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Review Article

Research on Highway Roadside Safety

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Frequent and serious traffic accidents have become a focal issue because they hinder the sustainable development of society. In China, roadside accidents account for 40% of fatalities resulting from traffic accidents. Roadside safety has become an important issue of traffic management departments worldwide, and performing research on roadside safety contributes to improving the level of road safety and reducing the number of traffic accidents and fatalities. By systematically sorting a large number of relevant studies, this paper analyzed the current development trends of roadside safety in terms of three aspects (i.e., the year of publication, the country of publication, and the source of publication) and then summarized the research status, existing gaps, and future development directions of roadside safety in terms of three aspects: the frequency of roadside accidents, the severity of roadside accidents, and the practice of roadside safety design. This paper reviewed the different prediction methods and evaluation models for the frequency and severity of roadside accidents. According to the number of times mentioned in the literature, the first five significant risk factors that cause frequent roadside accidents are small-radius curves, heavy traffic, objects adjacent to the lane (such as poles and trees), narrow lanes, and narrow shoulders, and the first five significant risk factors that cause fatal roadside accidents are driver age ≤25 or ≥65, alcohol, speeding, failure to use seat belts, and heavy trucks. Future research on the frequency and severity of roadside accidents should focus on quantitatively analyzing the probability of roadside accidents and occupant injury risk and developing methods for identifying roadside accident blackspots. For roadside safety design, roadside clear zones and safety slopes should be precisely quantified based on a cost-benefit analysis in future studies.

1. Introduction

Improvements in behavioral safety and vehicle safety are strategic long-term tasks. The progressive development of society, science, and technology indicates that traffic safety must undergo a long-term improvement process. In addition, traffic accidents are inevitable and occur in different degrees; thus, the threat of traffic accidents to human life cannot be completely eradicated. According to the "Global Status Report on Road Safety" published by the World Health Organization, despite improvements in road safety, approximately 1.25 million people still die from traffic injuries each year. In the 20th century, 25.85 million people died in traffic accidents worldwide, which exceeds the number of deaths in World War I. According to the statistics of the Roadside Safety Research Program of the Federal Highway Administration (FHWA) (2018), roadside accidents accounted for more than 50% of all traffic fatalities [1]. According to China's Road Traffic Accident Statistical Annual Report (2018), roadside accidents account for approximately 8% of the annual total number of crashes but cause 13% of the death rate [2]. Compared with other crash types, based on the high fatality rate of roadside accidents and the significant difference in the risk factors that affect roadside accidents and multivehicle accidents [3], relevant research must be carried out on roadside safety.

Some developed countries (such as the United States and Australia) have realized that improving behavioral safety and vehicle safety is a long-term arduous task. By analyzing the causative mechanism of roadside accidents, some scholars have explored the risk factors that affect the frequency and severity of roadside accidents [4] and then implemented corresponding measures to improve roadside safety and reduce roadside accident losses, such as driver management, vehicle review, and road optimization design [5, 6]. From the perspective of driver management and vehicle detection, poor driving behavior and poor vehicle performance are often significant factors that lead to roadside accidents. From the perspective of road design, numerous design elements have an impact on traffic safety, and they can be generally categorized into alignment design, including horizontal, vertical, and cross section alignments, and roadside design, including the roadside clear zone (RCZ), roadside guardrail, and roadside obstacles. It is generally believed that different road alignment designs and roadside designs have different effects on the improvement of traffic safety. Strict driver management, regular vehicle maintenance, and humanized alignment design based on drivers, vehicles, and roads can eliminate certain inevitable traffic accidents. "Forgiving roadside design" can reduce the probability of casual traffic accidents and the crash loss after the vehicle enters the roadside.

Since the 1960s, the number of traffic deaths in the United States has fluctuated at approximately 40000 [7]. Considering that the numbers of vehicles and vehicle miles of travel in the United States have increased 7.5 times over the previous period, the death rate per 100 million vehicle miles has actually fallen by more than half. In most countries and regions, especially in developing countries of Asia and Pacific, the death rate from traffic accidents has been on the rise, while in the United States, the death rate has been on the decline. These trends mainly profit from the concept of "forgiving roadside design"; corresponding planning and design methods which began in the 1960s were improved and promoted for approximately 40 years and became widely accepted by society and industries [8]. The concept of forgiving roadside design considers that the driver's fault should not be compensated at the cost of life; that is, an RCZ should be provided for the driver who has to run off the road to regain control of their vehicle and return to the road surface. Even if the driver cannot return to the road surface, some degree of fault will be eliminated in the area to minimize the severity of traffic accidents [9]. Therefore, the RCZ should be relatively flat and free of obstacles and offer an area where the out-of-control vehicle can return to its normal route [8]. In highly motorized countries, this concept is extensively incorporated in most highway construction, which reflects the importance of roadside design for traffic safety.

An analysis of relevant research indicates that the following three aspects are investigated in the field of roadside safety:

(1) Frequency of roadside accidents: based on roadside accident data, various statistical analysis models are employed to explore the risk factors that affect the frequency and number of roadside accidents.

(2) Severity of roadside accidents: based on roadside accident data, the risk factors that influence the severity of roadside accidents are identified by analyzing the risk of occupant injuries and applying statistical analysis models.

(3) Roadside safety design: design elements include the width of the RCZ, roadside slope, design of roadside guardrail, protection and optimization design of roadside traffic facilities, and method of setting the RCZ based on a cost-benefit analysis.

This paper is divided into five sections. Section 1 presents the introduction. Section 2 analyzes the current development trend of roadside safety in terms of the year of publication, country of publication, and source of publication. Section 3 reviews the different prediction methods and evaluation models for the frequency and severity of roadside accidents and carries out the statistical analysis of significant risk factors for frequent and fatal roadside accidents. Section 4 summarizes the practices of roadside safety design. Section 5 examines the gap between the current research and the future development trend. Section 6 presents the conclusions.

2. Analysis of Publication Retrieval Results

2.1. Method of Publication Retrieval. In this paper, a comprehensive and systematic search of published literature and books in the field of roadside safety from 1980 to 2020 was conducted. These publications were extracted from 5 databases: Web of Science, Google Scholar, Elsevier, CNKI, and digital libraries of educational research institutions. The research contents covered traffic engineering, traffic accidents, vehicle engineering, and other relevant fields. Patents and commercial products related to roadside safety protection technology were beyond the scope of this paper. The following keywords were utilized for the retrieval: roadside accident, single-vehicle accident, rollover crash, run-off-road, roadside safety, RCZ, roadside obstacle, and roadside barrier. According to these retrieval steps, 5310 journal papers, conference papers, and books were extracted. After excluding publications irrelevant to roadside safety, 3612 studies were finally obtained to analyze the development trend of roadside safety, and 103 representative publications were selected for review.

2.2. Year of Publication. Research on roadside safety began in the 1960s, so there are some early study results. Based on work by the research team represented by Zegeer, research in the field of roadside safety has gradually increased since 1980. Figure 1 shows the annual trend of the number of publications from 1960 to 2020. From 1960 to 2002, the number of publications exhibits a slow growth trend. Since 2003, the number of publications has shown an obvious rise, which indicates that scholars are gradually committed to research on roadside safety. Moreover, compared with 2010, the number of publications increased by approximately 49% in 2012 and has maintained a continuous growth trend. This finding is related to the fourth edition of the *Roadside Design Guide* (RDG), which was first published by the American Association of State Highway and Transportation Officials (AASHTO) in 2011.

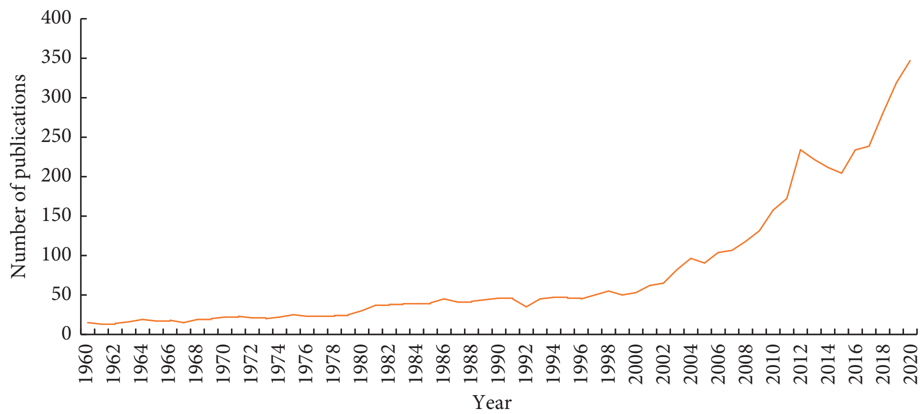

Figure 1: Annual trend of the number of publications.

2.3. Country of Publication. The number of academic achievements obtained by a country can, to some extent, measure the country's research interest and innovation level in a certain field. According to the current residence of the first author, this paper sorts the distribution of academic achievements of roadside safety in different countries. According to the number of publications, the distribution of academic achievements of the top 20 countries is shown in Figure 2. The top 5 countries are the United States (33%), China (24%), United Kingdom (7.5%), Australia (6.6%), and Canada (4.7%). In terms of the percentage of publications, the United States and China currently occupy a relatively dominant position.

2.4. Source of Publication. After 132 electronic books were removed from 3612 publications, the remaining 3480 publications were analyzed. According to the number of papers from different journals and international conferences, Figure 3 shows the top 20 publishers. Compared with other journals, Accident Analysis & Prevention (AAP), International Journal of Crashworthiness (IJC), Traffic Injury Prevention (TIP), and Transportation Research Record (TRR) account for the majority of publications. With the exception of TRR, which is a designated publication for the Transportation Research Board (TRB) conference, the publishers belong to professional journals related to traffic safety, collision injury, and traffic accidents. In addition, AAP, as an authoritative journal in the field of crash analysis, ranks first in the number of papers.

3. Research Status of Roadside Safety

Most studies are generally based on a large volume of traffic accident data to explore the significant factors that affect the risk of roadside accidents by constructing statistical analysis models and proposing targeted schemes and measures for roadside safety design. Considering that the risk factors that affect the frequency and severity of roadside accidents and the corresponding statistical analysis models differ, associated reviews should consider their differences [10]. This section discusses the research results on the frequency and severity of roadside accidents with regard to the aspects of road factors, vehicle factors, driver factors, and environmental factors; reviews the development of research methods for the frequency and severity of roadside accidents; and carries out a statistical analysis of significant risk factors for frequent and fatal roadside accidents.

3.1. Frequency of Roadside Accidents

3.1.1. Literature Review. There are many reasons for a vehicle to deviate from its normal route, such as inappropriate avoidance, driver inattention or fatigue, high speeds on curves, or understeering, and road design and roadside design have an important role in whether human error can contribute to a crash. In terms of road factors, the American Traffic Safety Services Association (ATSSA) published a manual based on various case studies to provide traffic practitioners with safety strategies for roadside accidents. In this manual, pavement safety measures are considered to be the most effective way to reduce the number of roadside accidents [11]. By evaluating causes related to roadside accidents, Liu et al. concluded that road alignment and geometry have a significant impact on the frequency of single-vehicle crashes, and small-radius curves are a key factor of roadside accidents [12–14]. Moreover, a previous investigation showed that approximately 30% of roadside accidents occur on curves [15].

Lord et al. examined roadside accident data on rural roads in Texas. The investigation factors included lane width, shoulder width and type, roadside geometry design, roadside obstacles, horizontal curve curvature, longitudinal slope, number of lanes, and road condition. The results show that a wider shoulder can reduce the occurrence of roadside accidents in horizontal curve sections, and narrow lanes will increase the frequency of roadside accidents because the requirement of sharing a lane with other vehicles increases the probability of collision while the number of lanes has a minimal influence on roadside accidents [16]. Similarly, Ewan et al. analyzed the influence of road geometric and roadside features on the frequency of roadside accidents with low traffic volumes. The research shows that roads narrower than 12 feet are more likely to have roadside accidents than those with a standard width of 12 feet [17]. In addition, roads with narrow shoulders or no shoulders are more

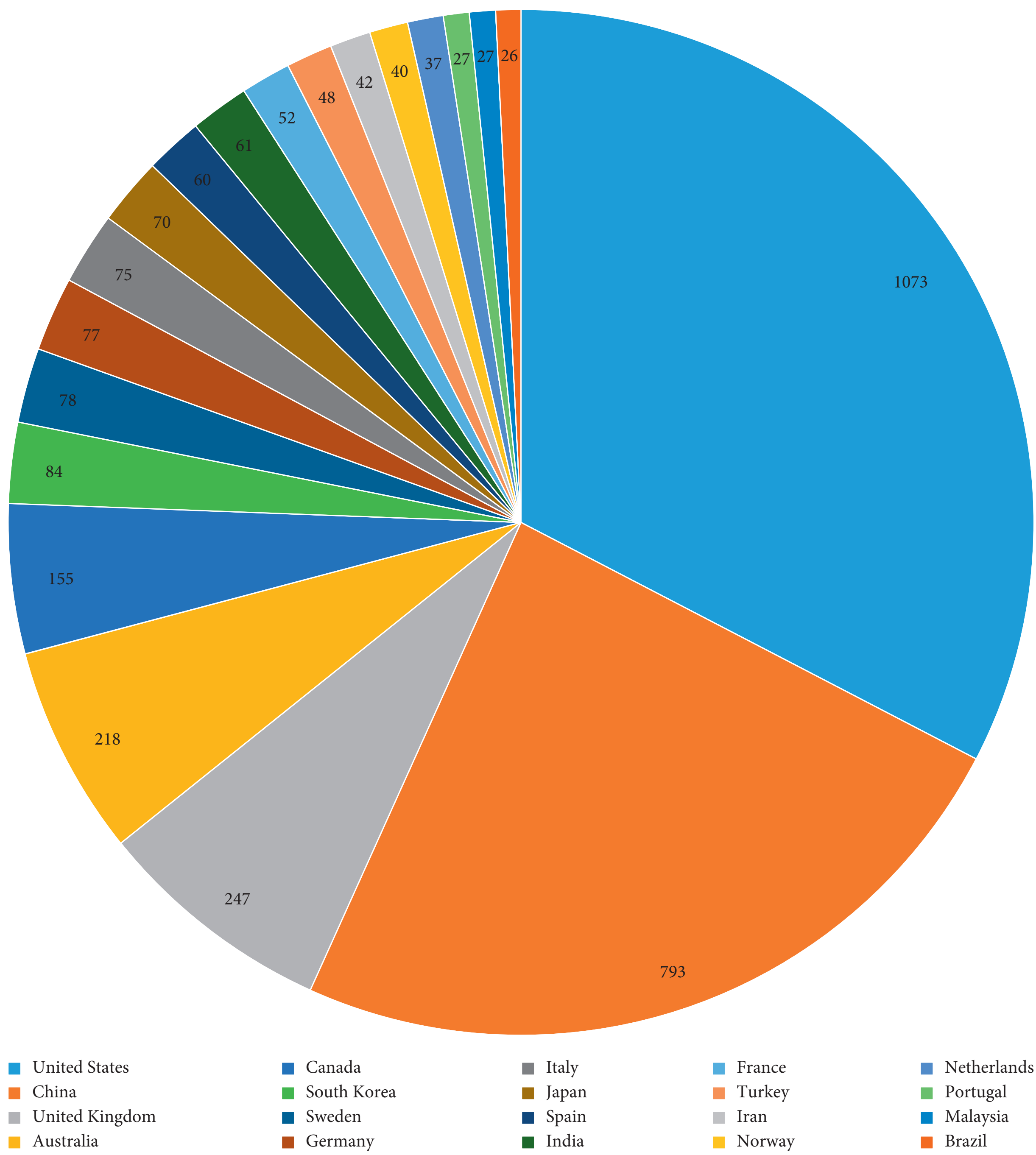

Figure 2: Distribution of academic achievements on roadside safety in different countries.

likely to have roadside accidents than roads with shoulder widths of 4 to 5 feet. Jiang et al. explored the influence of different shoulder types (shoulder with curbs, hard shoulder without curbs, and soft shoulders) on crash frequency; the study concludes that shoulders with curbs do not increase the frequency of roadside accidents on freeways [18]. Liu and Subramanian confirmed that the pavement edge drop-off and low friction of pavement surfaces tend to contribute to a high frequency of single-vehicle crashes [12].

In further research of roadside design, Ogden investigated the relationship between increasing the width of the RCZ and the number of crashes and discovered a correlation between an increase in the RCZ width and gradual decreases in the number of roadside accidents [19]. Australian researchers suggested that a minimum clear zone width of 2 m from the curb edge could significantly reduce the consequences for vehicles that leave the road [20]. Sax et al. proposed that a 4~5 feet width of RCZ could reduce the number of roadside-fixed crashes by 90% [21]. However, Jurewicz and Pyta's research showed that even a clear zone width of 29.5 feet did not prevent numerous roadside accidents [22]. Extensive survey data and computer simulations also showed that when a vehicle lost control, it would travel more than 29.5 feet if it was not blocked by

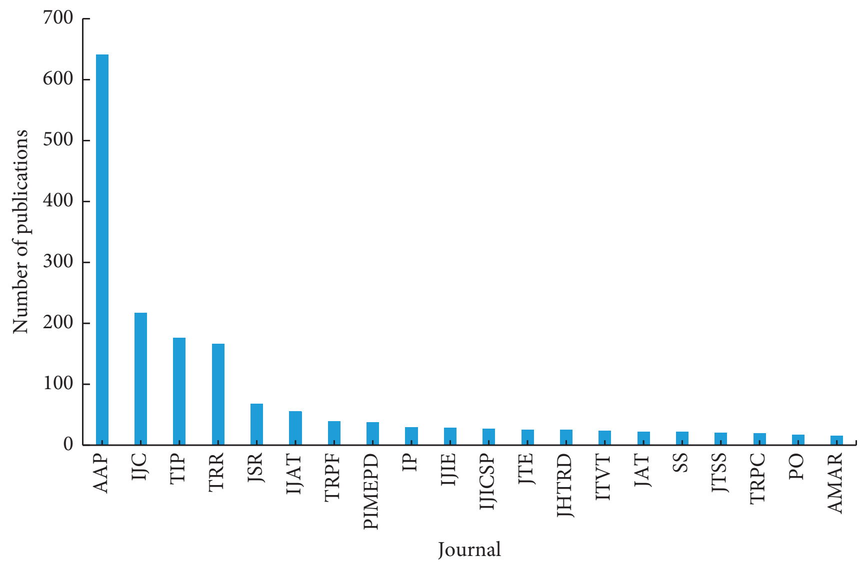

Figure 3: Number of publications from different journals. Note: AAP is Accident Analysis & Prevention; IJC is International Journal of Crashworthiness; TIP is Traffic Injury Prevention; TRR is Transportation Research Record; JSR is Journal of Safety Research, IJAT is International Journal of Automotive Technology; TRPF is Transportation Research Part F: Traffic Psychology and Behavior; PIMEPD is Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering; IP is Injury Prevention; IJIE is International Journal of Impact Engineering; IJICSP is International Journal of Injury Control and Safety Promotion; JTE is Journal of Transportation Engineering; JHTRD is Journal of Highway and Transportation Research and Development; ITVT is IEEE Transactions on Vehicular Technology; JAT is Journal of Advanced Transportation; SS is Safety Science; JTSS is Journal of Transportation Safety & Security; TRPC is Transportation Research Part C: Emerging Technologies; PO is PLOS One; AMAR is Analytic Methods in Accident Research.

obstacles [23]. By analyzing freeway crash data in Washington DC, Lee and Mannering studied the influence of roadside characteristics on the frequency of roadside accidents. The results showed that reducing the number of roadside trees and increasing the offset of lamp posts can reduce the frequency of roadside accidents [4]. Similarly, El Esawey and Sayed correlated the location of signal and lighting poles with the frequency of roadside accidents and discovered that increasing the offset of poles could significantly reduce the number of roadside accidents compared with increasing the distance between two poles [24]. Furthermore, Zegeer et al. discovered that the rollover crash could be reduced by 27% by adjusting the slope gradient from 1 : 2 to 1 : 7 or more gently [25]. Further analysis showed that the side slope had a significant influence on single-vehicle traffic accidents, with decreases in the side slope from 1 : 3 to 1 : 7 or even flatter corresponding to a steady decrease in the crash rate but decreases from 1 : 2 to 1 : 3 having a minimal influence. The results indicate that a side slope less than 1 : 5 is an effective measure to reduce traffic accidents [26].

In terms of vehicle factors, to explore the effectiveness of electronic stability control (ESC) systems in roadside accidents, Koisaari et al. investigated roadside accidents that involved ESC systems and confirmed that the most common risk factor in roadside accidents is improper steering [27]; however, a vehicle equipped with an ESC system can substantially avoid losing control. Lyckegaard et al. have shown that ESC systems can reduce the risk of occupant injuries in roadside accidents by 31% [28]. The National Highway Traffic Safety Administration (NHTSA) evaluated various vehicle safety technologies and confirmed that the integrated effect of both antilock brake system (ABS) and ESC on reducing roadside accidents is more obvious [29]. With the extension of vehicle service time, the risk of a roadside accident will also increase; therefore, improving vehicle conditions can reduce the risk of a roadside accident by at least 3% per year [6].

To identify driver factors, McLaughlin et al. conducted a natural driving test of 100 vehicles. During the test, it was determined that a roadside accident had occurred when the tested vehicle passed or touched the road boundary (such as a marked edge line and road edge). The results show that the most common factors that affect roadside accidents include distraction and following closely, and 36% of roadside accidents are caused by distraction resulting from nondriving tasks [15]. According to crash data statistics, the NHTSA regarded driver fatigue, alcohol, speeding, road familiarity, and gender as important factors of roadside accidents [29]. In another study, Shauna et al. applied naturalistic driving data from the Highway Research Project to assess drivers' behaviors on rural two-lane curves and evaluated the probability of a vehicle entering the roadside by taking into account driver, road, and environmental characteristics. The results show that a vehicle is more likely to deviate to the right on the inside of a curve than the outside of a curve [30].

In terms of environmental factors, Hosseinpour et al. developed and compared seven accident prediction models by collecting traffic accident condition, including Poisson (PM), negative binomial (NB), heterogeneous negative binomial (HTNB), zero-inflated Poisson (ZIP), zero-inflated negative binomial (ZINB), hurdle Poisson (HP), and hurdle negative binomial (HNB) models. These models are described below, respectively.

(1) PM and NB Model. The Poisson regression model is taken as the starting point for modeling when the mean is equal to the variance. However, the variance is usually greater than the mean in most accident data, which is known as overdispersion. Therefore, the NB model accommodates the overdispersion by including an error term ε_i in the Poisson model and allows the variance to differ from the mean as follows:

$$Y_i|\mu_i \sim Poisson(\mu_i), \tag{1}$$

$$u_i = \exp(\beta_i \cdot X_i) \cdot \exp(\varepsilon_i), \tag{2}$$

$$\mathrm{Var}(y_i) = E(y_i) \cdot (1 + \alpha \cdot E(y_i)) = E(y_i) + \alpha \cdot E(y_i)^2, \tag{3}$$

where u_i is the expected number of accidents on segment i, β_i is a vector of estimable coefficients, X_i is the vector of covariate, and exp (ε_i) is the gamma distributed with mean one and variance α.

The probability density function (PDF) of the NB model is given by

$$\Pr(Y_i = y_i) = \frac{\Gamma(y_i + \theta)}{\Gamma(\theta) \cdot y_i!} \cdot \left(\frac{\mu_i}{\mu_i + \theta}\right)^{y_i} \cdot \left(\frac{\theta}{\mu_i + \theta}\right), \tag{4}$$

where θ is the inverse dispersion parameter $1/\alpha$, and $\Gamma(\cdot)$ is the value of the gamma distribution.

(2) HTNB Model. To increase the flexibility and accuracy of parameter estimates, a prominent extension of the NB model is the HTNB model, as a function of roadway characteristics, which allows the dispersion parameter to vary across segments. Similar to the traditional NB model, the HTNB model uses the same PDF (see (4)). However, dispersion parameter is a function of site-specific attributes in the HTNB model, as follows:

$$\alpha_i = \exp(\gamma_0 + \gamma_1 \cdot Z_{i1} + \gamma_2 \cdot Z_{i2} + \cdots + \gamma_m \cdot Z_{im}), \tag{5}$$

where $Z_i = (Z_{i1}, \ldots, Z_{im})$ is a vector of site-specific variables, which are not necessarily the same as those used for estimating μ_i, and γ_m is a vector of estimable parameters.

(3) ZIP Model. The ZIP model is used for modeling when there is an amount of zeros or more zeros than expected in accident data. Let P_i be the probability of segment i being an excess zero and $(1 - P_i)$ be the probability of accident counts derived from the Poisson distribution. Generally, the PDF for the ZIP model is

$$P(Y = y_i) = \begin{cases} P_i + (1 - P_i) \cdot \exp(\mu_i), & y_i = 0, \\ (1 - P_i) \cdot \dfrac{\exp(-\mu_i) \cdot \mu_i^{y_i}}{y_i!}, & y_i > 0, \end{cases} \tag{6}$$

where y_i is the number of roadside accidents for segment i, and μ_i is the expected outcome for segment i as a function of its covariates, $\mu_i = \exp(\beta \cdot X_i)$.

The probability of being in the zero-accident state is often fitted using a logistic regression model, as follows:

$$\mathrm{logit}(P_i) = \ln\left(\frac{P_i}{1 - P_i}\right) = \gamma_0 + \gamma_1 \cdot Z_1 + \cdots + \gamma_N \cdot Z_N, \tag{7}$$

where Z_N is a function of the explanatory variables and γ_N is the estimable coefficients.

(4) ZINB Model. While the ZIP model can accommodate overdispersion caused by excess zeros, it does not handle overdispersion resulting from both excess zeros and unobserved heterogeneity. To deal with this problem, a ZINB model is applied; its PDF is given by

$$P(Y = y_i) = \begin{cases} P_i + (1 - P_i) \cdot \dfrac{1}{(1 + \alpha\mu_i)^{1/\alpha}}, & y_i = 0, \\ (1 - P_i) \cdot \dfrac{\Gamma(y_i + (1/\alpha))}{\Gamma(y_i + 1) \cdot \Gamma(1/\alpha)(1 + \alpha\mu_i)^{y_i + (1/\alpha)}}, & y_i > 0, \end{cases} \tag{8}$$

where α is the dispersion parameter and $\Gamma(\cdot)$ is the gamma function for the ZINB model.

(5) HP Model. To describe the HP model, let the probability of zero count be given by P, and the probability of a nonzero count be given by $(1 - P)$. Thus, an accident can be obtained from a truncated Poisson with a probability of $(1 - P)$. The PDF of the HP model is given as follows:

$$P(Y = y_i) = \begin{cases} P_i, & y_i = 0, \\ (1 - P_i) \cdot \dfrac{\exp(-\mu_i) \cdot \mu_i^{y_i}}{(1 - \exp(-\mu_i)) y_i!}, & y_i > 0, \end{cases} \quad \mathrm{logit}(P_i) = \ln\left(\frac{P_i}{1 - P_i}\right) = \beta_0 + \beta_1 \cdot Z_1 + \cdots + \beta_N \cdot Z_N, \tag{9}$$

where P_i and μ_i are fitted by logit and count models, respectively.

(6) HNB Model. Similar to the HP model, if we use a logit method to model the probability of a zero versus and a nonzero count and a left truncated NB density for the count process, then the PDF of HNB model is

$$P(Y = y_i) = \begin{cases} P_i, & y_i = 0, \\ (1 - P_i) \cdot \left(1 - \dfrac{1}{(1 + \alpha\mu_i)^{1/\alpha}}\right) \cdot \dfrac{\Gamma(y_i + (1/\alpha))}{\Gamma(y_i + 1) \cdot \Gamma(1/\alpha)} \cdot \left(\dfrac{((\alpha\mu_i)^{y_i})}{(1 + \alpha\mu_i)^{y_i + (1/\alpha)}}\right), & y_i > 0, \end{cases} \tag{10}$$

where α is the dispersion parameter, $\Gamma(\cdot)$ is the gamma function, and μ_i is the predicted number of accidents derived from left truncated NB model.

Vuong test (V-test) was used to check if overdispersion exists in the roadside accident. Given that $P_1(y_i|x_i)$ and $P_2(y_i|x_i)$ are the predicted probability of the standard models (PM or NB models) and the two-state models (ZIP or HP models), respectively, the V-test can be expressed as

$$V_i = \ln\left(\frac{\sum_i P_1(y_i|x_i)}{\sum_i P_2(y_i|x_i)}\right). \tag{11}$$

If V is greater than 1.96, then the test favors HP/ZIP or ZIP/ZINB over Poisson/NB; if V is lower than -1.96, the PM or NB model is favored; a value of $-1.96 < V < 1.96$ indicates neither model is preferred over the other. Additionally, Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) were used to compare both the nested and nonnested models; they are defined as follows:

$$\begin{aligned} \mathrm{AIC} &= -2 \cdot \mathrm{LL} + 2 \cdot P, \\ \mathrm{BIC} &= -2 \cdot \mathrm{LL} + P(\ln(n)), \end{aligned} \tag{12}$$

where LL is the logarithm of the maximum likelihood estimation for each model, P is the number of model parameters, and n is the number of observations. A model with the lowest AIC and BIC values is preferred.

According to the results of model tests by V-test, AIC, and BIC, authors concluded that the HTNB was the best-fit model compared to the others to model the frequency of accident, and light traffic volumes (LVTs) and speed limits were positively correlated with crash frequency while heavy traffic volumes (HVTs) were negatively correlated with crash frequency [31]. Moreover, light vehicles are more likely to have roadside accidents.

To investigate the influence of interactions between various factors of roadside accidents, Shankar et al. built the ZINB model (see (8)) that combined road design, traffic, weather, and other factors. After the model validation by V-test (see (11)), the results show that the interaction between the snow cover on a road and the horizontal radius of the road has a significant effect on the frequency of roadside accidents [32].

Rusli et al. investigated the influence of road geometry design, traffic, and weather on roadside accidents in mountainous areas using the NB model (see (1)–(4)) with random parameters and concluded that rainfall and steep slope significantly increased the probability of roadside accidents, while wider shoulder and setting of highway contour lines could effectively reduce the occurrence of roadside accidents [33]. Therefore, the improvement in the geometric design of curves can reduce the negative effects caused by curvature and roadside objects.

In addition, Lord et al. determined that the frequency of roadside accidents was relatively high during weekends, which was speculated to be due to people's tendency to drive under the influence of alcohol during this period [16, 34]. Roadside accidents are also affected by regional characteristics, population density, and lighting conditions [35, 36]. All of these factors have a direct or indirect effect on changes in vehicle speeds, with increased speed increasing the likelihood of crashes.

3.1.2. Research Methods' Review. Various statistical analysis models and methods have been applied to identify risk factors that affect the frequency of roadside accidents. However, there have been statistical analysis problems (such as omitted-variable bias, endogeneity, and underreporting of crashes) in the research data and methods, which may cause errors in the research results [10]. To solve these problems, researchers are devoted to continuously improving and constructing various statistical analysis models to obtain more objective and real research conclusions.

Initially, Zegeer and Deacon developed a lognormal regression model (see (13)) to study the relationship between roadside accident frequency and annual average daily traffic (AADT), shoulder width, lane width, terrain, and RCZ width [37], and in further research, they included the density and offset of roadside barriers in the model [38].

$$f(x, \mu, \sigma) = \frac{1}{\sqrt{2\pi} x\sigma} e^{-\left((\ln x - \mu)^2 / 2\sigma^2\right)}, \tag{13}$$

where x is the variable, μ is the mean of the logarithm, and σ is the standard deviation of the logarithm.

However, the accuracy of this traditional regression model in accident prediction was subsequently determined to be low, and the results were often erroneous [39]. With the continuous development of traffic safety research, scholars have discovered that traffic accident occurrence often conforms to the Poisson distribution over time. Therefore, the Poisson model (see (1)), which is more suitable for crash frequency prediction, has been extensively applied [33]. In the research process of crash prediction models, because the crash mean and variance values are often not equal, Hauer and Ng improved the Poisson distribution model and constructed an NB regression model (see (2)–(4)) [40]. To solve the problem of zero-inflated counting processes in crash frequency analysis, the ZIP (see (6) and (7)) and ZINB (see (8)) regression models have gained considerable acceptance [18, 31]. With constant improvements to the research level, to obtain more objective and scientific research conclusions, a series of derived statistical analysis models are produced, such as the HTNB model (see (5)) [31], bivariate Poisson lognormal (BPL) model (see (14)–(16)) [41], and univariate negative binomial condition autoregression (NB-CAR) model (see (17) and (18)) [42].

(1) BPL Model. Let Y_{it}^k represent the accident frequency on roadway segment i during day t, which belongs to accident types k. In BPL, it is assumed that

$$Y_{it}^k|\lambda_{it}^k \sim Poisson\left(|\lambda_{it}^k\right), \tag{14}$$

where λ_{it}^k is the Poisson rate, which is modeled using a lognormal distribution:

$$\log\left(\lambda_{it}^k\right) = X_{it}^k\beta^k + \varepsilon_{it}^k, \tag{15}$$

where X_{it}^k is the set of explanatory variables for accident type k, β^k is corresponding vector of estimable coefficients, and ε_{it}^k is the error term.

The probability of Y_{it}^k is given by

$$P\left(Y_{it}^k = y_{it}^k|\lambda_{it}^k\right) = e^{-|\lambda_{it}^k\left(|\lambda_{it}^{ky_{it}^k}/y_{it}^k!\right)}. \tag{16}$$

(2) NB-CAR Model. Based on the NB model, the NB-CAR model is defined as

$$y_i \sim NB\left(\lambda_i, \alpha\right), \tag{17}$$

$$\log\left(\lambda_i\right) = \beta_0 + \beta X_i + \varphi_i, \tag{18}$$

where φ_i is set to follow a CAR prior, which represents the spatial relationship between road segments by a proximity matrix W with entry w_{ij} reflecting the spatial association between segments i and j.

The deviance information criterion (DIC) is used for above models validation. DIC combines the measure of fit $\overline{D}$ and the measure of model complexity p_D, as follows:

$$\mathrm{DIC} = \overline{D} + p_D = D\left(\overline{\theta}\right) + 2p_D, \tag{19}$$

where $D(\overline{\theta})$ is the deviance evaluated at the posterior means of the parameters of interest $\overline{\theta}$, p_D is the effective number of parameters, and $\overline{D}$ is the posterior mean of the deviance $D(\theta)$. The same as the AIC, models with smaller DIC are usually favored.

3.1.3. Statistical Analysis of Risk Factors. Scholars employ different statistical analysis models to carry out studies, and the collected crash data have regional and integrity differences; thus, their research results are not fully universal. Therefore, by summarizing and sorting similar research conclusions about the frequency of roadside accidents obtained by different authors from 3447 collected publications, more authentic risk factors of frequent roadside accidents can be obtained. Figure 4 shows the number of publications that correspond to different risk factors of roadside accidents. The greater the number of publications, the greater the likelihood that researchers would agree with the corresponding research conclusions.

Figure 4 shows that 24 risk factors contribute to roadside accidents. Based on the number of publications, the top 5 factors are small-radius curves, heavy traffic, objects adjacent to the lane (such as poles and trees), narrow lanes, and narrow shoulders. With the exception of the heavy traffic factor, all risk factors are related to road design. Therefore, for the road with frequent crashes, traffic management departments should focus on the optimization design of road geometry and roadsides.

3.2. Severity of Roadside Accidents

3.2.1. Literature Review. Before the identification of severity risk factors of roadside accidents, the risk of roadside accidents should be assigned a grade. For example, Zegeer et al. divided the roadside risk into 7 levels according to roadside characteristics, such as the width of the RCZ, side slope, guardrail, and obstacles. The higher the level, the more dangerous the roadside [25]. Shankar and Mannering collected 5 years of historical crash data in Washington and employed a multiple logit (ML) model (see (20)) to classify the severity of roadside accidents into 5 levels: property damage, possible injury, obvious injury, serious injury, and death [43].

$$P_n(i) = \frac{\exp\left(\beta_i X_n\right)}{\sum_I \exp\left(\beta_I X_n\right)}, \tag{20}$$

where $P_n(i)$ is the probability that accident n is of severity i, β_i is a vector of estimable coefficients, I is the set of possible severities, and X_n is a vector of measurable characteristics that determine the severity. β_i is estimated by standard maximum likelihood methods.

According to the *Roadside Safety Design Guide* from the Western Traffic Construction Science and Technology Project (WTCSTP) of the Ministry of Transport of China (2008), the roadside safety should be divided into 4 levels based on the width of the RCZ, depth of the roadside, side slope, and dangerous objects [44]. Fang et al. carried out a roadside environmental safety assessment from two levels, namely, the possibility of a vehicle entering the roadside and the characteristics of roadside safety. The objective characteristic risk index of the roadside was represented on the X-axis, and the probability of vehicle encroachment on the roadside was represented on the Y-axis to form a plane area. The roadside accident risk was divided into 5 levels by the comprehensive evaluation index of the model [45]. There is no essential difference in the various classification methods for the levels of roadside accident risk, which are qualitatively processed according to the main factors that affect the

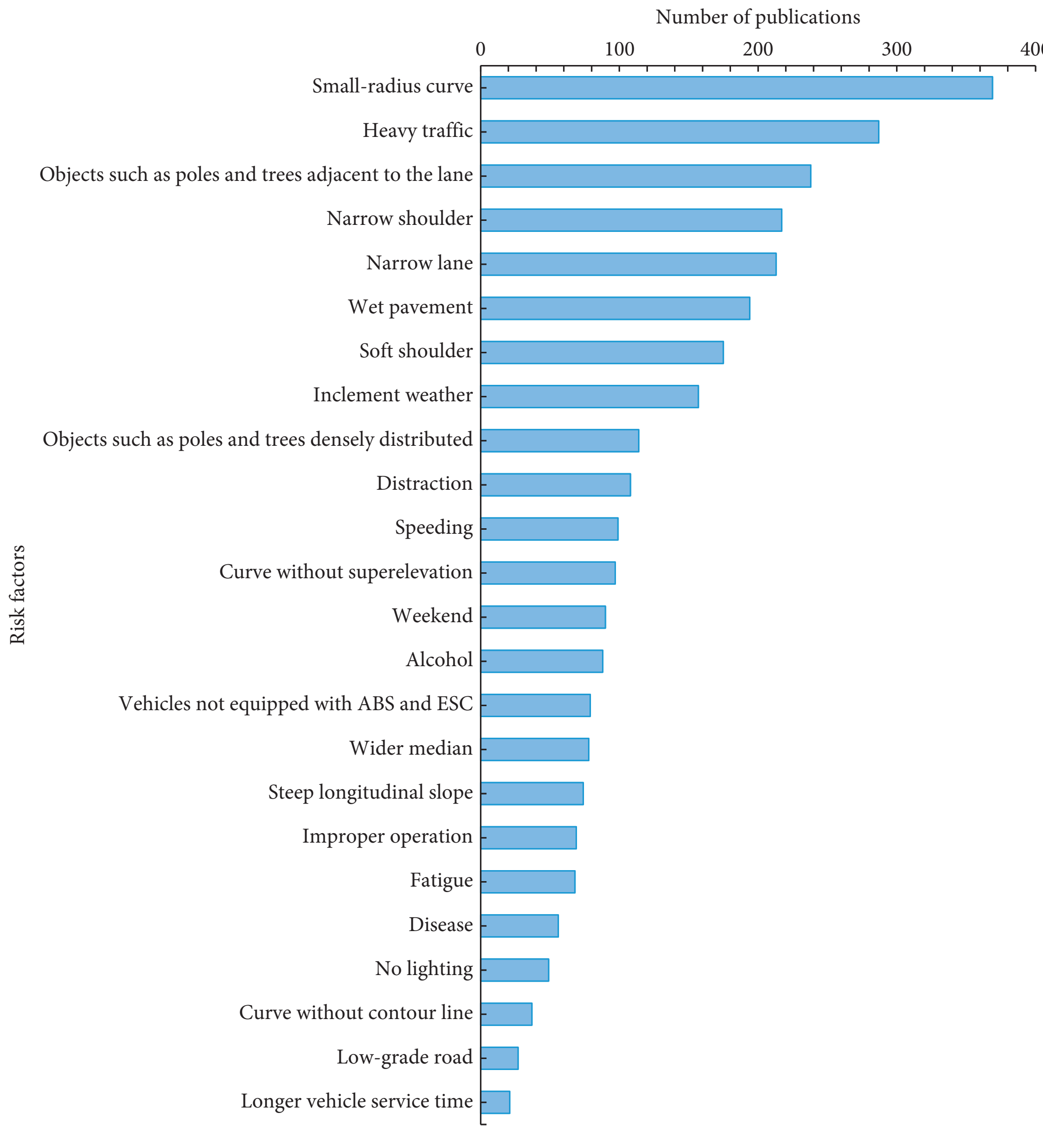

Figure 4: Risk factors of roadside accidents.

roadside risk. Therefore, Long et al. proposed a roadside risk classification method based on occupant risks. VPG3.2 and LS-DYNA971 software were utilized to carry out collision simulation experiments for different vehicle types, and the fish optimal segmentation method was employed to reasonably classify roadside risks [46].

Based on the classified level of roadside accident risks, many scholars carry out risk factor identification research with regard to different aspects. In terms of the road factors, researchers focus on the impact of roadside objects on roadside accidents. Taking into account the structure and material characteristics of roadside objects, it is necessary to investigate the influence of different types of objects on occupant injuries to carry out effective countermeasures [47]. For example, Ayati et al. proposed an index to measure roadside risk based on an evidential reasoning method and concluded that ditches, rigid objects, guardrail ends and transitions, and embankments were the main factors that affect roadside risks. The proposed index considered the decision-maker's subjective evaluation factors and could be used as a reference for future optimization roadside design [48]. In addition, Holdridge et al. and Xie et al. successively applied multiple nested logit (MNL) model (see (21)) and latent class logit (LCL) model (see (22)) to evaluate the important factors that affect the severity of crashes that involve roadside objects.

(1) MNL Model

$$P_{ni} = \frac{e^{S_{ni}+\theta_i L_{ni}}}{\sum_{\forall i_, \in I} e^{S_{ni_,}+\theta_{i_,} L_{ni_,}}}, \tag{21}$$

where P_{ni} is the probability of driver n being in severity category i, S_{ni} is the propensity of driver n toward injury severity category i, θ_i is the coefficient, L_{ni} is the inclusive value, which represents the overall propensity of the lower nest under upper level outcome i, and I denotes all outcomes at that level.

(2) LCL Model. This model assumes that the entire accident data set can be categorized into m different classes, as follows:

$$\text{Prob}(\text{class} = m) = \frac{\exp(V_{im}(\theta))}{\sum_{c=1}^{m} \exp(V_{ic}(\theta))}, \quad (22)$$

where V_{im} (θ) and V_{ic} (θ) are the linear-in-parameters combination of a constant and several covariates.

The estimable parameters of above models are estimated simultaneously using maximum likelihood method. The results revealed that the front end of piers, large trees, and poles increased the possibility of fatal crashes [49, 50].

Considering that the MNL model and LCL model are limited to the homogeneity assumption of risk factors and cannot include unobserved heterogeneity factors, Roque et al. utilized a mixed logit model (see (23)) to analyze the roadside accident cases on Portuguese highways. The mixed logit model is a generalization of the multinomial structure that allows the parameter vector β_i to vary across each driver or most severely injured occupant, as follows:

$$P_{ij} = \int_x \frac{e^{\beta_i X_{ij}}}{\sum_x e^{\beta_i X_{ix}}} f(\beta|\phi) \mathrm{d}\beta, \quad (23)$$

where X_{ij} is a vector of explanatory variables, $f(\beta|\phi)$ is a density function of β, and ϕ is a vector of parameters. To assess the estimated coefficients of model, elasticities are calculated, which measure the magnitude of the impact of specific variables on the injury outcome probabilities, as follows:

$$E_{X_{ik}}^{P_{ij}} = (1 - P_{ij})\beta_j X_{kj}, \quad (24)$$

where P_{ij} is the probability of outcome j and X_{kj} is the value of variable k for specific injury severity level j. Finally, the research results show that steep slopes and small-radius curves are more likely to contribute to fatal roadside accidents [14].

As a kind of roadside protection facility, guardrails can effectively reduce the occurrence of serious roadside accidents [51]. Park et al. showed that collisions with roadside guardrail are less severe than rollover or collisions with roadside poles [52]. To explore the protective performance of different types of guardrails, LS-DYNA simulation software was adopted by Ferdous et al. to evaluate the collision injuries in sections with mediate cable barrier (MCB) and roadside cable barrier (RCB). The results show that the MCB and RCB can reduce the number of fatal crashes by 34.8% and 100%, respectively [53]. In addition, when barriers are installed for 2–5 years, the changes in safety performance tend to be more stable. Daniello and Gabler analyzed 3600 crashes that involved vehicles and roadside objects in the United States from 2004 to 2008 and concluded that the risk of death from collisions with objects was significantly higher than that from collisions with the ground, and collisions with trees are 15 times more likely to be fatal than collisions with the ground [54]. Some studies also showed that trees were the major factor of disability and fatal injuries [55, 56]. To analyze occupant injuries in roadside tree crashes, Cheng et al. employed PC-Crash software to carry out collision simulation experiments between different vehicle types and roadside trees based on the acceleration severity index (ASI), head injury criteria (HTC), and chest resultant acceleration (CRA) as indexes of occupant injures. The results show that the larger the spacing of roadside trees is, the lower the chance that a vehicle will experience a second collision and the lower the risk of occupant injury are [57].

In terms of the vehicle factors, Chen and Chen adopted a mixed logit model (see (23)) and conducted a study of the injuries of truck drivers in roadside accidents on rural roads by evaluating key risk factors, such as crash times, driver, vehicle, road, environment, and crash characteristics [58]. Jiang et al. investigated the severity of roadside accidents at the entrance of the tunnel using the ordered probit (OP) model (see (25)–(27)) and suggested that heavy trucks were more likely to have serious roadside accidents [59]. Yau determined the risk factors of roadside accidents for different vehicle types in Hong Kong using a mixed logit model (see (23)). For example, the vehicle service time, crash time, and lighting conditions at night have a significant influence on the severity of car crashes, and the use of seat belts and day of week have a significant influence on the severity of truck crashes [5].

In terms of the driver factors, Rezapour et al. applied the ordered logit (OL) model (see (25)–(27)) to draw a conclusion that alcohol, gender, seat belt usage, and driver behavior affect the severity of roadside accidents [60]. In some literature, the OP, LCL, and mixed logit model were successively employed to study the severity of driver injuries. The results show that driver age ≥65, speeding, alcohol, drugs, overtaking, driving at night, improper operation, and emergency turning are related to serious roadside accidents, while road conditions (such as wet, oily, or sandy surfaces) have a minimal relationship with the severity of roadside accidents [61–63]. Arora et al. investigated the relationship between traffic accidents and alcohol consumption in India, and the results showed that 23% of the fatal traffic accidents involve drivers who had been drinking and most of the victims were between 21 and 40 years old [64]. Moreover, Islam et al. applied ML models (see (20)) and the mixed generalized ordered probit (MGOP) model (see (30) and (31)) to estimate the differences between drivers of different ages in terms of crash injuries [65, 66]. In further studies, young drivers were confirmed to be more likely to have serious roadside accidents [67–69]. By collecting crash data from New Mexico rural and urban areas, Wu et al. utilized the MNL model (see (21)) and the mixed logit model (see (23)) and concluded that the influence of drivers of different regions and genders on the severity of roadside accidents was significantly different [70]. Compared with female drivers, male drivers are more likely to have serious roadside accidents [71].

(1) OL/OP Model. The standard ordered response logit model is derived by defining an unobservable variable z:

$$z = \beta X_i + \varepsilon_i, \quad (25)$$

where X_i is a vector of variables determining the discrete ordering of each accident observation, β is a vector of estimable parameters, and ε_i is a random error term. If ε_i is assumed to be independent and identically distributed with the logistic distribution, an OL model is derived. However, an OP model would be used if ε_i is assumed to be normally distributed across observations. According to the above equation, observed injuries y can be defined as

$$\begin{aligned} &y = 1, \quad \text{if } z \leq \mu_0 \text{ (no injury)},\\ &y = 2, \quad \text{if } \mu_0 \leq z \leq \mu_1 \text{ (non incapacitating and possible injury)},\\ &y = 3, \quad \text{if } \mu_1 \leq z \leq \mu_2 \text{ (fatal injury)}, \end{aligned} \tag{26}$$

where μ_i is the unknown estimable parameter. The probability that an accident belongs to either of the i categories is defined as

$$P(y = i) = \Lambda(\mu_i - \beta X) - \Lambda(\mu_{i+1} - \beta X), \tag{27}$$

where $\Lambda(\cdot)$ is the standard logistic cumulative distribution function, and μ_i and μ_{i+1} represent the upper and lower thresholds for outcome i.

(2) Generalized Ordered Logit/Probit (GOL/GOP) Model. The basic idea of the model is to represent the threshold parameters as a linear function of exogenous variables. Thus, the thresholds are expressed as

$$\tau_{ij} = \text{function of}\left(Z_{ij}\right), \tag{28}$$

where Z_{ij} is a set of exogenous variables i associated with j threshold. Further, to ensure the accepted ordering of observed discrete severity, the parametric form is defined as

$$\tau_{i,j} = \tau_{i,j-1} + \exp\left(\delta_{ij} Z_{ij}\right), \tag{29}$$

where δ_{ij} is a vector of estimable parameters.

(3) Mixed Generalized Ordered Logit/Probit (MGOL/MGOP) Model. The MGOL/MGOP model is characterized by the enabling β vector and ψ thresholds to vary across observations, which is accomplished by subscripting these parameters with the index n. Thus, the model can then be written as follows:

$$y_n^* = \beta_n' X_n + \varepsilon_n, \tag{30}$$

$$y_n = i, \quad \text{if}\left(\psi_{n,i-1} < y_n^* < \psi_{n,i}\right), \tag{31}$$

where y_n^* is the latent propensity for occupant n in a given accident, which is translated into observed severity outcomes y_n by threshold parameters ψ_i, and X_n is the vector of covariates.

The parameter estimates of the above models are implemented using the log likelihood estimate. For a population of N accident observations, the likelihood function is shown as

$$\text{LL} = \sum_{n=1}^{N} \sum_{i=1}^{I} \delta_{in} \text{LN}\left(\Lambda(\mu_1 - \beta X_n) - \Lambda(\mu_{1+1} - \beta X_{n+1})\right), \tag{32}$$

where δ_{in} is equal to one if the observed discrete outcome is i, and zero otherwise.

In terms of environmental factors, by collecting data on serious roadside accidents in Beijing, Yuan et al. proposed that the crash time, crash date, and number of passengers are important factors that affect the severity of the roadside accident and that driving at night, driving on a work day, and driving alone are significantly correlated with fatalities and proposed corresponding security measures [61]. Li et al. employed the method of finite mixed random parameters to explore the influence of different variables on the severity of driver injuries in low-visibility weather [72]. In further research, they performed LCL model (see (22)) and applied the mixed logit model (see (23)) to carry out a study and concluded that vehicles on countryside roads are prone to severe roadside accident [63]. Recently, they also utilized the above two models to analyze roadside accident data in the rainfall weather model, and the results show that truck drivers are less likely to be seriously injured in roadside accidents [73]. These research results can provide a reference for making corresponding countermeasures to reduce the crash injuries of drivers in inclement weather.

3.2.2. Research Method Review. Similar to the research method to determine the frequency of roadside accidents, there are some statistical analysis problems with the data and methods employed to study the severity of roadside accidents. To solve these problems, researchers have continuously incorporated improved parameters and indicators into various statistical models to improve their statistical validity and robustness.

In terms of the severity of roadside accidents, the commonly used statistical analysis models are divided into disordered models (such as ML, MNL, and mixed logit models) and ordered models (such as OR, OL, GOR, and GOL models). Overall, the basis on which researchers choose a model mainly depends on the nature of the dependent variable and the applicability of different models to the data. The choice of a model for the analysis of ordered discrete variables has sparked considerable debate. For example, by comparing the test effects of different models, Eluru and Yasmin discovered that the GOL model (see (28) and (29)) overcame some shortcomings of the traditional ordered model and had true ordered equivalence when testing ordered discrete variables compared with the disordered multiple logit model [74, 75].

Generally, not all accidents are reported because, for example, some states only report those accidents involving property damage above a specific threshold dollar amount or require the degree of vehicle damage to be above a certain level. In addition, most accident databases are based on police reported data. It is well known that individuals involved in no injury or minor injury accidents are far less likely to have their accidents reported to police (in an effort to avoid the possible issuance of traffic citations and the involvement of insurance companies). The traditional ordered model is particularly vulnerable to the impact of crash data underreporting while the disordered framework model is not affected by these limitations. Therefore, in further research, Manner and Wünsch-Ziegler showed that the GOL model (see (28) and (29)) can solve this problem. In addition, the traditional ordered model tends to restrict the influence of explanatory variables on severity outcomes [76], which causes these factors to either increase the probability of lesser severity or increase the probability of greater severity [77]. Therefore, Eluru et al. built a mixed generalized ordered logit (MGOL) (see (30) and (31)) model to overcome this problem and allow the thresholds in the standard OL model (see (25)–(27)) to vary based on observed and unobserved characteristics [78].

In the development process of the disorder model, to overcome the inefficiency of the traditional ML model, Boyd and Mellman introduced the mixed logit model (see (23)) to traffic accident research, which can fully consider the heterogeneity factors not observed in the crash risk [79]. With advancements in traffic safety research and based on the original model, the mean heterogeneous mixed logit model (see (33)) has been successively developed. To account for unobserved heterogeneity, based on the mixed logit model (see (23)), the parameter is expressed as a linear combination of a fixed parameter and a stochastic term, as follows:

$$\beta_{ni} = \beta_i + \Gamma_i \nu_{ni}, \tag{33}$$

where β_i is the fixed parameter that is identical for all individual drivers, ν_{ni} is a stochastic term, and Γ_i is a parameter matrix providing the covariance and possible correlation matrix of parameters in the distribution of β_{ni}. The parameter estimates are also computed using the log likelihood estimate (see (32)). The developed model can achieve better goodness of fit of the model and contribute to in-depth analysis of risk factors that affect the severity of occupant injuries [80].

3.2.3. Statistical Analysis of Risk Factors. With reference to the statistical analysis method in Section 3.1.3, Figure 5 shows the risk factors that affect the severity of roadside accidents and indicates that the severity of roadside accidents involves 27 risk factors. Based on the number of publications, the top 5 factors are driver age ≤25 or ≥65, alcohol, speeding, failure to use seat belts, and heavy truck. Except for the heavy truck factor, all risk factors are related to driver factors. Therefore, to reduce the loss of roadside accidents, traffic management departments should focus on driver behavior control and education.

In addition, 14 risk factors are presented in Figures 4 and 5: alcohol, speeding, trees and poles, small-radius curves, no lighting, low-grade roads, inclement weather, fatigue, crash time, improper operation, vehicle service time, traffic volume, vehicle safety device (i.e., ESC), and narrow shoulders. These factors can lead to frequent and fatal crashes; therefore, these factors should be taken into account when carrying out roadside accident prevention and roadside safety design.

4. Practice of Roadside Safety Design

Since the late 1960s, roadside safety design has become a controversial topic of highway design. The concept of the RCZ was first presented in a conference paper of the Highway Research Board (HRB) in 1963 and was formally written into the *Highway Safety Design Manual* in May 1965. After two revisions in 1973 and 1978, the manual was incorporated into the application of highway project construction. In 1989, the first edition of the RDG was published by AASHTO; the second edition was published in 1996; and the third and fourth editions were published in 2002 and 2011.

In the fourth edition of the RDG, the RCZ is defined as "Clear Zone—The unobstructed, traversable area provided beyond the edge of the through traveled way for the recovery of errant vehicles. The clear zone includes shoulders, bike lanes, and auxiliary lanes, except those auxiliary lanes that function like through lanes" [8]. As indicated by the definition of the RCZ, this area should provide fault tolerance space with sufficient width for out-of-control vehicles as well as a gentle slope and no obstacles. When carrying out RCZ design, methods of determining the width and slope of the RCZ according to different regional characteristics, road characteristics, and traffic conditions and mitigating existing obstacles in the RCZ to ensure the minimum loss of vehicles that lose control along the roadside have been ongoing topics in academia.

In terms of RCZ width, the fourth edition of the RDG gives the recommended values of RCZ width in a straight section and the correction coefficient of the curve section. The recommended value of the RCZ in a straight section is selected based on the design speed, AADT, slope form (i.e., fill or cut), and slope gradient [8], and the use of these research results is prevalent internationally. Considering that the recommended values in the fourth edition of the RDG are reasoned based on limited empirical data, although these empirical data provide a reference for roadside safety design in the road construction of most countries, the characteristics of the road network, vehicle ownership, driving behavior, roadside obstacle distribution characteristics, and economic level of each country are quite different. Thus, researchers adjust various measures to the local conditions to analyze roadside safety design according to their national conditions.

The *Specifications for Highway Safety Audit (JTG B05-2015)* of China provides a graphic method for the width of the RCZ on fill and cut subgrades. The selection of the RCZ width in straight sections is based on running speed and one-way AADT, and the width in curve sections is determined by the correction coefficient according to the curve radius and operating speed [81]. Fan and Xing analyzed the main factors that influence the width design of the RCZ, including driver reaction time, state of vehicles that leave the road, and distance traveled by vehicles within the clear zone and established a calculation model for the width of the RCZ [82]. However, the basic assumption is that the slope is flat, which is inconsistent with the actual situation. In a study of driver behavior, Fitzpatrick et al. explored the influence of two variables, i.e., the width of the RCZ and the density of roadside vegetation, on driver behavior in terms of speed and lateral position. The results show that a wider RCZ corresponds to faster speed. As the width of the RCZ increases, drivers tend to drive closer to the road edge [83, 84].

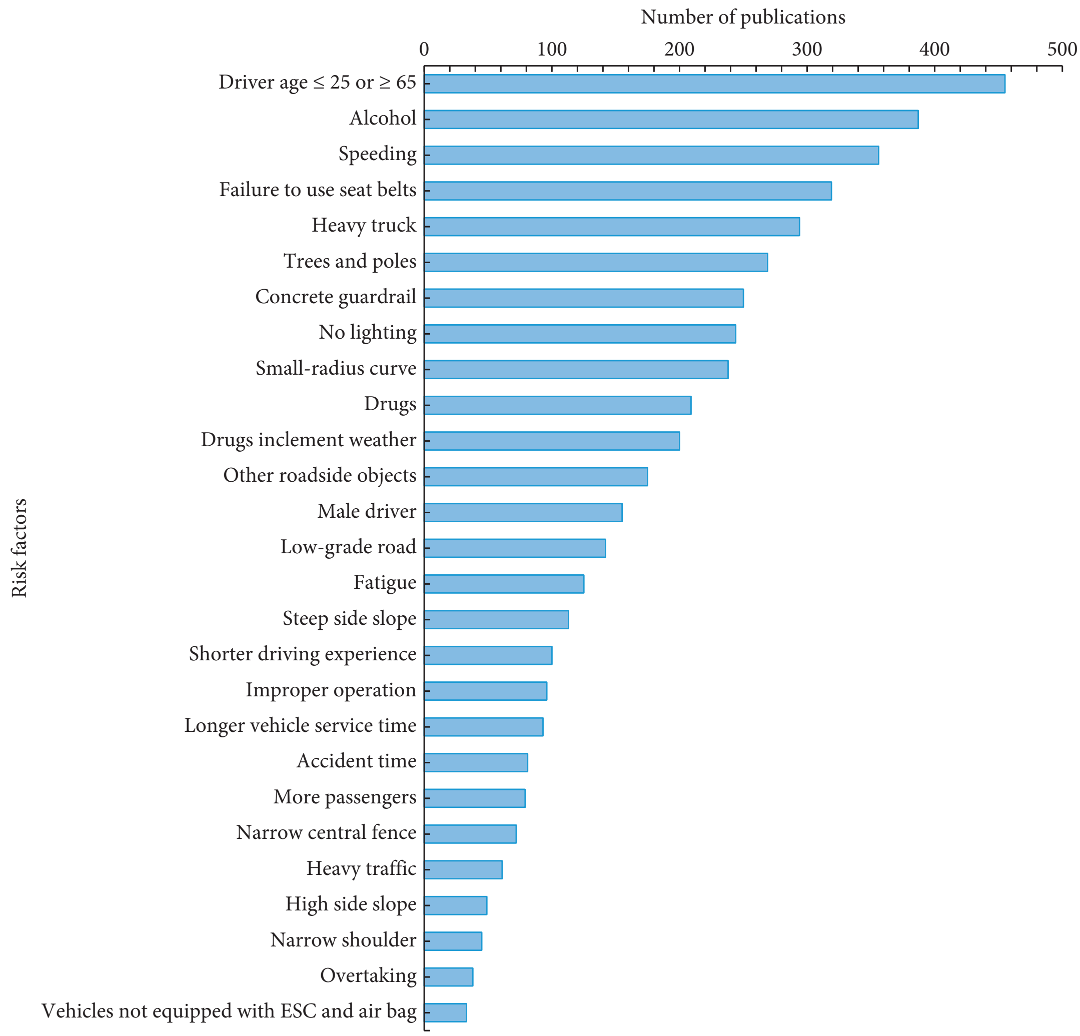

Figure 5: Risk factors for severity of roadside accidents.

In terms of roadside slope, the fourth edition of the RDG gives the slope standard in the RCZ, as shown in Figure 6. A slope equal to or less than 1 : 4 is considered recoverable, and a slope between 1 : 3 and 1 : 4 is considered unrecoverable. In addition, when the roadside does not have the conditions for setting a recoverable slope, additional buffer areas (clear runout area) can be set at the foot of the nonrecoverable slope to reduce crashes losses, and it is stipulated that the slope gradient in this area should be equal to or less than 1 : 6 [8]. According to China's *Specifications for Highway Safety Audit (JTG B05-2015)*, the filling slope cannot be regarded as an effective safety clear zone when the slope is steeper than 1 : 3.5. When the slope of the fill is between 1 : 3.5 and 1 : 5.5, a 1/2 slope width can be considered a safe clear zone, and when the slope gradient is less than 1 : 6, the whole slope width can be considered a safe area [81]. However, these regulations only refer to the research results of the AASHTO and do not give its theoretical basis.

In roadside guardrail design, to fully address the protective role of guardrail in roadside accidents, Johnson et al. improved the level of protection of guardrail stipulated in the fourth edition of the RDG by collecting data on real vehicle tracks in roadside accidents [85]. Rosenbaugh et al. developed an increased height approach guardrail transition (AGT) section and conducted two full-size crash tests to evaluate the safety performance of the AGT in accordance with the test standards of the *Manual for Assessing Safety Hardware* by the AASHTO [86]. For different types of guardrail structures, Lee et al. evaluated the vehicle collision performance of guardrails with three different column structures based on the aspects of maximum deflection, shock absorption energy, and occupant risk index [87]. Zou et al. employed the mixed logit model (see (23)) to evaluate the risk of occupant injuries in single-vehicle collisions. The results show that a guardrail should be preferred over a concrete wall and a cable barrier should be preferred over a guardrail, where the road and traffic conditions allow [52].

Aimed at different road characteristics and roadside environments, to determine the reasonable roadside guardrail level, Chen et al. established the decision model of the roadside guardrail level using AHP analysis and proposed the selection method of guardrail after comprehensively considering factors such as roadside lateral distance, slope condition, and guardrail deformation [88].

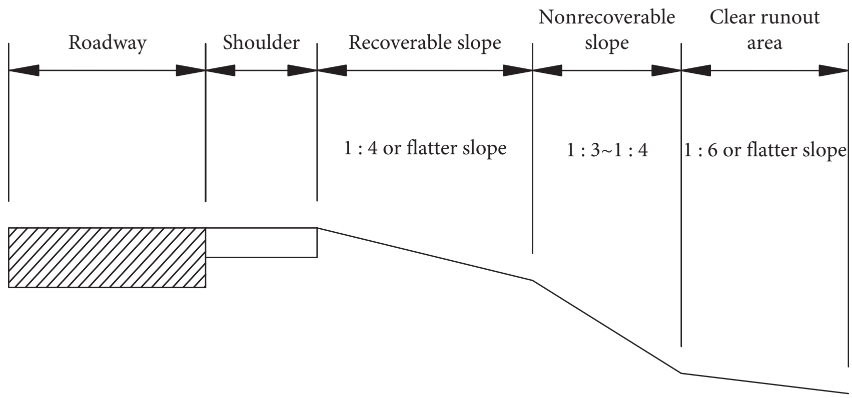

Figure 6: Setting standard of slope in the RCZ.

Based on UC-win/Road, Han et al. conducted emergency avoidance driving simulation tests at different speeds, used the Adams/Car vehicle-road coupling model to carry out simulations, and established a model of collision speed, collision angle, curve radius, steering, operating speed, and hard shoulder width by performing regression analysis. The analysis results showed that the reasonable grade of roadside guardrail should be determined according to the characteristics of road alignment and operating speed [89]. According to the *Design Specification for Highway Safety Facilities (JTG D81-2017)* of China, the guardrail protection level is divided into 1 to 8 levels, and it is stipulated that the guardrail protection level is selected according to the severity of the crash (low, medium, and high) [90]. The *Design Guidelines for Highway Safety Facilities (JTG/T D81-2017)* of China further details the guardrail grading situation that corresponds to the severity of crashes [91]. However, the severity of crashes mainly involves roadside facilities and obstacles and does not take into account the movement state and possible damage of vehicles after running into the roadside.

In the design of roadside traffic facilities protection and optimization, by the statistics and analysis of a large number of roadside accidents, Stonex concluded that 35% of injuries in roadside accidents are caused by inappropriate roadside design, such as impenetrable obstacles and sharp traffic facilities [92]. As a result, hazards in the RCZ are either removed or relocated. Otherwise, it is necessary to determine whether these hazards need to be redesigned or equipped with safety auxiliary facilities. For example, a disintegrating energy-dissipating separation design is adopted for roadside lamp posts, poles, and metal fixtures, etc., to absorb the energy that is generated instantly when vehicles collide with them [16]. Placing warning signs or protective measures (e.g., guardrail or cushion) around trees, boulders, and other dangerous objects can effectively reduce roadside accidents by more than 38% [93]. To evaluate the protective effect of poles with a separate design on occupant injuries, Xu et al. investigated the evaluation and structural design of the connection mode between a pole and its base. Two brittle joint structures were designed by finite element simulation. By using ANSYS software, the force data of concave and hole connection design of structures were given. The results show that the maximum tensile stress data of the two kinds of connecting structures are larger than the ultimate tensile strength of steel and can be separated in the collision to ensure occupant safety during crashes [94]. Holdridge et al. analyzed the service performance of roadside traffic facilities in Washington. The study results show the significant impact of the end of facilities on fatal traffic accidents, which emphasizes the importance of using well-designed end and reveals the need to upgrade the design standards for the end of facilities adjacent to bridges and other hazards [50].

In the method for setting the RCZ, a safety benefit/cost analysis system named ROADSIDE was proposed in the first version of the RDG for roadside design decisions on specific road sections [95]. Road design engineers need to weigh the risk of death and injury to road users against the cost of installing and maintaining safety facilities. Following the publication of the RDG (2002 version), the first Roadside Safety Analysis Program (RSAP) was developed to assess the effectiveness of roadside safety improvement based on the National Cooperative Highway Research Program (NCHRP) 22-9 and 22-9(2) projects. The RSAP is designed based on the approach of “encroachment probability” and incorporates two complete programs: the main analysis program, which includes cost-benefit programs and algorithms, and the user interface program, which provides a user-friendly environment for data input and results review. Compared with the ROADSIDE system, the RSAP has shown significant improvement in how encroachments and final crashes were allocated using a random solution rather than a deterministic method [96].

In addition, Ayati and Shahidian provided the optimal clear zone width by balancing the construction cost and safety improvement benefits obtained by increasing the roadside area. The research shows that, for curves with radii less than 195 m, the wider roadside recovery area is an important factor that affects roadside safety [97]. Considering the scarcity of land resources, Shahidian demonstrated the reasonable allocation of limited resources among different roadside safety schemes in the form of charts via the investigation of limited resources. According to the developed chart, road designers and planners are able to choose between the installation of guardrails and the gentle slopes of embankments from two perspectives: economic safety and roadside safety [98]. By listing numerous traffic protection measures and considering various factors, such as AADT, average collision cost, and discount rate, Roque and Cardoso analyzed the comprehensive safety benefits obtained by implementing various measures and the generated investment cost, operation cost, and maintenance cost; selected an alternative scheme according to the proposed incremental benefit cost ratio; and developed a computer-aided program [99].

5. Future Work

Although scholars in various countries have made some achievements in roadside safety, there is still a larger gap between the current research level and the actual application demand. Currently, a set of reasonable and effective roadside safety design method systems is still lacking. Although many problems exist in the field of roadside safety, the efforts of researchers are undeniable, and their attempts to establish new ideas and methods have increased people's knowledge of roadside safety. The following aspects warrant further study.

To determine the frequency of roadside accidents, researchers mainly rely on traffic accident data, construct and improve various statistical regression models to predict the number or frequency of roadside accidents, explore the key factors that affect the occurrence of roadside accidents, and carry out analyses to determine the frequency of roadside accidents but rarely conduct probability prediction of roadside accidents. Based on the complex causes of roadside accidents, scholars focus on analyzing the frequency with regard to the aspects of the driver, vehicle, road, and environment, which are often considered incomplete. In addition, the obtained research results based on crash number or crash frequency are often affected by different regions, traffic characteristics, and other factors and are not universal. Considering that the probability of crashes can better represent the degree of frequent crashes, it is necessary to conduct probability predictions of roadside accidents in the future. Various statistical regression models can predict the number or frequency of roadside accidents but are not suitable for calculating the probability of roadside accidents. Moreover, a discussion of identification methods for roadside accidents blackspot is lacking. A few studies have applied traditional technology to identify the blackspots of roadside accidents. Considering that the causative mechanism of roadside accidents is different from that of other types of traffic accidents, whether the traditional identification method is applicable to roadside accidents still needs to be verified. Therefore, an exploration of mature and effective identification methods for the potential blackspots of roadside accidents is expected.

To address the severity of roadside accidents, researchers have analyzed a large volume of crash data and explored the key factors that affect the severity of roadside accidents by assessing occupant injuries in crashes. Although the conclusions conform to the objective facts, the influencing factors that are taken into account are not complete and the obtained research results are also affected by different regional factors, which are not universal. In addition, occupant injury risk assessments may adopt the expert scoring method (i.e., several representative experts give the evaluation scores of each risk index according to the evaluation criteria based on their own experience and then calculate the weighted values), which cannot guarantee objectivity; such work may also focus on researching roadside hazards without considering the influence of slope gradient and height; however, these studies rarely involve the quantitative analysis of the impact of roadside guardrails on occupant injuries. Considering the numerous factors that affect the occupant injury risk and the correlation between them, it is difficult to directly apply existing methods to assess the occupant injury risk in roadside accidents according to specific road conditions and roadside characteristics. To a large extent, this assessment still depends on the experience judgment of designers and researchers.

For roadside safety design, the results obtained for the RCZ are mostly based on the ideal road surface while few studies have comprehensively considered the benefits involving roadside slope, which is inconsistent with the actual situation. Because of the land resource limitations and social stability problems associated with the concept of "forgiving roadside design," such a design concept is difficult to effectively implement in all areas. Therefore, the RCZ should be set according to the roadside accident probability, land use indexes for different road grades, construction costs, safety benefits, and other factors. However, current technical standards, such as China's *Technical Standards of Highway Engineering (JTG B01-2014)* and *Design Specification for Highway Alignment (JTG D20-2017)*, do not consider the conditions that should be set for the RCZ.

Using the RDG as a reference, China's *Specifications for Highway Safety Audit (JTG B05-2015)* divides the RCZ width into the calculated width and the actual width and presents a graphical method for calculating the RCZ width in straight sections based on the operating speed and one-way AADT. The RCZ width in curve sections is corrected according to the adjustment coefficient determined by the curve radius and operating speed, and the slope gradient, which can achieve an effective safety slope surface, is also specified [81]. However, problems associated with this method include the following: (1) The AADT is related to the probability of roadside accidents but should not be applied as the basis for determining the width of the RCZ; (2) the influence of vehicle type, longitudinal slope, superelevation slope, shoulder, and slope adhesion coefficient is not considered; (3) the effectiveness of the graphic method is limited, which hinders accurate calculation of the RCZ width; and (4) the quantitative relationship between the effective safety slope width and the slope gradient is not expressed, and findings for the actual RCZ width are not accurate enough. Therefore, from the perspective of roadside safety design, an accurate quantitative calculation method for the width of the RCZ and safety slope gradient as well as research on the setting conditions based on a cost-benefit analysis is still lacking.

In terms of the frequency of roadside accidents, a quantitative analysis of the probability of roadside accidents and an identification method for the roadside accidents blackspot are still lacking. In terms of the severity of roadside accidents, there is no mature method to quantitatively measure occupant injury risk. In roadside safety design practice, the precise quantification of the RCZ and safety slope, which involves the costs and benefits, has not been considered.

With the rapid development of computer technology, traffic safety research should also follow the trend. Considering the lack of universality of the research results obtained from crash cases, Cheng et al. utilized PC-Crash computer simulation software to obtain research data and carried out mechanism analyses of roadside accident causes and injured occupant risk assessment [57]. However, compared with real cases, the reliability of simulation data is still a topic to be discussed. Therefore, the advantages of different data acquisition methods should be fully considered in future studies. For example, computer simulation technology can be used to carry out the experiment of vehicle exiting roads instead of conducing real vehicle test to research RCZ design under the condition of low collision costs. Moreover, although Fitzpatrick et al. used a driving simulator to study the influence of the RCZ width and the density of roadside vegetation on the driver's behavior [83, 84], current driving simulation technology is not equipped with the analogue function of vehicles leaving the lane and entering the roadside. Moreover, in the popular field of driverless technology [100, 101], methods of fully exploiting computer vision technology to effectively detect and locate the roadside obstacles when the vehicle is about to enter or has entered the roadside to successfully avoid crashes or reduce crash losses constitute a research hotspot, and these topics should be explored in the future. The development of reasonable and effective roadside safety design methods based on the research statutes via advanced computer techniques to reduce the frequency and severity of roadside accidents is an important topic.

6. Conclusions

This paper analyzes the current development trend of roadside safety based on a literature review from multiple perspectives, such as the year of publication, country of publication, and source of publication; summarizes the research status of roadside safety in terms of three aspects, namely, frequency of roadside accidents, severity of roadside accidents, and practice of roadside safety design; and identifies existing problems and future research directions.

From the perspective of research methods, this paper reviews the development process of different prediction methods and evaluation models for the frequency and severity of roadside accidents. This paper statistically analyzes the risk factors and summarizes the significant ones that lead to frequent and fatal roadside accidents. The research results can provide a reference and suggestions for future roadside accident prevention and roadside safety design.

Currently, the rate of roadside accidents is still high, and research on roadside safety is ongoing. Future research should focus on quantitatively analyzing roadside accident probabilities and occupant injury risks, identifying roadside accident blackspots, developing accurate quantitative calculation methods for the RCZ width and safety slope gradient, and determining the conditions to be set for the RCZ based on a cost-benefit analysis as well as the computer technology for roadside safety to develop a more rational and effective roadside design method and reduce roadside accident rates and crash losses.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors do not have any conflicts of interest with other entities or researchers.

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