



Analysis of Factors Affecting the Vulnerability of the Hazardous Materials Transportation System

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ARTICLE INFO	ABSTRACT
<p>Article history: Received 18 March 2025 Received in revised form 20 April 2025 Accepted 21 April 2025 Available online 21 April 2025</p> <p>Keywords: Hazardous materials; transportation system; vulnerability; supply chain; DEMATEL</p>	<p>A method for identifying key vulnerability factors in hazardous materials transportation systems is proposed, combining qualitative and quantitative analytical techniques. First, we establish a conceptual framework that integrates definitions of hazardous materials, their transportation systems, and vulnerability (including supply chain vulnerability). Through qualitative analysis, we identify critical factors that contribute to systemic vulnerability. Subsequently, the interrelationships among these factors are quantified using the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method. By applying DEMATEL, we model causal relationships and prioritize key factors based on centrality and causality indices. Finally, we proposed targeted mitigation measures aligned with these prioritized factors to enhance the resilience of hazardous materials transportation systems.</p>

1. Introduction

In recent years, there has been a growing prevalence of hazardous materials in everyday life. However, the risk of accidents during the transportation phase of hazardous materials (HAZMAT) is significantly heightened due to three interrelated factors: the inherent dangers of the substances themselves, the complexity of the factors involved in the transportation, and the vulnerability of transport, such as geological disasters, adverse weather conditions, and infrastructure maintenance activities[1]. The following real-world transportation accidents exemplify these risks. The first example is the explosion of a liquefied petroleum gas tank in Zhejiang Province, China, on June 13, 2020. This incident resulted in enormous societal and economic consequences, including 20 fatalities, 175 injuries, and the destruction of 900 surrounding houses. The second example is the Beirut port explosion in Lebanon on 4 August 2020, which was caused by the prolonged illegal storage of over 2000 tons of ammonium nitrate. The detonation triggered widespread devastation, encompassing human losses, structural failures, and enduring environmental degradation. The third case is a fire aboard a cargo ship off the west coast of Sri Lanka on 20 May 2021. The incident, triggered by the leakage of nitric acid from hazardous materials containers, generated severe marine pollution and

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ecological disruption. Notably, accidents in the hazardous materials transportation system (HMTS) directly manifest the vulnerability of HMTS. It is essential to qualitatively analyze the factors influencing the vulnerability of HMTS, construct a quantitative analysis model for these factors, and propose corresponding control measures based on the analysis results to abate the endangerment of HMTS and the probability of mishaps in HMTS.

Guided by the Human-Conveyance-Environment-Object (HCEO) framework, we classify vulnerability factors into four dimensions: human aspects, conveyance situation, environmental conditions, and hazardous material properties. Huang et al. [2] proposed a systematic approach that combines failure mode and effect analysis and trapezoidal intuitionistic fuzzy information axiomatic design to identify the risk of HMTS. Mohammadfam et al. [3] developed a model that utilizes Bayesian networks for causality modeling of the material release scenarios and fuzzy set theory for estimating the health effects and severity impact coefficient. López et al. [4] presented the development of an efficiency related metric from the Coherent Data Envelopment Analysis method for assessing the vulnerability levels of the supply chain system. In this paper, the decision-making Trial and Evaluation Laboratory (DEMATEL) method is applied to model relationships among these factors based on the HCEO framework. The advantage of DEMATEL is that it can combine qualitative analysis with quantitative analysis, which helps to reveal the interaction between various factors in the system and their influence, so as to provide a clear decision basis for decision makers. By calculating the centrality and causality of the vulnerability factors through the analysis model, the key factors, causal factors, and result factors affecting the vulnerability of HMTS are identified, aiming to provide a theoretical reference for advancing the safety level of HMTS and lessening the likelihood of calamity in HMTS.

2. The Overview of Basic Theory

HAZMAT encompasses a broad range of substances characterized by explosiveness, flammability, toxicity, corrosiveness, radioactivity, and environmental contamination risks[5]. Although HAZMAT demands rigorous handling protocols during transportation and storage because of their vulnerable traits, these objects remain indispensable in modern industrial and domestic applications.

2.1 The Transportation System for HAZMAT

The transportation of HAZMAT is a critical component of contemporary logistics[6]. This process involves multiple stages, each posing risks of leakage, damage, or other incidents that threaten human safety, public infrastructure, and environmental integrity. As a result, stringent and cautious precautions are imperative. Compounding these challenges, hazardous materials exhibit three inherent characteristics: extensive utilization, diverse categories, and elevated risks. These characteristics exacerbate the complexity of transportation operations, heightening the challenges associated with ensuring safety and compliance. Given these traits, the intricacy of managing the transportation of hazardous materials is substantially increased, necessitating a high level of expertise and vigilance to mitigate potential dangers.

Regarding transportation for hazardous materials, Zhao et al. [7] proposed that the driving factors of the evaluation factor system include equipment/facilities, operations, emergency response, and training. Huang et al. [8] categorized risk factors affecting the normal operation of HMTS into five domains: human, machine, material, environment, and management factors. Thus, the HMTS is highly heterogeneous and complex, and a failure in any of its components can potentially lead to a tragedy[9]. Taking the above literature into comprehensive consideration, this paper adopts the

HCEO security framework to conceptualize the HMTS as an interdependent network of these four components. The framework posits that systemic failures can arise from vulnerabilities in any single element. Currently, hazardous materials logistics account for a substantial share of the global freight market. Furthermore, the inherent instability of these materials, which is manifested in properties such as volatility, explosiveness, corrosivity, and low ignition thresholds, elevates their risk profile. These characteristics increase the likelihood of accidents during transit, which can inflict severe harm on populations, infrastructure, and ecosystems. Consequently, research targeting systemic risk mitigation in hazardous materials transportation holds critical societal and economic relevance.

2.2 The Theory of Supply Chain Vulnerability

The concept of vulnerability was first utilized in a few disciplines, such as environmental science, ecology, and disaster studies. Over time, its application has expanded into social sciences, though interpretations vary across domains. In ecology, vulnerability denotes the instability of ecosystems, predisposing them to transformative shifts[10]. In disaster research, it refers to a system's capacity to absorb catastrophic impacts and recover post-event[11].

Within supply chain systems, vulnerable elements, such as logistics nodes exposed to geological hazards, extreme weather, or human interventions, often fail to withstand disruptions, triggering congestion and systemic cascades. Recent years have seen growing global scholarly interest in supply chain vulnerability (SCV) theory, risk assessment models, and safety impact frameworks. Ruel et al. [12] conceptualized SCV as exposure to severe interruptions resulting from supply chain risks as well as extrinsic supply chain consequences. Zhao et al. [13] developed an innovative theoretical model (PC-3E) to affirm the interrelationships among influential factors for SCV and to evaluate regional SCV. Karwasra et al. [14] put forward a method to identify decisive drivers of SCV and construct a model applying interpretive structural modeling (ISM) and a graph theory approach (GTA) to compute the index of SCV. While research on network vulnerability has been conducted both domestically and internationally, only a small fraction has focused on the vulnerability of transportation systems, and even less on the vulnerability of transportation systems specifically for HAZMAT. Thus, this paper aims to examine the vulnerability of transportation systems from the perspective of HAZMAT based on the theories established by previous scholars.

3. Identification of Factors Affecting the Vulnerability of HMTS

Regarding the classification method of influencing factors on the vulnerability of transportation systems, it has not developed a unified approach within this field. Currently, some scholars have explored the factors affecting the vulnerability of transportation systems and achieved certain results, as shown in Table 1.

Table 1 Identified influential factors for the vulnerability of HMTS

Author	Factors division
Karwasra et al. [14]	Direct vulnerability Indirect vulnerability
Song et al. [15]	Internal supply chain factor External disturbance factors
Guo et al. [16]	Demand-side Supply-side Internal factor External factor

Torretta et al. [17]	Geographical Date Demographics Date Meteorological Date
Cordeiro et al. [18]	Inherent Damage Environmental vulnerability Population Vulnerability
Huang et al. [8]	Human factors Material factors Organizational factors External factors
Sharma et al. [19]	Supply chain structure Organizational complexity Supply chain relationship complexity Information management

These studies, summarized in Table 1, primarily analyze factors affecting the vulnerability of transportation systems while overlooking the role of material-specific characteristics. This gap neglects how cargo properties (e.g., chemical instability) affect systemic vulnerability, thereby limiting the practical relevance of these frameworks.

Transportation systems are operationally defined as integrated processes for moving materials between locations, involving personnel, equipment, routes, and environmental conditions. Similarly, HMTS shares a similar essence, but the transported objects are changed. HAZMAT varies significantly in its properties and is mostly highly unstable, requiring extra caution during transportation. Hence, the HAZMAT transportation process encompasses four main aspects: the personnel involved, the conveyance used, the environmental conditions, and the object transported. Grounded in the HCEO security system analysis method, this paper categorizes the factors influencing the vulnerability of HMTS into four levels: human aspect, conveyance aspect, environment aspect, and object aspect, and conducts an in-depth analysis of each.

3.1 Human Aspect

Existing literature identifies human factors as critical determinants of the vulnerability of HMTS. These factors encompass transportation personnel experience, physical and mental fitness, professional knowledge proficiency, route selection criteria, safety compliance awareness, regulatory violations, and emergency response capabilities. Table 2 summarizes these factors that influence the vulnerability of HMTS.

Table 2 Human aspect

Criteria	Measurement index	Author
Human aspect	Unsafe human actions, lack of safety knowledge, low safety awareness, bad safety habits, bad safety physiological status, and bad safety psychological status	Huang et al. [8]
	Driver fatigue, lack of driver experience, route planning, delivery speed, driver confidence in vehicle security systems, and qualification of drivers	Batarliene [20]
	Incorrect handling, examiner's operation error, low skill level, concealment and false alarm, negligence of the escort, human-induced, freight forwarder's operation error, and warehouse keeper's operation error	Fa et al. [21]
	Physical discomfort and poor working environment, inaccurate work attitude and operation of staffs, staffs are	Huang et al. [22]

lack of technical and knowledge during all aspects of transportation processes, the staffs of dangerous materials manufacturers illegally overload or entrain goods, and non-personnel's illegal dangerous materials stealing Unsafe behaviors of drivers include speeding; fatigued driving, and some illegal operations (such as making phone calls, smoking, eating, emergency braking or slamming the steering wheel in case of emergency)	Guo et al. [23]
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3.2 Conveyance Aspect

According to the references, maintenance of conveyance, type of conveyance, running speed, and technical equipment condition of conveyance affect the vulnerability of HMTS, with specific factors listed in Table 3.

Table 3 Conveyance aspect

Criterion	Measurement index	Author
Conveyance aspect	Failure of transportation equipment, failure of dangerous materials storage equipment, and failure of loading and unloading equipment in the handling stations	Huang et al. [22]
	Poor packaging quality, poor technical condition of the vehicle, container problems, equipment failure, and mechanical action	Fa et al. [21]
	Vehicle load-bearing capacity, average vehicle speed, and vehicle performance	Jiang et al. [24]
	Unsafe conditions of transport vehicles include equipment aging, vehicle failure, vehicle does not match hazardous materials, and refit the vehicle at will	Guo et al. [23]

3.3 Environment Aspect

The environment of the transportation system refers to the sum of various conditions encountered during transportation. Extensive literature shows that factors such as weather conditions, natural disasters, and traffic accidents can affect the vulnerability of the HMTS, as shown in Table 4.

Table 4 Environment aspect

Criterion	Measurement index	Author
Environment Aspect	The extreme weather conditions, the transportation line conditions, and the sudden natural disaster	Huang et al. [22]
	Weather conditions, physical environment, natural disasters, sudden large-scale disease, and chaotic social order	Fa et al. [21]
	Traffic capacity, path alignment, and accident rate	Jiang et al. [24]
	The adverse weather environment includes: ice and snow days, strong winds, rainy days, fog, and high temperatures	Guo et al. [23]

3.4 Object Aspect

HAZMAT exhibits unique intrinsic properties due to variations in type and physical states (e.g., solid, liquid, gaseous). Moreover, these properties can affect the vulnerability of HMTS in various forms and to different extents. Referring to extensive literature, it is eminently evident that factors

such as the type and attributes of HAZMAT, their packaging, and the freight volume of HAZMAT in transportation can influence the vulnerability of HMTS, as illustrated in Table 5.

Table 5 Material aspect

Criterion	Measurement index	Author
Material aspect	The characteristics of the substance transported (pressure and temperature), and the amount of substance that is transported and that can be released in an accident	Torretta et al. [17]
	Dangerous nature of the loaded and transported materials, packaging of dangerous materials, and volume of the dangerous materials	Huang et al. [22]
	Unsafe material, and the energy of unsafe material.	Huang et al. [8]
	The physical and chemical properties	Guo et al. [23]

This paper applies the HCEO security system analysis method to identify and summarize the key factors affecting indicator identification for the vulnerability of HMTS. The analytical results of these influencing factors are visually presented in Table 6.

Table 6 The indicator identification for the vulnerability of HMTS

Dimensional factors	Factors
Human	Transportation personnel experience (x_1)
	Physical and mental fitness (x_2)
	Professional knowledge proficiency (x_3)
	Transportation route selection (x_4)
	Safety compliance awareness (x_5)
	Regulatory violations and emergency response capabilities (x_6)
Conveyance	Maintenance of conveyance (x_7)
	Types of conveyance (x_8)
	Running speed (x_9)
	Technical equipment condition of conveyance (x_{10})
Environment	Transport route condition (x_{11})
	Weather condition (x_{12})
	Natural disaster (x_{13})
	Traffic accident (x_{14})
Object	Types and attributes of HAZMAT (x_{15})
	Packaging of HAZMAT (x_{16})
	Freight volume of HAZMAT (x_{17})

4. Analysis of Vulnerability Influencing Factors in HMTS based on DEMATEL

4.1 Modeling Procedure of DEMATEL

The research problem addressed in this paper is the key factors affecting indicator identification for the vulnerability of HMTS. As indicated by the vulnerability index system for HMTS presented in Table 6, the factors influencing the vulnerability of this system encompass four aspects: human, conveyance, environment, and object, each of which includes several specific sub-factors. Moreover, these vulnerability-influencing factors interact with each other, forming a complex system. Therefore, this paper will employ DEMATEL to quantitatively analyze the impact of these four dimensions on the vulnerability of HMTS. Then, a model of influencing factors will be constructed to identify the key

factors. Finally, corresponding solutions will be proposed for these key factors. The DEMATEL method is a systematic factor analysis approach that utilizes the principles of graph theory and matrix theory and fully leverages the expertise and knowledge of experts to address complex social issues, particularly for systems with uncertain element relationships. Through quantitative analysis of the mutual influences among factors, DEMATEL determines the degree of influence, the degree of being influenced, the centrality, and the causality of factors, ultimately yielding the causal relationships and important influencing factors. The calculation process of DEMATEL is as follows.

Step 1: Determine the influencing factors for the vulnerability of HMTS and obtain the direct influence relationship matrix X

The factors of the vulnerability of HMTS in Table 6 are denoted as $X_i (i=1,2,\dots,17)$. The relationship between each pair of vulnerability factors is denoted as X_{ij} . Expert scoring is used to determine the degree of influence between each pair of vulnerability factors, which is then categorized into seven levels. $X_{ij} = 0$ indicates that X_i does not influence on X_j ; $X_{ij} = 1$ indicates that X_i has a very weak influence on X_j ; $X_{ij} = 2$ indicates that X_i has a weak influence on X_j ; $X_{ij} = 3$ indicates that X_i has a moderate influence on X_j ; $X_{ij} = 4$ indicates that X_i has a strong influence on X_j ; $X_{ij} = 5$ indicates that X_i has a significant influence on X_j ; and $X_{ij} = 6$ indicates that X_i has a very strong influence on X_j .

This paper employs DEMATEL to determine the influence degrees among the vulnerability factors, thereby constructing the direct influence matrix A . The data in the influence matrix are obtained through scoring by corporate transportation personnel and related practitioners in the field of transportation system vulnerability, based on their respective experiences. A total of 11 questionnaires were distributed for this survey, all of which were collected. Set X is the direct influence matrix of vulnerability factors, where $X_{ij} (i=1,2,\dots,17; j=1,2,\dots,17)$ is an element of matrix A . The direct influence matrix A for the factors of the vulnerability of HMTS is established as shown in Table 7. Where n represents the number of impact factors, X_{ij} denotes the degree of influence factor i on j . If $i = j$, we have $X_{ij} = 0$.

$$A = \begin{bmatrix} X_{11} & \cdots & X_{1n} \\ \vdots & \ddots & \vdots \\ X_{n1} & \cdots & X_{nn} \end{bmatrix} \quad (1)$$

Step 2: Normalize the direct influence relationship matrix according to the following two formulas.

$$B = \frac{A}{S} \quad (2)$$

$$S = \max_{1 \leq i \leq n} \left(\sum_{j=1}^n x_{ij} \right) \quad (3)$$

Step 3: Construct the comprehensive influence relationship matrix Z . It represents the sum of the direct and indirect effects between vulnerability influencing factors, where I is the unit matrix.

$$Z = \lim_{k \rightarrow \infty} (B + B^2 + B^3 + \cdots + B^k) = B(I - B)^{-1} \quad (4)$$

Step 4: Calculate the influence degree R_i and the influenced degree C_j by the following formulas.

$$R_i = \sum_{j=1}^n z_{ij}, i = 1, 2, \dots, n \quad (5)$$

$$C_j = \sum_{i=1}^n z_{ij}, j = 1, 2, \dots, n \quad (6)$$

Step 5: Calculate the degree of centrality M_i , and the degree of causality N_i for each factor in the comprehensive influence relationship matrix.

$$M_i = R_i + C_j, i = j \tag{7}$$

$$N_i = R_i - C_j, i = j \tag{8}$$

4.2 Result Analysis

The specific steps of DEMATEL described above are followed to obtain a series of relation matrices and parameters, using the MATLAB software. The direct influence relationship matrix A for the vulnerability of HMTS is shown in Table 7, the comprehensive influence relationship matrix Z for the vulnerability of HMTS is shown in Table 8, and the details of the relation parameters including influence degree R_i , influenced degree C_j , the degree of centrality M_i , and the degree of causality N_i for the vulnerability of HMTS are presented in Table 9.

Table 7 The direct influence relationship matrix

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}
X_1	0.0	1.5	3.2	1.8	2.6	3.3	1.1	0.0	2.9	0.0	0.0	0.0	0.0	3.5	0.0	0.0	0.0
X_2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0	2.2	0.0	0.0	0.0
X_3	0.0	0.0	0.0	2.7	4.1	4.5	1.7	0.0	3.2	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
X_4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	2.9	0.0	0.0	1.3	0.0	0.0	0.0
X_5	0.0	0.0	0.0	3.6	0.0	3.1	1.5	0.0	4.3	3.4	0.0	0.0	0.0	0.0	0.0	4.2	2.3
X_6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
X_7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
X_8	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	1.3	1.8	0.0	0.0	0.0	0.0	0.0	2.1	3.7
X_9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
X_{10}	0.0	0.0	0.0	0.0	0.0	4.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.2	1.8
X_{11}	0.0	0.0	0.0	2.5	1.3	1.9	0.0	0.0	3.7	0.0	0.0	0.0	0.0	3.9	0.0	0.0	0.0
X_{12}	0.0	0.0	0.0	3.9	2.1	3.8	0.0	0.0	4.6	0.0	4.5	0.0	4.9	4.6	0.0	0.0	0.0
X_{13}	0.0	0.0	0.0	4.2	1.8	3.4	0.0	0.0	4.2	0.0	5.1	0.0	0.0	4.7	0.0	0.0	0.0
X_{14}	0.0	0.0	0.0	3.7	1.1	3.3	0.0	0.0	3.9	0.0	3.6	0.0	0.0	0.0	0.0	0.0	0.0
X_{15}	0.0	0.0	0.0	0.0	0.9	3.7	0.0	0.0	0.0	3.7	0.0	0.0	0.0	0.0	0.0	5.2	2.4
X_{16}	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.5
X_{17}	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	1.7	3.3	0.0	0.0	0.0	0.0	0.0	1.8	0.0

Table 8 The comprehensive influence relationship matrix

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}
X_1	0.00	0.05	0.11	0.11	0.11	0.17	0.05	0.00	0.16	0.04	0.01	0.00	0.01	0.13	0.00	0.02	0.01
X_2	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.07	0.00	0.01	0.00	0.00	0.09	0.00	0.00	0.00
X_3	0.00	0.00	0.00	0.11	0.14	0.19	0.06	0.00	0.14	0.13	0.00	0.00	0.01	0.00	0.00	0.04	0.02
X_4	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.04	0.01	0.11	0.01	0.00	0.05	0.01	0.00	0.02	0.01
X_5	0.00	0.00	0.00	0.13	0.00	0.14	0.05	0.01	0.16	0.15	0.00	0.00	0.01	0.00	0.00	0.17	0.11
X_6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
X_7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.01	0.00
X_8	0.00	0.00	0.00	0.04	0.00	0.02	0.00	0.00	0.05	0.08	0.00	0.00	0.00	0.00	0.00	0.09	0.15
X_9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
X_{10}	0.00	0.00	0.00	0.00	0.00	0.16	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.12	0.09

X_{11}	0.00	0.00	0.00	0.11	0.05	0.09	0.00	0.00	0.16	0.02	0.02	0.00	0.01	0.14	0.00	0.01	0.01
X_{12}	0.00	0.00	0.00	0.22	0.10	0.21	0.01	0.01	0.26	0.04	0.22	0.00	0.18	0.22	0.00	0.02	0.01
X_{13}	0.00	0.00	0.00	0.20	0.08	0.17	0.00	0.01	0.21	0.03	0.20	0.00	0.01	0.19	0.00	0.02	0.01
X_{14}	0.00	0.00	0.00	0.15	0.04	0.14	0.00	0.01	0.16	0.02	0.13	0.00	0.01	0.02	0.00	0.01	0.01
X_{15}	0.00	0.00	0.00	0.00	0.03	0.17	0.00	0.00	0.01	0.15	0.00	0.00	0.00	0.00	0.00	0.21	0.12
X_{16}	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.12
X_{17}	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.06	0.12	0.00	0.00	0.00	0.00	0.00	0.08	0.02

Table 9 The details of the relation parameters

Factor	R_i	C_j	$M_i = R_i + C_i$	$N_i = R_i - C_i$
X_1	0.993	0.000	0.993	0.993
X_2	0.183	0.053	0.236	0.131
X_3	0.856	0.112	0.968	0.744
X_4	0.292	1.108	1.400	-0.816
X_5	0.924	0.578	1.502	0.347
X_6	0.000	1.607	1.607	-1.607
X_7	0.067	0.188	0.254	-0.121
X_8	0.445	0.081	0.527	0.364
X_9	0.000	1.470	1.470	-1.469
X_{10}	0.366	0.955	1.320	-0.589
X_{11}	0.629	0.610	1.238	0.019
X_{12}	1.510	0.000	1.510	1.510
X_{13}	1.147	0.267	1.415	0.880
X_{14}	0.699	0.793	1.491	-0.094
X_{15}	0.698	0.000	0.698	0.698
X_{16}	0.210	0.819	1.030	-0.609
X_{17}	0.318	0.697	1.015	-0.379

4.3 Identify the Key Affecting Factors of HMTS

According to the calculation results in Table 9, the summary includes several relation parameters for the vulnerability of HMTS. Among them, the degree of centrality and the degree of causality are indispensable indicators of crucial factors. Using centrality and causality as the horizontal and vertical coordinates, a scatter plot is drawn with the aid of Visio diagramming software, and it forms a causal relationship diagram for the vulnerability of HMTS. This diagram is used to analyze the interaction relationships, and it is shown in Fig. 1.

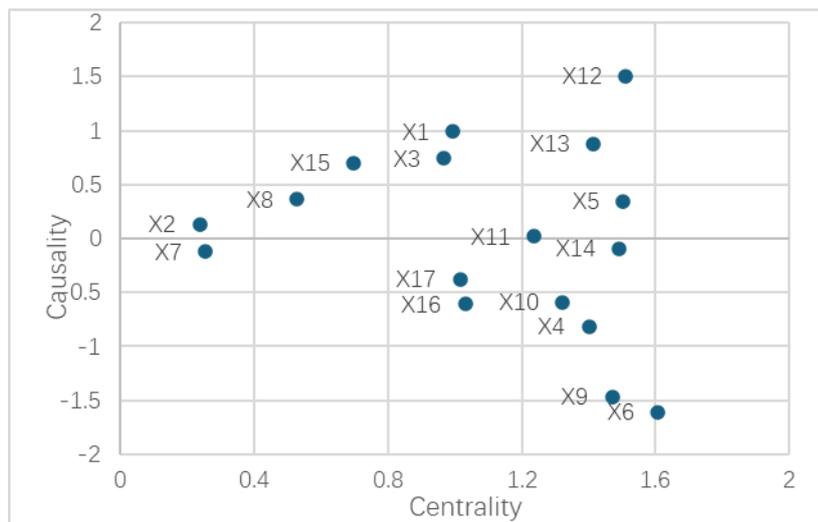


Fig. 1. Causal graph of factors affecting the vulnerability of HMTS

It can be shown in **Fig. 1.** that the sequence of vulnerability factors is $X_6 > X_{12} > X_5 > X_{14} > X_9 > X_{13} > X_4 > X_{10} > X_{11} > X_{16} > X_{17} > X_1 > X_3 > X_{15} > X_8 > X_7 > X_2$, and these elements are divided into causal group and effect group. According to **Fig. 1.**, the cause factors are ranked as $X_{12} > X_1 > X_{13} > X_3 > X_{15} > X_8 > X_5 > X_2 > X_{11}$. The centrality values of x_{12} and x_5 rank first and second respectively among all the causal factors, and their influence degrees rank first and fourth. Among all the causal factors, they have a relatively strong influence degree and a relatively weak influenced degree. Therefore, x_{12} (weather conditions) and x_5 (safety compliance awareness) are the key causal factors contributing to the vulnerability of HMTS. Similarly, the effect factors are sorted as $X_{14} > X_7 > X_{17} > X_{10} > X_{16} > X_4 > X_9 > X_6$. Among them, the centrality values of x_6 and x_9 rank first and third respectively among all the result factors, and their degrees of being influenced rank first and second. Moreover, compared with other result factors, they have a higher degree of being influenced and a lower degree of influence. Therefore, x_6 (regulatory violations and emergency response capabilities) and x_9 (running speed) are the key result influencing factors leading to the vulnerability of HMTS.

5. Analysis of Control Countermeasures of Key Vulnerability Influencing Factors

To mitigate the vulnerability of HMTS, the corresponding measures are proposed in response to the identified critical factors: weather conditions, safety compliance awareness, regulatory violations and emergency response capabilities, and running speed. Therefore, the following four solutions are proposed accordingly.

5.1 Selecting Appropriate Routes for HAZMAT Conveyances Based on Weather Fluctuations

In addressing the issue of severe weather impacting the stability of HMTS, with the HCEO security system analysis methodology, we recognize that adverse weather conditions can significantly affect the operational capabilities of transportation personnel, the maneuverability of conveyances, the state of transportation infrastructure, and the stability of the HAZMAT being transported, potentially leading to transportation incidents. In recent years, a review of accident cases reveals a plethora of incidents where conveyances have suffered damage and HAZMAT has leaked due to severe weather conditions such as torrential rain, snow accumulation, and high winds. Moreover, adverse weather

typically coincides with a constellation of unfavorable factors. For example, heavy rain and snow may severely degrade transportation conditions, compromising the operational decision-making of transportation personnel and affecting the stability of moving conveyances. Therefore, it is paramount for transportation operators to maintain vigilant monitoring of weather patterns both before and during the transportation of HAZMAT. Firstly, transportation companies need to provide systematic driving knowledge training to their transportation operators. These individuals often have extensive driving experience and a high level of professional expertise. They can rely on their rich experience and professional knowledge to make timely emergency judgments, ensuring the relative stability of HMTS in the face of severe weather. Secondly, transportation personnel must constantly monitor weather conditions while driving. When unfavorable conditions arise during transit due to uncontrollable factors, prompt alterations to the driving route can be made to ensure the normal operation of the conveyances. Lastly, transportation companies can anticipate weather conditions in advance. In the event of severe weather, they can adjust transportation times and routes. If adjustments are not possible, companies should enhance their transportation equipment and facilities, such as providing additional protective measures for HAZMAT and equipping conveyances with emergency devices. Weather fluctuations cannot be altered by human will, and in the face of uncontrollable factors, companies can only strive to fortify their facilities and equipment to better manage the risks posed by these unpredictable elements.

5.2 Enhance the Security Awareness of Personnel in HMTS

We must recognize that the lack of security awareness among transportation personnel can indirectly affect their control over conveyance operations and their judgment in responding to emergencies. Unsafe behavior is the most dangerous factor affecting the normal operation of HMTS. For relevant managers and operators, it is necessary to take more risk-reduction measures[25]. Therefore, it is particularly crucial to enhance the security awareness of personnel in HMTS. Firstly, companies should regularly provide employees with security knowledge training to ensure that transportation personnel are familiar with the dangers of HAZMAT and the severity of accidents, thereby raising awareness in their subconscious. Secondly, standardize the operational procedures for transporting HAZMAT to improve the accuracy of transportation personnel's handling. Security awareness is a crucial factor throughout the entire journey in HMTS. HAZMAT transportation companies should fully utilize the point during every transportation operation stage to control the risks in the HMTS.

5.3 Improve the Emergency Rescue Capabilities of Personnel in HMTS

Enterprises should not only improve emergency rescue education and practical training for transportation personnel but also innovate emergency rescue equipment and facilities. Many controllable and uncontrollable factors can trigger the vulnerability of the transportation system for HAZMAT. These factors have varying degrees of impact on the entire transportation system at any time. Therefore, it is of great significance to enhance the emergency rescue capabilities of relevant transportation personnel to maintain the stability of the HMTS. Firstly, enterprises can conduct regular emergency rescue training for transportation personnel, simulating the dangers that may be encountered during transportation to test their emergency rescue capabilities. For any shortcomings identified, additional training can be provided to strengthen and consolidate the skills, and then they can improve the efficiency and capabilities of the transportation personnel in emergency rescue

situations. Secondly, enterprises can prepare the necessary items and equipment for emergency rescue in advance, aiming to minimize transportation risks.

5.4 Restrict the Speed of Conveyances Transporting HAZMAT

Enterprises must not only regulate the speed requirements for conveyances transporting HAZMAT but also provide security awareness and driving skills training for the drivers in HMTS. Analyzing past accident cases reveals that speeding is a significant factor in a large proportion of accidents. Moreover, when an accident occurs, it can potentially threaten traffic capacity, as well as the safety of the route line and the conveyances. Therefore, it is particularly indispensable to standardize driving speed. Firstly, enterprises should strictly review the job applications of HAZMAT drivers, and those with poor driving skills or insufficient driving experience should not be hired. After being employed, drivers should receive regular training on relevant driving skills. Secondly, enterprises can monitor the conveyance conditions, the actions of transportation personnel, and the status of HAZMAT in real-time by installing GPS devices. If any irregularities in driving speed or abnormal driving behavior are detected during transportation, appropriate disciplinary actions will be taken according to the company's regulations.

6. Conclusions and Prospects

This article starts with concepts and theories related to vulnerability, analyzing the factors affecting the vulnerability of HMTS through the HCEO security system analysis method and identifying the specific factors and their proportions. By using DEMATEL, a quantitative analysis of vulnerability factors is conducted to identify the key factors. Finally, corresponding solutions are proposed for these key factors.

Based on the above factor analysis and data calculation, we identified four crucial factors and proposed four corresponding solutions. By comparing the causes and countermeasures of the most current hazardous materials road transportation safety accidents, it is found that the analysis results are consistent with actual situations. This indicates that it is feasible to utilize DEMATEL to analyze the vulnerability factors of HMTS.

This paper reveals the relevant factors affecting the vulnerability of HMTS based on the theory of vulnerability. A quantitative analysis of the influencing factors of the vulnerability of HMTS is conducted by using DEMATEL, identifying the key factors, and corresponding solutions are proposed based on the conclusions. Firstly, preventive measures should be implemented to address the issue of harsh weather conditions affecting the stability of HMTS. Secondly, security awareness training should be enhanced to tackle the problem of low security awareness in HMTS operations. Thirdly, realistic emergency rescue training simulations should be strengthened in response to the insufficient emergency rescue capabilities of transportation personnel. Finally, standardized speed limits should be enforced to regulate the irregular driving speeds of HAZMAT conveyances. In addition to focusing on the vulnerability influencing factors at the four levels of the HCEO security framework, solving the problem of vulnerability factors in HMTS can also draw on other relevant aspects. For example, companies can enhance the stability of HMTS from a management perspective, utilize more advanced information technology to control transportation risks and enrich and improve the data information database in HMTS. It is beneficial for compensating for the current lack of relevant data in HMTS and facilitates subsequent researchers' continued study of topics related to HAZMAT. However, the obtained theories still lack practical application. It is hoped that, with

sufficient funds and practical conditions, this theoretical achievement can be applied to real life in the future.

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Conflicts of Interest

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