Research Article

Identification of Influencing Variables on Improving Resilience of High-Speed Railway System

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In recent years, frequent natural disasters have brought great challenges to the stable operation of the high-speed railway (HSR). Improving the resilience of the HSR system is an urgent problem to be solved. This study aims to explore how to improve the resilience of the HSR system. Based on an in-depth literature review and case study, 11 variables and 15 hypothetical paths were proposed. Then the questionnaires were distributed to professionals from academia and industry. A total of 270 valid responses were received. Finally, the structural equation model was used to evaluate these variables’ influence degree and their influence path. The results indicated that the infrastructure components (i.e., quality control and equipment operation and maintenance) play a positive role in the persistence ability. The organizational operation and maintenance components (i.e., organizational structure and organizational efficiency) promote the speed of function restoration. The interactive system components (i.e., technical system and system operation and maintenance) also have a positive effect on adaptability and transformability. The three components of the HSR system play a positive role in different resilience attributes (i.e., persistence ability, function restoration, adaptability, and transformability), which further positively impacts the effectiveness of improving resilience. Based on the accepted hypothetical paths, five strategies for improving resilience were discussed, such as a certain degree of redundancy of key organizations or members, encouragement of self-organized decision-making, and establishment of the “health records” of each HSR line. This study would enrich the theoretical system of resilience and help practitioners better understand the influencing variables and influencing paths of the resilience of the HSR system.

1. Introduction

According to the International Union of Railway Organization (UIC), high-speed railway (HSR) refers to a newly built railway with a design speed of 250 km/h or more, or upgraded railways; its design speed can reach 200 km/h or even 250 km/h [1]. HSR has the properties of high speed, high density, high punctuality rate, and low fault tolerance rate [2]. After the great success of Shinkansen in Japan, European countries and China began to innovate HSR technology [3]. According to the report released by the Ministry of Transport, the total mileage of HSR in China has exceeded 38,000 kilometers by 2020, which ranks first in the world. As an important transportation model, HSR has played an essential role in promoting regional economic development and accelerating the flow of social resources [4, 5]. In this context, the stable operation of HSR is particularly important [6].

At present, the research on HSR mainly focuses on risk management and technology application. In the aspect of risk management, it mainly includes construction risk [7, 8], safety risk [9–11], railway inherent risk [12–14], ecological risk [15, 16], political risk [17], and social risk [16, 18]. The research on the application of HSR technology is more abundant, which can be mainly divided into infrastructure fault diagnosis technology [19] and new technology development [20]. New generation technologies such as 5G and the Internet of Things are widely used in HSR [21, 22]. However, research on HSR resilience is relatively scarce. In related research, some scholars are concerned about the
stability improvement of the HSR subsystem. By improving fault monitoring of traction power supply system [23–25], braking system [26], electromechanical system [27], railway signal system [28, 29] etc., timely maintenance and repair can effectively reduce the accident rate. Other scholars believe that the resilience of infrastructure system such as railway networks significantly impacts the stable operation of high-speed trains [30, 31]. Extreme weather conditions will increase the vulnerability of HSR infrastructure; tunnels and foundations are the most vulnerable to heavy rains or flash floods [32]. But there are highly coupled relationships among telecom system, power system, and trains [33]. As a result, the improvement of the reliability of single equipment may not guarantee the safety and stability of operation. According to the literature review, this study defines the HSR system as a complicated system engineering. It not only includes facilities, equipment, and the relevant personnel, but also includes the norms, standards, and processes for the normal operation of the system. In the meantime, this study defines the resilience of the HSR system as follows: during the operation stage, in the face of uncertain disturbances and limiting conditions, it is the ability of HSR system to absorb external disturbances, maintain key functions, and improve the overall adaptability [34–37]. At present, the existing research mainly focuses on the HSR subsystem and infrastructure, but it seldom emphasizes how the HSR system as a whole can improve resilience.

Therefore, this study regards the HSR system as a whole and reflects on how to improve the system operation level from the perspective of resilience. The questions guiding the research are (1) which variables can affect the resilience of the HSR system? (2) How do those variables affect the resilience of the HSR system? (3) How to improve the resilience of the HSR system? To answer these questions, this study conducted several steps. Firstly, this study reviewed the literature on HSR system and infrastructure resilience to identify the influence variables and propose the hypothetical paths. Secondly, the questionnaire was designed and distributed to professionals from academia and industry. Finally, the structural equation model was used to verify the hypothetical paths, and the resilience improving strategies were proposed. This study would expand the theoretical resilience system and enrich the research in the HSR operation context. The research results are aimed to help practitioners better understand the influencing variables and mechanism of the resilience of the HSR system and improve the safety and anti-interference ability of HSR operation.

2. Literature Review

2.1. Definition of Resilience. Resilience has been widely studied in engineering [38], psychology [39, 40], sociology [41, 42], cities [43, 44], infrastructure [45, 46], and other fields. Reviewing the development of resilience theory, it has undergone two more thorough revisions and developments. The first is from engineering resilience to ecological resilience, and the second is from ecological resilience to evolutionary resilience [44]. Engineering resilience focuses on a single equilibrium. It is believed that resilience is the speed at which the system recovers to the initial state after temporary perturbation [47]. The concept of ecological resilience arose as scholars realized that resilience might help systems not only return to an initial equilibrium state, but also reach a new equilibrium state. Ecological resilience is the concept of change, which emphasizes alternative and multiple states. Zampieri [48] pointed out that resilience is the magnitude of disturbance that a system can absorb before changing its structure. Evolutionary resilience abandons the pursuit of equilibrium and emphasizes adaptability. In this view, resilience is a dynamic system attribute that is closely related to the ability to adjustment [44]. Different definitions of resilience are shown in Table 1.

Evolutionary resilience is widely used in complex adaptive systems, such as urban resilience research, community resilience research, and infrastructure resilience research. Therefore, as a complicated system engineering, it is necessary to refer to the view of evolutionary resilience as a benchmark for the study of resilience of HSR system. For the definition of resilience of HSR system, please see Introduction.

2.2. Variable Identification. Francis pointed out that the three abilities of resilience are absorption, restoration, and adaptation [45]. In the field of infrastructure resilience, Bruneau [49] proposed four community infrastructure indicators (rapidity, redundancy, robustness, and resource allocation). Rehak et al. [50] considered that technical resilience and organizational resilience are the main variables affecting the resilience of critical infrastructure, and improving organizational resilience can effectively increase the resilience of infrastructure [51]. Guo et al. [52] constructed a safety resilience assessment system of subway from 27 indicators in four dimensions: stability degree, redundancy degree, efficiency degree, and fitness degree. Liu et al. [53] constructed an evaluation system for waterlogging disaster resilience capability of the subway from 16 indicators in three dimensions: defense, recovery, and adaptation. Wu et al. [24] emphasized the importance of early warning and proposed an early fault estimation method for HSR traction devices. Johnsen and Veen [54] found that through scene training, organizational redundancy, and technical redundancy, the resilience of railway communication infrastructure system can be improved. Azadeh et al. [55] identified the index system from the perspective of system resilience to evaluate the performance of the HSR transportation system. All of these studies have a common shortcoming, which is that they ignore the integrity of the HSR system.

In this study, a total of 11 influencing variables were identified from a comprehensive review of the relevant literature and case analysis, as shown in Table 2. The selection of cases is mainly divided into two parts. The first is to collect the cases of HSR accidents in China, Japan, and other countries and analyze the causes and treatment measures. The second is to collect successful cases of HSR construction and operation and then analyze the reasons for success. Rehak et al. [50] divide the variables that determine the
resilience of critical infrastructure into technical and organizational components. UIC [71] divides the Rail System Forum into five sectors, including Track and Structures, Train Track Interaction, Control, Command, Signaling and Operations (CCS and OP), Energy Management, and Rolling Stock. Therefore, HSR system components can be divided into three subcomponents based on the existing research results. The first is infrastructure components, including “quality control” and “equipment operation and maintenance.” The second is organizational operation and maintenance components, including “organizational structure” and “organizational efficiency.” The last is interactive system components, including “technical system” and “system operation and maintenance.” What needs to be emphasized is that “equipment operation and maintenance” emphasizes the maintenance, repair, or replacement of hardware equipment. “System operation and maintenance” emphasizes the use of certain technologies, experiences, and institutions to guarantee the proper operation of the software system.

### 2.3. Hypothesis Development

#### 2.3.1. System Resilience Attributes

The complexity of the system is caused by adaptability [72]. “Adaptation” becomes the combination point of complex adaptive system theory and resilience theory [73]. Holland [72] believed that when the environment of the system changed, adaptive subjects could interact with each other and spontaneously adjust their own structure and behavior, thus guiding the overall upgrade and reorganization of the system. Rehak et al. [50] also pointed out in their study that the components of critical infrastructure system affect redundancy and adaptability, thus determining technical resilience and organizational resilience. The HSR system is a complex adaptive system, in the face of risk factors, such as a sudden change in the external environment (natural disasters, man-made damage) and pressure changes (rail wear, line aging, etc.), through the composition of operation system changes to affect the disturbance warning, persistence ability, function restoration, adaptability, and transformability. In this way,

### Table 1: Summary and comparison of different definitions of resilience.

<table>
<thead>
<tr>
<th>Classification of resilience</th>
<th>State of equilibrium</th>
<th>Essential target</th>
<th>Definitions of resilience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering resilience</td>
<td>Single equilibrium</td>
<td>Recover initial equilibrium</td>
<td>Resilience is the speed at which the system recovers to the initial state after temporary perturbation</td>
</tr>
<tr>
<td>Ecological resilience</td>
<td>Two or more equilibrium</td>
<td>Reaching a new equilibrium, emphasizing buffer capacity</td>
<td>Resilience is the magnitude of disturbance that a system can absorb before changing its structure</td>
</tr>
<tr>
<td>Evolutionary resilience</td>
<td>Abandoned the pursuit of equilibrium</td>
<td>Emphasis on adaptability, including learning, transformation, and innovation</td>
<td>Resilience is a dynamic system attribute that is closely related to the ability to adjust</td>
</tr>
</tbody>
</table>

### Table 2: Influencing variables of the resilience of the HSR system.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Variables</th>
<th>Cases</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>System components</td>
<td>Quality control (QC)</td>
<td>It is the standardized management of Beijing-Shanghai railway.</td>
<td>Wanberg, Harper, Hallowell, and Rajendran [56]; Xue, Xiang, Jia, and Liu [57]</td>
</tr>
<tr>
<td></td>
<td>Technical system (TS)</td>
<td>Beijing seismic fortification intensity grade is 8 and Changchun is 7.</td>
<td>Janic [58]; Lu and Cai [59]</td>
</tr>
<tr>
<td></td>
<td>Organizational structure (OS)</td>
<td>Strict organizational structures in Britain and France reduce the accident rate.</td>
<td>Dressler [60]; Andersson, Caker, Tengblad, and Wickelgren [61]</td>
</tr>
<tr>
<td></td>
<td>Organizational efficiency (OE)</td>
<td>Organizational efficiency is based on the three elements of “rights, responsibilities, and interests” in China.</td>
<td>Brown et al. [51]; Ochman [62]</td>
</tr>
<tr>
<td></td>
<td>Equipment operation and maintenance (EM)</td>
<td>70% of traffic accidents in 2017 resulted from poor equipment.</td>
<td>He, Li, and Duan [63]</td>
</tr>
<tr>
<td></td>
<td>System operation and maintenance (SM)</td>
<td>It happens in the health records of Beijing-Zhangjiakou railway.</td>
<td>Lu and Cai [59]; Rehak et al. [50]</td>
</tr>
<tr>
<td>System resilience attributes</td>
<td>Function restoration (FR)</td>
<td>It is “7.23” of major accidents on Yongwen line.</td>
<td>Johnsen and veen [54]; T. Li and rong [64]</td>
</tr>
<tr>
<td></td>
<td>Adaptability and transformability (AT)</td>
<td>It is the frozen soil solution for Beijing-Harbin HSR.</td>
<td>Coaffee and Clarke [65]; Rehak et al. [50]</td>
</tr>
<tr>
<td></td>
<td>Persistence ability (PA)</td>
<td>It is used in the construction of Harbin-Dalian railway for alpine climate conditions.</td>
<td>Ho, Chen, Hsieh, and Chou [66]; Huang and Pai [67]</td>
</tr>
<tr>
<td></td>
<td>Disturbance warning (DW)</td>
<td>D6228 did not give timely emergency warning which resulted in the accident.</td>
<td>T. Li et al. [68]; wen et al. [29]</td>
</tr>
<tr>
<td>System resilience</td>
<td>Effectiveness of improving resilience (EIR)</td>
<td>It is the world’s first intelligent HSR, Beijing-Zhangjiakou HSR.</td>
<td>Saltzman, Lester, Milburn, Woodward, and Stein [69]; Zhou and Chen [70]</td>
</tr>
</tbody>
</table>

...
the resilience of the HSR system can be improved to ensure the secure and efficient operation. Therefore, the following hypotheses were proposed:

Hypothesis 1a (H1a): DW has a positive impact on the EIR.
Hypothesis 1b (H1b): PA has a positive impact on the EIR.
Hypothesis 1c (H1c): FR has a positive impact on the EIR.
Hypothesis 1d (H1d): AT has a positive impact on the EIR.

2.3.2. Infrastructure Components. The quality of the HSR project is the primary goal of HSR construction. In the preoperation test of Ji-Qing HSR in 2018, the performance of traction power supply, contact network, and communication signal system was mainly verified. At the same time, the applicability of subgrades, tracks, bridges, tunnels, and other structural engineering was checked. Through step-by-step test to ensure the safety and stability of the line during operation, Zhao, Zeng, and Wang [74] emphasized the importance of strengthening quality control of HSR steel for the safe operation of trains. Keeping the rail in good condition is also important once the HSR is in operation [59]. Sa’adin et al. [32] stressed that precautionary measures (predisaster) should be considered for resilient infrastructure. Jiang, Cai, and Jian [75] proposed a new concept for train collision early warning system (TCEWS), which aims to improve the early warning capability of HSR. Therefore, the following hypotheses were proposed:

Hypothesis 2a (H2a): QC has a positive impact on the PA.
Hypothesis 2b (H2b): EM has a positive impact on the DW.
Hypothesis 2c (H2c): EM has a positive impact on the PA.

2.3.3. Organizational Operation and Maintenance Components. In the case of Shiwu Line of Beijing-Guangzhou Railway, Guodian Hubei Company concentrated on repairing two ice-covered power transmission lines within two days, which reflected the advantage of coordination between command and execution in the organization. Ho et al. [66] also stressed the importance of institutions and synergy. To improve the HSR service quality, communication system and high skilled train dispatchers must cooperate in a disciplined way. After the disaster, the HSR system control center lacks experienced train dispatchers, which may exacerbate the impact of the disaster [76]. Therefore, the following hypotheses were proposed:

Hypothesis 3a (H3a): OS has a positive impact on the FR.
Hypothesis 3b (H3b): OE has a positive impact on the FR.

2.3.4. Interactive System Components. The technical system is crucial to ensure the safe operation of HSR [57]. Johnsen and Veen [54] pointed out that redundancy of the technical system can ensure acceptable quality of service in the event of a communication system failure. The establishment of technical system mainly depends on technological reform and innovation. At the same time, the establishment and improvement of technical system play a guiding and normative role in quality control and equipment operation and maintenance. The summary of major accidents is an important way to improve the technical system [77], which can avoid the recurrence of the same interference.

With the development of information and communication technologies such as mobile Internet, cloud computing, big data, and the Internet of Things, the collection, utilization, control, and sharing of information have become faster and more convenient. Lu et al. [4] combined BIM technology with fault prediction and health management (PHM) system to establish an intelligent railway operation and maintenance system, realizing automatic monitoring, detection, and analysis of railway. Ho et al. [66] built a new multiagent system (MAS) to help train dispatchers to reduce the impact of disasters more effectively when disasters occur. The results can also be used to guide the next disaster treatment plan. Therefore, the following hypotheses were proposed:

Hypothesis 4a (H4a): TS has a positive impact on the PA.
Hypothesis 4b (H4b): TS has a positive impact on the AT.
Hypothesis 4c (H4c): SM has a positive impact on the DW.
Hypothesis 4d (H4d): SM has a positive impact on the PA.
Hypothesis 4e (H4e): SM has a positive impact on the FR.
Hypothesis 4f (H4f): SM has a positive impact on the AT.

According to the presented analysis, Figure 1 demonstrates the relationship between these variables.

3. Research Methodology

3.1. Questionnaire Design and Data Collection. The questionnaire design was divided into three stages. Firstly, a preliminary questionnaire was formed through literature review and case analysis. Secondly, a presurvey was conducted by inviting a number of front-line practitioners in the industry and well-known researchers in related fields to fill the questionnaire. At the same time, we collected experts' opinions on the influencing variables. According to their views and suggestions, the questionnaire was adjusted and refined. The expression, content, and structure of the questionnaire were revised to form the final questionnaire. Finally, a large-scale questionnaire survey was conducted. The target respondents are front-line practitioners in the
field of HSR, scholars interested in the HSR system and resilience. The specific sampling method adopted in this study is the snowball sampling method [78].

The final questionnaire contained three parts. The first part was an introduction to the primary research situation and a simple explanation of related concepts. The second part was the basic information of the respondents. The third part was quantifying the influence of variables on the improvement of resilience. Experts score according to their own experience and knowledge. The 5-Point Likert Scale was used to score the degree of influence of each variable from 1–5, where 1 = the weakest degree of influence and 5 = the strongest degree of influence.

Eventually, a total of 535 questionnaires were sent out and 303 were received, among which 270 were valid. The recovery rate of effective questionnaires was 50.46%. In the analysis of questionnaire survey data, the number of valid questionnaires is usually 5–10 times of the observed variable (number of questions) [79], and the number of valid questionnaires should be greater than 100. From the perspective of regional classification, 22 questionnaires were from foreign practitioners and researchers, and 248 questionnaires were from domestic-related researchers and front-line practitioners. Regarding job categories, 102 were from academics and 168 were from front-line workers in the industry. The basic statistical information of the questionnaire is shown in Table 3.

3.2 Measures. The variables selected in this study belong to the category of latent variables, so observation variables were set for each latent variable to reduce the size of the measurement error. Next, how to determine the measurement items of each variable will be introduced in detail.

3.2.1 Measurement of Independent Variables. Technical system (TS): according to the studies of Xue et al. [57] and Janic [58], the establishment of a technological system was a necessary measure to ensure the operation safety. HSR product technology, engineering construction technology,
operation and maintenance technology, and perfect technical standards provide the core support for HSR safety [59]. Quality control (QC): following the work of Xue et al. [57] and Wanberg et al. [56], quality control of HSR can be strengthened in three stages. (1) Implement a special supervision system during the investigation stage. (2) Strictly implement relevant technical standards and quality management system during the construction phase. (3) Joint debugging is carried out in the preoperation stage.

Equipment operation and maintenance (EM): three items proposed by He et al. [63] were referred to measure EM (acceptance system, quality inspection, and compatibility).

Organizational structure (OS): according to the studies of Witmer [80] and Andersson et al. [61]; a 3-item scale was established to measure the effect of organizational structure on resilience. Responsibility clarity, agility, and improvisation were the three measurement variables.

Organizational efficiency (OE): following the work of Ochman [62] and Brown et al. [51], teamwork consciousness, redundancy of key members, and independent decision-making were selected as three measurement indexes.

System operation and maintenance (SM): the stable operation of the HSR system can be guaranteed by improving the emergency command system by using information technology and establishing information files of each line [50,59].

Disturbance warning (DW): the ability of disturbance warning is mainly reflected in the improvement of early warning management, high degree of automation, real-time, and efficiency [29,50,68].

Persistence ability (PA): according to the studies of Rehak et al. [50], crisis preparedness, detection ability, and responsiveness were selected to establish a 3-item scale.

Function restoration (FR): referring to the study of Johnsen and Veen [54] and Rehak et al. [50], resource redundancy, technical redundancy, and recovery processes were selected as the measurement indicators of function restoration.

Adaptability and transformability (AT): according to the studies of Coaffee and Clarke [65] and Rehak et al. [50], a 3-item scale was established to measure adaptability and transformability.

3.2.2. Measurement of Dependent Variables. Effectiveness of improving resilience (EIR): Zhou and Chen [70] defined resilience increase as an improvement in the rate of recovery from impact. Saltzman et al. [69] considered that resilience increase is an improvement in the ability to cope with pressure and change. At the same time, it is assumed that a resilience increase can improve the safety and punctuality of HSR. Therefore, this construct was measured using a 3-item scale in this paper.

3.3. Data Analysis Tool. The structural equation model (SEM) is an important tool for multivariate data analysis that is widely used to analyze the structural relationship of latent variables and their observable indicators [81, 82]. This method is commonly used in confirmatory factor analysis, high-order factor analysis, path, and causal analysis. SEM consists of the measurement model and the structural model. The measurement model refers to the relationship between indicators and latent variables, while the structural model refers to the relationship between latent variables [83]. Compared with other statistical methods, SEM has the characteristics of (1) simultaneous processing of multiple dependent variables, (2) allowing measurement errors in independent variables and dependent variables, and (3) allowing more flexible measurement models [84]. Given the above characteristics, the SEM technique was used to test the hypothesis of this study. First, reliability analysis was conducted to verify the reliability of the data. Then confirmatory factor analysis was used to test construct validity. When the measurement model was reliable and the fit was good, the structural model was used for path analysis to test the hypothetical relationships among the 11 latent variables.

4. Results

4.1. Descriptive Results and Measurement Model Evaluation. Descriptive statistical analysis is a method to analyze the dispersion degree and distribution characteristics of sample data. First, the aggregation and dispersion of sample data were tested by means of mean, maximum and minimum, variance, and standard deviation. Then the skewness and kurtosis of the data were calculated to test whether the data followed the normal distribution. As shown in Table 4, the mean values of the measurement items were between [3.60, 4.10], which were relatively convergent. At the same time, the column of “skewness” was tested, and the maximum value of absolute skewness was 1.073 < 2. The “kurtosis” column was tested, and the maximum value of absolute kurtosis was 1.580 < 3. Both skewness and kurtosis tests met the requirements, indicating that the sample data basically obeyed normal distribution.

Before the validity test and goodness of fit test of the sample scale, the preconditions and feasibility of factor analysis were firstly analyzed. The specific methods were KMO analysis and Bartlett’s test of sphericity. The results are shown in Table 5. It can be seen that the KMO index of 0.955 (>0.5) and Bartlett’s test of sphericity (significance of 0.000 < 0.05) were considered suitable for confirmatory factor analysis (CFA) [85].

After that, Cronbach alpha values of each variable were measured to test the reliability of the data. It is generally believed α > 0.9 indicates that the scale is very reliable, and α ≤ 0.5 indicates that it is unacceptable and needs to be redesigned. SPSS 25.0 was used for reliability analysis. It was found that Cronbach alpha values of each latent variable were all greater than 0.8, so the reliability level of the measurement scale met the requirements. Then CFA was used to test the structural validity of the scale. The test standard is that when CR is greater than 0.7 and the AVE value is greater than 0.5, the convergence validity of the latent variable is good [86]. Then, AMOS 26.0 was used to calculate the relevant parameters of the validity test, and the results were shown in Table 4. It can be found that all the
indicators met the requirements, which verifies the effectiveness of the model convergence.

Finally, the goodness of fit test was carried out. According to the analysis results, the ratio of chi-square and freedom degrees is 1.446. Absolute fit, incremental fit, and parsimonious fit all met the standards, which indicated a high degree of consistency between the sample data and the theoretical model. Specific data are shown in Table 5.

4.2. Results of Path Analysis. The structural model was used to test 15 sets of hypotheses. As shown in Table 6, among the 15 hypothetical paths, 13 paths are supported and 2 paths are not. Obviously, “EM→DW”, “OS→FR”, “TS→AT”, “SM→DW”, “SM→PA”, “SM→AT”, “PA→EIR”, “FR→EIR”, and “AT→EIR” were significant at the $P = 0.001$ level. “EM→PA” was significant at the $P = 0.01$ level, “QC→PA”, “OE→FR”, and “SM→FR” were significant at the $P = 0.05$ level. “TS→PA” and “DW→EIR” were not significant, so these two paths were deleted. Since “DW→EIR” was the influence relationship between the mediator variable and the dependent variable, all paths through disturbance warning were not considered. Therefore, eight paths between the independent variable and dependent variable were finally obtained, which were “TS→AT→EIR”, “QC→PA→EIR”, “DM→PA→EIR”, “OS→FR→EIR”, “OE→FR→EIR”, “SM→PA→EIR”, “SM→AT→EIR”, and “SM→FR→EIR”. The product between standardized path system could be used to calculate the size of the influence effect between independent variables and dependent variables, among which SM (0.295) had the most significant influence effect, followed by OS (0.129), EM (0.106), TS (0.059), and OE (0.040).

5. Discussion

Figure 2 shows that the values of the four variables are proportional to EIR. Therefore, all loading values are positive. Further, with respect to impacting effect of each
variable, EIR is also shown. To obtain an insight into the impact of the variables, the influencing mechanism of these variables in SEM on EIR is discussed below.

5.1. Infrastructure Components

5.1.1. The Influence of Variables. Regarding the influence of quality control (QC) on the improvement of resilience, its influence effect ranked third (0.129). Engineering quality is the primary consideration in the construction process. Strengthening engineering quality control is the fundamental guarantee of construction safety [56]. Liu et al. [53] found that quality control impacted the subway’s waterlogging disaster resilience capability. In addition to the quality control of infrastructure being essential to the safe operation of HSR [31], the importance of the reliability of equipment such as electromechanical system cannot be ignored [27]. QC is a management behavior for the whole life cycle of the system, which is closely related to the stage before and after. For example, the design standards are not implemented and effectively controlled in the equipment manufacturing stage. No matter how standard the installation and construction process are, no matter how comprehensive the operation and maintenance stage are, the problem of substandard parts quality cannot be solved, which will bring a lot of subsequent effects.

Regarding the influence of equipment operation and maintenance (EM) on the improvement of resilience, its influence effect ranked fourth (0.106). The fixed facilities, mobile devices, and supporting facilities in the HSR system not only interact with each other, but also have their own operation and maintenance standards and norms. In the operation stage, the maintenance and repair of various equipment are an important part of ensuring the safety of HSR and also a key element that directly affects its operation ability and operation safety. The results are consistent with work of Mudigonda. Mudigonda et al. [87] pointed out that timely maintenance of equipment and the use of emergency apparatus in the process of responding to disasters will significantly affect the recovery capability.

5.1.2. Driving Path. Among all the paths involving infrastructure components, the hypothesis that DW positively affected EIR was not valid. The research results are contrary to the point of Guo et al. [52], who believe that the use of early warning technology can effectively improve the level of subway safety resilience. According to the follow-up interviews with respondents, the definition of EIR in this study is to incorporate actual operation situations into the framework of resilience theory and to use operational results such as “safety”, “on-time rate,” and “carrying capacity” to understand the influencing variables. However, DW is a relatively static state because it does not require an action behavior for the daily operation and emergency handling of the system. It neither maintains its own function through emergency response nor repairs the system through organizational actions, nor can it be incorporated into the overall adaptability of the system. Therefore, there was no direct connection between DW and EIR.

The hypothetical path of “QC—PA—EIR” was accepted. It indicates that strengthening the level of quality control will effectively improve the persistence ability of the HSR system and then realize the practical improvement of system resilience. Therefore, the improvement of the quality of each member in the HSR system and the establishment of the relevant system can ensure the strict implementation of

<table>
<thead>
<tr>
<th>Table 5: Results of KMO analysis and Bartlett’s test of sphericity and goodness of fit.</th>
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<tbody>
<tr>
<td>Indicator</td>
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<tr>
<td>KMO measure of sampling adequacy</td>
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<tr>
<td>Bartlett’s test of sphericity</td>
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<tr>
<td>Approximate chi-square</td>
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<tr>
<td>Degree of freedom (df)</td>
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<tr>
<td>Significance</td>
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<tr>
<td>$\chi^2$/df</td>
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<tr>
<td>GFI</td>
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<td>RMSEA</td>
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<td>CFI</td>
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<th>Table 6: Path coefficients and significance.</th>
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technical standards in the construction management. Thus, the capacity of the HSR system to maintain normal operation confront with risks or pressure is increased, and its resilience in the operation stage is enhanced. The results of this paper support the views of Villalba Sanchis et al. [31].

5.1.3. Countermeasures for the Infrastructure Components. The resilience improvement strategy is to improve the standardized quality management system and innovate management methods regarding the infrastructure components. The first is the standardized management and control level, which has two dimensions. (1) Establish a comprehensive quality management system and deepen the integrated construction of quality management. (2) Promote the integrated construction of daily management and maintenance management of HSR, and strengthen coordination and unified thinking. Secondly, at the level of innovative management and control, the application of information technology can be promoted to realize real-time monitoring of the operation of facilities and equipment.

5.2. Organizational Operation and Maintenance Components

5.2.1. The Influence of Variables. In terms of the influence of organizational structure on the improvement of resilience, its influence effect ranked second (0.180). OS is the most essential structural basis to realize process operation and achieve organizational goals. The three connotations of OS are (1) the rationality of the structure and the unity of responsibilities and rights; (2) smooth information transmission channels and efficient operation between command and implementation; and (3) active adaptation to changes and new requirements for structural adjustment and process reengineering. The cornerstone of teamwork is organizational structure. Teamwork can be understood as the way in

![Figure 2: Path test results.](image-url)
which everyone in an organization has and uses their own unique skills to perform their respective roles and work together more efficiently. Moreover, teamwork reduces the possibility of human error and helps to enhance the reliability of work results [55].

In terms of the influence of organizational efficiency on the improvement of resilience, its influence effect ranked sixth (0.040). To promote organizational efficiency, firstly, it is necessary to attach importance to the members of the organization. At the same time, it is also necessary to ensure the redundancy and substituting of key members. Finally, it is necessary to clarify the responsibilities, rights, and interests among members so as to achieve a balanced distribution. Only in this way the enthusiasm and subjective initiative of members can be fully mobilized to achieve the highest degree of cooperation within the organization, so that efficient collaboration and mutual cooperation are maintained in the daily operation and emergency situations.

5.2.2. Driving Path. The hypothetical path of “OS→FR→EIR” was accepted. It indicated that strengthening the rationality of organizational structure will significantly improve the functional restoration of the HSR system and then improve its resilience. Organizational structure is the basic carrier to realize functional recovery and the objective attribute of the organization. A reasonable organizational structure will guarantee the effective transmission of information when disasters occur. That is to ensure the efficient delivery of rescue instructions, the rapid use of redundant infrastructure, and the implementation of emergency plans. Thus, the recovery capacity of the HSR system can be effectively improved, helping it to reflect good self-recovery efficiency in the face of disasters. Bruyelle et al. [88] made the same point in their study of subway resilience. In the event of an explosion or fire, communication in both directions through a reasonable organizational structure can speed up the rescue efforts. One direction is to inform the relevant department of the situation, and the other is to provide necessary information to passengers.

5.2.3. Countermeasures for the Organizational Operation and Maintenance Components. The number one measure is organizational structure change and organizational process reengineering. First of all, the responsibilities and rights of each part or member of the organization should be defined through the organizational adjustment to make them clear and uniform, which is the basis for realizing organizational goals. Secondly, although it is believed that the flat
organizational structure is conducive to the transmission of information within the system, the overall design of the HSR system is intricate, and the functions of each organization are different. Therefore, based on the characteristics of the HSR system, it is necessary to actively seek the renewal and reform of the organizational structure and the reengineering of the operating procedure and information transfer process to improve the efficiency of information exchange. Finally, after the destruction of the HSR system, it is not easy to allocate resources and restore functions quickly by relying on the ability of a department or a station. It is necessary to achieve the regular operation of the system through a unified arrangement from top to bottom.

The second measure is that key organizations or members have a certain degree of redundancy, and self-organized decision-making is encouraged. Key organizations or members need to have a certain degree of redundancy, because they are often the key to solving problems and restoring system functions. For example, if the electric engineer assigned by the dispatching department cannot reach the site due to the damage of HSR lines, it is particularly important for the on-site conductor and engineer to be trained, have certain basic electric knowledge, and be able to report in detail or even simply deal with the site situation. Secondly, the role of organization members is strengthened through self-organization decision-making. The process of transferring information up and down can cause obstacles and delays to emergency response and even produce the butterfly effect. Therefore, the members of the organization can make reasonable and legal decisions under special circumstances and give play to the subjective initiative of the members, which can effectively help the system restore operation.

5.3. Interactive System Components

5.3.1. The Influence of Variables. In terms of the influence of technical system on the improvement of resilience, its influence effect ranked fifth (0.059). The technical scheme of the HSR system usually refers to the collection of technical standards and management norms such as design standards, construction standards, manufacturing standards, quality control system, operation management system, and equipment maintenance standards. The establishment of a technological system mainly depends on technological reform and innovation. The improvement of a technical system is often related to the summary of practical application, failure cases, and other experiences. Janic [58] expressed the same view in his research on multidimensional evaluation of HSR performance, believing that the establishment of a technical system will effectively ensure the safe operation of HSR.

Regarding the influence of system operation and maintenance on the improvement of resilience, its influence effect ranked first (0.295). SM emphasizes the use of emergency command process updates and emergency relief management system to standardize the overall response process and response efficiency of the system. At the same time, the principle of integrity is emphasized. Through cross-disciplinary knowledge exchange and application experience, the overall operation and maintenance of the system are updated. Meanwhile, the operation and maintenance management system and emergency warning system are informationized to realize the overall efficiency, security, and rapid response [59]. He et al. [63] proposed strengthening the application of big data technology to achieve cross-system data integration and information sharing to enhance HSR operation status data monitoring and management.

5.3.2. Driving Path. Among all the paths involving interactive system components, the hypothesis of the positive impact of TS on PA was not valid, indicating that the degree to which the HSR system maintains its own capacity in the face of disasters and risks was not closely related to the technical standards of facilities and equipment. Through interviews with industry experts, it was known that the standards of facilities and equipment were unique and targeted in actual operation. For example, “different HSR are designed based on different seismic prevention intensities”. The standards of HSR are adapted to local conditions, so after the completion of design and construction, the ability of facilities and equipment to resist risk pressure (such as earthquake disasters) has been relatively fixed. However, evolutionary resilience is a process of dynamic change and constant adaptation. Therefore, fixed technical standards cannot significantly affect the persistence ability of the HSR system in a constantly changing environment. As a result, it was reasonable to conclude that TS had no significant favorable influence on PA.

The hypothetical path of “SM—AT—EIR” was accepted, indicating that adaptability and transformability could be increased by improving the system operation and maintenance ability. This is a powerful way to enhance the resilience of the HSR system. The self-reflection, learning, and adjustment of the HSR system based on accident cases and theoretical experience can effectively promote the continuous iteration and update of various management system and management processes and promote the development and application of new technologies. In this way, the system operation and maintenance ability can be improved to constantly adapt to new environments and challenges, thus helping the system resilience significantly improve. This approach was proposed from the holistic level of the system, which required the transformation of system adaptability in the process of continuous learning and updating to improve the system’s overall resilience. By reviewing the application of artificial intelligence (AI) in HSR, Yin et al. [89] proposed that active learning and intelligent decision-making of HSR system can be realized based on analysis and mining of historical data, thereby improving operational safety.

5.3.3. Countermeasures for the Interactive System Components. The first measure is establishing “two systems and one platform”: informationized HSR emergency command system, rescue and relief management system, HSR
operation data integration platform. The emergency command system and rescue and relief management system are constructed with the dispatching station and the station emergency command center as the core, and the two lines of “driving command and emergency check” as the mainline. At the same time, Internet technology is used to promote the construction of an integrated platform for HSR operation data, and operational information is made public and shared to a certain extent in the form of digitization and informatization. In this way, centralized management, integrated operation, and visualized process of HSR operation can be realized. Thus, the efficiency and accuracy of the system operation and maintenance are improved, and the resilience of the HSR system is improved.

The second one is establishing and improving the “health records” of each HSR line. Referring to the concept of psychological research, the “health records” of the HSR lines are established. In addition to recording the daily operating parameters of the infrastructure, “health records” also need to sort out the risks and accident cases of HSR. At the same time, it is necessary to track and analyze the information data, as well as learn and reflect on the operational experience. In this way, the management system, management process, and technical standards are constantly iterated, and new technologies are developed to meet new challenges. Table 7 shows the questionnaire.

6. Conclusions

This study attempted to explore paths to improve the resilience of the HSR system. Based on case analysis, literature review, and expert interviews, a total of 11 influencing variables and 15 hypothesis paths were identified. Then, the questionnaire data combined with SEM method were used for empirical evaluation to verify the hypothesis and estimate the influence degree and influence path of different variables. The results showed that the key variables affecting the effectiveness of resilience improvement were “system operation and maintenance”, “organizational structure,” and “quality control”. Finally, according to the empirical results, this study proposed five strategies to improve resilience.

The theoretical significance of this study is to treat the HSR system as a complex adaptive system. By introducing the “evolutionary resilience” of the resilience theory, it makes up for the problems that previous studies focused on risk identification and risk management, and it enriches and expands the theoretical research on the resilience of the HSR system. The practical significance is to face and solve a series of practical problems such as the agglomeration of safety risks and the increment of scheduling difficulty in HSR operation. At the same time, it would help practitioners better understand the influencing variables and action paths of the resilience of the HSR system. Improving resilience can enhance emergency response capacity and anti-risk ability under emergencies and improve operational safety. So that it ensures the quality of HSR passenger service and better guarantees the stable and rapid development of regional and even national economies.

The main limitation of this study is that it is conducted too much from the background of CHSR. Due to cultural differences and different technical standards in foreign countries, different results may be produced. In addition, since it is impossible to predict whether the practitioners are willing to participate in the survey, the received questionnaires can be regarded as nonprobability samples, which were considered as representative samples. Finally, the HSR system is complex and has many influencing variables. Although this study comprehensively identified the influencing variables from all aspects, there may still be situations where influencing variables were missed.

Further research would be conducted to examine the resilience improving strategy of the HSR system in different countries to increase the practical validity. In addition, maglev and HSR are very similar modes of transportation, but there are differences in some infrastructure such as rails. The applicability of the results of this paper to maglev can be discussed in the future. With the development of science and technology, the emergence of autonomous driving technology provides a new direction for the development of HSR technology, and the application of this technology will change the existing technical system and organizational structure. Therefore, in the context of the application of autonomous driving, the applicability of the current resilience improvement strategies of HSR system is also a direction of further research.

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Data Availability

The data generated or analyzed during the study are available from the corresponding author on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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