The risk of passenger behaviors that influence accident type and severity in metro operation: case-based Monte Carlo analysis

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Article

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The risk of passenger behaviors that influence accident type and severity in metro operation: case-based Monte Carlo analysis

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HIGHLIGHT:
1. 234 metro operation accidents caused by passengers’ unsafe behaviors were counted and quantified to establish a comprehensive dataset
2. Monte Carlo algorithm was introduced to research the behavioral risk of different metro operation accidents caused by the 12 categories of passengers’ unsafe behaviors
3. The differences of the probabilities in different risk levels of each accident type caused by the various passengers’ unsafe behaviors were captured
4. Targeted risk mitigation strategies and measures based on the behavioral risk characteristics were clarified
Abstract: This study aims to examine the risk of each category of behavior related to different accident types and consequences by introducing the Monte Carlo algorithm. Totally about 234 cases were collected to construct a structured dataset, and 12 categories of passengers’ unsafe behaviors related to the four types of metro operation accidents including escalator injury, crowd stampede, pinched by a shielding barrier and fall injury were considered for this analysis. Results showed that although the total behavioral risk of each accident type obeys normal distribution with means between (4, 6] in the Moderate risk level, the variances of pinched by a shielding barrier (1.29) and crowded stampede (1.08) are much higher than escalator injury (0.60) and fall injury (0.59). The top four contributors that resulted in the accident behavioral risks were irregular behavior on the escalator, go on boarding even after the door-close alarm sounded, push each other, and pay no attention to the ground. It was concluded that due to the uncertainty of the behavior occurrence and its consequences, there are differences of the probabilities in different risk levels of the four accidents caused by the various passengers’ unsafe behaviors. Based on the results, risk mitigation measures for different accident types are recommended. This paper provides a quantitative method to compare and analyze the effect of passengers’ unsafe behaviors related to different accident types and severities, which has relative comparative significance and improves the accuracy of judging the probability distribution of risk degree that can provide basis for risk mitigation in metro operation.

Keywords: Passenger behaviors; Metro operation safety; Risk assessment; Monte Carlo algorithm; Risk mitigation measures

1. Introduction

As a modern mode of advantageous transportation with large capacity, high speed, low pollution and energy saving, metro is being constructed in many cities of China, which has driven the city extended outward and promoted economic development (Xing, Dissanayake, Lu, Long, & Lou, 2017; Li, Song, List, Deng, Zhou, & Liu, 2017). At the end of 2020, a total of 45 cities in China have opened 244 urban rail transit operating lines with a total length of 7969.7 kilometers. Among them, the metro operating line is 6280.8 kilometers, accounting for 78.8% (Statistical and Analysis Report of Urban Rail Transit in 2020, 2020). As more and more new metro lines are brought into service, new challenges and demands for reliable and safe metro operation has become important (Wang, & Dong, 2019; Wan, Li, & Yuan, 2014). Due to the different safety qualities of passengers, frequent unsafe behaviors, and the train operation being easily disturbed by small events, the situation of safe metro operation is not optimistic (Wan et al., 2014; Dinkel, Baumert, Erazo, & Ladwig, 2011; Karl-Heinz, & Baumert). Report shows that there were 1,023 metro operation incidents with delays exceeding 5 minutes in China in 2020, which resulted in casualties and serious property losses (Statistical and Analysis Report of Urban Rail Transit in 2020, 2020).

Among risk factors such as human factors, equipment factors, management factors and environment factors of metro operation, accidents caused by passengers' unsafe behavior account for the highest proportion, due to the lack of safety awareness, less traffic safety training, as well as the metro riding rules are not as strict and explicit as traffic regulations, and sometimes can be violated.
without a similarly stringent punishment in China (Wan et al., 2014; Bai, Sun, & Zhao, 2014; Zhao, Wu, & Wang, 2018; Wang, Huang, J Wang, Sulaj, & Kuang, 2020). Moreover, metro passengers’ unsafe behaviors are diverse, and the accidents caused by them are uncertain, which increases the difficulty of risk management. These behaviors include go on boarding or alighting even after the door-close alarm sounded (Li, Song, Deng, Zhou, & Liu, 2017), irregular behavior on escalators (Xing Y et al., 2017; Chi, Chang, Tin-Chang, & Tsou, 2006), pushing each other (Wang Qiquan, 2018) and so on. Some behaviors induce dangerous accidents, and some lead to escalator injuries, pinched by a shielding barrier, fall injury and even crowded stampedes (Wang Qiquan, 2013). It can be seen that there are diverse unsafe behaviors cause metro operation accidents, and the relations of unsafe behaviors that influence accident risk in metro operation deserve more in-depth discussion.

Risk assessment of unsafe behavior is a significant approach to identify risk source and reduce injuries and even accidents (Tong, Li, Zhang, Yang & Ma, 2021). Due to the growing proportion of passengers' unsafe behaviors and their grave consequences in metro operation accidents, it is an urgent need to examine the passengers' unsafe behaviors risk that affect accident type and severity of metro operation for improving the pertinence and effectiveness of risk mitigation countermeasures. The risk of unsafe behavior consists of the possibility of behavior and the severity of consequence that caused by the behavior. In order to quantitatively explore the risk of passengers' unsafe behaviors, it is necessary to understand the uncertainty of behavioral risk, find out the effect of each passenger’s unsafe behavior on the accident type and severity of metro operation (Tong & Ma, 2018; Tong et al., 2021). The choice of appropriate analytical methods and the selection of comprehensive passenger’s unsafe behaviors are two important considerations for establishing an accurate risk assessment model to study each passenger’s unsafe behavior related to different metro accident types and risk levels.

In regard to the possibility of behavior, statistical analysis of metro operation accidents is an effective means to obtain the frequency of different passengers' unsafe behaviors contributed to the accident. Previous studies mainly focus on the influencing factors related to passengers' unsafe behavior (Thomas et al., 2012; Wang, Gao & Wang, 2020; Basir, Yaziz, Zamri & Halim, 2017). For instance, Thomas et al. (2012) made a statistical study of 292 suicides from the aspects of passenger physiology, subway station characteristics and environmental factors, and found that subway type, station congestion and drug use have a significant impact on passengers' suicidal behavior. Wang et al. (2020) constructed a disordered multi-classification logistic regression model to analyze 894 escalator accidents in Beijing subway from 2016 to 2018. The results show that wet and slippery steps, crowding and unsafe escalator behaviors occur frequently, which are the main factors leading to the accidents. Basir et al. (2017) found that the main factors leading to escalator accidents are dynamic and complex passenger factors. These studies have explored which influencing factors are related to passengers' unsafe behavior before it occurs, while they have not solved the consequences or risks once unsafe behavior occurs.

In fact, the high frequency of unsafe behavior does not mean that the accident caused by it is serious. Although statistical analysis such as descriptive analysis and logistic regression model have important superiority in measuring the influencing factors related to one type of passengers' unsafe behavior or one type of metro injury accident, it cannot explain the degree of risk caused by the behavior as they have shortcomings in dealing with interactions between multiple behaviors and
various consequences.

Considering the complexity of consequences caused by multiple passengers' unsafe behaviors, non-linear models have attracted more attentions to measure the interactions between unsafety behaviors and severity of consequence in recent years (Wan & Yuan, 2014; Xie, & Liu., 2019; Wang, Wan, Mao, Li & Wang, 2020; Li, Wang, Xing, Zhao & K Wang, 2021). For instance, Wan et al. (2014) used Petri net to identify the critical paths of passengers’ abnormal behavior affecting metro operation, and believed that conflicts between passengers and invading boundaries were the key paths to cause accidents. Xie et al. (2019) used ISM-DEMA TEL to explore the relationship among escalators, passengers and environment in subway station. In 2020, Wang et al. (2020) analyzed 40 typical metro operation accidents which were divided into four levels according to the severity of consequence including high, medium, low and insurance accidents. The conditional configurations among passengers' unsafe behaviors and the four levels of consequence were studied by using Fuzzy Set Qualitative Comparative Analysis (fsQCA). Results showed that there are 12 types of conditional configurations which were finally classified into weak safety awareness type, lack of supervision type and others influence type to put forward risk management countermeasures. Li, H. et al. (2021) conducted a Bayesian network analysis of 950 subway escalator accidents in terms of occurrence probability and severity. It was found that standing instability was the most likely factor to induce accidents, and among the types of injuries caused to passengers, head and neck injuries were more serious.

Although these non-linear models have important superiority in revealing the relevance of passengers’ unsafe behaviors and accident consequences (Wan Xin et al., 2014; Xie & Liu., 2019; Wang Rubing et al., 2020; Li et al., 2021), it may appear a low prediction of accident risk, as they did not consider the effect of different behaviors on the accident type and severity of metro operation. Besides, due to the uncertainty of behavior occurrence and its consequence, behavioral risk is not a certain value but obeys a certain distribution in statistical significance, which is always omitted. These may lead to the potential difference of behavioral risk cannot be captured, thus reducing the accuracy of preventive measures. Therefore, the general deterministic risk assessment methods which are usually used to study the overall risk of unsafe behavior in the entire accident dataset, are not applicable to dealing with the uncertainty of behavioral risk.

The Monte Carlo algorithm, as a numerical calculation method based on probability and statistics theory, can effectively resolve the uncertainty in risk assessment in the form of probability distribution. By simulating the real environment with thousands of repetitive random numbers, it can better reveal the statistical distribution of uncertain phenomena based on priori probability and risk function (Xu Zhongji, 1985; Tong & Ma, 2018; Tong et al., 2021). Therefore, the Monte Carlo algorithm, combined with multidimensional dataset containing comprehensive passenger’ unsafe behaviors and their consequences, could provide more powerful insights than applying a general deterministic risk assessment model to accurately measure the risk of each type of behavior related to different accident consequences.

In this study, the Monte Carlo algorithm are firstly used to quantitatively reveal the risk of passengers’ unsafe behaviors related to different accident type and severity of metro operation. Specifically, based on the comprehensive dataset of 234 metro operation accidents caused by
passengers’ unsafe behaviors, the behavioral risk function was established to support for the statistical simulation analysis of Monte Carlo algorithm by splitting the entire data into several homogeneous groups, which accurately revealed the uncertainty of various behavioral risk. This analysis could help us understand the question of “which are the high-risk unsafe behaviors associated with high incidence of severe casualties in metro operation”. The results will provide useful sights for solving the question of “how to improve prevention and control for different unsafe behaviors in metro operation, especially for high-risk behavior.”

2. Materials

2.1. Identification of accident type and unsafe behavior

The validity of Monte Carlo-based behavioral risk assessment depends on the sample data with comprehensive passenger unsafe behaviors and their accident injury types. The incomplete expression of passenger unsafe behaviors and their correspondence with accidents will affect the performance and results of Monte Carlo analysis. Thus, the key to construct a valid dataset is to identify the possible accident types and behaviors for clarifying the structure of the dataset based on the actual cases (P. N., J. P. and D. J., 1997; Cho, Kim, Kim, Park & Kim, 2020). The research material was collected by the authors, via utilizing official data from public reports, which shows that total of 234 metro operation accidents caused by passengers’ unsafe behavior had occurred in China from 2002 to 2020. The aim of structured the dataset was to identify all the unsafe behaviors and their possible accident injury types that metro operation needs to consider when preparing for risk control measures. Four main types of these accidents were identified including escalator injury, pinched by a shielding barrier, crowded stampede and fall injury in the station. The related unsafe behaviors were divided into 12 categories.

Among these types of accident, escalator injury is the most studied (Zhao, Lu, Li & Tian, 2017; Lian, Mai, Song, Richard, Rui & Jin, 2017; Xie, Mei, Gui & Liu, 2018; MMD & Schreeb, 2019). The unsafe behaviors that lead to escalator injuries were divided into performing other tasks (Li et al., 2017), children making trouble and irregular behavior on escalator (Shiwakoti, Tay, Stasinopoulos & Woolley, 2017). While push each other, fights and spread rumors are more likely to cause crowded stampedes (Schminke, Jeger, Evangelopoulos, Zimmerman, & Exadaktylos, 2013). As for pinched by a shielding barrier and fall injury in the station, few studies focused on behaviors that cause such injuries. Through analyzing the causative factors of collected cases, we found that go on boarding or alighting even after the door-close alarm sounded, moving slowly and carrying large baggage were the most behavioral factors of pinched by a shielding barrier, and taking prohibited things such as pets, paying no attention to the ground and littering were contributed to fall injury in the station. All the behaviors and relevant accident types were categorized and numbered, as shown in Table 1.

<table>
<thead>
<tr>
<th>Accident type</th>
<th>Unsafe behavior</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Escalator injury (A)</td>
<td>Performing additional task</td>
<td>A1</td>
</tr>
<tr>
<td></td>
<td>Children make trouble</td>
<td>A2</td>
</tr>
<tr>
<td></td>
<td>Irregular behavior on escalator</td>
<td>A3</td>
</tr>
<tr>
<td>Pinched by a shielding</td>
<td>Go on boarding or alighting even after the</td>
<td>B1</td>
</tr>
</tbody>
</table>
barrier (B)  
Moving slowly  B2
Carrying large baggage  B3

Crowded stampede (C)  
Push each other  C1
Fighting  C2
Spread rumors  C3

Fall injury in the station (D)  
Taking prohibited things (e.g. pets)  D1
Paying no attention to the ground  D2
Littering  D3

2.2. Classification of accident severity

In order to quantitatively analyze the risk levels caused by different passengers’ unsafe behaviors, it is necessary to classify the severity of the accident to illustrate the relationship between unsafe behaviors and the different consequences. According to the Chinese official document “Emergency Plan for National Urban Rail Transit Operation Emergencies”, operational emergencies are classified into four levels, which are I (catastrophic, more than 30 deaths, or more than 100 seriously injured, or more than 100 million RMB of direct economic loss), II (destructive, 10-30 deaths, or 50-100 seriously injured, or 50-100 million RMB of direct economic loss, or metro operation delay for more than 24 hours), III (severe, 3-10 deaths, or 10-50 seriously injured, or 10-50 million RMB of direct economic loss, or 6-24 hours delay), and IV (ordinary, less than 3 deaths, or less than 10 seriously injured, or 0.5-10 million RMB of direct economic loss, or 2-6 hours delay).

However, most accidents caused by passengers’ unsafe behaviors are near accidents or ordinary operational emergencies. Therefore, scholars have proposed some relatively more detailed classification to focus on the impact of unsafe behaviors on metro shutdown time and casualties (Wang et al., 2020; Office of the State Council, 2021; Song Jian & Yang Yao., 2009). For instance, literature divided subway operation accidents into high-impact accident, medium-impact accident, low-impact accident, and near-missing accident. Take low-impact accident as an example, 1-2 injuries or less than 1 hour delay will be classified as this level of accident. By comparing the classification of previous studies, combined with our research needs, the metro operation incidents caused by passengers are divided into five levels in this study, as shown in Table 2. In addition, different degrees of severity were assigned to corresponding values, so that the consequences can be quantified for the structured dataset.

### Table 2  Classification of accident severity levels

<table>
<thead>
<tr>
<th>Accident severity level</th>
<th>Description</th>
<th>Metro stop time (t) unit: min</th>
<th>Quantitative score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level I</td>
<td>More than 5 people died, or more than 10 people were seriously injured, or more than 50 people were slightly injured</td>
<td>t &gt; 60</td>
<td>10</td>
</tr>
<tr>
<td>Level II</td>
<td>1 to 5 people died, or 5 to 10 people were</td>
<td>30 &lt; t ≤ 60</td>
<td>8</td>
</tr>
</tbody>
</table>
seriously injured, or 20 to 50 people were
slightly injured

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
<th>Condition</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>III</td>
<td>1 to 5 people were seriously injured, or 5 to 20 people were slightly injured, no deaths</td>
<td>$15 &lt; t \leq 30$</td>
<td>6</td>
</tr>
<tr>
<td>IV</td>
<td>1 to 5 people with minor injuries, no serious injuries or deaths</td>
<td>$0 &lt; t \leq 15$</td>
<td>4</td>
</tr>
<tr>
<td>V</td>
<td>No one was injured or killed</td>
<td>No delay</td>
<td>2</td>
</tr>
</tbody>
</table>

According to Table 1 and Table 2, the 234 metro operation accidents can be transformed into a structured dataset, which could count and characterize the metro operation accidents caused by different passengers' unsafe behaviors through the unified symbolic and quantitative expression. For example, on November 24, 2019, a man at Zhifang Street Station of Fuzhou Metro Line 7 made a phone call while riding on the escalator and fell down, and hit a passenger behind him. Both were slightly injured. According to Table 1, the accident was classified as an escalator injury, and the unsafe behavior involved in the accident was performing additional task (A1). According to Table 2, 2 people were slightly injured in the accident, and no one was seriously injured or killed. The subway doesn't stop. Therefore, the accident severity level is level IV, and the quantitative score is 4. The structured dataset provides a good basis for Monte Carlo algorithm to establish an accurate risk assessment model to study each passenger’ unsafe behavior related to different metro accident types and risk levels.

3. Methods

3.1 The key steps of Monte Carlo modeling

The process of using Monte Carlo method to solve problems is based on the mathematical probability model. According to the description of this model, a series of random numbers conforming to a specific probability distribution are generated. The statistics of the experimental results are taken as the approximate solution of the problem (Xu Zhongji, 1985; Tong & Ma, 2018; Tong et al., 2021). Therefore, when using Monte Carlo method to simulate and solve practical problems, it generally includes three steps, which are constructing a mathematical function to describe the probability process, sampling from the known or priori probability distribution, and analyzing the simulation results.

Fig.1 illustrates the workflow of the proposed approach to assess the passengers' unsafe behavior risk considering the impact of uncertainty. The probability distribution of each behavior was calculated based on the structured dataset to provide initial parameters for Monte Carlo modeling. Based on the initial parameters and constructor function of behavioral risk, the Monte Carlo algorithm was used to establish a total behavioral risk assessment model through statistical simulation, which can quantitatively analyze the risk of each behavior related to different accident consequences. The obtained behavioral risk is a kind of probability distribution but not a certain value, which can provide more powerful insights to reveal the difference of various passengers' unsafe behaviors and the corresponding potential risks.
3.2. Establish constructor function of behavioral risk

Because risk is a function of the possibility and consequence, only consider the frequency of behavior in the accident samples cannot accurately reflect the risk. Considering both the possibility of behaviors and the consequences caused by the behaviors contributed to a certain type of accident, a risk-based function is constructed as a mathematical model for Monte Carlo simulation as shown in equation (1). It can be seen from Table 1 that each type of accident can be caused by multiple unsafe behaviors. The risk of this accident is a comprehensive measure of the probability and consequences of the various unsafe behaviors.

\[ R = \sum_{i=1}^{n} P_i \times S_i \]  

In formula (1), there are \( n \) categories of passengers' unsafe behaviors that could induce the same type of accident. \( R \) represents the total behavioral risk of this accident. \( P_i \) represents the probability of the \( i \)-th unsafe behavior. \( S_i \) represents the loss caused by the \( i \)-th unsafe behavior.

3.3. Sampling from the priori probability distribution

3.3.1 Determine the probability distribution of accident severity caused by unsafe behavior

The unsafe behaviors under each accident type are independent and obey their respective
probability distributions. According to formula (1), the probability of unsafe behavior $P_i$ is determined by the frequency that the behavior contributed to the accident in the dataset, which is a fixed value. As for $S_i$, it is a random variable. That is because there are multiple categories of unsafe behaviors that lead to the same type of accident, and even the same category of unsafe behavior, the consequences caused by it are different in each case. In other words, the accident losses caused by the same category of unsafe behavior are random.

Therefore, as a function of $P_i$ and $S_i$, the behavioral risk of this accident $R$ is also a random variable, which has the properties of uncertainty. In addition, science the accident severity was classified into five levels in Table 2 and the sum of $P_i$ is 1, the value of $R$ theoretically varies between 0 and 10, which is consistent with the classification of Table 2. Thus the risk levels include five degree, which are Level V (0, 2], Level IV (2, 4], Level III (4, 6], Level II (6, 8] and level I (8, 10], from the lowest to the highest, as shown in Table 3.

<table>
<thead>
<tr>
<th>Risk value</th>
<th>Risk level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0, 2]</td>
<td>very low</td>
<td>Level V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The risk of accidents caused by the passengers’ unsafe behaviors is expected to be very low (No injury and death, on train delay). Risk management is not needed.</td>
</tr>
<tr>
<td>(2, 4]</td>
<td>low</td>
<td>Level IV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The risk of accidents caused by the passengers’ unsafe behaviors is expected to be minor (certain minor injuries and no death, a little impact on the delay). Risk management could be considered.</td>
</tr>
<tr>
<td>(4, 6]</td>
<td>moderate</td>
<td>Level III</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The risk of accidents caused by the passengers’ unsafe behaviors is expected to be general (certain serious injuries and no death, notable impact on the delay). Risk management is recommended.</td>
</tr>
<tr>
<td>(6, 8]</td>
<td>high</td>
<td>Level II</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The risk of accidents caused by the passengers’ unsafe behaviors is expected to be serious (serious injuries or deaths, major impact on the delay). Risk management is needed.</td>
</tr>
<tr>
<td>(8, 10]</td>
<td>very high</td>
<td>level I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The risk of accidents caused by the passengers’ unsafe behaviors is expected to be more serious (more serious injuries or deaths, significant impact on the delay). Risk management is obligatory.</td>
</tr>
</tbody>
</table>

### 3.3.2 Monte Carlo simulation

After determining the probability of unsafe behaviors and the probability distribution of accident losses caused by them, we could generate random numbers and conduct sampling by Monte Carlo algorithm. A series of random numbers generated by sampling are used as the sampling input of the system for numerical simulation experiments. And a large number of simulation experiment values will be obtained. Since the behavioral risk function are composed of various random variables form the probability of the unsafe behaviors and the probability distribution of accident losses, the simulation results of behavioral risk will also obey various probability distributions. This is the process to realize Monte Carlo simulation for establish an accurate risk assessment model to study each passenger’ unsafe behavior related to different metro accident types and risk levels.

The probability distribution of common random variables is generally divided into two categories.
One is discrete distribution (binomial distribution, position distribution, etc.) and the other is continuous distribution (uniform distribution, exponential distribution, normal distribution, etc.). The random numbers of each random variable obey a specific probability distribution. The parameter estimation method of normal distribution used in this paper is introduced below.

The normal distribution, denoted as \( N(\mu, \sigma^2) \), is the distribution of a continuous random variable with two parameters \( \mu \) and \( \sigma^2 \). The first parameter \( \mu \) is the mean value of the random variable, and the second parameter \( \sigma^2 \) is the variance of this random variable. The density function of the random variable \( X \) is \( f(X) \) as shown in formula (2).

\[
f(x) = \frac{1}{\sqrt{2\pi \sigma}} e^{\frac{-1}{2\sigma^2} (x - \mu)^2}
\]

(2)

Its probability distribution function is shown in formula (3).

\[
F(x) = \frac{1}{\sqrt{2\pi \sigma}} \int_{-\infty}^{x} e^{\frac{-1}{2\sigma^2} (y - \mu)^2} dy
\]

(3)

The maximum likelihood of \( \mu \) is estimated as \( \hat{\mu} = \frac{1}{n} \sum_{i=1}^{n} x_i = \bar{x} \)
The maximum likelihood of \( \sigma^2 \) is estimated as \( \hat{\sigma}^2 = \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2 = s^2 \)
However, due to \( E(s^2) = \sigma^2 \frac{n-1}{n} \), the sample variance \( s^2 \) is not an unbiased estimate of the population variance \( \sigma^2 \). The following corrections (see formula (4)) are made to \( s^2 \).

\[
s^2 = \frac{(n-1)s^2}{(n-1)} = 1/ (n-1) \sum_{i=1}^{n} (x_i - \bar{x})^2
\]

(4)

Finally, the Monte Carlo simulation was carried out through the Oracle Crystal Ball 11.1, based on the constructed behavioral risk function and the prior probability distribution obtained from the structured dataset. The number of experiments was set to 10000, with a confidence of 95%. When the sampling is sufficient, the simulation results are statistically processed to calculate the statistical characteristic parameters of behavioral risk under each accident type. In addition, sensitivity analysis of each unsafe behavior was conducted to measure the contribution of each behavior to accident risk.

4 Results

4.1. Probability distribution of unsafe behavior and accident severity

Based on the structured dataset, the probability distribution of each unsafe behavior caused the accident types and losses were analyzed by splitting the entire data into several homogeneous groups. Anderson-Darling test (A-D test) was used to verify the goodness-of-fit of the distributions. The detail results are shown in Table 4.

It was found that the probability distribution of accident severity caused by each unsafe behavior generally obeys the normal distribution. The obtained frequencies and the probability distributions of each behavior will be used to provide initial parameters for the following Monte Carlo modeling.

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Probability distribution of unsafe behaviors and consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of accident</td>
<td>Unsafe behavior category</td>
</tr>
<tr>
<td>escalator</td>
<td>Perform</td>
</tr>
<tr>
<td>Injury Type</td>
<td>Additional Tasks</td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>-------------------------------------------------------</td>
</tr>
<tr>
<td>Pinched by a shielding barrier</td>
<td>Children make trouble</td>
</tr>
<tr>
<td></td>
<td>Irregular behavior on escalators</td>
</tr>
<tr>
<td></td>
<td>Go on boarding or alighting even after the door-close</td>
</tr>
<tr>
<td></td>
<td>alarm sounded</td>
</tr>
<tr>
<td></td>
<td>Moving slowly</td>
</tr>
<tr>
<td></td>
<td>Carrying large items</td>
</tr>
<tr>
<td></td>
<td>Push each other</td>
</tr>
<tr>
<td>Crowded stampede</td>
<td>Fighting</td>
</tr>
<tr>
<td></td>
<td>Spread rumors</td>
</tr>
<tr>
<td></td>
<td>Carrying prohibited items</td>
</tr>
<tr>
<td>Fall injury in the station</td>
<td>Not paying attention to the ground</td>
</tr>
<tr>
<td></td>
<td>Littering</td>
</tr>
</tbody>
</table>

$\mu$: Mean.
$\sigma$: Standard deviation.

4.2. Behavioral risk of each type of accident

According to the Monte Carlo simulation, the probability distributions of the behavioral risks for the four types of metro operation accident caused by the 12 categories of passengers’ unsafe behaviors were obtained as shown in Figure 2. The total behavioral risk of each type of accident obeys the normal distribution. The mean values of risk are between (4, 6). Among them, the means value of crowded stampede was the highest at 5.14, and fall injury in the station was the lowest at 4.14, indicating the differences of accident severities caused by multiple unsafe behaviors. The variance of
pinched by a shielding barrier is the highest at 1.29, followed by the crowded stampede of 1.08. The variance of the escalator injury and the fall injury in the station are 0.60 and 0.59, which are much lower than the previous two accidents, indicating the differences of behavioral risk fluctuations related to each type of accident.

Fig. 2 Probability distribution of behavioral risk for each accident type

In regard to the risk levels of each type of accident, a box plot was drawn in Figure 3. The results of risk levels related to each type of accident are not invariant values, but a series of values that reflect the possible risk levels of each accident. Among the highest values of the total behavioral risk, the crowded stampede was at 8.92, followed by pinched by a shielding barrier at 8.76, and both of them reached the level I range (8, 10]. While escalator injury and fall injury are 7.17 and 6.93, which reached the level II range (6, 8]. Among the lowest values, pinched by a shielding barrier is only 0.08, followed by the fall injury in the station at 1.36, crowded stampede at 1.37, and escalator injury at 1.72. These values all belong to the lowest risk level range of Level V (0, 2].

Fig. 3 Box diagram of behavioral risk for each accident type

The cumulative probability of the total behavioral risk for each accident type is shown in Figure
4. It shows that there are obvious differences among the four accident types in each risk level intervals. In the interval (0,2], the cumulative probabilities of the escalator injury, pinched by a shielding barrier, crowded stampede, and fall injury in the station are 0% to 0.04%, 0% to 2.10%, 0% to 0.21%, and 0% to 0.27%. In the interval (2,4], the cumulative probabilities of these 4 accident types are 0.04% to 18.59%, 2.10% to 39.65%, 0.21% to 20.84%, and 0.33% to 40.92%. In the interval (4,6], the increases are 18.59% to 94.82%, 39.65% to 92.95%, 20.84% to 86.79%, and 40.92% to 99.21%. When the cumulative probability reaches 100%, the total behavioral risk values of these 4 types of accidents are 7.65, 8.71, 8.82, and 6.85.

4.3. Sensitivity analysis of unsafe behaviors to each accident type

Spearman rank correlation coefficient method was used for sensitivity analysis to measure the influence of each unsafe behavior contributed to the total behavioral risk of each accident (Xingyou et al., 2015). The greater the sensitivity, the greater the impact of passengers' unsafe behavior on the type of accident. The results of sensitivity analysis are shown in Figure 5.
Among the unsafe behaviors related to escalator injury, irregular behavior on escalators (A3) has the highest sensitivity of 59.3%, which is manifested that passenger did not grasp the handrails, did not pay attention to the stairs and so on. The sensitivity of performing additional tasks (A1) is 21.8%, as passengers carrying luggage, playing with mobile phones or communicating with others while taking the escalator. The sensitivity of children make trouble (A2) is 18.9%, and the main performances include children press the emergency button induced other passengers to fall down or children fall down by themself due to disporting on the escalator.

As for pinched by a shielding barrier, go on boarding or alighting even after the door-close alarm sounded has the highest sensitivity of 76.3%, indicating that this category of behavior contributed the most to being pinched when the metro shielding barrier is about to be closed. The sensitivity of carrying large baggage (B3) is 13.8%, due to it take too much time to carry the baggage when getting on and off the train. The sensitivity of moving slowly (B2) is 9.9%, mainly happens to social vulnerable groups such as elderly and disabled group being pinched and injured due to their inconvenient movement.

Among the unsafe behaviors related to crowded stampede in metro operation, the sensitivity of pushing each other (C1) is highest at 70.1%, mainly happens during the peak passenger flow for getting on and off the train in time. While spread rumors (C3) is 22.5%, as spreading false news such as fires and terrorist attacks causing panic among the passengers. The sensitivity of fighting (C2) is lowest at 7.3%, as sometimes a big fight is caused by a small friction.

About the fall injury in the station, the sensitivity of paying no attention to the ground (D2) is the at 53.4%, due to using a mobile phone or other situations while walking. Taking prohibited things (D1) is at 27.4%, mainly refers to passengers bring items such bicycles, pets, etc. resulting in instability and fall. The sensitivity of littering (D3) is 19.2%, due to discarded garbage such as banana peelings cause other passengers to fall.
5. Discussion

5.1. Differences of behavioral risk characteristics related to different accident types

From the obtained probability distributions of behavioral risks, we found that although the total behavioral risk of each accident type obeys normal distribution, there are differences in the parameter values of the distributions. As the parameter values are the outcomes of statistical calculation from the 10000 numerical simulation experiments, they quantitatively reflect the impact of behavioral uncertainty on the consequences of the accidents. The reason of the differences is related to the uncertainty of both the behavior occurrence and consequence (Tong et al., 2021), which is first revealed by Monte Carlo simulation in the studies.

In terms of means ($\mu$) seen in Fig.2, crowded stampede is the highest at 5.14, followed by escalator injury (4.72), pinched by a shielding barrier (4.42) and fall injury (4.14). The mean values are all in the range of (4, 6], indicating that the average risk degrees of each type of accident caused by the passengers’ unsafe behaviors are Moderate (level Ⅲ).

However, it was found that although the average risks of the four accidents are at the same level, the highest risks are different. The highest value of crowded stampede (8.92) and pinched by a shielding barrier (8.76) reached the level I (Fig.3), while escalator injury (7.17) and fall injury (6.93) only reached level II (Fig.3). This shows that crowded stampede and pinched by a shielding barrier are more likely to lead to serious consequence than escalator injury and fall injury in the station.

This is also confirmed by the results of variance ($\sigma^2$). The variances of pinched by a shielding barrier (1.29) and crowded stampede (1.08) are much higher than escalator injury (0.60) and fall injury (0.59), revealing the differences of the volatility of risks related to different accident types. The high volatility of crowded stampede is due to the consequence of this accident could be large or small. We also found an interesting phenomenon that the variance of pinched by a shielding barrier is higher than crowded stampede, which deviated from our original cognition. The expiration of the phenomenon is that it may cost more time to recover from delay, which increases the severity of the consequence of pinched by a shielding barrier.

The cumulative probability of the four accident types shows little difference in the risk interval (0, 2]. But in the interval (2, 4], the cumulative probability of fall injury increases from 0.33% to 40.92%, and in (4, 6] from 40.92% to 99.21%, which indicates that the risk of fall injury accidents in the station is mostly in level V (low) or level III (moderate). Different with the fall injury, the cumulative probability of escalator injury increases from 18.59% to 94.82% only in the interval (4, 6]. It could be interpreted that although the unsafe behaviors of the two accident types related to pay no attention to the stairs (A3) or ground (D2), the consequences on the escalator are more serious than on the ground (Wan Xin et al., 2014). Therefore, the risk of escalator injury in level III (moderate) is much higher than the fall injury. At the end of the interval (4, 6], the cumulative probability of pinched by a shielding barrier and crowded stampede are 92.95% and 86.79%, which is also consistent with the previous analysis of means and variances. It’s concluded that there are differences of the probabilities in different risk levels of the four metro operation accidents caused by the multiple passengers’ unsafe behaviors, which should not be omitted for improving the pertinence of the risk mitigation countermeasures in metro operation.
5.2. Risk mitigation implications

In practical implications, the most recommended risk control measures of unsafe behaviors for metro safety interventions are to implement safety education (Basir et al., 2017; Xie & Liu., 2019), revise the metro safety regulation to increase the punishment of unsafe riding behaviors (Schminke et al., 2013; Xie & Liu., 2019) and split-flow during the peak period of metro traffic (Ca, Jr & Raa, 2019). However, these countermeasures treat all behaviors equally, and did not consider both the risk characteristics of each accident and the contributions of each behavior to the accident types and risk levels, thus unable to provide more precise guidance for the targeted countermeasures.

5.2.1. Risk mitigation strategies based on the behavioral risk characteristics

From the macro perspective, risk mitigation strategy could be divided into three stages which are pre-prevention, in-process control and emergency afterwards, according to the accident development process (Jian, Wmg & Yby, 2020). Although countermeasures at all stages need to be considered for each accident type, some of them should be given priority according to the characteristics of the behavioral risks. Among pre-prevention measures, safety education is a prevalent finding in studies of passengers behavior correction (Wang Qiquan., 2018; Basir et al., 2017; Xie & Liu., 2019), which is suggested firstly for the four accident types. The other risk mitigation strategies for different accident types are analyzed as below, and the comparison is shown schematically in Figure 6.

Since the total behavioral risk of escalator injury is concentrated in the interval (4, 6] (Fig.4), we called it ‘High frequency in medium risk’ accident. The consequences of this accident are not particularly serious, but the frequency is supposed to be very high, which is consistent with the conclusion (Al-Sharif, Dado, Habash, Rawashdeh & Al-Shubbak, 2012; Jiao, Lei, Zong, Cai & Zhong, 2022; Cirilli & Schera, 2018), thus the risk mitigation strategy should be focused on prevention in advance. Because the cumulative probability of crowded stampede is the highest in the interval (6, 10] (Fig.4), and its highest value of the total behavioral risk is at 8.92, we called it ‘Relative high frequency in high risk’. It is more likely to have serious consequences than other accidents, which may require more adequate emergency resources such as first medical aid deal with crush asphyxia or fracture, crowd evacuation, multi-authority co-operation, traffic evacuation outside the subway station, etc (Koski, Kouvonen & Nordquist, 2021). The risk mitigation strategy should be focused on both prevention and emergency preparedness of this accident type. Although the highest risk value of pinched by a shielding barrier is at 8.76 (Fig.3), the cumulative probability is mainly concentrated in the interval (2, 6] (Fig.4), indicating that the severity of its consequence is widely distributed. We called it ‘Possible frequency in all risk’. The pre-prevention and in-process control measures are recommended to this type of accident. The risk of fall injury accidents is mostly in level V (low) and level III (moderate) (Fig.4), which was called ‘High frequency in relative low risk’. Preventive measures should be given priority when making risk mitigation decisions.
5.2.2. Safety countermeasures for the most high-risk behaviors

From the micro perspective, well-directed countermeasures for the high-risk behaviors under the corresponding risk strategy are very necessary for improving the capacity of risk prevention and response while saving resources. It was found that irregular behavior on escalator (A3), go on boarding or alighting even after the door-close alarm sounded (B1), pushing each other (C1), and paying no attention to the ground (D2) have the greatest impact on the total behavioral risks of each accident type (Fig.5). These four behaviors are supposed to be given priority. The other 8 categories of behaviors have the relatively low effect on behavioral risks, but it should not be ignored.

According to the results of sensitivity analysis, irregular behavior on escalator (A3) has the greatest impact on the total behavioral risk of escalator injury. Studies have shown that 50% of passengers did not grab the handrails when riding on the escalator (Wang et al., 2020). In addition, Chi et al. believed that the escalator injury was mainly caused by perform additional tasks (Chi et al., 2006), and 13% of 3270 people are slippery while carrying luggage on escalators, which are consistent with the sensitivity of behavior A1 in this study. We also found that children make trouble (A2) is contributed of 18.9% of escalator injury in metro operation. Warning signs and loudspeakers are suggested to be set around the escalator to remind passengers pay attention to the most likely behaviors. This paper is in favor of revising the metro safety regulation to increase the punishment of irregular behaviors (Wang Rubing et al., 2020), as it has the highest sensitivity. It’s also suggested that dynamic public service advertisements of metro safety regulation on the electronic screens in metro stations and the train carriages will play a better preventive effect than advertising board.

Among the unsafe behaviors that lead to stampede accidents, pushing each other (C1) has the greatest impact, followed by spread rumors (C3) and fighting (C2). Wang analyzed the causative factors of metro stampedes, found that collision of crowd has the largest weight of 0.54, followed by passengers running suddenly of 0.15 and quarrel of 0.11 (Wang, 2018; Wang, 2013). The ranking of the most causative factors is consistent with this study. The difference is this study focused more on behaviors, which is more pre-test than the causative factors. For instance, pushing each other (C1) may cause the conflict of crowd-flow and spreading rumors (C3) may lead passengers suddenly to run.
Because the most influential behavior C1 mainly happens during the peak time, the control of the maximum number of passengers allowed to enter the station as well as guide passengers through movable barriers are recommended among preventive measures (Santos-Reyes & Olmos-Pe, 2017; Illiyas, Mani, Pradeepkumar & Mohan, 2013; Alkhadim, Mohammed, Gidado, Kassim, Painting, & Noe, 2018). Emergency drill for stampede is also suggested, as it’s an effective means to find out the problems of emergency preparedness, such as insufficient emergency resources, uncoordinated command, poor evacuation route and so on.

The total behavioral risk of pinched injury is mainly caused by passengers go on boarding or alighting even after the door-close alarm sounded (B1). Scholars have acknowledged the importance of arrange staff to be on duty for the PSD and train doors of the metro operator (Zhao et al., 2020; He, Liang & Fang, 2016). The elderly, children and passengers with luggage should be taken the focus attention. Staff on duty can also help correct unsafe behaviors of other passengers in a timely manner (Wan et al., 2014). However, we found that even if there are staff on duty, serious accident may still occur for the uncertainty of stuff’s ability to control the incident in-process. A typical case occurred recently in January 22th, 2022 at Shanghai Metro Line 15 in China (Shanghai passenger tragically died after being trapped in subway screen door, 2022). The monitoring showed that an old woman was caught by the PSD when she got off the train. The staff rushed there at once, tried to pull her out but failed (Fig.7 a). Then the staff pressed the emergency button of the shielding door trying to open the door manually, but the train still started with the trapped woman (Fig.7 b). Then the staff ran to the wall near the door and press the emergency stop button (Fig.7 c). The train stopped, and the passenger was sent immediately to hospital. But unfortunately, the passenger died.

![Fig.7 The stuff operation process of the “1.22” pinched died accident in Shanghai Metro, China](image)

Although the cause of the accident is still under investigation, some experts believe that the staff has operational errors. When he first pressed the manual button of PSD, the signal linkage between the shielding door and the train door was cut off, resulting in the train starting at the moment of opening the shielding door, and the passenger was instantly drawn into the gap between the train and the shielding door by the suction of the train (Shanghai passenger tragically died after being trapped in subway screen door, 2022). The right operation is that first press the emergency stop button on the wall and then open the shielding door, so that the clamped passenger would be successfully rescued. The case reflects the impact of the uncertainty of stuff’s ability on the incident control in-process, which did not get enough attentions before. It is suggested to carry out special education and emergency drill on pinched by a shielding barrier accidents for staffs on duty, which would help prevent and control this accident to reduce the total behavioral risk.

As the ‘High frequency in relative low risk’ accident, fall injury in the station mainly happened
by slipping due to water or other objects (e.g., banana peel) on the ground while walking without paying attention to the surroundings. Scholars (Wang, 2018; Xie & Liu, 2019) proposed that the metro operator organize an efficient cleaning team and set up regulations to keep the ground clean. Strengthen security check to make sure passengers bring no prohibited items into the station is also believed to be effective (Wang, 2018; Xie & Liu, 2019). The author added that some special preventive measures should be considered in the rainy and snowy weather, such as increase the frequency of ground cleaning, set up anti-slip mats when necessary and so no.

To sum up, there are various passengers’ unsafe behaviors that lead to different metro operation accidents. Due to the uncertainty of both the behaviors occurrence and the consequences caused by them, the total behavioral risks of the accidents exhibited different characteristics. When making risk mitigation decisions, we should consider both the risk characteristics of each accident and the contributions of each behavior to the accident types and risk levels for improving the scientific and pertinence of countermeasures.

6. Conclusions

In recent years, the research objects of passengers' unsafe behaviors are mainly focus on the influencing factors leading to the behavior before it occurs, while they have not solved the relations of the behavior to the consequences or risks once it occurs. Thus, management experience with strong industry restrictions is not fully applicable to the metro operation with a high interrupted risk of passengers’ unsafe behaviors. In fact, due to the uncertainty of both behavior occurrence and its consequences, the high frequency of unsafe behavior does not mean that the accident caused by it is serious, which increased the challenges of risk mitigation in metro safety operation. This paper introduced the Monte Carlo algorithm, combined with the multidimensional dataset of 234 metro operation accidents and the behavioral risk function, quantitatively examined the risk of passengers’ unsafe behaviors related to different accident types and severities of consequence, which revealed the difference and uncertainty of the behavioral risks under different accident types in metro operation.

The results revealed that the although the total behavioral risk of each accident type obeys normal distribution with means between (4, 6] in the Moderate risk level, the highest values of crowded stampede was at 8.92, followed by pinched by a shielding barrier at 8.76, and both of them reached the Very High risk level (8, 10]. While escalator injury and fall injury are 7.17 and 6.93, which only reached the level II (6, 8]. Besides, the variances of pinched by a shielding barrier (1.29) and crowded stampede (1.08) are much higher than escalator injury (0.60) and fall injury (0.59). Among the 12 categories of passengers' unsafe behaviors, the top four contributors that resulted in the behavioral risks of the four accident types were irregular behavior on the escalator, go on boarding even after the door-close alarm sounded, push each other, and pay no attention to the ground. It was concluded that due to the uncertainty of the behavior occurrence and its consequences, there are differences of the probabilities in different risk levels of different accidents caused by the various passengers’ unsafe behaviors, which should not be omitted when making safety decisions for improving the pertinence and accuracy of countermeasures.

Targeted risk mitigation strategies and measures were clarified based on the behavioral risk characteristics in this study. Through the uses of the structured dataset and the Monte Carlo algorithm,
the accuracy of the judgment of the probability distribution in different risk degree is improved, which can provide a basis for targeted risk mitigation strategies and measures. However, the detailed description and statistics of metro operation accidents caused by various passengers' unsafe behaviors are still lacking at present. Although the author collected as many cases as possible, the A-D tested statistical parameters of the priori probabilities of the 12 category behaviors may have slight changes as the number of samples would be increasing in the future. It is suggested at last that both the detailed statistically work of metro operation accident and the research on the complexity of various unsafe behaviors and their relations to accident risk need to be strengthened in the future.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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