exit signs, and the number of advance exit signs varies from 0 to 4. The advance exit signs are followed by a diagrammatic guide sign (see Table 1), and finally, an exit sign is placed at the exit location. Warning signs, exit guide signs, the number of lanes and the merging conflicts have been proven to impact road safety in previous studies (Chen et al., 2009; Jørgensen & Wentzel-Larsen, 1999; Twomey, Heckman, Hayward, & Zuk, 1993; Zhao et al., 2015). According to the facility information included on the survey and street view maps, five indicators are extracted, namely, the number of warning signs, the number of advance exit signs and the complexity of the diagrammatic guide signs, which belong to traffic control devices, and the number of lanes and merging conflicts within 500 m, which are road conditions.

The five indicators are defined as follows:

- The number of warning signs is obtained from survey maps. The warning signs include cautionary pedestrian signs, speed limit signs, speed cameras, cautionary danger signs and lane-merging signs.
- There are several advance exit signs ahead of an interchange exit. The number of advance exit signs varies from exit to exit. Figure 2 shows an example of the advance exit signs in one direction of the Wanghe interchange (an interchange on Beijing's North Fourth Ring Road).
- Diagrammatic guide signs are usually placed before exits and after the advance exit signs in Chinese interchanges (see Figure 2). There are 37 types of diagrammatic guide signs in China. Through several questionnaire analyses, cognitive experiments, simulated driving experiments and real car experiments, Li et al. (2018) described the recognition characteristics and electroencephalography (EEG) characteristics of drivers for different complexity levels of diagrammatic guide signs and proposed detailed criteria to classify the complexity of diagrammatic guide signs (see Table 1).
- The number of lanes could be obtained directly from survey maps. The road before an interchange exit in a Beijing expressway is usually a three- or four-lane road.
- Considering that merging conflicts may have some impact on driving safety, the index of merging conflicts is presented. A merging conflict indicates whether there is an intersection within 500 m away from the exit.

2.8. Data integration

The case study takes the area from the North Third Ring Road to the North Fifth Ring Road of Beijing as an example for analysis. The traffic volume in this region is large, which can reflect the overall traffic situation of Beijing. Five different interchanges are selected, and 500 m before the exit in four directions of each interchange is the research area of this study. The five interchanges are Gujiazhuang interchange, Laiguangying interchange, Huguang interchange, Anhui interchange and Wanghe interchange, as shown in Figure 3. The data were collected from drivers who used the navigation software when passing through the five interchanges from October 1 to October 15, 2017.

All types of data are combined by matching their time and road ID. Table 2 shows the variable types of the database. Except for the indicator of the distance to the exit from the driving behavior events, the other indicators were converted to units per hour, such as the frequency of events of

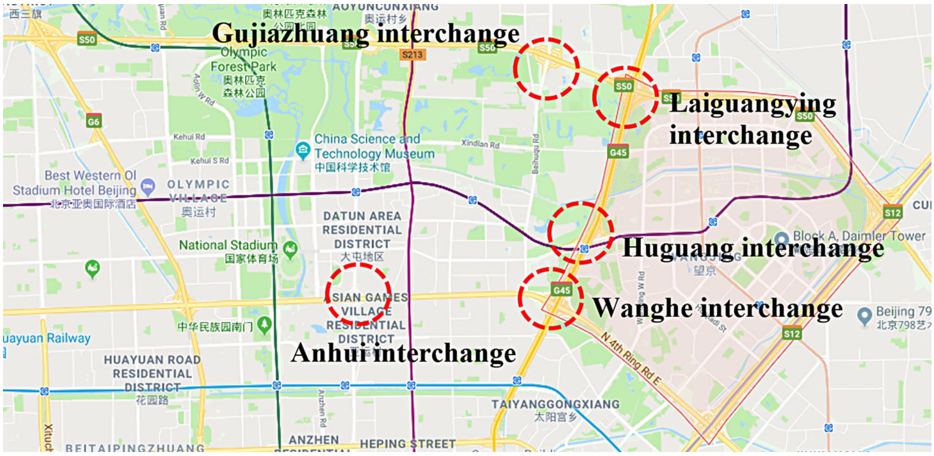


Figure 3. Five interchanges of this study.

driving behavior per hour and the hourly CI. In other words, the driving behavior data is the statistical data of aggressive driving behavior event frequency within one hour, the congestion index is the hourly average data, and the grade of road safety is calculated based on hourly driving behavior and speed variation. The total frequency of aggressive driving behaviors of all drivers within 500 m before the interchange exit is counted, together with the speed variation, reflects the safety grade of the interchange exit.

The conversion or calculation methods of the indexes are as follows:

The driving behavior event data is converted to the driving behavior event data of the unit user proportion, reflecting the frequency of driving behavior events occurring in a unit vehicle in a unit period. By unifying the dimension, the influence of user size on driving behavior events is avoided. The calculation method is shown in Equation (3).

- Frequency of event of driving behavior (FE):

$$FE_{ijk} = \frac{\mathrm{sum}(event_{ijk})}{UP_{ijk}} \tag{3}$$

where j is the direction of an interchange (a total of 4 directions * 5 interchanges), i is the time interval (i o'clock to $i+1$ o'clock with $i=0, 1, 2, \ldots, 23$), k is the date ($k=1, 2, \ldots, 15$), and UP is the user proportion (the unit is expressed as the vehicle ratio (vr)).

To more intuitively see the total frequency of driving behavior events at each interchange exit, the driving behavior data distribution without considering the user proportion is shown in Figure 4. Within 500 m of the exits of 5 interchanges, the maximum number of driving behavior events is

Table 2. The variable types in the database.

Index	Unit	Description
Date	Day	2017.10.k, $k=1, 2, \ldots, 15$
Time	Hour	Time interval of i o'clock to $i+1$ o'clock, $i=0, 1, 2, \ldots, 23$
FE of sharp acceleration FE of sharp deceleration FE of sharp merge into the left lane FE of sharp merge into the right lane FE of sharp left turn FE of sharp right turn	times/(vr *hour)	Equation (2)
Name of the interchange	——	Gujiazhuang interchange, Laiguangying interchange, Huguang interchange, Anhui interchange, and Wanghe interchange
The exit direction of the interchange	——	North, south, east, and west
The distance to the exit from the driving behavior events	m	Equations (3) and (4)
Merging conflicts within 500 m **(road condition)**	——	With or without an intersection within 500 m
The number of lanes **(road condition)**	——	3 lanes or 4 lanes
The number of warning signs (**traffic control devices**)	——	0, 1, 2, 3, 4, and 5
The number of advance exit signs (**traffic control devices**)	——	No advance exit signs, one-level advance exit signs, two-level advance exit signs, tree-level advance exit signs, and four-level advance exit signs
The complexity of the diagrammatic guide signs (**traffic control devices**)	——	No diagrammatic guide sign, low complexity, medium complexity, and high complexity
Congestion index	——	Equation (1)
Grade of road safety	——	Safe road, general road or risky road

65 per hour, with an average of 5.15 per hour during all hours and 6.84 per hour during peak hours.

Conversion method between GPS position and distance to the exit from the driving behavior events:

$$c = \arccos(\cos(90 - LO_{exit})*\cos(90 - LO_{event}) + \sin(90 - LO_{exit}) * \sin(90 - LO_{event})*\cos(LA_{exit} - LA_{event})) \quad (4)$$

$$L = \mathrm{R}*\frac{c}{180}*\pi \quad (5)$$

where c is the spherical distance to the exit from the driving behavior events, R is the Earth's radius (approximately 6,371 km), and L is the distance to the exit from the driving behavior events.

The traffic control devices and road conditions at 20 interchange exits (5 interchanges*4 directions) obtained from survey and street view maps are shown in Table 3.

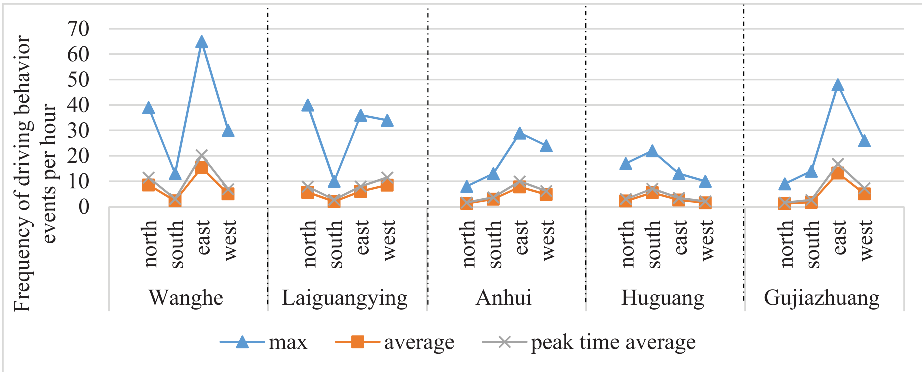


Figure 4. Driving behavior data distributions at the 20 interchange exits.

Table 3. Traffic control devices and road conditions at the different exit directions of the interchanges.

Interchange name	Direction	The number of warning signs	The number of advance exit signs	The complexity of the diagrammatic guide sign	The number of lanes	Merging conflicts
Wanghe	N	4	2	no signs	3	without
	S	1	2	low complexity	3	without
	E	3	3	no signs	4	without
	W	3	4	low complexity	4	without
Laiguangying	N	2	4	low complexity	3	without
	S	1	3	no signs	3	without
	E	2	4	low complexity	3	without
	W	3	4	low complexity	3	without
Anhui	N	1	1	low complexity	3	with
	S	4	1	low complexity	3	with
	E	2	3	medium complexity	4	without
	W	1	3	medium complexity	4	without
Huguang	N	2	2	no signs	3	without
	S	2	0	no signs	3	without
	E	2	0	no signs	4	with
	W	0	2	low complexity	3	with
Gujiazhuang	N	0	0	no signs	3	without
	S	3	1	low complexity	3	with
	E	5	4	medium complexity	3	without
	W	3	4	medium complexity	3	without

3. Results and discussion

After calculating the indicators of 20 interchange exits (5 interchanges*4 directions) and creating a database, the safety characteristics and the distribution of the driving behavior events for the different traffic control devices and under different road conditions are described. Then, an SEM is built to describe the influences of traffic control devices and road conditions on road safety.

3.1. Feature analysis

The sum of the FE values of all driving behavior events is calculated at 20 interchange exits, and the distribution of driving behavior events at the 20

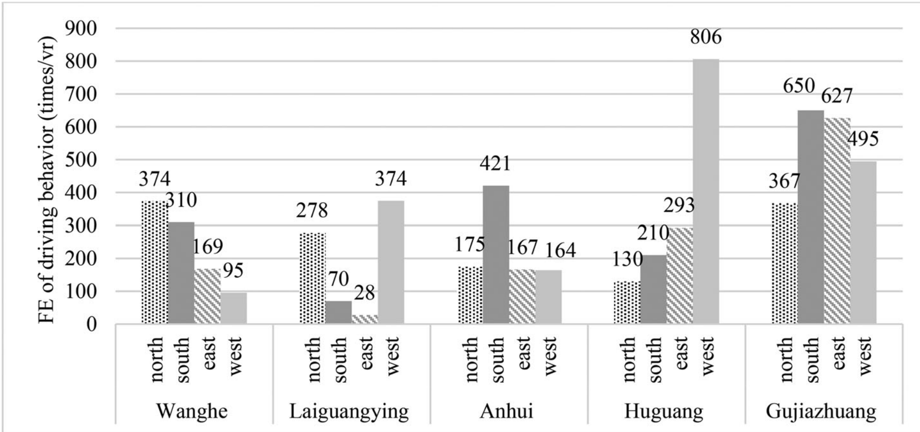


Figure 5. Driving behavior events at the 20 interchange exits.

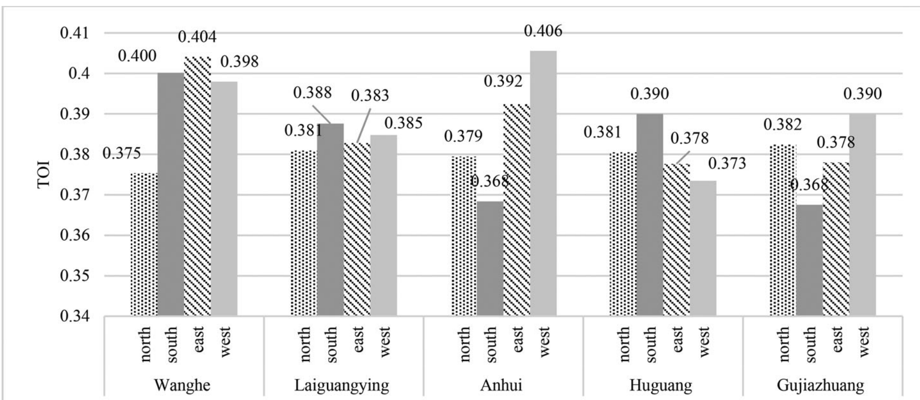


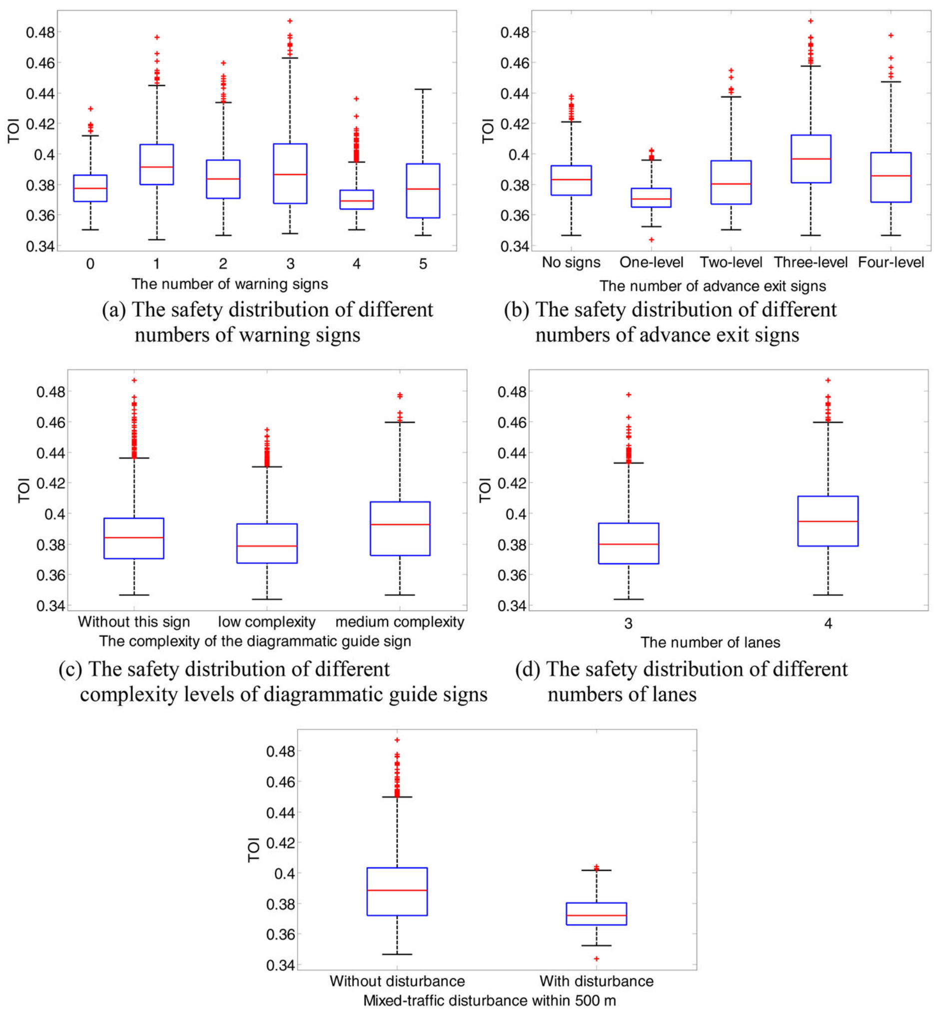
Figure 6. TOIs at the 20 interchange exits.

interchange entrances is shown in Figure 5. It can be seen from the figure that the total number of driving behavior events in the different directions at different interchanges are different. The method of analysis of variance (ANOVA) is used to test whether the effects of the different interchange exits on driving behavior are statistically significant, and the results show that, at the 95% confidence level, there are significant differences in the driving behaviors of the different interchange exits ($F = 6.541$, $p < 0.001$). These differences in driving behavior events also lead to differences in road order.

The TOI is an index reflecting the degree of road order (Yao et al., 2019). The smaller the TOI is, the greater the road risk. The distribution of TOIs at each interchange exit is shown in Figure 6. The TOI is obtained by calculating the mean value of TOIs under different interchange exits during 15 days. The method of ANOVA is used to test whether the effects of the different interchange exit on road safety are statistically significant, and the results show that, at the 95% confidence level, there are significant differences in the safety of different interchange exits ($F = 132.393$, $p < 0.001$). Therefore, it is necessary to conduct an in-depth analysis of the causes of risk at the interchange exits. The study hypothesized that these differences are due to differences in traffic control devices and road conditions. The impacts of traffic control devices and road conditions on road safety are discussed in the following sections.

3.2. General safety characteristics of traffic control devices and road conditions

By calculating the TOIs for different traffic control devices and under different road conditions, their safety characteristics could be obtained (see Figure 7).



(a) The safety distribution of different numbers of warning signs

(b) The safety distribution of different numbers of advance exit signs

(c) The safety distribution of different complexity levels of diagrammatic guide signs

(d) The safety distribution of different numbers of lanes

(d) The safety distribution of mixed-traffic disturbance within 500 m

Figure 7. The safety distributions of different traffic control devices and road conditions.

Table 4. Significance testing of road safety for different traffic control devices and under different road conditions.

Source		Degrees of freedom (df)	Mean square	F	Sig. level
Traffic control devices	The number of warning signs	5	0.013	38.342	<0.001
	The number of advance exit signs	4	0.106	277.849	<0.001
	The complexity of diagrammatic guide sign	2	0.048	112.154	<0.001
Road conditions	The number of lanes	2	0.016	48.237	<0.001
	Merging conflicts within 500 m	1	0.326	824.988	<0.001

Figure 7 shows that both traffic control devices and road conditions influence road safety. More warning signs do not always improve safety. Roads are safer when there are one to three warning signs. The safety distribution of different numbers of advance exit signs is shown in Figure 7b. The tree-level advance exit sign is safer than the other advance exit signs. The reason is that drivers undertake lane change behavior more reasonably at exits with three-level advance exit signs. Thus, there are fewer driving behavior events (e.g., sharp accelerations, sharp decelerations, sharp turns and sharp lane merges) and fewer speed variations, which leads to a safer and more orderly exit of the road with a three-level advance exit sign. The influence of the complexity of the diagrammatic guide sign on road safety is shown in Figure 7c. Roads with low-complexity diagrammatic guide signs are less safe and orderly, and the safety and order of medium-complexity interchanges are good. Because there are few high-complexity interchanges, high-complexity interchanges are not included in this study. In future studies, more interchange samples would be considered to further improve the database. Figure 7d shows that the road of the interchange's exit with more lanes is safer and has a better order. This result is because the more lanes there are, the clearer the road is and the smoother vehicles are driven, so there are fewer driving behavior events. As shown in Figure 7e, if there is an intersection within 500 m before the exit of an interchange, there will be merging conflicts on the roads, which will result in more driving behavior events and larger speed variations, and road safety decreases significantly.

Table 4 describes the results of univariate analysis of the road safety for different traffic control devices and under different road conditions. All the TOIs have significant differences between the different traffic control devices and road conditions (significance (sig.) level <0.05). This result means that traffic control devices and road conditions have significant impacts on road safety. Measures to improve road safety could be taken from the two perspectives of setting reasonable traffic control devices and road planning.

3.3. Partitioned safety characteristics of road conditions and traffic control devices

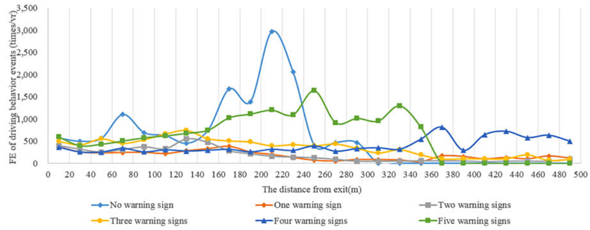
By calculating the occurrence position of each driving behavior event and counting the sum of the FE values of all events every 20 m from an exit, the occurrence situations of events at different positions for different traffic control devices and under different road conditions could be observed.

As shown in Figure 8a, different warning signs have different locations where events occur more frequently. There are many driving behavior events on the road section from 140 to 240 meters from an exit without warning signs. When there are 5 warning signs, the driving behavior events are concentrated between 160 m and 360 m away from the exit. However, when there are 4 warning signs, more events occur 360 meters away from the exit. When there are 1 to 3 warning signs, the occurrence frequency of events is relatively stable with the change in distance, and there are no positions with a particularly high frequency. This finding suggests to a certain extent that more warning signs are not always better and that one to three warning signs are sufficient, except for other factors that may affect the safety of interchanges.

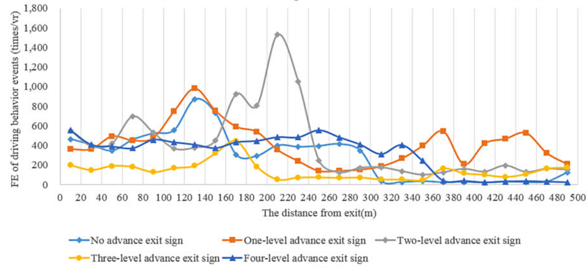
As shown in Figure 8b, the locations of the events vary with the number of advance exit signs. In an interchange with no advance exit signs or one advance exit sign, drivers usually have many operation behaviors from 120 m to 140 m away from the exit. At an intersection with two advance exit signs, the positions of driving behavior events move backward from 200-240 m. However, at an interchange with three or four warning signs, the overall operations of drivers are relatively stable, and there is no event location with a high frequency, indicating that drivers undertake the behavior of changing lanes in advance when passing multiple advance exit signs; drivers could drive their vehicles more smoothly and safely when approaching interchanges.

As shown in Figure 8c, with the different complexity levels of the diagrammatic guide signs, the position of the driver to operate their vehicle (e.g., lane change, acceleration and deceleration) is also different. There are more driving behavior events from 120 m-140 m away from the exit of the interchange without a diagrammatic guide sign. In an interchange with low-complexity diagrammatic guide signs, drivers often generate driving events between 200 m and 220 m, and in an interchange with medium-complexity diagrammatic guide signs, drivers often generate driving events between 160 m and 180 m.

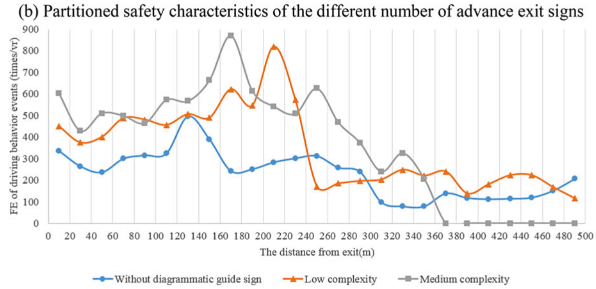
As shown in Figure 8d, the position of the driver to take action is also different for different numbers of lanes. When driving on a three-lane road, drivers exhibit more driving behavior events from 120 m to 160 m away from the exit. Drivers perform certain lane change actions earlier



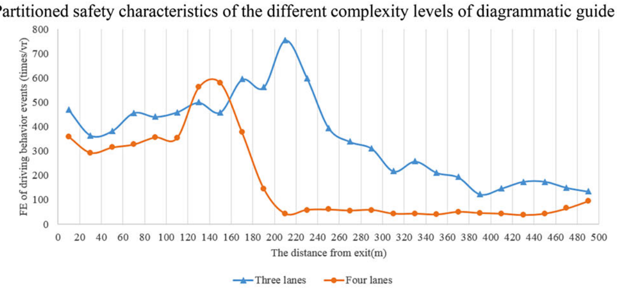
(a) Partitioned safety characteristics of the different number of warning signs



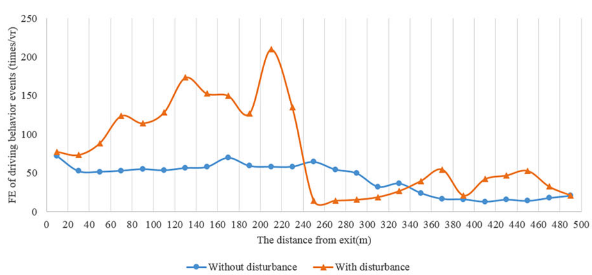
(b) Partitioned safety characteristics of the different number of advance exit signs



(c) Partitioned safety characteristics of the different complexity levels of diagrammatic guide signs



(d) Partitioned safety characteristics of the different number of lanes



(d) Partitioned safety characteristics of merging conflicts within 500 m

Figure 8. Partitioned safety distributions of the different traffic control devices and road conditions.

when driving on four-lane roads. As seen from the results, there are more driving behavior events from 200-200 m.

As shown in Figure 8e, the influence of merging conflicts on driving events is very clear. When there is an intersection within 500 m of the exit of an interchange, the FE values of driving behavior events within 240 m are significantly higher than those on a road without merging conflicts. Merging conflicts significantly reduces the safety of an interchange exit.

Partitioned safety characteristics provide a more intuitive appreciation of the relationship among traffic control devices, road conditions and driving behaviors and explore in detail the causes of driving behavior events. A feature analysis lays the foundation for optimizing traffic control devices and road conditions. The following model construction quantifies the relationship among traffic control devices, road conditions and road safety, and the model could determine which factor should be considered first in the optimization process.

3.4. Modeling road safety for different traffic control devices and under different road conditions

Structural equation modeling is a form of causal modeling that includes a diverse set of mathematical models, computer algorithms, and statistical methods that fit networks of constructs to data (Kaplan, 2008). An SEM has the ability to impute relationships between unobserved constructs (latent variables) from observable variables. Given that certain latent variables cannot be measured directly, an SEM is used in this research. The influences of different traffic control devices and road conditions on road safety are explored.

The hypotheses are as follows: (1) Traffic control devices and road conditions have a significant effect on the grade of road safety; (2) the CI of the road and the time also have a significant effect on the grade of road safety; and (3) the traffic control devices, road conditions, CI, and time have different influences on road safety. Given that the grade of road safety is determined by driving behavior and speed variation, driving behavior is also reflected in this model.

Thus, an SEM is established based on these hypotheses and the results of principal component analysis. The SEM was built and analyzed using AMOS 21.0. The traffic control devices, road conditions, CI, and time are considered to be the independent variables of the model, reflecting the influence of road safety and driving behavior events. The structural equation model is constructed according to the evaluation of the influencing factors of road safety. In the process of model construction, according to the principle of adding a covariant relationship for the pair of observed

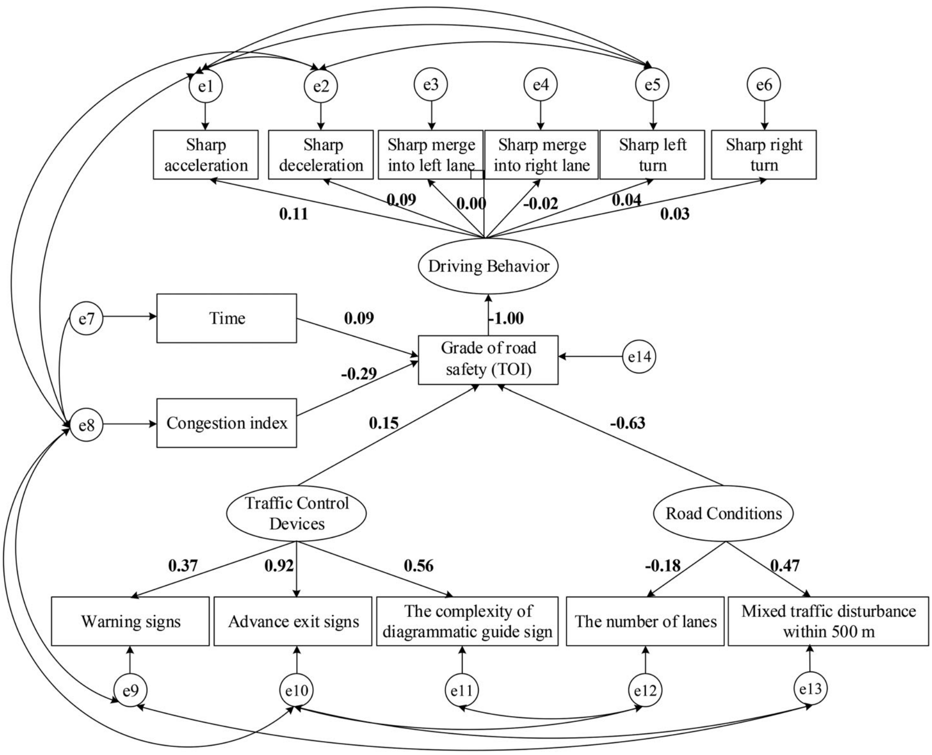


Figure 9. SEM after revision.

variables with the largest M.I. value, the model was continuously revised until the model fitness index reached the standard, and the model structure was finally formed as shown in Figure 9.

To test the fitness of the revised SEM, the following 7 indicators were examined, namely, $\chi2$/df, goodness-of-fit index (GFI), adjusted goodness-of-fit index (AGFI), root mean square error of approximation (RMSEA), normed fit index (NFI), comparative fit index (CFI), and parsimony normed fit index (PNFI). The fit indexes are presented in Table 5. The values of $\chi2$/df are less than 5, which indicates that the model fits the data well. Additionally, the RMSEA is less than 0.08, and the other fit indexes are greater than 0.9, indicating that the model has an acceptable fit (Zhang et al., 2018). All the indexes meet their respective criteria, indicating that the revised SEM fits the observed data well.

In the SEM, the path coefficient represents the degree of influence between the variables. As shown in Table 6, the traffic control devices, road conditions, CI, and time all have significant causal relationships with the grade of road safety ($p < 0.05$). The results show that the road conditions (β=-0.628) have the greatest impact on road safety, followed by the congestion level (β=-0.288) and traffic control devices (β=0.153), and the

Table 5. Results of the goodness of fit of the revised model.

Fit index	χ^2/DF	GFI	AGFI	RMSEA	NFI	CFI
Measured value	4.784	0.995	0.990	0.023	0.959	0.967
Standard value	<5	>0.9	>0.9	<0.08	>0.9	>0.9
Adaptation judgment	Yes	Yes	Yes	Yes	Yes	Yes

Table 6. Standardized path coefficient regression results of the revised model.

Dependent variables	Independent variables	Estimate (β)	Standard Error	Critical Ratio	P
Grade of road safety	Traffic control devices	0.153	0.027	11.047	<0.001
Grade of road safety	Congestion index	−0.288	0.019	−25.284	<0.001
Grade of road safety	Time	0.092	0.001	8.614	<0.001
Grade of road safety	Road conditions	−0.628	0.382	−7.411	<0.001

time of day (β=0.092) has the least impact on road safety. At the same time, it can be seen that the coefficient between the CI and grade of road safety is negative, indicating that road safety decreases as congestion increases.

By observing the relationship between latent variables and observable variables, the observed variables most closely related to potential variables could be found. In the relationship between driving behavior and observable variables, the coefficients of the sharp acceleration (β=0.11) and deceleration (β=0.09) are the largest, followed by those of sharp turns (sharp left turn, β=0.04, and sharp right turn, β=0.03) and finally that of sharp lane changes (β<0.02). The primary consideration for improving road safety is to reduce a driver's sharp acceleration behavior. Due to fewer drivers' behaviors of merging into another lane during the observation period, the impact of merging the right lane on safety grade is negative, which is the limitation of this study. Here, merging into another lane is considered to have little impact on safety grade. In the future, we will carry out further research on the effect of the merge lane behaviors on safety grades. In the relationship between traffic control devices and observable variables, the coefficient of advance exit signs (β=0.92) is the largest, followed by that of the complexity of the diagrammatic guide sign (β=0.56) and finally that of the number of warning signs (β=0.37). The measures to improve road safety based on traffic control devices should focus on placing advance exit signs reasonably. In the relationship between road conditions and observable variables, the coefficient of merging conflicts within 500 m (β=0.47) is the largest, followed by that of the number of lanes (β=-0.18). The result shows that when improving road conditions to improve road safety, one should focus on increasing the distance between interchanges and intersections.

In summary, to make an interchange safer, it is necessary to consider increasing the distance between the intersection and the overpass exit in urban road planning and design. The research of Baek and Hummer

(2008) showed that too many entrances on both sides of the highway would cause road safety problems. When the number of entrances increases and the spacing between entrances decreases, the number of accidents increases. This is consistent with the conclusion of this study.

At the same time, more lanes should be set up when conditions permit. Abdel-Aty and Radwan (2000) found that more lanes lead to more accidents, but Greibe (2003) found that the accident probability of a single-lane highway is higher than that of a multi-lane highway. The results of this study are consistent with Greibe.

In addition, congestion relief is also an important measure to improve road safety. Milton and Mannering (1998) used the negative binomial regression method to build the safety analysis model of traffic accidents in Washington state, which shows that the number of accidents increases with the increase of the number of vehicles. It is basically consistent with the conclusion of this study.

Then, improvements in traffic control devices should be considered. In the process of improving traffic control devices, it is most important to reasonably set the number of advanced exit signs, and three advanced exit signs work the best. Medium-complexity and low-complexity diagrammatic guide signs do not have a negative impact on road safety, and these signs could be placed at interchange exits. High-complexity diagrammatic guide signs still need further research. The interchange exit without warning signs could implement 1 to 3 warning signs to improve road safety. Huang et al. (2020) carried out the driving simulator experiment to evaluate the effect of guide signs on safety. The results show that the exit road with three-level warning signs can effectively guide drivers to produce more reasonable lane change behavior, so as to reduce the occurrence of aggressive driving behavior events. It is consistent with the actual road evaluation results of this study.

The results also show that it is feasible to study the influences of traffic control devices and road conditions on road safety based on the driving behavior data of large navigation samples, which could describe the time and space characteristics of driving behavior in detail. At the same time, the safety analysis method based on TOI proposed in this study is consistent with the traditional accident analysis results, which demonstrates the rationality of the method. Because the driving behavior data is more precise than accident sampling, some more detailed safety risk analysis results could be obtained, which provides theoretical support for improving the road safety level at the interchange exit. Five interchanges in Beijing are considered in this study as examples to analyze the safety of different traffic control devices and road conditions at interchange exits. In the case of an increase in the sample size, the results will be more accurate.

4. Conclusions

In this study, the relationship between different traffic control devices and traffic conditions on road safety at interchange exits is explored. Driving behavior data, map data, congestion data, crash data and user proportion data for 15 days were obtained from navigation software. Traffic control devices and road condition data were extracted through survey and street view maps. Through the description of the general and partitioned safety characteristics, the results demonstrate that there are significant road safety differences for different traffic control devices and under different road conditions at interchange exits. Moreover, the locations where emergency driving events frequently occur for different traffic control devices and under different road conditions are also different. An SEM is constructed to observe the influences of the traffic control devices, road conditions, congestion, and time on road safety at interchange exits.

The conclusions can be summarized as follows:

- The safety evaluation method of traffic control devices and road conditions based on driving behavior data collected from navigation software is feasible, and the method expresses the influences of traffic control devices and road conditions on driving behavior in a detailed manner. The method can be summarized as the following steps:

Step 1: Extract driving behavior data, map data, speed data, congestion index data, user quantity data, and other data from navigation to calculate the TOI of the road.
Step 2: Identify the road type to be analyzed, such as interchange exits in this research, intersections, curves, etc., and then get the data of the road conditions and traffic control devices in the research area.
Step 3: Analyze the safety features (TOI) under different road conditions and traffic control facilities.
Step 4: Build an evaluation model to observe the influences of traffic control devices and road conditions on road safety.
Step 5: Propose an optimization plan for traffic control devices and road conditions for a specific interchange exit or other research area based on the results of the research detailed above.

- All five indexes of traffic control devices and road conditions have significant influences on the road safety of interchange exits, including the number of warning signs, the number of advanced exit signs and the complexity of the diagrammatic guide signs, which are traffic control devices, and the number of lanes and merging conflicts within 500 m.

- Road conditions have the greatest impact on the safety of an interchange exit, followed by the CI, traffic control devices, and time.
- In terms of the road conditions, the interchange exit with a nearby intersection has a great impact on safety, and there are many emergency driving events within 240 m away from the exit. A four-lane road is safer than a three-lane road. At the same time, when driving on a four-lane road, drivers often change lanes and undertake other operations farther away from the interchange exit. In terms of the traffic control devices, the number of advance exit signs has a great impact on the safety of interchange exits. Three advance exit signs are the safest, and there are fewer emergency driving behavior events. Diagrammatic guide signs do not have a negative impact on safety. When there are diagrammatic guide signs, drivers change lanes and undertake other actions at a position farther away from the interchange exit. More warning signs are not better, and 1-3 warning signs are appropriate.

Based on the above conclusions, the results of this study could provide suggestions for traffic management departments to reconstruct or rehabilitate traffic control devices and enable reasonable road planning at interchange exits. At the same time, the safety evaluation method of traffic control devices and road conditions based on driving behavior data collected from navigation software could not only be applied to interchange exits but also lays the foundation for the safety evaluation of traffic control devices and road conditions of other roads. This method changes the traditional method of accident analysis or simulator experimentation and adopts large-scale driving behavior data to evaluate the safety of traffic control devices and road conditions, which provides a reference for road planning and traffic control device optimization.

The current method may have some limitations in practical application. First, the data source of aggressive driving behavior may be difficult to obtain for the safety management department. Second, different thresholds or definitions of aggressive driving behavior may lead to differences in the judgment results of safety grades. However, this research provides a new perspective for the safety evaluation of expressway exits, and more refined safety analysis results based on aggressive driving behavior could be obtained in the future safety evaluation process.

There are other research areas for future studies. First, the current study only examined medium- and low-complexity diagrammatic guide signs. In the future, the sample size will be further expanded, and high-complexity diagrammatic guide signs will be considered for comparison. Second, more types of roads will be considered for safety evaluation, such as intersections, curves, and ramps, to further improve the assessment of urban road facility safety systems. Third, the driving behaviors of different vehicle types may have different influences on road safety. Therefore, the safety of trucks and cars would be considered separately in a future study. In future research, based on further utilization of navigation prompt information, the interaction impact of traffic control devices and navigation information on road safety risks would be analyzed in-depth, and the interactive analysis of the impact of traffic control devices and road conditions on road safety would be further analysis by using visualizations of machine learning.

Funding

This work was supported by the project funded by the China Postdoctoral Science Foundation (NO. 2021M690272), National Natural Science Foundation of China (NO. 52072012), Transportation Engineering of Beijing University of Technology (NO. 2020BJUT2T02) and the Chaoyang District Postdoctoral Science Foundation, the Joint Laboratory for Future Transport and Urban Computing of AutoNavi, and the Beijing Key Laboratory of Traffic Engineering, Beijing University of Technology.

ORCID

Ying Yao http://orcid.org/0000-0002-9322-9386

References

Abdel-Aty, M. A., & Radwan, A. E. (2000). Modeling traffic accident occurrence and involvement. *Accident; Analysis and Prevention*, *32*(5), 633–642. doi:10.1016/S0001-4575(99)00094-9

Baek, J., & Hummer, J. E. (2008). Collision models for multilane highway segments to examine safety of curbs. *Transportation Research Record: Journal of the Transportation Research Board*, *2083*(1), 128–136. doi:10.3141/2083-15

Bared, J. G., Granda, T., & Zineddin, A. (2007). *Drivers' evaluation of the diverging diamond interchange*. Washington DC, United States: Federal Highway Administration.

Chen, H., Liu, P., Lu, J. J., & Behzadi, B. (2009). Evaluating the safety impacts of the number and arrangement of lanes on freeway exit ramps. *Accident; Analysis and Prevention*, *41*(3), 543–551. doi:10.1016/j.aap.2009.01.016

Chuan, L., Chaoyang, W., Qiaojun, X., & Yongfeng, M. (2011). Research on safety evaluation method for expressway off-ramp.*Xiandai Jiaotong Jishu*, *8*(6), 60–63.

Ding, H., Zhao, X., Rong, J., & Ma, J. (2015). Experimental research on the effectiveness and adaptability of speed reduction markings in downhill sections on urban roads: a driving simulation study. *Accident Analysis & Prevention*, *75*, 119–127. doi:10.1016/j.aap.2014.11.018

Farah, H., van Beinum, A., & Daamen, W. (2017). Empirical speed behavior on horizontal ramp curves in interchanges in the Netherlands. *Transportation Research Record: Journal of the Transportation Research Board*, *2618*(1), 38–47. doi:10.3141/2618-04

Federal Highway Administration. (n.d). *Travel time reliability – making it there on time, all the time [online]*. Retrieved from https://ops.fhwa.dot.gov/publications/tt_reliability/brochure/ttr_brochure.pdf

Fitzpatrick, K., Chrysler, S. T., Nelson, A. A., & Iragavarapu, V. (2013). *Driving simulator study of signing for complex interchanges*, *Transportation Research Board 92nd Annual Meeting,* Washington DC, United States, No. 13–1682.

Greibe, P. (2003). Accident prediction models for urban roads. *Accident; Analysis and Prevention*, *35*(2), 273–285. doi:10.1016/S0001-4575(02)00005-2

Huang, L., Zhao, X., Li, Y., Ma, J., Yang, L., Rong, J., & Wang, Y. (2020). Optimal design alternatives of advance guide signs of closely spaced exit ramps on urban expressways. *Accident; Analysis and Prevention*, *138*, 105465. doi:10.1016/j.aap.2020.105465

Jeon, H., Kim, J., Moon, Y., & Park, J. (2021). Factors affecting injury severity and the number of vehicles involved in a freeway traffic accident: investigating their heterogeneous effects by facility type using a latent class approach. *International Journal of Injury Control and Safety Promotion*, *28*(4), 521–530. 10.1080/17457300.2021.1972320

Jørgensen, F., & Wentzel-Larsen, T. (1999). Optimal use of warning signs in traffic. *Accident; Analysis and Prevention*, *31*(6), 729–738. doi:10.1016/S0001-4575(99)00036-6

Kanungo, T., Mount, D. M., Netanyahu, N. S., Piatko, C. D., Silverman, R., & Wu, A. Y. (2002). An efficient k-means clustering algorithm: Analysis and implementation. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *24*(7), 881–892. doi:10.1109/TPAMI.2002.1017616

Kaplan, D. (2008). *Structural equation modeling: Foundations and extensions*. London, United Kingdom: Sage Publications, p. 10.

Kim, T. Y., Kim, K. H., & Park, B. H. (2011). Accident models of trumpet interchange S-type ramps using by Poisson, negative binomial regression and ZAM. *KSCE Journal of Civil Engineering*, *15*(3), 545–551. doi:10.1007/s12205-011-0665-3

Li, Y., Zhao, X., He, Q., Huang, L., & Rong, J. (2018). Comprehensive evaluation and classification of interchange diagrammatic guide signs' complexity. *Journal of Advanced Transportation*, *2018*, 1–11. doi:10.1155/2018/9865305

Llopis-Castelló, D., Findley, D. J., & García, A. (2021). Comparison of the highway safety manual predictive method with safety performance functions based on geometric design consistency. *Journal of Transportation Safety & Security*, *13*(12), 1365–1386. doi:10.1080/19439962.2020.1738612

Milton, J., & Mannering, F. (1998). The relationship among highway geometrics, traffic-related elements and motor-vehicle accident frequencies. *Transportation*, *25*(4), 395–413. doi:10.1023/A:1005095725001

Persaud, B., & Lyon, C. (2006). *Safety performance assessment of freeway interchanges, ramps, and ramp terminals. 2006 Annual Conference and Exhibition of the Transportation Association of Canada: Transportation Without Boundaries*, Held 17-20 September, Charlottetown, Prince Edward Island.

QuestMobile. (2019). *China Mobile Internet Annual Report in 2017 [online]*. Retrieved from http://www.questmobile.com.cn/research/report-new/18

Traffic Accident Lawyers. (2017). *About 63,000 people died in traffic accidents in 2017 [online]*. Retrieved from http://www.nj0827.net/news/309.html.

Turner, B., Breen, J., & Howard, E. (2015). Road safety manual: a manual for practitioners and decision makers on implementing safe system infrastructure.

Twomey, J. M., Heckman, M. L., Hayward, J. C., & Zuk, R. J. (1993). Accidents and safety associated with interchanges. *Transportation Research Record*, *1385,* 100–105.

Upchurch, J., Fisher, D. L., & Waraich, B. (2005). Guide signing for two-lane exits with an option lane: Evaluation of human factors. *Transportation Research Record: Journal of the Transportation Research Board*, *1918*(1), 35–45. doi:10.1177/0361198105191800105

World Health Organization. (2015). *Global status report on road safety 2015*. Switzerland: World Health Organization.

Wu, P., Meng, X., & Song, L. (2021). Identification and spatiotemporal evolution analysis of high-risk crash spots in urban roads at the microzone-level: Using the space-time cube method. *Journal of Transportation Safety & Security*, 1–21. doi:10.1080/19439962.2021.1938323

Yao, Y., Zhao, X. H., Zhang, Y. L., Ma, J. M., Rong, J., Bi, C. F., & Wang, Y. J. (2019). Development of urban road order index based on driving 1 behavior and speed variation. *Transportation Research Record: Journal of the Transportation Research Board*, *2673*(7), 466–478. doi:10.1177/0361198119853576

Zhang, W., Hu, Z., Feng, Z., Ma, C., Wang, K., & Zhang, X. (2018). Investigating factors influencing drivers' speed selection behavior under reduced visibility conditions. *Traffic Injury Prevention*, *19*(5), 488–494. doi:10.1080/15389588.2018.1453134

Zhao, X. H., Huang, L. H., & Rong, J. (2015). Influence of the interchange pattern guide sign on running speed in an urban complex interchange. *Beijing Gongye Daxue Xuebao/Journal of Beijing University of Technology*, *41*(9), 1405–1414.