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METHODS

A New Stopping Sight Distance Model and Fuzzy Reliability Analysis Comparison

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ABSTRACT Aiming at the problem that the existing stopping sight distance model is out of sync with the development of the times, this paper puts forward a new stopping sight distance model considering the fuzziness and randomness of design parameters, and deduces the calculation method of fuzzy reliability of stopping sight distance. Firstly, the actual braking process of vehicle is divided into three stages: driver's reaction stage, braking force rising stage and continuous braking stage. Based on MATLAB/Simulink software, the calculation model of complete braking stage is simulated and analyzed, and then the calculation model of stopping sight distance of ESC system is proposed. Secondly, considering the fuzziness of operating speed, the fuzzy reliability theory is introduced to establish the function of the fuzzy reliability of the stopping sight distance. Using the Gaussian fuzzy number and the center point method, the reliability index and failure probability of stopping sight distance are obtained, and the safety and reliability of stopping sight distance are described. Finally, according to the ''Unified Standard for Reliability Design of Highway Engineering Structures'', the traditional reliability calculation method and fuzzy reliability calculation method are respectively used to calculate the stopping sight distance value corresponding to the highway safety level. Taking the calculated value of ESC system stopping sight distance model at the design speed of 120 km/h as a reference, the reliability index and failure probability of the two reliability calculation methods are calculated. The results show that the new stopping sight distance model is closer to reality than the existing stopping sight distance model in the continuous braking stage. Compared with the traditional reliability calculation method, the fuzzy reliability calculation method has high reliability index, low failure probability and high calculation accuracy. Implementing road design based on the stopping sight distance value calculated by the new stopping sight distance model and fuzzy reliability theory can improve road safety.

INDEX TERMS Stopping sight distance, fuzzy reliability, Gaussian fuzzy number, reliability index, failure probability.

I. INTRODUCTION

The driver judges the road alignment through vision, motion sense and feeling that changes with time, when the car is driving at a high speed. The choice of speed and driving route depends on the road conditions ahead and the surrounding instantaneous environment that the driver can clearly see, and it needs to have a far enough line of sight to predict the line direction, longitudinal slope, select lanes and avoid other vehicles and obstacles on the road with a high degree of accuracy, and stop in time and avoid danger in case of danger. Sufficient sight distance and clear vision are the most important factors to ensure safe driving, and also an important factor to enhance the visual and psychological sense of security and comfort of the drivers and passengers. If the line of sight is insufficient, the driver cannot take timely measures when encountering an emergency, and an accident is inevitable [1]. Since a reasonable stopping sight distance can effectively reduce the occurrence of highway emergencies [2], many scholars have carried out research on

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the influencing factors of stopping sight distance, which are mainly divided into three aspects: vehicle, road and driver. Vehicle start from the academic performance to the braking system of the vehicle, and a new stopping sight distance model is proposed [3]–[5]. The road aspect mainly involves the design of the stopping sight distance, and the stopping sight distance design is divided into two-dimensional plane design [6]–[8] and three-dimensional design [9]–[10]. The driver aspect mainly considers the driver's characteristics, such as age [11], driving age, reaction time, etc. Scholars usually focus on insufficient stopping sight distance. But they ignore that with the development of the times, the car performance is continuously improved [12]–[16], and the stopping sight distance changes. It has been 30 years since Chinese standard adopted the stopping sight distance index [17], but the rationality of its value is still open to question.

Stopping sight distance is affected by many factors, and each influencing factor varies greatly with time and space, and various relationships are intricate and full of uncertainty. These uncertainties come from the randomness and ambiguity of the influencing factors. Both the Chinese standard [17] and the American Green Book [18] use fixed indicators that ignore the influence of randomness and ambiguity of influencing factors on the stopping sight distance, resulting in an inaccurate stopping sight distance. Fuzzy reliability theory combines fuzzy mathematics with traditional reliability theory. It can deal with both ambiguity and randomness and it has been used in the reliability design of highway engineering [19]–[22]. Scholars have applied the traditional reliability theory to the stopping sight distance design [23]–[25], but no one has been involved in the application of the fuzzy reliability theory to the stopping sight distance design. Therefore, considering the influence of randomness and ambiguity of influencing factors on the calculation accuracy of stopping sight distance, it is of great significance to apply fuzzy reliability theory to reliability analysis of stopping sight distance.

In order to solve the problem that the stopping sight distance model is out of sync with the development of the times, this paper establishes a seven-degree-of-freedom vehicle model based on the ESC system, conducts vehicle dynamics simulation research with the help of MATLAB, analyzes the simulation results, and proposes a new stopping sight distance model. Considering the ambiguity and randomness of the design parameters in the new model, on the basis of the traditional reliability theory, a Gaussian membership function is introduced to deduce the calculation method of the fuzzy reliability of the stopping sight distance, and the new calculation method is applied to the design of the stopping sight distance.

II. ESTABLISH A STOPPING SIGHT DISTANCE MODEL

The Chinese standard divides the stopping sight distance into two parts, one is the distance traveled by the vehicle within the driver's reaction time, and the other is the distance traveled by the vehicle within the time from the start of braking to the stop of the vehicle [17]. Stopping sight distance model, as shown in Eq. (1)

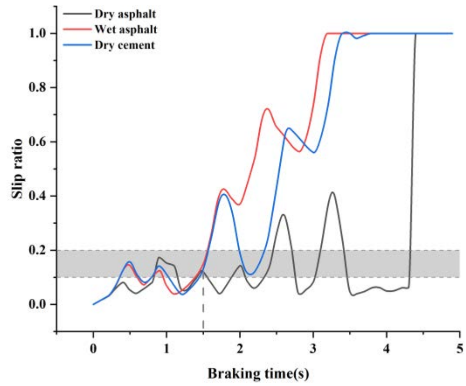

FIGURE 1. Relationship between slip ratio and braking time.

$$S_c = \frac{v_0}{3.6} t_c + \frac{(v_0/3.6)^2}{2gf} \tag{1}$$

In the formula, v_0 is the initial speed of vehicle braking; f is the longitudinal friction coefficient; g is the acceleration of gravity; t_c is the reaction time of the driver, and the value is 2.5s.

According to the research of Fambro *et al.* [26], [27], considering the influence of many conditions such as the distance of the object, the driver's visual acuity, the type of road, etc. The American Green Book [18] has a long-term friction coefficient stopping sight distance model. To improve, use the braking deceleration to replace the longitudinal friction coefficient, and establish the braking deceleration stopping sight distance model, as shown in Eq. (2).

$$S_a = 0.278 v_0 t_a + 0.039 \frac{v_0^2}{a} \tag{2}$$

In the formula, v_0 is the initial speed of vehicle, a is braking deceleration, and the value is 3.4 m/s^2; t_a is the reaction time of the driver, and the value is 2.5 s.

A. ESC SYSTEM DYNAMICS SIMULATION

Relevant research shows that [27], the stopping sight distance is only divided into reaction stage and full braking stage, which deviates from the actual situation of vehicle emergency braking. Vehicle electronic stability control system (ESC) is a further expansion of the functions of vehicle anti-lock braking system (ABS) and traction control system (TCS), so that the vehicle can have certain control ability and maintain high braking force in case of emergency braking. In order to comprehensively consider the influence of the ESC system on stopping sight distance, the whole vehicle model of ESC system is established based on MATLAB. At the operating speed of 20 km/h, the dynamic simulation research under the conditions of dry asphalt, wet asphalt and dry cement is carried out respectively, and the relationship curve between slip ratio and braking time is obtained. As shown in Fig. 1.

It can be seen from Fig. 1 that in the braking time of 1.5 s, the variation law of the slip ratio is roughly the same under the three road conditions, and the slip ratio varies between 0.1

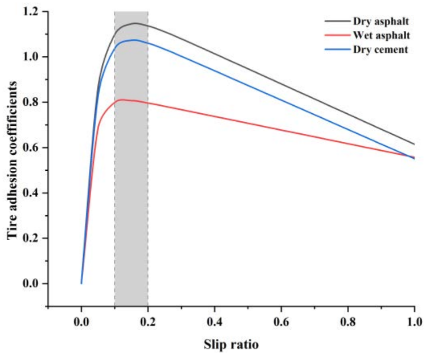

FIGURE 2. Relationship between tire adhesion coefficient and slip ratio.

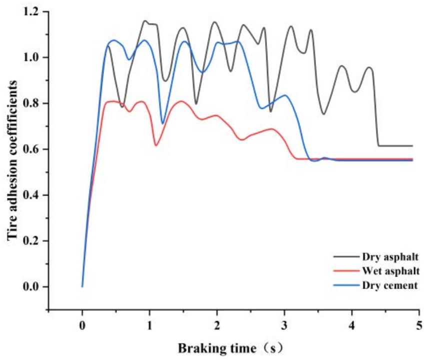

FIGURE 3. Relationship between adhesion coefficient and braking time.

and 0.2. Under the condition of wet asphalt pavement and dry cement pavement, the variation range of slip ratio increases and shows an upward trend, while under the condition of dry asphalt pavement, the slip ratio still maintains a small variation range.

Slip ratio is an important motion parameter of the ESC system. It refers to the proportion of the tire rolling when the tire changes between rolling and sliding, and it is usually expressed by η, when $\eta = 0$, the tire is in a rolling state; when $\eta = 1$, the tire is in a slipping state. Scholars [28], [29] studied the tire adhesion coefficient in different states and found that tires in different states have different adhesion coefficients, and the relationship between it and the slip ratio is shown in Fig. 2.

It can be seen from Fig. 2 that under the three road conditions of dry asphalt, wet asphalt and dry cement, the tire adhesion coefficient increases with the increase of slip ratio, showing the law of first increasing and then decreasing. Under three road conditions, in the interval of slip ratio 0.1-0.2, the tire adhesion coefficient can obtain the maximum value, the maximum value is called the peak adhesion coefficient, recorded as φ_P. The minimum value can be obtained, which is called the slip adhesion coefficient, recorded as φ_1. According to the relationship between the slip ratio and the adhesion coefficient, the relationship curve between the adhesion coefficient and the braking time of the vehicle in the continuous braking phase is shown in Fig. 3.

It can be seen from Fig. 3 that compared with the wet asphalt pavement condition, the tire adhesion coefficient under the dry asphalt pavement condition has a more obvious variation between the peak adhesion coefficient and the sliding adhesion coefficient. It indicates that the performance of the ESC system is better under the dry asphalt pavement condition. As the adhesion coefficient decreases, the number of times the tire adhesion coefficient reaches its peak decreases, and the braking performance of the ESC system weakens.

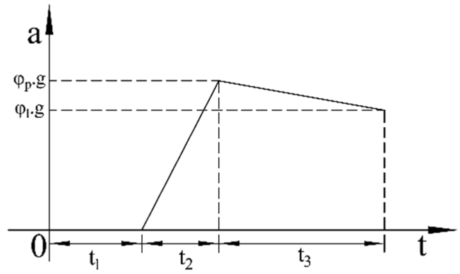

FIGURE 4. Vehicle braking process.

In summary, when the slip ratio is in the range of 0.1-0.2, a higher tire adhesion coefficient can be obtained. The ESC system can maintain the slip ratio in the range of 0.1-0.2 under the condition of dry asphalt pavement. to obtain the highest braking force. Under the condition of dry cement and wet cement road, the performance of maintaining the slip ratio in the range of 0.1-0.2 is weakened, and the braking force is reduced. Compared with the tire locking condition, it still has a good braking force.

B. THE NEW MODEL OF STOPPING SIGHT DISTANCE

The research results of Fambro *et al.* [27] show that the braking process of the vehicle braking system has nothing to do with the initial speed. Considering the consistency with the normative conditions, this paper simplifies the vehicle braking process into the three stages shown in Fig. 4 based on the simulation results under wet asphalt pavement conditions.

In Fig.4, t_1, t_2, and t_3 are the driver's reaction time, the braking force rise time, and the continuous braking time. Assuming that the vehicle runs at a constant speed in the driver's reaction phase, the initial braking speed is v_0, and the braking reaction distance is S_1.

$$S_1 = \frac{v_0 t_1}{3.6} \tag{3}$$

Assuming that the vehicle reaches the braking deceleration of the peak adhesion coefficient in the braking force rising stage a_f, the vehicle deceleration at any time (t_2') in this stage is

$$a_2 = \frac{dv}{dt_2'} = -\frac{a_f}{t_2} t_2' \tag{4}$$

a_f is the absolute value of the maximum braking deceleration.

The operating speed of the vehicle at any time(t_2') is

$$\int_{\frac{v_0}{3.6}}^{v_2} dv_2 = \int_0^{t_2'} a_2 dt_2' \tag{5}$$

$$v_2 = \frac{v_0}{3.6} - \frac{a_f}{2t_2} t_2'^2 \tag{6}$$

According to formula (6), the driving distance of the vehicle in the braking force rising stage is S_2.

$$S_2 = \int_0^{t_2} v_2 dt_2' = \frac{v_0}{3.6} t_2 - \frac{a_f}{6} t_2^2 \tag{7}$$

Assuming that the braking acceleration in the continuous braking phase conforms to a linear function, the braking deceleration (a_3) at any time (t_3') in this phase is

$$a_3 = g\left(jt_3' + h\right) \tag{8}$$

$$j = -\left(\frac{\varphi_p - \varphi_1}{t_3}\right) \tag{9}$$

$$h = \varphi_p + \frac{\left(\varphi_p - \varphi_1\right) t_2}{t_3} \tag{10}$$

j is the coefficient of the linear term of the linear function, h is the constant term of the linear function.

The vehicle speed v_3 at any time(t_3') during the continuous braking phase is

$$\int_{v_m}^{v_3} dv_3 = \int_0^{t_3'} a_3 dt_3' \tag{11}$$

$$v_3 = v_m - g\left[\varphi_p t_3' + \frac{t_2\left(\varphi_p - \varphi_1\right)}{t_3} t_3' - \frac{\left(\varphi_p - \varphi_1\right)}{2t_3} t_3'^2\right] \tag{12}$$

v_m is the operating speed of the vehicle at the starting point of the continuous braking phase.

During the continuous braking time, the vehicle reduces the initial operating speed to 0 with the braking deceleration (a_3), and the time is t_3, then

$$v_m = g\left[\frac{\varphi_p + \varphi_1}{2} t_3 + \left(\varphi_p - \varphi_1\right) t_2\right] \tag{13}$$

When the vehicle reaches the peak adhesion coefficient in the braking force rising stage, the operating speed of the vehicle is

$$v_m = \frac{v_0}{3.6} - \frac{a_f t_2}{2} = \frac{v_0}{3.6} - \frac{g\varphi_p t_2}{2} \tag{14}$$

Eq. (13) and Eq. (14) can be obtained simultaneously

$$t_3 = \frac{2v_0}{3.6g\left(\varphi_p + \varphi_1\right)} - \frac{\left(3\varphi_p - 2\varphi_1\right)}{\varphi_p + \varphi_1} \tag{15}$$

The distance S_3 traveled by the vehicle in this time period is as (16), shown at the bottom of the page.

TABLE 1. Values of tire adhesion coefficients under different operating speeds.

Design speed（km/h）	Sliding adhesion coefficient	Peak adhesion coefficient
20	0.44	0.64
30	0.44	0.64
40	0.38	0.55
60	0.33	0.48
80	0.31	0.45
100	0.3	0.43
120	0.29	0.42

By adding Eq. (3), Eq. (7) and Eq. (16), the braking distance(S_e) formula of ESC system is

$$S_e = S_1 + S_2 + S_3 \tag{17}$$

Substituting each parameter value in the specification and the Green Book into the longitudinal friction coefficient stopping visual-range model and the braking deceleration stopping visual-range model, can get

$$S_c = 0.014v_0^2 + 0.694v_0 \tag{18}$$

$$S_a = 0.011v_0^2 + 0.694v_0 \tag{19}$$

The results of scholars [30], [31] show that the adhesion coefficient is affected by the speed of operation. According to the ratio of the operating speed to the sliding adhesion coefficient in the specification, the value of the peak adhesion coefficient at different operating speeds is calculated, as shown in Table 1.

According to the research of Burckhardt [32], the time consumed by the vehicle in the braking force rising phase is generally 0.2 s. Table 2 gives the stopping sight distance model of the ESC system under the condition of different design speeds and wet asphalt pavement.

Assuming that the gradient of the longitudinal slope is zero, the three stopping sight distance models are divided into two parts, L_1 and L_2 by the degree of the operating speed polynomial. According to the three stopping sight distance models, the respective stopping sight distances are calculated respectively, as shown in Fig. 5.

In Fig. 5, the calculated value of the stopping sight distance in China is obtained by using the operating speed. When the design speed is 20∼30 km/h, the operating speed is equal to the design speed; when the design speed is 40∼60 km/h, the operating speed is equal to 90% of the design speed; when the

$$\begin{aligned} S_3 = \int_0^{t_3} v_3 dt_2' &= \left(\frac{0.0147\varphi_1 + 0.001\varphi_p}{\left(\varphi_p + \varphi_1\right)^2}\right) v_0^2 \\ &- \left(\frac{(0.773 + 0.553t_2)\,\varphi_p^2 + (0.824 + 0.276t_2)\,\varphi_1\varphi_p + (0.562 + 0.276t_2)\,\varphi_1^2}{\left(\varphi_p + \varphi_1\right)^2}\right) v_0 \\ &- \left(\frac{(1.639t_2 - 2.543)\,\varphi_p^2 + (0.819t_2 + 1.449)\,\varphi_1\varphi_p + (0.056 - 0.819t_2)\,\varphi_1^2}{\left(\varphi_p + \varphi_1\right)^2}\right) \end{aligned} \tag{16}$$

TABLE 2. Stopping sight distance model of ESC system.

Design speed (km/h)	ESC system stopping sight distance
20	$S_{e_1} = 0.0061v_0^2 + 0.1009v_0$
30	$S_{e_2} = 0.0061v_0^2 + 0.1009v_0$
40	$S_{e_3} = 0.0071v_0^2 + 0.1012v_0$
60	$S_{e_4} = 0.0081v_0^2 + 0.101v_0$
80	$S_{e_5} = 0.0087v_0^2 + 0.101v_0$
100	$S_{e_6} = 0.0091v_0^2 + 0.1024v_0$
120	$S_{e_7} = 0.0093v_0^2 + 0.1012v_0$

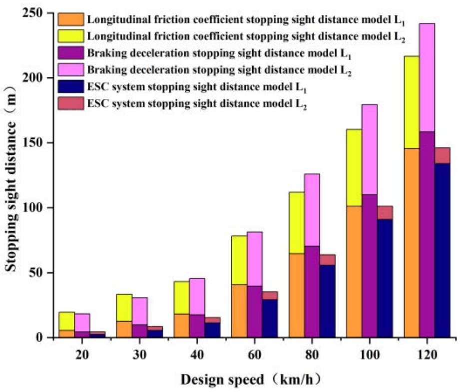

FIGURE 5. Three kinds of stopping sight distance calculation values.

design speed is 80∼120 km/h, the operating speed is equal to 85% of the design speed.

It can be seen from Fig. 5 that under the same conditions, the calculated value of the ESC system stopping sight distance model is smaller than the calculated value of the stopping sight distance in China and the United States. The greater the design speed, the greater the difference in the stopping sight distance. The difference is mainly manifested in the L_2 part, because there are differences in the value of the first-order coefficient of the stopping sight distance model. When establishing the stopping sight distance model of the ESC system, the vehicle in the full braking stage is regarded as a uniform deceleration movement, and the coefficient of the linear term in the Eq.(16) for solving the distance in this stage is negative, which is the same as the formula in the driver reaction stage. The first-order coefficients of (3) are added, so that the first-order coefficients of the stopping sight distance model of the ESC system are smaller than the first-order coefficients of the stopping sight distance in China and the United States.

III. FUZZY RELIABILITY ANALYSIS METHOD OF STOPPING SIGHT DISTANCE

A. ESTABLISH FUZZY RELIABILITY FUNCTION OF STOPPING SIGHT DISTANCE

Assume that the fuzzy reliability function is

$$Z = C - \tilde{D} \tag{20}$$

In the Eq. (20), C is the constant of design parameters provided by the highway. $\tilde{D}$ is the fuzzy variable of the driver's expected design parameter. Obviously, C and $\tilde{D}$ are independent of each other.

According to Eq. (20), the limit state equation can be obtained as follows

$$Z = C - \tilde{D} = 0 \tag{21}$$

If $Z > 0$, the route design parameters meet the design requirements;

If $Z = 0$, the route design parameters are at critical values;

If $Z < 0$, the route design parameters do not meet the design requirements and are in a failure state.

According to Eq. (18), Eq. (19) and Table 1, the fuzzy reliability function of stopping sight distance is derived as shown in Table 3.

TABLE 3. Performance functions of the three models.

Computational model	Performance function
Longitudinal friction coefficient stopping sight distance model	$Z_1 = C - 0.014\tilde{v}_0^2 - 0.694\tilde{v}_0$
Braking deceleration stopping sight distance model	$Z_2 = C - 0.011\tilde{v}_0^2 - 0.694\tilde{v}_0$
ESC system stopping sight distance model	$Z_3 = C - 0.0093\tilde{v}_0^2 - 0.1012\tilde{v}_0$.

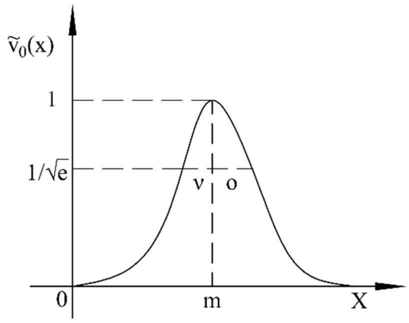

FIGURE 6. Gaussian fuzzy number.

In Table 3, ESC system stopping sight distance model is based on the stopping sight distance model with design speed of 120 km/h, and $\tilde{v}_0$ of the three model function functions is fuzzy operating speed.

B. SOLVE FUZZY OPERATING SPEED

It can be seen from Table 3 that the operating speed involved in the fuzzy reliability function is fuzzy number, which can be divided into triangular fuzzy number, trapezoidal fuzzy number and Gaussian fuzzy number, all of which are convex fuzzy number. In this paper, it is assumed that the operating speed $\tilde{v}_0$ is a Gaussian fuzzy number, and its membership function is a Gaussian function. Generally, the symbol $\tilde{v}_0\,(m, \nu, o)$ is used to represent the Gaussian fuzzy number, where m is the core element of the fuzzy number, corresponding to the value at $\tilde{v}_0\,(x) = 1$, and ν and o are the left and right variances corresponding to the standard deviation of Gaussian distribution which as shown in Fig. 6.

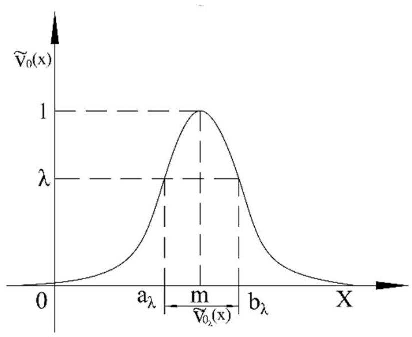

FIGURE 7. λ -cut set of operating speed.

The membership function [22] can be expressed as

$$\tilde{v}_0(x) = \begin{cases} \exp\left[-(x-m)^2/2\nu^2\right] & x < m \\ \exp\left[-(x-m)^2/2o^2\right] & x \geq m \end{cases} \tag{22}$$

Parameters ν, m and o in Gaussian number $\tilde{v}_0$ are calculated as follows [33]

$$\nu = \sqrt{2}(\tau - \varsigma) \tag{23}$$
$$m = \tau \tag{24}$$
$$o = \sqrt{2}(\upsilon - \tau) \tag{25}$$

ς, τ, and υ in Eq. (23) to (25) are the minimum, intermediate, and maximum values in the stopping speed data, respectively.

C. SOLVE FUZZY RELIABILITY OF STOPPING SIGHT DISTANCE

According to the definition of λ-cut set in fuzzy mathematics, under the condition of threshold $\lambda(\lambda \in [0, 1])$, $\tilde{v}_{0_\lambda} \in [a_\lambda, b_\lambda]$ is a classic set, as shown in Fig. 7.

For any threshold, there are

$$a_\lambda = m - \nu\sqrt{2\ln\lambda} \tag{26}$$
$$b_\lambda = m + o\sqrt{2\ln\lambda} \tag{27}$$

Suppose $\tilde{v}_{0_\lambda}$ obeys uniform distribution, its probability density function $f_{\tilde{v}_{0_\lambda}}(x)$ under the condition of threshold λ is

$$f_{\tilde{v}_\lambda}(x) = \frac{1}{b_\lambda - a_\lambda} \tag{28}$$

Taking $f_{\tilde{v}_{0_\lambda}}(x)$ as an integrand and integrating over λ, the probability density function is obtained as

$$\hat{f}_{\tilde{v}_{0_\lambda}}(x) = \int_0^\lambda \frac{1}{b_\lambda - a_\lambda} d\lambda = \frac{2\sqrt{\pi}}{(\nu + o)}\left(1 - 2\Phi\sqrt{\ln\lambda}\right) \tag{29}$$

In the formula, Φ represents the standard normal distribution function, and λ is equivalent to the membership function of Gaussian fuzzy number.

According to the knowledge of probability theory, the equivalence mean and equivalence variance are calculated as follows

$$\hat{\mu}_x = \int_{-\infty}^{+\infty} x\hat{f}_{\tilde{v}_{0_\lambda}}(x)dx \tag{30}$$

$$\hat{\sigma}_x = \sqrt{\int_{-\infty}^{+\infty} (x - \hat{\mu}_x)^2 \hat{f}_{\tilde{v}_\lambda}(x)dx} \tag{31}$$

Substituting Eq. (29) into Eq. (30) and Eq. (31) respectively, the mean value $\hat{\mu}_x$ and standard deviation $\hat{\sigma}_x$ of equivalent random variables are

$$\hat{\mu}_x = m + \frac{\sqrt{2\pi}}{4}(o - \nu) \tag{32}$$

$$\hat{\sigma}_x = \sqrt{\frac{2}{3}\nu o + \frac{(16 - 3\pi)(o - \nu)^2}{24}} \tag{33}$$

The performance function of the stopping sight distance is expanded into the Taylor series at the mean point $\hat{\mu}_x$ and retained to the primary term to obtain the simplified performance function Z_i' as follows

$$Z_i' = k_i v_0 + b_i \quad (i = 1, 2, 3) \tag{34}$$

In the formula, k_i is the first term coefficient of the performance function, and b_i is a constant term.

As the function Z_i' is a linear function of v_0, according to the properties of mean and variance in probability theory, it can be concluded that

$$\mu_z = k_i\hat{\mu}_x + b_i \tag{35}$$
$$\sigma_z = |k_i|\hat{\sigma}_x \tag{36}$$

The reliability of the stopping sight distance is usually expressed by the reliability index β and the failure probability P_f. The relationship between the two is shown in Fig. 8.

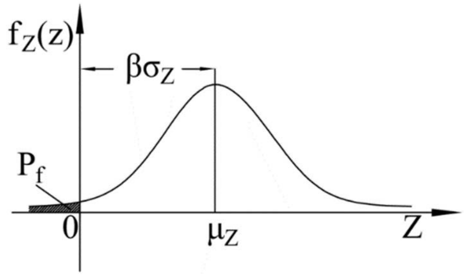

FIGURE 8. Relationship between reliability index and failure probability.

As can be seen from Fig. 8, the reliable index of stopping sight distance can be expressed by the ratio of mean value μ_Z and standard deviation σ_Z.

$$\beta = \frac{\mu_Z}{\sigma_Z} \tag{37}$$

The failure probability P_f of stopping sight distance can be expressed as

$$P_f = 1 - \Phi(\beta) \tag{38}$$

In the Eq. (38), Φ represents the standard normal distribution function. The expression shows that if the value of the reliability index is known, the failure probability of the stopping sight distance can be determined and can be used to evaluate the reliability of the stopping sight distance.

TABLE 4. Operating speed statistics(unit:km/h).

118.54	118.01	124.21	115.1	111.52	120.41
120.46	122.62	107.47	112.64	116.18	121.29
118.76	118.41	111.89	119.33	113.4	115.59

TABLE 5. Simplified performance functions of the three stopping sight distance models.

Computational model	Performance function
Longitudinal friction coefficient stopping sight distance model	$Z_1' = -3.89v_0 + 391.98$
Braking deceleration stopping sight distance model	$Z_2' = -3.2v_0 + 352.98$
ESC system stopping sight distance model	$Z_3' = -2.22v_0 + 331.32$

TABLE 6. Fuzzy reliability index and failure probability of three stopping sight distance models.

Computational model	Reliability index	Failure probability
Longitudinal friction coefficient stopping sight distance model	-1.39	0.92
Braking deceleration stopping sight distance model	-0.39	0.65
ESC system stopping sight distance model	3.69	0.01

IV. EXAMPLE ANALYSIS

A. ENGINEERING EXAMPLE

Select the data of operating speed in reference [34], as shown in Table 4.

According to the formula of Gaussian fuzzy number calculation parameters, the minimum value $\varsigma = 107.47$ km/h, the middle value $\tau = 118.21$ km/h, and the maximum value $\upsilon = 124.21$ km/h in Table 4 are selected respectively. Take the value into Eq. (20) and calculate the Gaussian membership function of the operating speed.

$$\tilde{v}_0(x) = \begin{cases} \exp\left[-(x-118.21)^2/461.35\right] & x < 118.21 \\ \exp\left[-(x-118.21)^2/143.99\right] & x \geq 118.21 \end{cases} \tag{39}$$

According to Eq. (32) and Eq. (33), the equivalent mean and standard deviation of the Gaussian fuzzy number of operating speeds are calculated as follows: $\hat{\mu}_x = 114.01$ and $\hat{\sigma}_x = 9.526$.

The highway design parameter constant C given by the Chinese specification takes the value of 210 m. The simplified performance functions of the three stopping sight distance models are derived according to Eq. (34), respectively, as shown in Table 5.

According to Eq. (37) and Eq. (38), the reliability indexes and failure probabilities of the fuzzy reliability of the three stopping sight distance models were calculated as shown in Table 6.

Based on the data in Table 4, the mean and standard deviation of the operating speeds were found to be $\mu_x = 116.99$, $\sigma_x = 4.37$. The reliability indexes and failure probabilities for the conventional reliability of the three stopping sight distance models were calculated, as shown in Table 7.

TABLE 7. Traditional reliability index and failure probability of three stopping sight distance models.

Computational model	Reliability index	Failure probability
Longitudinal friction coefficient stopping sight distance model	-3.62	0.99
Braking deceleration stopping sight distance model	-1.52	0.94
ESC system stopping sight distance model	6.81	0.02

TABLE 8. Different security levels correspond to reliability.

Safety level	First class	Second class	Third class
Road grade	Expressway	First class	Second class
Target reliability	0.95	0.9	0.85
Target reliability index	1.645	1.282	1.036

B. RESULTS ANALYSIS

The results of the reliability index and failure probability calculations in Table 6 and Table 7 are collated and plotted in Fig. 9.

As can be seen from Fig. 9, compared with the traditional reliability calculation method, the fuzzy reliability calculation method has higher reliability index and lower failure probability, which indicates that after considering the fuzziness of influencing factors, the calculation accuracy of reliability has been improved, and the calculation results are closer to reality. Comparing the results of the three stopping sight distance models, the ESC system stopping sight distance model has the highest reliability index and the lowest failure probability, which indicates that the ESC system shortens the braking distance of the vehicle and improves the driving safety of the vehicle.

The existing specification do not make clear provisions for the reliability of the stopping sight distance. Generally, since the degree of accidents caused by insufficient sight distance is closer to that caused by the pavement structure, the provisions of the Unified Standard for Reliability Design of Highway Engineering Structures [35] for the target reliability of the pavement structure are used as the basis, and the provisions are shown in Table 8.

According to the requirements of the highway safety level as the first level reliability index in Table 8, the required sight distance value of the highway is calculated by the stopping sight distance reliability function, and the target reliability is 95% by using the traditional reliability calculation method and the fuzzy reliability calculation method, respectively. Taking the calculated stopping sight distance value of the ESC system stopping sight distance model at 120 km/h of 146 m as the reference value, the reliability indexes and failure probability of the calculated values of the two methods are calculated and shown in Table 9.

TABLE 9. Calculation value and recommended value of stopping sight distance.

Design speed （km/h）	Traditional reliability calculation method			Fuzzy reliability calculation method		
	Stopping sight distance calculation value（m）	Reliability index	Failure probability	Stopping sight distance calculation value（m）	Reliability index	Failure probability
120	148	1.405	0.8	167	1.647	0.0498

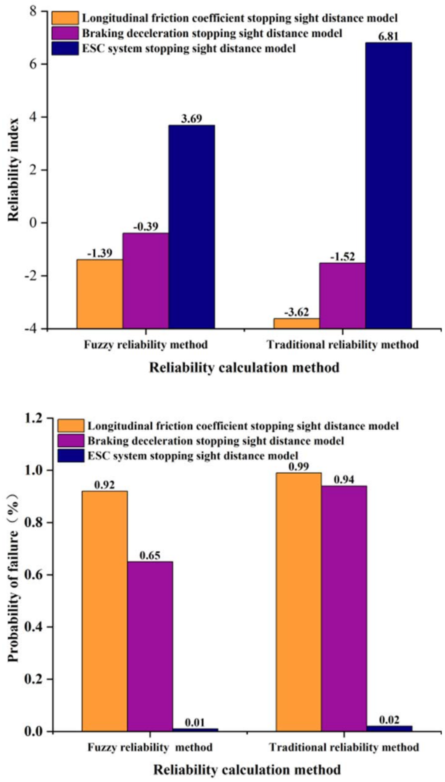

FIGURE 9. Comparison between fuzzy reliability and traditional reliability calculation result.

As can be seen from Table 9, compared with the traditional reliability calculation method, the value of the fuzzy reliability calculation method is closer to the requirements of the road corresponding to the safety level of first-class reliability index, and the recommended sight distance value is safer and more reliable.

V. CONCLUSION

In order to optimize and improve the existing stopping sight distance model, the stopping sight distance model of the ESC system is put forward based on MATLAB software simulation analysis, and the reliability of the stopping sight distance is analyzed by fuzzy reliability theory.

Firstly, starting from the actual braking principle of vehicle, the braking process is divided into driver's reaction stage, braking force rising stage and complete braking stage, and the stopping sight distance model of ESC system is established. Therefore, considering the stopping sight distance model of the whole process, under the same restriction conditions, the calculated stopping sight distance is less than the current standard value. Secondly, the fuzzy reliability analysis of three kinds of stopping sight distances is carried out. The research results show that compared with the traditional calculation method of stopping sight distances, the fuzzy reliability calculation method has higher reliability index, lower failure probability and higher calculation accuracy, which can improve highway safety. Finally, under the condition of the reliability index of safety level 1, the new model and method are used to calculate that the standard value of stopping sight distance is 170 m at 120 km/h.

Besides the randomness and fuzziness of the operating speed, other parameters in the stopping sight distance model have the same characteristics. In order to improve the safety and reliability of the recommended stopping sight distance, considering the randomness and fuzziness of the model parameters will become the main research content in the future. The reliability of stopping sight distance is not clearly defined in the existing specifications, and how to define the reliability of stopping sight distance is also a problem that needs to be studied in the future.

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