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Research Article

Unsafe Behavior Analysis and Risk Measurement of Traffic Accidents in Mountainous Highway Tunnel

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Traffic accidents in mountainous highway tunnels have resulted in significant negative effects and losses. Among the potential hazards that can lead to fatal injuries, human-related hazards have been recognized as the leading cause. Determining the risk management effectively and prioritizing unsafe human behavior are the basis for preventing and controlling traffic accidents in mountainous highway tunnels. Therefore, hazards that could potentially cause highway tunnel traffic accidents were identified by using a tail-biting fish diagram combined with the fault tree method. A risk assessment model was constructed based on probability, degree of importance, and loss. Furthermore, the probability can be calculated by assessing the degree of unreliability, which can be obtained by assessing the degree of importance of unsafe behavior in the fault tree, and the loss can be acquired from the authority. The case of 8–10 traffic accidents that occurred in the Qinling No. 1 Tunnel of the Ankang section of the Beijing-Kunming expressway was studied, and the values of the unsafe behaviors were assessed. According to the risk values, the priority for controlling unsafe behaviors can be acquired and tailored measures can be taken to prevent and control the risks, which provides a theoretical basis and new method for the effective control of mountainous highway tunnel traffic accidents.

1. Introduction

The highway is not only an important symbol of traffic modernization but also a symbol of national modernization [1]. By 2021, China's highway mileage is 169,000 km, accounting for 3.2% of the world's total highway mileage, ranking first worldwide.

With the fast construction of highways and extending to mountainous areas, tunnels, as a direct traffic facility crossing mountains, have been increased greatly, as the tunnels have the functions of improving alignment standards, ameliorating technical status, shortening operation distance, enhancing transport capacity, and protecting the ecological environment. According to statistics, the number of highway tunnels in China has exceeded 20,000, reaching 21316, and the total length has exceeded 20 million meters (21.999 million meters actually) by 2020, far more than the other countries in the world (Figure 1). Moreover, the number of long freeway tunnels in China increased rapidly from 2010 to 2020 (Figure 2). By 2020, the number of long freeway tunnels in China had reached 5541, with a total length of 9.633 million meters. Among them, the number of extra-long highway tunnels has reached up to 1394, with a total length exceeding 6.23 million meters.

Serious road traffic accidents often occur in tunnels worldwide. The earliest recorded tunnel traffic accident occurred in 1949 at the Holland Tunnel in New York City, where a dangerous chemical vehicle caught fire and generated a large amount of toxic gas, causing 66 people to be poisoned and 23 vehicles damaged. In 1982, a serious tunnel traffic accident occurred at the Salang Tunnel in Afghanistan, where a truck collided with a tanker, resulting in an explosion; more than 200 people were killed, and hundreds of vehicles were damaged. In 1999, a truck fire accident

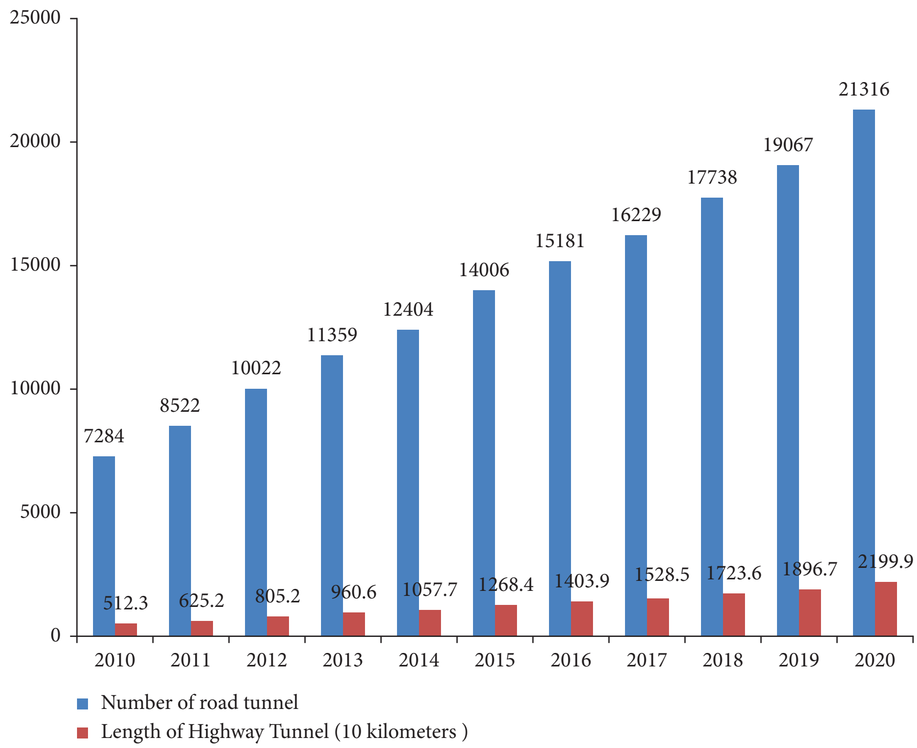

Figure 1: Statistics on the number and length of highway tunnels in China (2010–2020). Source: Transportation Knowledge Service System of China (2021).

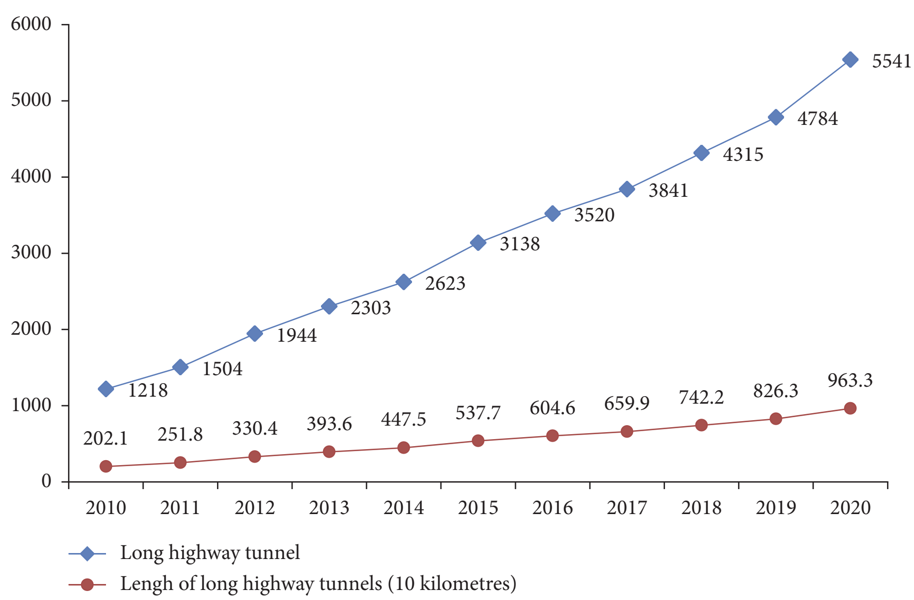

Figure 2: Statistics on the number and length of long highway tunnels in China (2010–2020). Source: Transportation Knowledge Service System of China (2021).

occurred at the French/Italian Mont Blanc tunnel, which led to fierce burning, the temperature exceeding 1000°C, and the asphalt pavement had been burned as the bus contained flour and cream. A total of 39 people were killed, 40 vehicles were damaged, and most of the casualties were caused by suffocation as a result of fire smoke and toxic gas [2]. In 2001, a truck fire accident occurred in the St. Gotthard Tunnel in Switzerland. The accident was caused by a collision between two trucks, which led to a heavy fire and smoke, resulting in 11 deaths, mainly due to smoke, gas suffocation, and high temperature. The high temperature also caused the collapse of the tunnel vault. In 2004, a series of rear-end collision fire accidents occurred in Japan's Takayama Tunnel [3], causing four-vehicle rear-end collisions and fires when a large truck hit a car parked near the road. Five people were killed, and 23 others, including the firefighters, were hospitalized after smoking. In recent years, a large number of highway tunnel traffic accidents have occurred in China (Table 1), resulting in serious economic losses and significant negative social impacts.

Owing to the particularity of traffic environments, tunnels have become the main spatial distribution points of accident-prone traffic sections, which seriously affects highway safety [4]. Compared with general roads, the death rate of highway accidents is twice higher [5], especially with the increasing frequency of traffic accidents in highway tunnels, which has affected traffic safety dramatically and caused significant social and economic losses. It shows that nearly 93% of accidents are caused by human internal risk factors [6], according to an analysis of 2258 traffic accidents by the National Highway Traffic Safety Administration (NHTSA). Statistical data from China also verified the conclusion that human factors are the main cause of traffic accidents. Moreover, road tunnel traffic accidents are dominated by rear ends and collisions [7], and tracing collisions account for 57.46% of total accidents [8]. A strong positive correlation exists between traffic accidents and driving speeds [9–11].

Currently, relevant theoretical research and technical measures are more interested in reducing the risk factors of vehicles and road environments, and less attention has been paid to reducing human risk factors. It has been verified that human factors are the primary and key factors in accidents, and research has also shown that accidents caused by unsafe behaviors are much higher than other unsafe hazards, such as machines, environments, and management [12]. Humans are the main body of multinomial collaborative systems. Therefore, unsafe behavior control has become a key factor in highway tunnel traffic safety management. The measurement of human factors in human-machine-environment systems is the focus of management [13]. However, few studies have focused on the measurement of the specific and single hazard of unsafe human behavior and rarely quantitative research on human unsafe behavior in highway tunnel traffic accidents. Therefore, to address the gaps in research knowledge, we conducted a study on the risk assessment of the unsafe behavior of humans in highway tunnel traffic accidents using a tail-biting fish diagram combined with the fault tree method. A risk assessment model was constructed to obtain the risk ranking of unsafe behaviors, which was intended to provide a theoretical basis for the effective control of unsafe behavior in highway tunnel traffic accidents.

The remainder of this paper is organized as follows: In Section 2, unsafe human behaviors that can potentially cause highway tunnel traffic accidents are identified. In Section 3, a risk assessment model composed of probability, importance degree, and loss is constructed and the method for assessing the probability and importance degree is proposed. In Section 4, we apply this model to the "8.10 traffic accident" that occurred in the Qinling No. 1 Tunnel of the Ankang Section of the Beijing-Kunming Expressway. Finally, we discuss and conclude the study in Section 4.

2. Identification and Analysis of Human Unsafe Behavior in Highway Tunnel Traffic Accidents

tThe mechanisms underlying traffic accidents in highway tunnels are complex. According to the accident causation theory, the highway tunnel traffic system can be expressed as a complex system composed of people, vehicles, roads, environment, and management. These five factors were coordinated and interacted with each other. If any factor has potential hazards, it will affect the safety status of the system and can lead to accidents. Therefore, tunnel traffic accidents can be expressed as a process in which people, vehicles, roads, the environment, and other dynamic and static factors are out of balance [14]. Among these factors, human factors account for approximately 80% of accidents [15], mainly manifesting as unsafe human behaviors. Human unsafe behaviors refer to the behavior characteristics when the man's ability is lower than the system's requirements in a specific space-time environment, which shows that human behavior does not meet the requirements of the system.

The adverse source of the accident was the quality of the man. Specifically, people are the dominant factors in accidents. The main cause of traffic accidents is the interaction between internal and external risk factors. Various external environmental risk factors affect the driver, stimulate individual internal risk factors, and ultimately lead to traffic accidents. When drivers experience severe traffic violations, such as distraction, fatigue, overspeed, mental workload, and drunk driving, traffic accidents are likely to take place during the driving process. In the causes of highway tunnel safety accidents, human unsafe behaviors are caused by a variety of factors, mainly including psychological causes, physiological factors, skills, working environment, and the influence of management. The first three aspects are subjective reasons (internal causes), and the latter two are objective reasons (external causes) [16]. Furthermore, the primary causative factors in highway traffic environments include drivers and passengers. According to the statistics, driver-induced factors are 8–9 times more than those of passengers. Therefore, in this study, we focused on the unsafe behavior of drivers.

2.1. Driver-Induced Factors. Drivers are the main participants in traffic behavior [17], and their psychological and physiological reactions directly affect traffic safety, with factors including physiology, psychology, technical experience, and traffic behavior. Simultaneously, the driver is affected by the driving environment, road conditions, weather conditions, and other factors:

(1) Some highway tunnels are located at high altitudes with low air pressure and low oxygen, which can easily lead to physiological discomforts such as plateau reactions, dizziness, heartbeat, acceleration, and other symptoms, thus affecting the driver's attention and reducing their ability to respond to emergencies.

Table 1: Major tunnel traffic accidents in China (2002–2022).

Serial number	Accident location	Time (years)	Type of accident	Consequence	Cause of accident
1	Gansu Tangjiafengtai Tunnel	2002	Rear-end collision	8 dead, 8 wounded	Miss operation
2	Zhejiang Shangsan Expressway Tunnel	2002	Rear-end collision	7 dead, many injured	Dim lights in the tunnel
3	Sichuan Fengdian Tunnel	2004	Rollover	5 dead, 27 injured	Over speed
4	Chongqing Jinyunshan Tunnel	2005	Collision	1 dead, 11 injured	Too fast
5	Chongqing Huangshi Tunnel	2006	Crashed into tunnel	4 dead, 3 wounded	Vehicle out of control
6	Guangdong Tianluyuan Tunnel	2007	Crashes into tunnel	2 dead, 3 wounded	Collision
7	Guangdong Dabaoshan Tunnel	2008	Rear-end fire	Tunnel collapse partially	Chemical explosion
8	Shaanxi Fengbaozhai Tunnel	2008	Vehicle collision	4 dead, 1 seriously injured	Over speed
9	Shandong Panlong Tunnel	2009	Tailgating fire	3 dead, 5 wounded	Fatigue driving
10	Zhejiang Daxiling Tunnel	2010	Spontaneous ignition	Facilities damaged, great economic loss	Semitrailer burning
11	Jiangsu huishan tunnel	2010	Fire	24 dead, 19 injured	Arson
12	Gansu xinqidaoliang tunnel	2011	Fire	4 deed, 1 injured, 3 vehicles burned, tunnel damaged	Rear-end fire and explosion
13	Sichuan longquanshan tunnel	2011	Vehicle collision	7 dead, 4 wounded	Brake failure
14	Shanghai Bund Tunnel	2012	Crashes into tunnel	3 dead, 1 injured	Disoperation
15	Shanxi Yanhou Tunnel	2013	Fire	40 dead, 12 injured, 43 vehicles burned	Illegal operation
16	Guangdong Kaoyishan tunnel	2014	Rear-end collision	5 dead, 13 injured	Fatigue driving
17	Shanxi Jincheng section Yanhou Tunnel	2014	Hazardous chemical explosion	40 killed, 12 injured, and 42 vehicles burned	Articulated train crash
18	Shaanxi Baojiashan Tunnel	2015	Vehicle collision	1 dead, 1 injured	Miss operation
19	Shaanxi Qinling No. 2 Tunnel	2016	Rear-end collision	2 dead, 2 wounded	Over speed
20	Yunnan Maanshan Tunnel	2017	Bus rollover	10 dead, 38 injured	Miss operation
21	Shandong Taojiakuang Tunnel	2017	Fire	13 dead (11 children)	Fire
22	Shaanxi Qinling No. 1 Tunnel	2017	Bus collision	36 dead, 13 injured	Collision
23	Zhejiang Wangzhai Tunnel	2018	Collision	1 dead, many injured	Over speed
24	Hubei Liziping Tunnel	2018	Collision	2 dead, many injured	Over speed
25	Zhejiang Maoliling Tunnel	2019	Fire	5 dead, 36 injured	Tires triggered fire
26	Guangxi Hezuo village Tunnel	2019	Collision	4 dead, 4 seriously injured	Out of control, collision
27	Sichuan Xudianzi Tunnel	2020	Bus collision	6 dead, 29 injured	Vehicle rollover
28	Jielong Tunnel	2021	Chain collision	4 dead, many injured	Over speed
29	Shanxi Yagou Tunnel	2022	Collision	5 dead, many injured	Lose control

(2) When driving in the tunnel, especially in freeway tunnel groups, the light changes frequently and the driver experiences a black hole and white hole effect in a very short time, which seriously affects the driver's visual perception [18]. Moreover, the high spirit concentration in tunnels causes fatigue, which can easily lead to accidents.

(3) Owing to the different usages of materials at the entrance and exit of the tunnel, there is a transition area that leads to a significant difference in the adhesion coefficient of the pavement inside and outside the tunnel. Under the stress of bad weather, such as rain and snow, the road adhesion coefficient changes dramatically and vehicles are easy to ski.

(4) In a depressed driving environment in a tunnel, drivers tend to leave the tunnel quickly and engage in illegal driving behaviors, such as speeding and overtaking. When the traffic flow in the tunnel is large or the road surface is wet, overspeed and overtaking are often prone to collisions or rear-end collisions and sometimes even lead to a series of rear-end accidents.

(5) In bad weather, drivers are prone to anxiety, irritability, misjudgment, missed operations, and other behaviors, coupled with the impact of wet and slippery roads on vehicle performance, which increases the possibility of traffic accidents.

(6) When driving at night, drivers can easily relax their vigilance and drive quickly. In addition, when driving in an external environment of dawn, dusk, and dim light, the driver's vision decreases significantly. Therefore, the accident rates at dawn and dusk are much higher.

Generally, when driving in the complex environment of a tunnel, the driver is likely to experience speed, fatigue, driving, overload, negligence, and other illegal driving behaviors owing to weak safety consciousness. Tunnel environment driving is prone to traffic accidents, particularly for drivers of dangerous chemical transport vehicles and trucks [19]. Therefore, driver factors include driver safety awareness, illegal traffic behaviors, improper operation, psychological changes, emergencies, and environmental impact.

2.2. Passenger-Related Factors. Passenger-related factors mainly refer to the factors that directly or indirectly lead to tunnel traffic accidents owing to passengers' unsafe behavior, such as carrying contraband goods (which may lead to fire and explosions), talking with the driver (which may affect safe driving), or even encouraging the driver to violate regulations and speed. Although passengers cannot control the vehicle directly as drivers, improper behavior increases the risk rate. In addition, passengers should fasten their seatbelts and escape abilities along with their self-rescue capabilities.

Owing to its closed distribution in space [20], a tunnel is the bottleneck of a freeway. Once a tunnel traffic safety accident occurs, it has serious impacts, including traffic congestion, vehicle damage, tunnel damage, and casualties [21]. Meanwhile, the limitations of the tunnel environment aggravate the consequences of accidents [22]. According to Table 1, once a traffic accident occurs in a freeway tunnel, it will seriously affect the traffic situation, leading to traffic jams. Personnel rescue, and vehicle dragging, which are very inconvenient, and the evacuation and rescue processing will be prolonged, further aggravating the situation and causing chain reactions and large seepage accidents in the surrounding environment. Moreover, tunnel traffic accidents, often prone to chain accidents or secondary damage such as chain tails, may also cause casualties [23]. If a vehicle fires in a tunnel, it can easily cause the pavement asphalt material to melt or even be on fire. Once a fire or explosion occurs, particularly when a truck or hazardous chemical vehicle explodes in a tunnel, an extremely high-temperature flame front or shock wave will be generated, which is accompanied by a large number of toxic and harmful gases. Owing to the relatively closed tunnel, people trapped in it are easily suffocated by smoke and the rescue work is extremely difficult, resulting in significant casualties and property losses [24]. Based on this, we drew a tail-biting fishbone figure: a chart with two fishbones, one biting another, to describe and analyse the accident risk factors, risk events, and risk loss based on Ishikawa Char (Fish Bone chart) (Figure 3, the diagram looks like two fishbones with one biting another); from the aspect of car insecurity, road and environmental defects, security management deficiencies and human unsafe behaviors, we acquired all the potential hazards and their impacts and losses systematically.

Simultaneously, the fault tree can be applied to the systematic analysis and quantitative evaluation of the special causes of system accidents, such as human factors. Combined with the results of the tail-biting fishbone figure, a fault tree model of traffic accidents in mountainous highway tunnels was established (Figure 4 and Table 2).

As shown in Figure 4 and Table 2, unsafe behaviors that cause traffic accidents in mountainous freeway tunnels include speeding (X_1), overload (X_2), irregular overtaking (X_3), drowsy driving (X_4), drunk driving (X_5), sudden illnesses (X_6), negative emotions (X_7), psychological shadows (X_8), and weak awareness of safety (X_9).

3. Risk Assessment of Human Unsafe Behaviors of Traffic Accidents in the Highway Tunnel

3.1. Risk Evaluation Model of Human Unsafe Behavior. To evaluate specific unsafe human behaviors and rank these activities, the risk values of each unsafe behavior should be assessed. Subsequently, tailored measures can be taken according to the risk values. The risk values can be calculated using possibility (P) and loss (L).

$$R_i = \cdot P_i \cdot L_i. \quad (1)$$

The possibility of unsafe human behavior risk is mainly measured by the human unreliability degree (HUD) and its degree of importance (I). Therefore, the risk evaluation model for unsafe human behavior can be revised as follows:

$$RH_i = HUD_i \cdot I_i \cdot L_i, \quad (2)$$

where RH_i is the risk value of unsafe behavior at time t; HUD_i is the unreliability of unsafe behavior i at time t; I_i is the importance of unsafe behavior i in the accident system; and L_i is the possible loss of the accident caused by the unsafe behavior i ◦

3.2. Assessment Model of Human Unreliability. In a system, human behavior is usually measured by reliability, that is, the probability of a person completing a specified task (or function) without an error within the specified time and under a given condition. Corresponding to human reliability is unreliability, which can be used to scientifically measure unsafe behavior.

Reliability is a function of time and can be expressed as a reliability function $R(t)$, which represents the probability of continuous operation during the period of $(0, t)$. The corresponding reliability is unreliable, which indicates the probability that people cannot complete a specified action

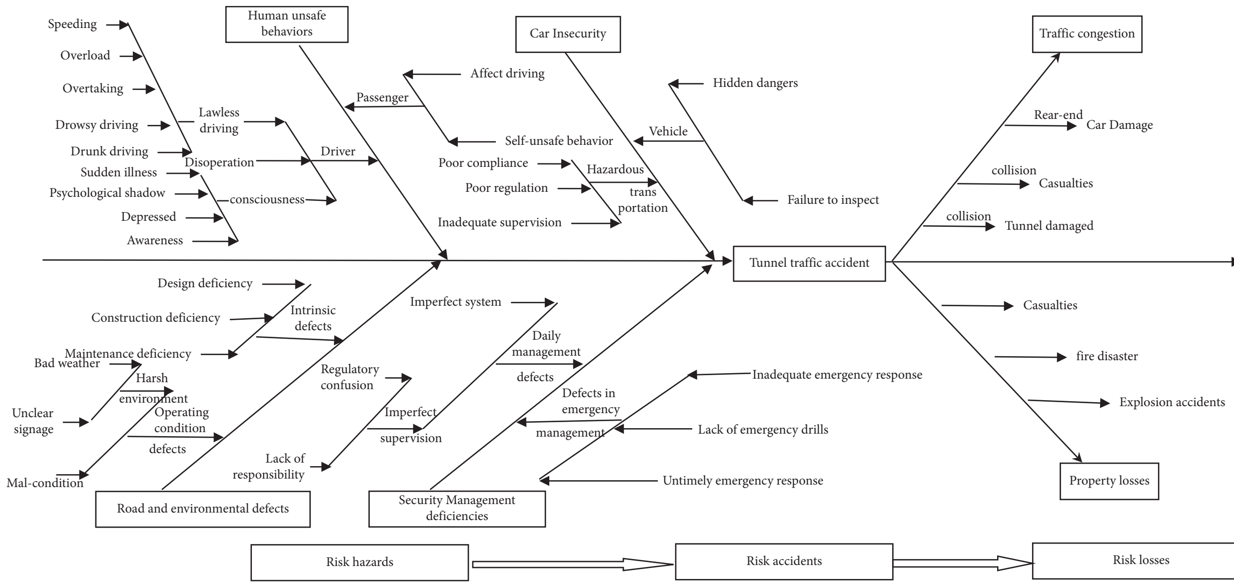

Figure 3: Tail-biting fishbone figure of a traffic accident in a mountainous highway tunnel.

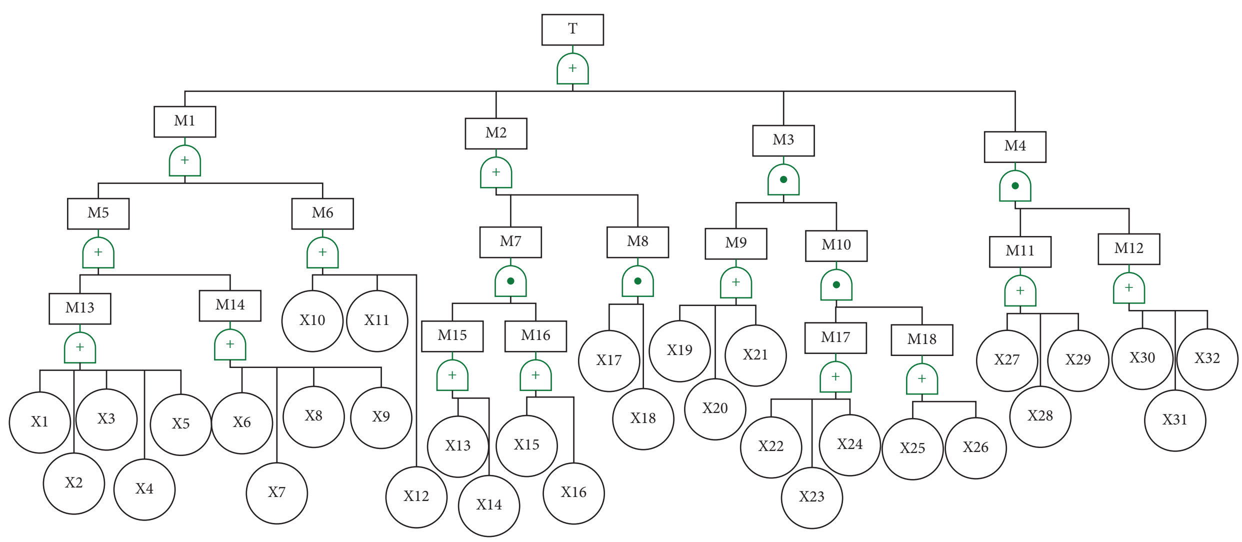

Figure 4: Fault tree of highway tunnel traffic accidents.

under a given condition and within a specified time. It is also known as the failure probability or failure rate and can be expressed as the available $F(t)$. It is apparent that $R(t)+F(t)=1$。

Let ξ represent the time from unit to failure, which is a random variable. According to the definition of reliability, the probability of an event being $\{\xi > t\}$ is the reliability of the unit at time. In other words, there is a probability that no failure will occur within the $(0,t)$ unit. If $R(t)$ is a reliability function, then

$$R(t) = P\{\xi > t\}. \tag{3}$$

Here, P represents probability and event $\{\xi \le t\}$ is the complement set of events $\{\xi > t\}$. Its probability is often referred to as the cumulative distribution function $(F(t))$.

$$F(t) = P\{\xi \le t\} = 1 - R(t). \tag{4}$$

Its physical meaning is the failure probability of the unit in the time interval $(0,t)$, that is, the degree of unreliability.

For a limited sample, the total number of products operated under the specified conditions is N_0 and $(0,t)$, and the cumulative number of failures for a product during its operating hours is $r(t)$. Reliability and unreliability were estimated as follows:

$$R(t) = \frac{N_0 - r(t)}{N_0},$$
$$F(t) = \frac{r(t)}{N_0}. \tag{5}$$

Table 2: Accident tree event description for mountain highway tunnel accidents.

Number	Meaning
T	Tunnel traffic accident
M_1	Human unsafe behaviors
M_2	Car insecurity
M_3	Road and environmental defects
M_4	Security management deficiencies
M_5	Driver-induced factors
M_6	Passenger-related factors
M_7	Vehicle factors
M_8	Hazardous material transportation
M_9	Tunnel defect
M_{10}	Defects conditions
M_{11}	Management defects
M_{12}	Defects in emergency management
M_{13}	Miss operation
M_{14}	Physical and mental deficiency
M_{15}	Vehicle safety hazards
M_{16}	Daily check not in place
M_{17}	Harsh environment
M_{18}	Emergency disposal defects
X_1	Speeding
X_2	Overload
X_3	Illegal overtaking
X_4	Drowsy driving
X_5	Drunk driving
X_6	Sudden illness
X_7	Psychological shadow
X_8	Being depressed
X_9	Weak awareness
X_{10}	Affect driving
X_{11}	No seat belts
X_{12}	Carrying flammable and explosive articles
X_{13}	On-the-road crash
X_{14}	Brake failure
X_{15}	Distraction
X_{16}	Inadequate daily maintenance
X_{17}	Poor compliance
X_{18}	Poor regulation
X_{19}	Complex lines
X_{20}	Low road adhesion coefficient
X_{21}	Design defect
X_{22}	Ventilation and lighting defects
X_{23}	Unclear traffic signs
X_{24}	Inclement weather
X_{25}	Slow emergency response
X_{26}	Roadblock
X_{27}	Inadequate management system
X_{28}	Inadequate on-site supervision
X_{29}	Insufficient safety education and training
X_{30}	Inadequate emergency response system
X_{31}	Lack of emergency drills
X_{32}	Untimely emergency response

Similarly, the degree of unreliability of unsafe behaviors may be defined as

$$HU\ D = 1 - \frac{N_r}{N_t}, \tag{6}$$

where N_{r} is the number of error-free operations completed and N_t means the total number of times the operational task was executed.

Therefore, the SOR model was used to assess the unreliability of unsafe behaviors. SOR is a theoretical model of "stimulus-organism-response," which was proposed by Mehrabian and Russel in 1974 in the field of environmental psychology [25]. The model considers that environmental factors can stimulate human emotions and cognition and elicit close or escape responses. The model primarily involved three variables: stimulation, organism, and response. The theory holds that the relationship between external stimuli and individual responses is neither direct nor mechanical, as the individual is an organism with rich thought and emotional activity and has a certain subjective initiative. When facing a stimulus, it is not a passive response but an active selection. The face of some external stimulation may have a certain psychological activity, which may affect the individual state; this also means that the internal state of the organism plays an essential role in it. According to the SOR model, a calculation method for determining the operational reliability of human beings was proposed by Professor Yachi Ichi Michizui of Tokyo University in Japan. He believes that the basic reliability of the operator is

$$\gamma = \gamma_1 \gamma_2 \gamma_3, \tag{7}$$

where γ_1 represents the basic reliability of the information input process, γ_2 refers to the basic reliability of the decision process, and γ_3 refers to the basic reliability of the operation output process [26]. The values for γ_1, γ_2, and γ_3 are presented in Table 3.

In this study, the reliability degree model was revised by considering operating time, operating frequency, physical and psychological conditions, degree of danger, and environmental conditions. After obtaining the basic reliability of the operator γ, it can be modified more precisely according to the operating conditions, operating time, operating frequency, risk, and psychological and physiological effects; the operation reliability R can be obtained as follows:

$$R = 1 - b c \mathrm{def}\,(1 - \gamma). \tag{8}$$

R is the revised reliability degree, b is the correction factor for the operation time, c is the correction factor for the operating frequency, d is the correction factor for the degree of danger, e is the correction factor for the physical and psychological conditions, f is the correction factor for the environmental conditions, and $1 - \gamma$ is the basic unreliability, with each correction factor covering a certain range (Table 4).

Based on the reliability R value, we can also get the corresponding unreliability U value as follows:

$$\begin{aligned} U &= 1 - R \\ &= 1 - [1 - b c \mathrm{def}\,(1 - \gamma)] \\ &= b c \mathrm{def}\,(1 - \gamma). \end{aligned} \tag{9}$$

The rolling quantitative fusion method is adapted to calculate the reliability degree, as in the method, the closer it is to the mean, the greater the data weight and there is no relationship with the data itself.

Table 3: Values of parameters in basic reliability.

Category	Content	γ_1, γ_3	γ_2
Simple	Few variables, ergonomic principles considered	0.9995–0.9999	0.999
General	Variables below 10	0.9990–0.9995	0.995
Complex	Variables over 10, inadequate consideration of ergonomic principles	0.990–0.999	0.990

Table 4: Value of the correction coefficient.

Coefficient	*b*	*c*	*d*	*e*	*f*
1.0	Sufficient slack time	Low	Safe	Good	Good
1.0–3.0	Insufficient slack time	Appropriate	Risky	Bad	Bad
3.0–10.0	No slack time	High	Fatal	Very bad	Very bad

Suppose that for the same behavior or operations, different experts' judgement according to the SOR model of an unreliability series is $U_{(1)}, U_{(2)}, \ldots, U_{(j)} \ldots, U_{(n)}$, which is arranged in order from small to large.

$$U = (u_1, u_2, \ldots, u_i, \ldots, u_n), \quad u_i \le u_{i+1}, \; i = 1, 2, \ldots, m-1. \tag{10}$$

This is calculated as

$$\xi_j = \frac{1}{m-j+1} \sum_{i=1}^{m-j+1} \sum_{k=i}^{i+j-1} \frac{u_k}{j}, \quad j = 1, 2, \ldots, m. \tag{11}$$

The unreliability quantitative fusion results can be obtained:

$$HU\ D = \frac{1}{m} \sum_{j=1}^{m} \xi_j. \tag{12}$$

3.3. Importance Degree Analysis Based on Fault Tree. As shown in Figure 4, Boolean algebra is used to solve the minimum cut set. The minimum cut set is a set of necessary and sufficient bottom events that leads to the occurrence of a fault tree. Using the fault tree analysis software FreeFta, 44 minimum cut sets of traffic accidents in highway tunnels were obtained as follows:

$$\left\{ \begin{array}{c} X_1, X_{10}, X_{11}, X_{12}, X_{13}X_{15}, X_{13}X_{16}, X_{14}X_{15}, X_{14}X_{16}, X_{17}X_{18}, X_{19}X_{22}X_{26}, X_{19}X_{23}X_{25}, X_{19}X_{23}X_{26}, \\ X_{19}X_{24}X_{25}, X_{19}X_{24}X_{26}, X_2, X_{20}X_{22}X_{25}, X_{20}X_{22}X_{26}, X_{20}X_{23}X_{25}, X_{20}X_{24}X_{26}, X_{27}X_{30}, X_{27}X_{31}, \\ X_{28}X_{30}, X_{28}X_{31}, X_{28}X_{32}, X_{29}X_{30}, X_{27}X_{31}, X_{27}X_{32}, X_3, X_4, X_5, X_6, X_7, X_8, X_9 \end{array} \right\}. \tag{13}$$

This shows that 44 possible routes can lead to traffic accidents in mountain highway tunnels and that there is at least one basic event in the minimum cut set, indicating that accidents can easily occur.

When the minimal cut set is determined, the importance of each basic event in the structure of the accident can be approximately calculated according to (14), which is used to analyse the impact of each basic event on the top event [27, 28].

$$I_\phi(i) = 1 - \prod_{x_i \in k_j} \left(1 - \frac{1}{2^{n_j - 1}}\right), \tag{14}$$

where $I_\phi(i)$ represents the structural importance of the underlying event i and n_j is the minimum cut set in which the base events are located for each event i.

For example, event X_4 has only one event in a minimal cut set and its structural importance.

$$I_\phi(4) = 1. \tag{15}$$

The event X_{13} exists in two minimal cut sets, and each cut set has two basic events: its structural importance as

$$I_\phi(13) = 1 - \left(1 - \frac{1}{2^{2-1}}\right)\left(1 - \frac{1}{2^{2-1}}\right) = 0.75. \tag{16}$$

The structural importance of each event is calculated as follows:

$$\begin{aligned} I(X_1) &= I(X_{11}) = I(X_{10}) = I(X_9) = I(X_8) = I(X_7) = I(X_6) = I(X_5) = I(X_4) = I(X_3) = I(X_2) = I(X_1) > I(X_{32}) \\ &= I(X_{31}) = I(X_{30}) = I(X_{29}) = I(X_{28}) = I(X_{27}) = I(X_{26}) = I(X_{25}) = I(X_{18}) = I(X_{17}) = I(X_{16}) = I(X_{15}) \\ &= I(X_{14}) = I(X_{13}) > I(X_{24}) \\ &= I(X_{23}) = I(X_{22}) = I(X_{21}) = I(X_{20}) = I(X_{19}). \end{aligned} \tag{17}$$

3.4. Loss Measurement Standard. According to the Road Traffic Accident Treatment Law in China (the NPC Standing Committee, 2003), the classification criteria for road traffic accidents are as follows.

3.4.1. Minor Accidents. This denotes a minor injury to one to two people or property loss of less than 1000 CNY.

3.4.2. General Accidents. This denotes serious injury in one to two people, mild injury in more than three people, or property loss of less than 30,000 CNY.

3.4.3. Major Traffic Accidents. It refers to an accident that causes one to two deaths, serious injury to more than three people and less than ten people, or property losses between CNY 30,000 and 60,000.

3.4.4. Extraordinarily Serious Traffic Accidents. It refers to an accident that causes more than three deaths, eleven serious injuries, one death, eight serious injuries, two deaths, five serious injuries, or loss of more than 60,000 CNY.

4. Case Studies

On August 10, 2017, at 23:34, a bus (number Yu C88858) travelled from Chengdu to Luoyang. When it passed through the south entrance of the Qinling No. 1 Tunnel (1164 km + 930 m) in the Ankang section of the Beijing-Kunming Expressway, a traffic accident occurred at the tunnel entrance, resulting in serious deformation and damage to the bus; 36 people were killed, and 13 people were injured in the accident.

The investigation found that the direct cause of the accident was that Baiming Wang, the driver, drove over the speed and fatigued when he passed the tunnel and did not take any safety measures such as steering and braking before the collision, which caused the vehicle to deviate from the right side of the road and collide frontally with the wall of the Qinling No. 1 Tunnel entrance. Furthermore, the fact that passengers are unattached to seat belts is another important cause of extremely serious secondary injuries.

In "8·10" traffic accidents, people's unsafe behaviors include driver's fatigue, driving at night and speeding passengers in a sleeping state, and not wearing seat belts; both the passenger and the driver become victims. The driver's driving speed was identified at speeds ranging from 80 to 86 km/h when entering the tunnel, which is higher than the speed limit (60 km/h for the bus), with 33% to 43% above the limit, and he drove continuously for 2.5 hours deep in the night with a severe fatigue state. Passengers did not tie any safety belts. Owing to the large inertia when the accident occurred, the loss of necessary protection caused a serious secondary injury. Night and fatigued driving are derived from human cognitive defects, which are often caused by the social environment, weak security awareness, and insufficient management of relevant departments [29–32].

According to the above assessment model of the probability and importance degree model, the "8·10" Special Major Road Traffic Accident on the Ankang Jingkun Expressway in Shanxi Province was studied and its unsafe behaviors were measured.

As shown in Figure 4 and Table 2, we consider overspeed (X_1) as an example. According to Table 5, the gradual cumulative results of the rolling average ξ_i and final fusion results of the reliability degrees are obtained as follows:

$$\begin{aligned}
&\xi_1 = 0.903096;\\
&\xi_2 = 0.898916;\\
&\xi_3 = 0.898916;\\
&\xi_4 = 0.903096,\\
\overline{HFP}_1 &= \frac{1}{m}\sum_{j=1}^{m}\xi_j,\\
&= \frac{1}{4}(0.903096 + 0.898916 + 0.898916 + 0.903096)\\
&= 0.901006.
\end{aligned} \tag{18}$$

Furthermore, the degree of importance of overspeed (X_1), as described in Section 3.3, is

$$I_\phi(1) = 1. \tag{19}$$

Therefore, the risk value of overspeed (X_1) is obtained as follows:

$$\begin{aligned}
RH_1 &= HFP_1 \cdot P_1 \cdot D_1\\
&= 0.901006 * 1 * L\\
&= 0.901006L.
\end{aligned} \tag{20}$$

L is the consequence of tunnel traffic accidents, and in this case, its quantitative value was 40 in this study, according to Table 6. Similarly, the risk value for drowsy driving (X_4) was obtained according to (11) and Table 7.

$$\begin{aligned}
\overline{HFP}_4 &= \frac{1}{m}\sum_{j=1}^{m}\xi_j,\\
&= \frac{1}{4}(0.938935 + 0.996555 + 0.996555 + 0.938935)\\
&= 0.967745.
\end{aligned} \tag{21}$$

And its importance degree refers to (12).

$$I_\phi(4) = 1. \tag{22}$$

Therefore, the risk value of drowsy driving (X_4) is obtained as follows:

$$\begin{aligned}
RH_4 &= HFP_4 \cdot P_4 \cdot D_4\\
&= 0.967745 * 1 * L\\
&= 0.967745L.
\end{aligned} \tag{23}$$

Table 5: Analysis table of overspeed driving.

Category	Expert1	Expert2	Expert3	Expert4
Stimulus reliability (γ_1)	0.992	0.993	0.9991	0.9996
Organism reliability (γ_2)	0.99	0.995	0.99	0.99
Response reliability (γ_3)	0.994	0.992	0.9995	0.99
Basic reliability (γ)	0.976188	0.980131	0.988614	0.979708
Correction factor of the operation time (b)	1.5	1.8	3	2
Correction factor of the operating frequency (c)	2	1	1	2
Correction factor of the degree of danger (d)	6	6	4	3
Correction factor of the physical and psychological conditions (e)	1	1.6	2	2
Correction factor of the environmental conditions (f)	2	2.8	3	2
Reliability $R_{(j)}$	0.14275072	0.038645	0.237882	0.025982

Table 6: Consequence and its value of traffic accidents.

Values	Extent of injuries	Losses caused by accidents (CNY)
10	1 to 2 people with minor injuries	Less than 1000
20	Serious injury of 1 to 2 people/more than 3 people with slight injuries	Less than 30,000
30	1 to 2 deaths/more than 3 people with grievous injuries	Between 30,000 and 60,000
40	More than 3 deaths/11 serious injuries/1 death, 8 serious injuries/2 deaths, 5 serious injuries	More than 60,000

Table 7: Analysis table of drowsy driving.

Category	Expert1	Expert2	Expert3	Expert4
Stimulus reliability (γ_1)	0.991	0.991	0.9991	0.993
Organism reliability (γ_2)	0.992	0.995	0.991	0.991
Response reliability (γ_3)	0.992	0.993	0.9993	0.992
Basic reliability (γ)	0.975207	0.979143	0.989415	0.97619
Correction factor of the operation time (b)	1.2	2	3	1
Correction factor of the operating frequency (c)	1.8	1.3	1	2
Correction factor of the degree of danger (d)	3.9	4.9	4	3
Correction factor of the physical and psychological conditions (e)	2.3	2.2	2	2
Correction factor of the environmental conditions (f)	2	2.5	3	2
Reliability $R_{(j)}$	0.039277763	−0.46147	0.237882	0.428572

According to the above risk values, the risk value for drowsy driving (X_4) was higher than that for high-speed driving (X_1). Accordingly, the priority level of X_4 is superior to that of X_1 when taking precontrol measures.

In view of the fact that the single risk value of drowsy driving is higher than that of speeding, drowsy driving should be given higher management authority and more resources when formulating management standards or taking management measures and unsafe behaviors that reach a specific risk value should be included in key supervision. For drowsy driving, the penalty standard (fine or deduction of driver's license points) should be formulated and its penalty standard should be higher than that of speeding. But, the reality is that we lack penalties standard for drowsy driving as it is difficult to identify fatigue driving. However, drowsy driving can be controlled through some technical means. For example, biological recognition technology and AI intelligence can be carried out for early warning and identification of drowsy driving before the vehicle is launched, the location information can be used to monitor continuous driving for a certain period of time (4 hours), and the black box video monitoring system can be used to record the driver's behavior. AI identification smart technology can be applied to early warning of unsafe behavior to achieve intelligent control and effective prevention of unsafe behavior.

Similarly, the risk values of other specific unsafe human behaviors can be obtained using this model and method. Finally, the risk ranking of a specific unsafe human behavior in highway tunnel traffic accidents can be obtained according to the risk values, and tailored measures can be taken to prevent and control hazards.

5. Discussion and Conclusions

The occurrence of an accident is a complex process, and most accidents have multiple causes. Hazard control is the main objective of safety management. Therefore, hazard identification and assessment are the base of risk management, which aims to establish a proactive safety strategy by investigating potential risks. This process is used to determine risk management priorities by evaluating the value of the hazards.

In this study, a tail-biting fishbone and fault tree model was used to establish a causal model for traffic accidents in mountainous highway tunnels. Based on the characteristics of unsafe human behaviors and their consequences, a human unsafe behavior risk measurement model for traffic accidents in highway tunnels was established, which was derived from the degree of human unreliability, the importance of the accident system, and possible loss after the accident. Moreover, a risk assessment model for unsafe human behavior was introduced to obtain the risk ranking. Methods for assessing the probability and degree of importance were proposed. Furthermore, the probability was obtained by assessing the unreliability degree of the unsafe behaviors, and the degree of importance was obtained by analysing the degree of influence in the fault tree using the Boolean algebra algorithm. Finally, the risk value was calculated, and the priorities for controlling the unsafe behaviors of humans were obtained, which provided a theoretical basis for the scientific, reasonable, and effective control of tunnel traffic accidents. This model may also be applied to other tunnel traffic accidents; however, some induced factors may change, so the model needs to be revised slightly. For other accidents, they may be assessed from unreliability, degree of importance, and loss and the model needs to adjust according to the actual situation. In the future, the process of unsafe human behavior and its mechanism can be analysed systematically, and its value can be assessed quantitatively. With the determined value, then the formulation of management standards and the optimization of management processes can be carried out to achieve fine and effective safety control.

The management standards of human unsafe behavior can be established, and tailored management measures can be taken, for example, classification/hierarchical control for drowsy driving, speeding, illegal overtaking, AI identification, and early warning of unsafe behavior with smart technology, to achieve intelligent control and effective prevention of unsafe behavior.

Data Availability

The data used to support the study conclusions were from some open-access articles that have been properly cited, and the assessment data are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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