Analysis and Application of Highway Tunnel Risk Factors Based on Traffic Accident Data

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Abstract. This paper aims to address the core challenge in highway tunnel operation safety: effectively identifying and forecasting complex, mutable risk sources to reinforce safety management and emergency response capabilities in high-traffic tunnels within Guangdong Province. By innovatively integrating big data analytics, this research deeply mines and quantifies the systemic, variable, and multi-layered features of tunnel operational safety risks, characteristics that traditional methods struggle to precisely capture. Initially, it consolidates and analyzes data from multiple tunnels across Guangdong, encompassing traffic volume, accident records, facility conditions, environmental variables, and management logs. Following this, leveraging advanced data analysis tools such as machine learning algorithms, these large datasets are cleansed, integrated, and patterns recognized to uncover underlying risk patterns. A risk indicator system is constructed systematically categorizing sources, including driver behavior, tunnel environment, facility condition, management effectiveness, and societal factors, ensuring comprehensive coverage of risk identification. The ultimate outcome establishes an interconnected "Driver-Vehicle-Tunnel-Management-Environment" risk source recognition system, which not only categorizes risks like driver violations, tunnel aging, management negligence, but also quantifies the likelihood and impact. Importantly, dynamic interdependencies among risks are revealed, such as peak hour traffic relevance with frequent accidents and delayed management responses exacerbating risks. The innovation lies in the application of big data analytics for refined, systemic risk source identification in tunnel operations, providing a scientific and technical framework for managing complex system safety and emergency response in similar scenarios.

Keywords: Highway Tunnels; Risk Source Identification; Big Data Analysis; Risk Prevention and Control

1 Introduction

By 2023, the total length of expressways in China has exceeded 180,000 kilometers,

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building the world's largest expressway network [1]. Among them, expressway tunnel, as an important part of expressway, shortens the mileage of expressway and makes travel more convenient, and brings higher operational risks due to its characteristics of confined space. Due to the relatively closed internal space of the tunnel, ventilation, lighting and other conditions are limited, the driver is easy to cause accidents during the driving process because of visual discomfort or improper operation. In addition, some tunnel designs have defects, such as slippery road surface and excessive curves, which also increase the risk of accidents [2][3][4]. Therefore, the analysis and management of the highway tunnel operation risk are particularly important in the highway tunnel traffic safety.

In general, through a comprehensive analysis of the tunnel operation risks, the potential safety risks can be identified, and targeted suggestions can be provided for the subsequent management [5]. Based on the theory of accident tree, this paper sorts out the whole factor risk sources covering the human-vehicle-tunnel-management-environment in the highway tunnel operation stage [6], and then proposes the key risk sources affecting the operation level of expressway tunnel, so as to provide theoretical support for the operation management and maintenance decision of expressway.

2 Safety Risk Source Analysis of Highway Tunnel Operation

The premise of the risk analysis is the risk identification, and the risk source is the specific factors such as the structure, environment, equipment and location that may induce the risk [7]. The safety risk of the expressway tunnel in service, as the core issue in the field of current engineering risk research, shares several inherent risks, such as damage potential, universality, objectivity and uncertainty. In view of the structural characteristics of the tunnel itself and its unique traffic environment, the dangers of the tunnel in the operation stage not only carry these basic attributes, but also show unique and significant characteristics, which are embodied in the following levels:

(1) Systemic characteristics

(2) Variability characteristics

(3) Multi-level characteristics

In risk identification, risk source analysis is a process of representing the abstract risk [8]. In order to fully identify the risks, it is necessary to conduct a complete risk source identification for the traffic accidents, fire, structural damage, natural disasters and other risks that may occur in the process of operation safety.

2.1 Risk Source of Traffic Accidents

The risk sources of traffic accidents caused by the operation of highway tunnels can be summarized into the following aspects:

(1) Lighting and visibility problems: insufficient lighting facilities or poor maintenance in the tunnel lead to poor visibility, especially in the moment of entering the tunnel (black hole effect) and the moment of leaving the tunnel (white hole effect), the problem of the driver's sight adaptation intensifies, which increases the risk of

collision.

(2) Traffic flow and vehicle distance management: the reduction of traffic distance caused by high traffic flow, especially in rush hours, where rear-end collisions occur frequently. Vehicles fail to maintain a sufficient safe distance, especially when emergency braking is easy to cause collisions.

(3) Driver behavior: including speeding, not obeying traffic rules, fatigue driving, distraction, slow reaction, illegal overtaking, unfamiliar with road conditions, etc. The poor condition of drivers directly affects the driving safety.

(4) Mechanical failure and vehicle problems: vehicle braking system failure, insufficient tire grip, lighting problems, overload and other poor vehicle performance, as well as vehicle failure parking in the tunnel, increase the risk of accidents.

(5) Insufficient emergency response and management: rescue channels are not smooth, emergency facilities (such as fire fighting, ventilation, evacuation instructions, emergency lighting) are not perfect, communication coverage in the tunnel is poor, management and emergency response efficiency is low, aggravating the consequences of the accident.

(6) Weather and environmental factors: under specific weather conditions, such as the visual impact caused by the contrast of strong light in sunny days, or the slippery road in rainy days increases the braking distance, which indirectly affects the safety of the tunnel.

(7) Tunnel design and maintenance: tunnel structure design defects, such as unreasonable design of entrances and exits, complex internal space layout, poor ventilation, poor skid resistance of road surface, etc., as well as risk sources caused by poor maintenance.

(8) Tunnel characteristics: the closed environment, narrow space, limited ventilation, lack of natural light, and the deterioration of the light environment in the middle section of the tunnel may affect the driver's attention and reaction ability.

In general, the risk sources of traffic accidents in operational tunnels cover multiple dimensions, such as vehicle, driver, tunnel design and maintenance, management, traffic conditions and environment, so comprehensive risk management strategies are needed to reduce the accident risk.

2.2 Tunnel Fire Risk Source

The potential fire risk sources in operating highway tunnels mainly include the following aspects:

(1) Vehicle factors: including spontaneous combustion caused by electrical system failure, oil leakage of oil circuit, high temperature parts contacting combustible materials; fire caused by fuel leakage, battery short circuit, electrical system damage, etc.; illegal loading of inflammable and explosive goods, increasing the fire risk; engine overheating and brake pads.

(2) Electrical equipment faults: including overheating, short circuit and fire cause caused by long-time operation of electrical equipment such as lighting, monitoring and ventilation in the tunnel, etc.

(3) Improper management and maintenance: including insufficient emergency preparedness, lack or lack of fire fighting facilities, and low risk awareness.

(4) Ventilation system problems: including poor ventilation, improper fire source control, etc.

(5) Traffic environment and design: including high traffic density, tunnel design to considering the fire risk, structural damage caused by special terrain further cause fire, etc.

(6) Human factors: such as intentional arson, throwing cigarette butts and other illegal acts and improper response to fire, delay the best fire fighting time, etc.

2.3 Risk Source of Tunnel Structure Damage

The risk sources of structural damage in operating expressway tunnels mainly include the following aspects:

(1) Geological and environmental factors: unstable geological conditions, including fault, soft soil and karst cave, which may lead to uneven settlement of foundation or tunnel cracking; change of groundwater level or groundwater erosion, increase the risk of water leakage in the tunnel, and weaken the structure stability under long-term action; natural disasters, such as earthquake, landslide, can cause direct damage to the tunnel structure.

(2) Construction quality problems: including design defects, improper construction, lax supervision, etc.

(3) Operation load and traffic pressure: including long-term high-load operation, illegal passage of overloaded vehicles, etc.

(4) Insufficient maintenance and management: including the delayed maintenance of discovered cracks and water leakage problems; imperfect monitoring system, unable to grasp the structure status in real time; ineffective implementation of management system, etc.

(5) Corrosion and chemical erosion: including the high environmental humidity in the tunnel, easy to cause corrosion of steel bars and reduce the structural bearing capacity; exhaust pollutants, such as acid in automobile exhaust, long-term accumulation may corrode tunnel structural materials.

(6) Vibration and impact: including vibration caused by high-speed vehicles, which may cause structural fatigue damage under long-term action; strong impact caused by special vehicles (such as heavy military vehicles) or accidents, directly cause structural damage.

3 Comparison of Traffic Accident Data Analysis Methods

In order to quantify the risk source and obtain the relevance and importance ranking of each risk, the method of traffic accident analysis is used to identify the importance level between each risk source.

3.1 Construction of the Tunnel Accident Database

This paper investigates a total of 597 accident data of traffic accidents in a tunnel section of Guangdong Province from 2020 to 2023, including the time, place, cause, weather, traffic flow before the accident, etc. From the linear shape, The main sections of traffic accidents are mostly poor linear sections, For example, the south entrance section of Tunnel B (K938 + 000-K939 + 600) and the south exit section of Tunnel C (K908 + 000-K909 + 100), In the form of the accident, rear-end collisions accounted for the majority, The reason is that the large traffic flow leads to a small traffic spacing, Easy to have rear-end collisions, From the cause of the accident, Insufficient safety distance and improper operation and other human factors account for the vast majority; From the weather of the accident, Sunny day accident probability is significantly higher than other weather, The reason is the black and white hole effect of tunnel sections, Even more pronounced when the weather is clear, Lead to traffic accidents easily.

Statistics of Tunnel Accidents from 2020 to 2023.

According to the analysis of tunnel accidents from 2020 to 2023 shown in Table 1, the number of traffic accidents in tunnel C and B in 2020 is more than that of tunnel A, while the number of accidents in tunnel A in 2021 and 2022 is significantly higher than that of tunnel C and B. Among them, the number of accidents in the Wuhan direction of tunnel A is twice that of Shenzhen, while tunnel C and tunnel B have A large number of accidents in the direction of Shenzhen, and the number of accidents shows obvious direction. In the later stage, targeted improvement measures can be implemented according to the needs. According to the statistics of tunnel traffic accidents from 2020 to 2022, we can see that there are 258 tunnel traffic accidents occurred in 2020,206 in 2021 and 133 in 2020. With the increase of years, traffic accidents are decreasing, and the tunnel maintenance work has achieved remarkable results. The existing mechanical and electrical facilities in the tunnel mainly include ventilation facilities, lighting facilities, power supply and distribution facilities, fire fighting facilities, environmental monitoring facilities, etc. In recent years, AR real scene monitoring system, tunnel import and exit lighting optimization research, tunnel fire extinguisher, fire hydrant, high and low online monitoring system of pools and other new technology pilots have been introduced. These technologies all guarantee the safety of the tunnel traffic operation to a large extent, reduce the occurrence of traffic accidents to a large extent, and play a positive role in the tunnel traffic safety.

According to the accumulated annual experience, the tunnel maintenance personnel have continuously improved the ability to control the occurrence of tunnel traffic accidents, and made some progress in the tunnel safety control work, laying a good foundation for the subsequent maintenance and safety management work. At the same time, the total amount of traffic accidents in Jiulianshan long tunnel is the highest, and the environmental situation and risk factors of the special tunnel are more prominent compared with other tunnel problems, which should be the key object of tunnel traffic safety control. The safety control experience of the special tunnel is also of important reference significance for other tunnels. In recent years, there have been 27 traffic accidents in the tunnel resulting in injuries and six deaths. Once the tunnel accident

occurs, it will have serious consequences, so we should pay great attention to it. The frequency of major accidents resulting to deaths and injuries is similar, and there is no obvious difference.

Table 1. Statistical Table of Tunnel Accidents from 2020 to 2022

	Number of accidents / cases in 2020	Number of accidents / cases in 2021	Number of accidents / cases in 2022
Tunnel A	71	86	50
Tunnel B	92	53	35
Tunnel C	95	67	48
Tote	258	206	133

Statistical Analysis of Tunnel Accidents.

As is shown in Table 2, By analyzing the pattern of tunnel accidents from 2020 to 2023 and the pattern of tunnel accidents in the past four years, it can be clearly found that rear-end collision and collision are the main causes of tunnel traffic accidents, accounting for more than 90% of the proportion of tunnel traffic accidents. Follow-up risk assessment should focus on these two aspects. Among them, the main causes of rear-end accidents are speeding, not keeping a safe distance from the vehicle in front, not stopping according to the regulations, random and illegal overtaking, the driver's poor condition and not timely response, overloading driving, random lane change, and the braking performance of the vehicle does not meet the requirements. More attention should be paid to the causes of accidents, and the corresponding control can effectively reduce the incidence of tunnel traffic accidents.

Table 2. Statistical Table of Tunnel Accident Forms from 2020 to 2023

Particular year	Pileup	Vehicle fault	Collision collision fixture	Fire
In 2020,	178	76	2	2
In 2021,	98	104	2	1
In 2022,	59	72	2	0
In 2023,	43	13	1	0

The following figure shows the accident patterns of tunnel A, C and B respectively. Compared with the overall accident form, it can be found that tunnel A accidents are mostly caused by vehicle failure, while tunnel C and tunnel B are mainly traffic accidents caused by rear-end collisions. The difference in accident form between long and short tunnels may be due to the poor light environment in the long tunnel and the tunnel restriction.

In 2021 and 2022, analyze the cause of tunnel accident by accident scale can clearly found that the two workshop distance is the important cause of the tunnel accident, the proportion is as high as eighty percent, two car distance is easy to lead to collision, collision and other traffic accidents, seriously affect the driving personnel life and property safety, through management means to control the tunnel vehicles with distance

can effectively reduce the accident risk. In addition, improper operation is also an important factor leading to the accident, so it can be seen that the emergency response of drivers under special circumstances is also an important influencing factor.

Specific from the different tunnel analysis in Table 3, the cause of the accident, the main cause of the three tunnel accident is insufficient distance, the cause of the distance mainly brake not timely, the driver is not timely, tunnel road anti-skid resistance, driving too fast without enough safe distance, insufficient spacing caused by two cars collided, the impact of insufficient spacing caused by traffic accident, is also the main cause of the tunnel accident, subsequent targeted to improve.

Table 3. Causes of Tunnel Accidents from 2020 to 2023

Particular year	Distance is insufficient	Misoperation	Mechanical breakdown	Emergency avoidance
In 2020,	Not recorded	Not recorded	Not recorded	Not recorded
In 2021,	63	8	1	0
In 2022,	26	3	0	1
In 2023,	Not recorded	Not recorded	Not recorded	Not recorded

Weather State Analysis during the Tunnel Accident.

The weather at the time of the tunnel accidents from 2020 to 2023 was analyzed in Table 4 and fig.1. In 2022, there were 94 traffic accidents in the sunny day tunnel and 8 traffic accidents in the tunnel in rainy days. Firstly, the traffic flow is higher than rainy days, the number of sunny days and the number of traffic accidents is higher; on the other hand, the brightness difference inside and outside the sunny hole is large, and the tunnel white hole and black hole effect is obvious, which is also the important reason of the tunnel accidents.

Table 4. Weather statistics of tunnel accidents from 2020 to 2023

Particular year	Fine	Rain
In 2020,	Not recorded	Not recorded
In 2021,	67	5
In 2022,	27	3
In 2023,	Not recorded	Not recorded

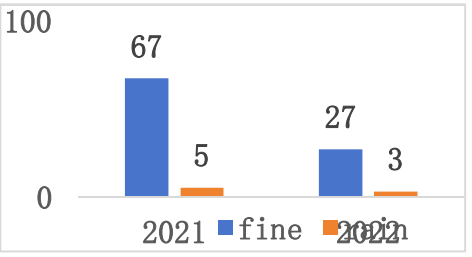

Fig. 1. Weather Ratio of Tunnel Accidents from 2020 to 2023

Distribution Pattern of Accident Hours.

The hour distribution pattern of the tunnel traffic accidents from 2020 to 2023 was analyzed as follows (table 5). According to the traffic accidents occurring every hour and draw a line chart for analysis.

Table 5. Statistical Table of Hourly Distribution of Tunnel Accidents from 2020 to 2023

Hour period	Number of accidents in 2020	Number of accidents in 2021	Number of accidents in 2022	Number of accidents in 2023
0：00-1：00	6	6	1	0
1：00-2：00	5	6	2	1
2：00-3：00	5	0	2	0
3：00-4：00	2	1	4	0
4：00-5：00	0	4	2	0
5：00-6：00	0	1	1	0
6：00-7：00	5	2	3	0
7：00-8：00	5	3	4	0
8：00-9：00	6	10	2	1
9：00-10：00	12	13	7	5
10：00-11：00	14	13	13	9
11：00-12：00	21	14	10	9
12：00-13：00	16	12	7	2
13：00-14：00	29	13	7	8
14：00-15：00	26	21	9	5
15：00-16：00	17	20	12	8
16：00-17：00	35	13	15	3
17：00-18：00	17	15	12	2
18：00-19：00	11	11	8	1
19：00-20：00	6	8	1	0
20：00-21：00	6	5	3	1
21：00-22：00	6	9	2	0
22：00-23：00	2	4	1	0
23：00-24：00	6	2	5	2

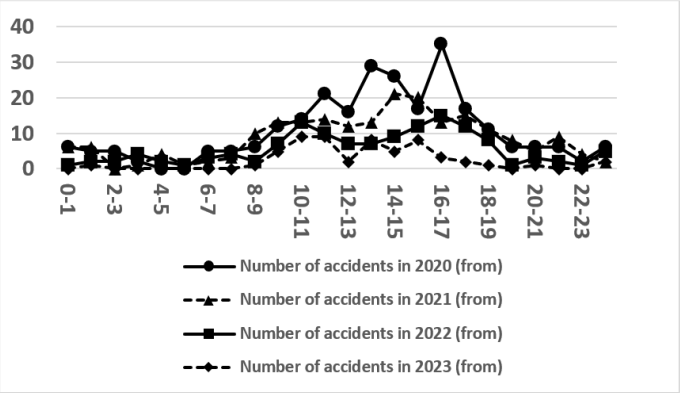

Fig. 2. Line chart of accident statistics by hour

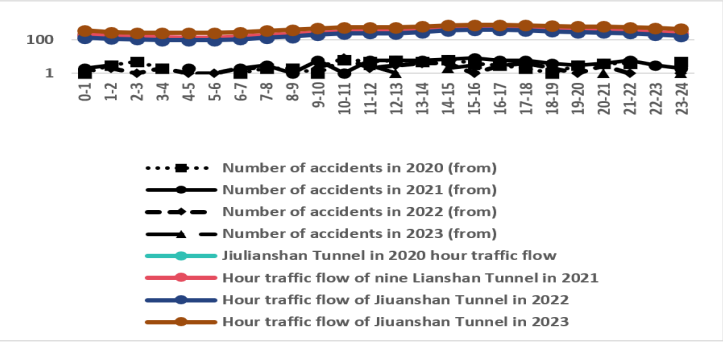

Fig. 3. Hourly distribution pattern of tunnel A accidents

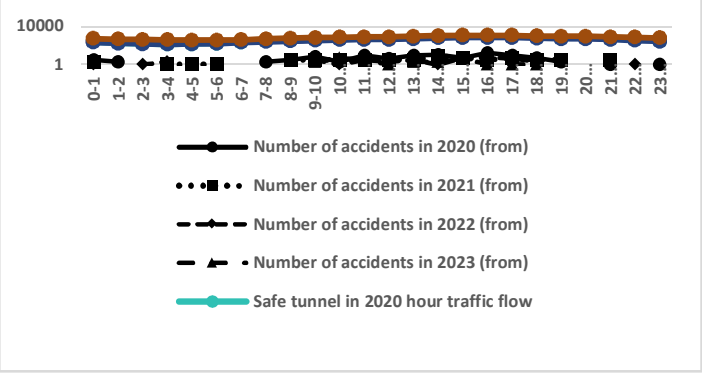

Fig. 4. Distribution pattern of accident hours in tunnel B

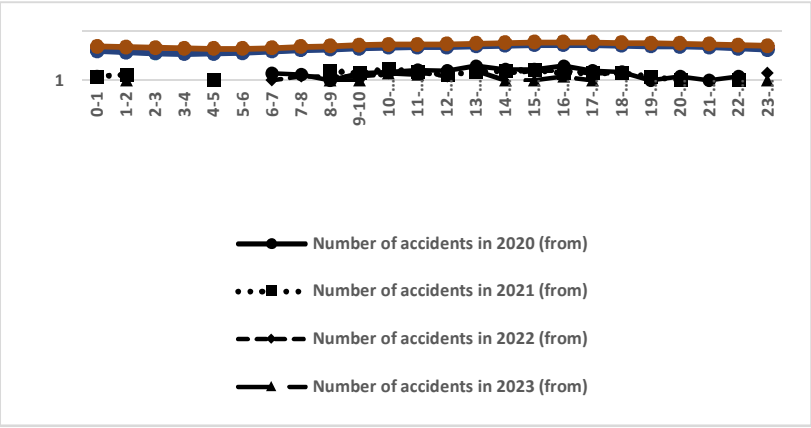

Fig. 5. Hour distribution pattern of accidents in tunnel C

It can be seen from the fig.2, fig.3, fig.4 and fig.5 that the time period with a large number of accidents is concentrated in the afternoon, especially from 13:00 to 15:00 and 16:00-17:00, when the traffic flow is large, which is easy to cause traffic accidents of different degrees. It can be seen that the number of accidents is closely related to the traffic flow. In the safety control of expressway tunnel, we should focus on the operation of the large traffic flow to avoid the occurrence of accidents.

The following is the graph of the accident hours of the three tunnels respectively. It can be seen from the figure that the high incidence of accidents are concentrated in the afternoon, and the concentration of the occurrence of accident time in tunnel C is higher than that in tunnel A. The main period is 16:00-17:00. Highway driving for a long time is easy to produce fatigue, especially in the afternoon period, combined with the lack of light in the tunnel, complex environment and other factors, the driver may not respond in time, this kind of situation is easy to lead to traffic accidents, should be focused on.

Combined with the analysis of hourly traffic flow data in this section, the time period of traffic flow is easy to lead to frequent traffic accidents, large traffic flow is easy to cause congestion, rear-end collision caused by delayed braking, and accidents caused by drivers' unconcentration. And the afternoon traffic flow increased sharply, coupled with the speed of the highway, these are the safety risks leading to accidents.

Distribution Law of the Accident Section.

In the case of statistical traffic accidents in distribution areas, the influencing factors of three sections are mainly considered, mainly the tunnel entrance section, tunnel middle section and tunnel exit section. Due to the long number of kilometers in the middle section of the tunnel, the interval of the same distance according to the pile number shown in Table 6.

Table 6. Statistical Table of Distribution Rules of Accident Sections in Tunnel A from 2020 to 2022

Tunnel A (Shenzhen direction)	Number of accidents in 2020	Number of accidents in 2021	Number of accidents in 2022
K841+500-K842+000	0	0	2
K842+000-K842+500	1	5	6
K842+500-K843+000	4	4	2
K843+000-K843+500	1	4	2
K843+500-K844+000	4	3	2
K844+000-K844+500	2	1	3
K844+500-K845+000	3	2	1
K845+000-K845+500	3	1	1
K845+500-K846+000	0	1	1
K846+000-K846+500	0	3	1
K846+500-K847+000	1	4	3
K847+000-K847+500	2	0	0

The traffic accidents of tunnel A in the past three years are mainly concentrated in the transition section and the middle section of the tunnel. Because tunnel A is the only A 5.5km long tunnel, the light environment in the middle section of the tunnel is poor, the semi-closure characteristics of the tunnel are obvious, and the visual fatigue and energy concentration caused by driving in the tunnel for a long time are easy to lead to frequent traffic accidents in the middle section of the tunnel.

Table 7. Statistical Table of Distribution Patterns of Tunnel B Accident Sections from 2020 to 2022

Tunnel B	Number of accidents in 2020	Number of accidents in 2021	Number of accidents in 2022
K938+000-K938+500	45	30	18
K938+500-K939+000	6	5	9
K939+000-K939+500	0	1	3
K939+500-K940+000	5	0	0
ZK938+000-ZK938+500	1	1	4
ZK938+500-ZK939+000	3	9	3
ZK939+000-ZK939+500	33	18	10
ZK939+500-ZK940+000	2	3	1

As is shown in Table 7, the number of traffic accidents in tunnels C and B has shown the same trend both in both Shenzhen and Wuhan in the past three years. The two tunnels are kilometers, the tunnel environment and facilities are roughly the same, so the data show the same trend. The obvious feature is that the entrance section of the two tunnels in the direction of Shenzhen shows the peak number of traffic accidents,

which is the most significant in 2020. The sudden change of the light environment at the entrance section is one of the reasons for the increase in the number of accidents. The curve trend of the two tunnels in Wuhan direction is quite obvious, and the high incidence of accidents is concentrated in the middle section of the tunnel. Similarly, the probability of traffic accidents in the exit section of both tunnels is lower and the entrance section is higher. The design and condition of the tunnel exit section can be used as a reference to prevent traffic accidents.

Statistical Analysis of Tunnel Accidents.

According to the different lines of accidents, the accident incidence of the uphill and downhill sections in three years is analyzed. (Note: Tunnel C slope is the same, so this impact factor is not considered).

Table 8. Linear Statistics of Tunnel Accidents from 2020 to 2022

Tunnel	a particular year	Number of accidents in uphill section	Number of accidents in downhill section
Tunnel A	In 2020,	27	45
	In 2021,	32	54
	In 2022,	20	32
Tunnel B	In 2020,	55	40
	In 2021,	50	22
	In 2022,	34	14

As is shown in Table 8, the number of traffic accidents in the downhill section of tunnel A is significantly higher than that in the uphill section, while the tunnel B is the opposite, and the number of traffic accidents in the uphill section is significantly higher than that in the downhill section. For the long tunnel, nearly half of tunnel A is in the downhill section, and the speed of the downhill section is easy to be too fast, and the ground skid resistance is worse than that of the uphill section. Therefore, the long-distance downhill section is easy to lead to the increase of the accident probability under these factors. It can be seen that the influence factors of long tunnel and long tunnel have different accident lines.

4 Conclusion

Through the statistical analysis of the total number of accidents, accident form, accident cause, accident line shape, weather condition, hour distribution rule, month distribution rule and section distribution law of expressway Province:

(1) with the increase of the year tunnel traffic accidents in constantly decrease, tunnel maintenance work, tunnel custody personnel according to the accumulated experience every year improve the ability to control tunnel traffic accidents, in the tunnel safety control work made certain progress, for the subsequent maintenance and safety management work laid a good foundation.

(2) From the perspective of accident form, rear-end accidents account for the majority, the reason is the large traffic flow, which is leads to rear-end accidents. From the perspective of accident cause, the insufficient safety distance and improper operation account for the majority; the probability of accident in sunny days is significantly higher than other weather, due to the black and white hole effect of tunnel sections, when the weather is clear, it is likely to lead to traffic accidents.

(3) The insufficient distance between the two workshops is an important reason for the tunnel accident. The main reasons for the insufficient distance are delayed braking, not timely driver response, poor skid performance of the tunnel road, not enough safe distance too fast, and the collision between the two cars caused by insufficient spacing. It can be seen from the distribution law of accident hours that the time period with a large number of accidents is concentrated in the afternoon, during which the traffic flow is large, which is easy to cause traffic accidents of different degrees. It can be seen that the number of accidents is closely related to the traffic flow.

(4) Traffic is a high incidence of accidents and is concentrated in the middle section of the tunnel. The light environment in the middle section of the tunnel is poor, and the semi-closed characteristics of the tunnel are obvious. Driving in the tunnel for a long time leads to visual fatigue and unconcentration.

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