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Risk Analysis of Heavy-cargo Transportation Accidents based on DEMATEL-ISM

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ABSTRACT

Safety problems of heavy-cargo transportation have been one of the key problems that hinder industrial development. With implementing the "One Belt, One Road" strategy and the "traffic-based state development" strategy, large infrastructural projects increase quickly, which proposes higher requirements for the safety management of heavy-cargo transportation. It is necessary to comprehensively explore and analyze safety accident risk factors of heavy-cargo transportation. This study analyzed the heavy-cargo transportation process systematically, and basic evaluation units were determined and recognized. Risk sources were recognized from five aspects of "workers, vehicles, cargo, environment and management". A heavy-cargo transportation safety system model was constructed using the integrated DEMATEL-ISM method. The mutual influencing degrees of risk factors were analyzed, and influencing factors and action mechanisms of heavy-cargo transportation safety accidents were explored. Results showed that inadequate professional knowledge of managers is the intrinsic cause of heavy-cargo transportation safety, while human factors and management factors are important causes. Hence, strengthening the safety consciousness and behaviours of workers and improving the professional level of managers are keys to decreasing the rate of heavy-cargo transportation accidents and increasing the safety level.

Keywords: Heavy-cargo Transportation, Accidents, Risk Factors, DEMATEL-ISM Method

1. Introduction

Heavy-cargo transportation refers to road transport of a single non-disassembled good when at least one of the total length, total width, total height, total mass and axial load of vehicle and cargo exceeds regulations of Limits of Dimension, Axle Load and Masses for Motor Vehicles, Trailers and Combination Vehicles (GB1589). Recently, with the implementation of the "One Belt, One Road" strategy and the booming infrastruc-

ture construction in China, the transport demands for supporting large-sized infrastructure equipment have increased gradually. Heavy cargo transportation serves as a guarantee for the transportation of key national projects in China, and there is no doubt about the importance of safe transportation.

However, road heavy-cargo transportation in China has a short history of development, a slow development rate and immature technologies. The safety management level of enterprises is still not optimistic, thus resulting in occasional occurrences of accidents during transport. On the one hand, these accidents not only threaten the life and safety of workers but also cause damage to the surrounding facility's equipment. On the other hand, damage to heavy cargo may cause considerable economic loss and hinder the progress of key national projects. Therefore, improving the safety guarantee and service level of heavy-cargo transportation from the management and technological levels to decrease occurrences of accidents is a problem that has to be solved urgently at present.

Studies on heavy-cargo transportation mainly focus on some specific working procedures in transport organizations, and the core studies of transport safety focus on specific working procedures, including the selection of channels and vehicles, binding and reinforcement, accessibility of bridges, and so on. Concerning the selection of transport channels and vehicles, Li et al. (2021) constructed a multi-objective channel selection decision-making model for heavy-cargo transportation by using the improved analytic hierarchy process (AHP) of principal component analysis (PCA) to provide references for decision-making· Concerning the binding of heavy cargo, He et al. (2018) verified a feasible and effective binding strengthening program through three-dimensional modelling, which involves determining criteria, formulating schemes, constructing models and checking strength. Concerning the access safety of bridges, Sun et al. (2020) proposed a complete evaluation process for the access ability of bridges. They elaborated several common evaluation methods for the bearing capacity of bridges· Jia et al. (2019) defined oversized cargo by the practical transportation level from the perspective of practical transportation by combining oversized cargo transportation experiences in several international engineering logistics projects, summarizing various practical conditions for oversized cargo transportation, and analyzing the main modes for oversized cargo transportation on the market at present. They paid high attention to the thorough conclusion of risks in oversized cargo transportation. Moreover, systematic countermeasures were proposed with comprehensive consideration of various risk factors. Liang (2022) proposed a comprehensive evaluation method of road transport risk levels of hazardous goods based on a two-dimensional cloud model to address the increasing road transport risks caused by adverse effects of various risk factors. Based on this model, he evaluated road transport risk levels of hazardous goods comprehensively and objectively. Li et al. (2022) proposed a road and bridge transport risk evaluation technique based on combination weighting and regrets theory to evaluate road and bridge transport risks of hazardous goods effectively and solve excessive subjectivity of existing relevant evaluation methods. Zhang et al. (2020) analyzed accidents thoroughly by using the STAMP model to prevent occurrences of accidents in railway transport systems for hazardous goods, thus getting relevant safety constraints of control structures, inadequate control behaviours and causes, as well as safety dynamic changes of the system. Secondly, correlations among causes of accidents were analyzed by ISM and levels were divided. Finally, the system improvement schemes were proposed based on STAMP and ISM analysis results.

To sum up, it currently lacks comprehensive safety management of heavy-cargo transportation. In this study, potential risk factors in different procedures were recognized from the perspective of the whole heavy-cargo transportation process. Correlations and causality paths among risk factors were analyzed. On this basis, risk control measures were proposed, aiming to decrease the occurrence of heavy-cargo transportation accidents.

2. Basic Process and Risk Recognition of Heavy-cargo Transportation

2.1. Basic Process of Heavy-cargo Transportation

For the convenience of recognizing risk sources, comprehensive implementation of the evaluation task, and avoidance of missing, the whole process of heavy-cargo transportation was firstly divided reasonably, and the basic units of evaluation were determined and recognized. Through literature review and combined with a field survey, the whole process of road heavy-

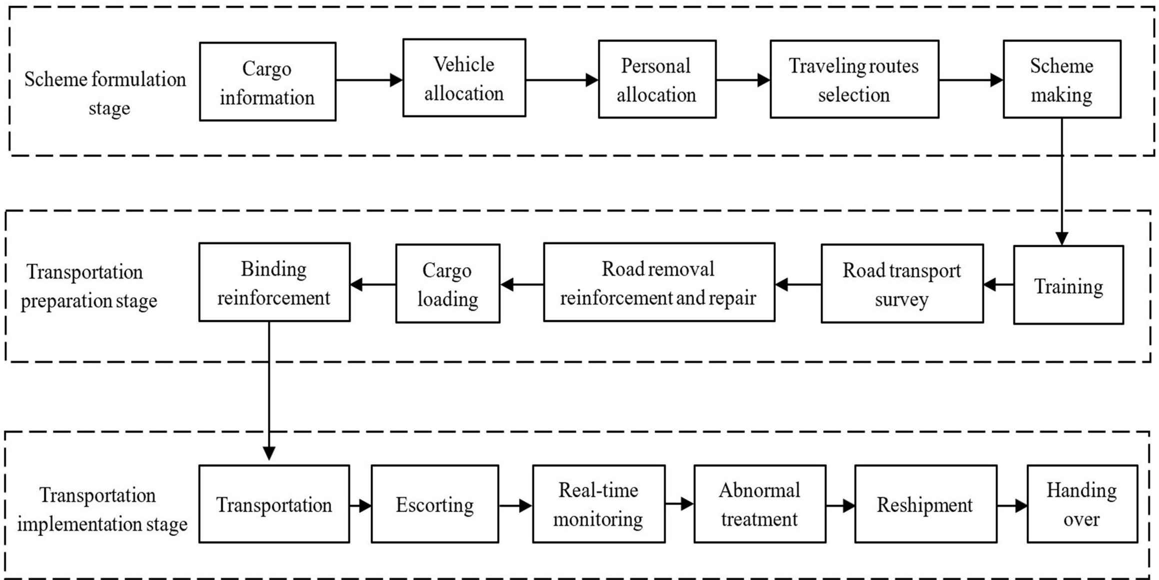

Figure 1. Process of heavy-cargo transportation

cargo transportation was divided into three stages: scheme formulation stage, transportation preparation stage and transportation implementation stage. These three stages were used as the basic units of risk recognition (Figure 1)

Enterprises qualified for heavy-cargo transportation shall know cargo information, origin & destination, general information of travelling routes as well as their own vehicle and personal allocation first when accepting the transport projects, and formulate transportation schemes to evaluate the feasibility of the transportation project. This is the scheme formulation stage. After preliminary evaluation, a series of preparations before transportation shall be made according to the perfected general scheme, including training, road survey, barrier clearance, and load strengthening. This is the transportation preparation stage. The final stage is the transportation implementation stage, including monitoring and abnormal treatment in the transportation way as well as reshipment and handing over at the destination.

2.2. Risk recognition of Heavy-cargo Transportation

The road heavy-cargo transportation risks were recognized through information analysis and field surveys. The index system of risk factors was determined.

Firstly, influencing factors of heavy-cargo transportation were extracted through a literature review and accident cases. The division of risk factors of heavy-cargo transportation is referred to in Table 1. Considering the excessive length, excessive width, excessive height and excessive weight of heavy-cargo vehicles and cargos, risks were recognized in this study from the perspectives of workers, vehicles, cargo, environment and management.

Literature source	**Risk factor division of heavy-cargo transportation**
Leng et al. (2017)	Road transport risks, railway transport risks, waterway transport risks, reshipment risks
Li et al. (2011)	Environmental risks, technological risks, economic risks, bidding risks, management and organization risks, transport risks
Min (2015)	personnel risks, vehicle risks, cargo risks, environmental risks

Table 1. Risk factor division of heavy-cargo transportation and literature sources

Combined with heavy-cargo transportation accident cases, the risk factors of five aspects materialized above. According to statistical analysis of vehicle-hitting bridge accidents during heavy-cargo transportation on the Shanghai-Chongqing Highway, vehicle-hitting pier accidents during heavy-cargo transportation on Hailar-Zhangjiakou Highway in 2020, collision accidents of heavy semi-trailers for heavy-cargo transportation, vehicle falling in water due to bridge collapse, rollover accidents at turns, rollover accidents of bridge-type vehicle group for large devices on highways in 2015, many causes can be summarized. Most causes can originate from "people's unsafe behaviours" (e.g. rule-breaking operations or fatigued driving of drivers, poor safety consciousness of workers, no road survey or great survey errors) and "unsafe state of goods" (e.g. vehicle faults, unreasonable cargo loading and poor road accessibility).

Secondly, a field survey of heavy-cargo transportation enterprises was carried out in Hebei, Sichuan, and Chongqing to comprehend more information about development status and risk points that shall be a concern in practical operation, such as the reasonability of transport route planning, the reasonability of personnel allocation, and reasonable loading according to cargo characteristics. Therefore, the risk factor system can be further perfected from the perspective of freight enterprises. The field survey results are shown in Table 2.

Survey enterprises	Main business	Operation time	Survey time
Hebei Hongda Large-cargo Transportation Co., Ltd	Wind power heavy-cargo transportation	18 years	09:00-12:00, August 11, 2020
Baoding Erbiao Transportation Co., Ltd	Wind power heavy-cargo transportation	13 years	14:00-17:00, August 11, 2020
Shijiazhuang Ludean Automobile Rental Co., Ltd	Automobile rental	10 years	09:00-12:00, August 12, 2020
Sichuan Dongfang Logistics Group Co., Ltd	Electromechanical engineering project	16 years	14:00-16:30, August 25, 2020
Dongfang Electric Group Large-cargo Logistics Co., Ltd	Electromechanical product transportation	13 years	14:00-17:00, August 26, 2020
Chongqing Yajie Transportation Co., Ltd	Heavy-cargo transportation	20 years	09:00-11:30, August 27, 2020
Chongqing Xindayun Logistics Co., Ltd	Wind power heavy-cargo transportation	19 years	14:00-17:00, August 27, 2020

Table 2. Field survey results

Combining with data analysis and field survey, risk factors of road heavy-cargo transportation accidents were recognized and classified into "three stages and five aspects". According to multiple rounds of discussion and modification by experts from China Water Resource and Electric Power Association on Physical Distribution, 10 risk factors were extracted finally (Figure 2).

***(1) Weak Safety Consciousness** refers to risks in operation activities caused by operators' weak safety consciousness. Although this consciousness may not participate in man-machine mutation directly, it influences safety behaviours, such as ignorance of safety signs and lack of risk consciousness.*

***(2) Personnel Misconduct** refers to risks in operation activities caused by unsafe behaviours of operators during interaction with devices, such as using unsafe facility and device tools, touching risk positions, using immature operation technologies, poor cooperation of multiple workers, fatigue driving, and so on.*

(3) Inherent defects of vehicles: *This refers to defects in vehicles that are caused by design, manufacturing, installation, and other reasons, exist for a long time, and may cause accidents during*

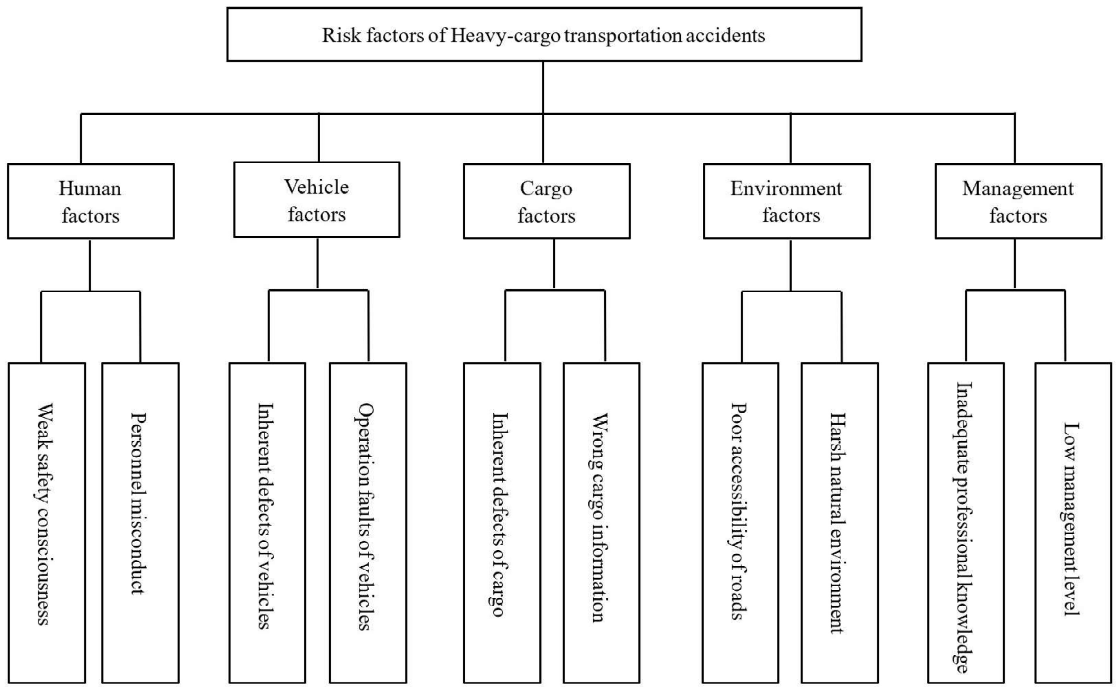

Figure 2. Risk factor systems of road heavy-cargo transportation accidents

operation and downtime. Examples include exposure to sharp parts, unclear safe signs, and non-standard vehicle manufacturing.

(4) Operation faults of vehicles: *these refer to risks caused by loss of regulated functions of a position or part during the operation of vehicles, such as failure of control device, failure of protective device, failure of attention device, out-of-energy control, looseness and breakage of parts, etc.*

(5) Inherent defects of cargo: *Accidents during loading and unloading, carrying, and transportation are caused by the cargo's inherent properties, such as spontaneous combustion and decaying radioactive substances.*

(6) Wrong cargo information *refers to accidents during loading and unloading, carrying, and transportation caused by wrong information provided by consignors, consignees, and convoy men, such as understatement of weights, poor packing, concealment, and wrong reporting of cargo name and properties.*

(7) Poor accessibility of roads: *This refers to accidents during transportation caused by road and traffic problems or inaccurate information from road surveys, such as pavement quality, slope, accessibility at turns, limit in bearing capacity of bridges, traffic jams, accidents, road reinforcement, barrier clearance, imperfect repair, etc.*

(8) Harsh natural environment: *The natural environment and the operating environment directly or indirectly influence the normal operation of heavy-cargo transportation, such as bad weather conditions, poor operating conditions, and force majeure like floods, earthquakes, tsunamis, extreme storms, etc.*

(9) Inadequate Professional Knowledge: *This refers to risks caused by managers' lack of relevant professional knowledge and skills, such as mismatching vehicle configuration and cargo transportation requirement, improper cargo binding scheme or loading & unloading design, unreasonable equipment of operators, etc.*

(10) Low Management Level: *it refers to potential risks caused by failure to form a perfect cargo transport safety guarantee system, imperfect rules and regulations and unclear responsibility, such as unreasonable formulation of transportation schemes, imperfect vehicle maintenance, unreasonable personal allocation, physiological fatigue of drivers, poor monitoring over driving states of drivers, cargo and vehicles, imperfect safety early warning mechanism, etc.*

3. Methods

3.1. DEMATEL-ISM Method and Model Introduction

To investigate the importance degree and accident-causing mechanism of many influencing factors of the complicated accident systems, the statistical model can be applied to accident data, such as finite mixed regression model, quantile regression method, and so on (Athanasios, 2017; Eljko et al., 2018). However, a statistical method often assumes that factors are independent mutually, and the quantitative analysis results might be separate from reality. The occurrence of heavy-cargo transportation accidents is the collaborative consequence of complicated factors. Although the factor association analytical method is closer to reality (Jiang et al., 2020; Feng et al., 2014), it isn't easy to quantify the influencing degree of causing factors. To further analyze the influencing mechanism and degree of influence of causing factors, Xiao et al. (2010) analyzed key factors of green logistics development using the DEMATEL method. Su et al. (2009) analyzed the influencing factors

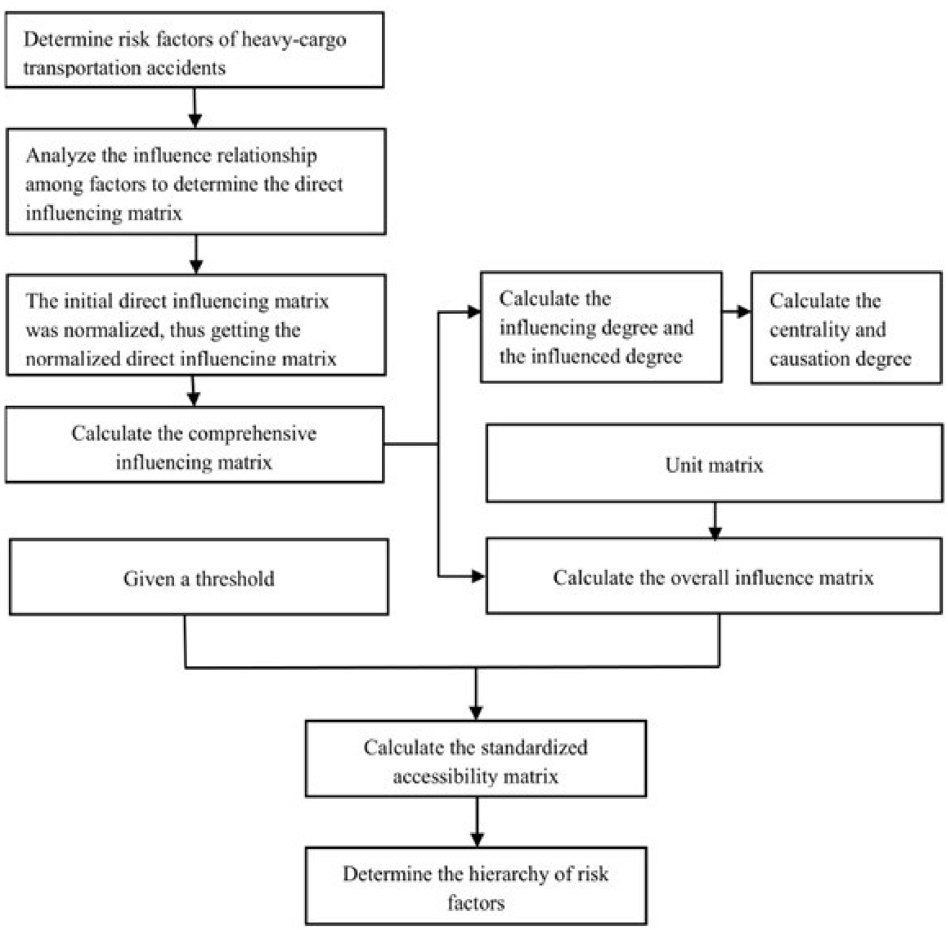

Figure 3. DEMATEL-ISM modelling process of heavy-cargo transportation safety system

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of the selection of the logistic mode of manufacturing enterprises. Specifically, the DEMATEL method can analyze the causal relationships among system factors, but the influencing mechanism among factors cannot be determined. The ISM method can transform the complicated relations of factors in the system into an intuitive and clear multilevel hierarchical structural model. However, it has some disadvantages, such as a complicated computation process. The DEMATEL and ISM methods have some association and complementarity (Zhu et al., 2020). As a typical "man-machine-environment-management" system, the complicated risk factor system of heavy-cargo transportation accidents can be described as a multi-level hierarchical system model with good structural relations by using the integrated DEMATEL-ISM method, thus enabling the analysis of causal relationships and action mechanism of risk factors. The DEMATEL-ISM modelling process of risk factors of heavy-cargo transportation accidents is shown in Figure 3.

3.2. Steps of DEMATEL-ISM method

(1) Determine risk factors of heavy-cargo transportation accidents: $a_1, a_2, \ldots, a_n$, where n refers to the number of risk factors.

(2) Generate the initial direct influencing matrix. According to the experiences of experts and field technicians k (k=1, 2, …, m) of the large-cargo transportation industry, the mutual influencing degrees were judged according to four levels: strong (3), moderate (2), weak (1) and absent (0). The direct influencing matrix (B) among factors was gained in this way. The averaging method combined the evaluation results of multiple experts, thus getting the initial direct influencing matrix=B.

$$\beta_{ij} = \frac{1}{m}\sum_{k=1}^{m} \beta_{ij}^{k} (k = 1, 2, \ldots, m) \qquad (1)$$

(3) The initial direct influencing matrix was normalized, thus getting the normalized direct influencing matrix C:

$$C = \frac{1}{\max\limits_{1 \le i \le n} \sum_{j=1}^{n} \beta_{ij}} B \qquad (2)$$

(4) Calculate the comprehensive influencing matrix T.

$$T = C_1 + C_2 + \cdots + C_n = \sum_{i=1}^{n} C^i \qquad (3)$$

(5) Calculate the influencing degree (f_i) and the influenced degree (e_i) of accident factors. The influencing degree of factors is the sum of rows in T, and the influenced degree of factors is the sum of columns in T.

(6) Calculate the centrality (M_i) and causation degree (N_i). They are the sum and difference between influencing degree and influenced degree, respectively.

(7) Calculate the overall influence matrix H $\left(H = \left[h_{ij}\right]_{n \times n}\right)$:

$$H = I + T \qquad (4)$$

(8) To get the standardized accessibility matrix, elements in the overall influencing matrix have to be processed. Given a threshold (λ), the accessibility matrix K $\left(K = \left[k_{ij}\right]_{n \times n}\right)$ can be calculated:

$$k_{ij} = 1, \quad if \quad h_{ij} \ge \lambda (i, j = 1, 2, \ldots, n) \qquad (5)$$

$$k_{ij} = 0, \quad if \quad h_{ij} \le \lambda (i, j = 1, 2, \ldots, n) \qquad (6)$$

(9) The accessibility matrix (K) was divided according to different levels. According to the ccessibility set, cause set and highest-level element set, the risk factors were divided into different levels and the hierarchical structure of factors was plotted.

A questionnaire was formed according to the risk factor system of heavy-cargo transportation accidents. It was sent to relevant workers and experts of enterprises. The mutual influencing degree of factors was determined through scoring of experts. The initial direct influencing matrix after averaging is shown in Table 3.

B	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}
a_1	0.0	2.5	0.3	1.0	0.0	0.8	0.8	0.8	1.0	1.3
a_2	0.5	0.0	0.0	1.5	0.0	1.0	0.5	0.5	0.5	1.3
a_3	0.0	1.3	0.0	2.8	0.0	0.3	0.8	0.5	0.8	1.0
a_4	0.0	1.0	0.3	0.0	0.3	0.0	1.5	1.3	0.0	0.8
a_5	0.0	0.3	0.0	0.3	0.0	1.0	0.5	0.0	0.3	0.0
a_6	0.0	0.3	0.0	0.5	0.0	0.0	0.5	0.0	0.5	0.5
a_7	0.0	1.5	0.0	1.5	0.0	0.0	0.0	0.5	0.5	0.3
a_8	0.3	1.3	0.0	1.5	0.0	0.0	1.8	0.0	0.0	0.3
a_9	2.0	1.8	0.0	1.8	0.0	0.8	0.0	0.0	0.0	2.3
a_{10}	1.5	1.8	0.0	0.5	0.0	1.3	0.0	0.0	1.3	0.0

Table 3. The initial direct influencing matrix *B*

According to DEMATEL-ISM steps (3-7), C, T influencing degree, influenced degree, centrality, causality and centrality ranking were calculated, and attributes of different factors were determined. Results are shown in Table 4.

Accident factors	Influencing degree	Influenced degree	Causality	Centrality	Centrality ranking	Attributes of factors
a_1 Weak safety consciousness	2.839	1.607	1.232	4.446	5	Cause
a_2 Personnel misconduct	1.922	3.777	-1.855	5.699	1	Result
a_3 Inherent defects of vehicles	2.444	0.208	2.236	2.652	8	Cause
a_4 Operation defects of vehicles	1.603	3.465	-1.862	5.068	2	Result
a_5 Inherent defects of cargo	0.641	0.131	0.510	0.773	10	Cause
a_6 Wrong cargo information	0.818	1.725	-0.908	2.543	9	Result
a_7 Poor accessibility of roads	1.465	2.131	-0.666	3.596	6	Result
a_8 Harsh natural environment	1.606	1.423	0.184	3.029	7	Cause
a_9 Inadequate professional knowledge	3.074	1.607	1.468	4.681	4	Cause
a_{10} Low management level	2.299	2.636	-0.337	4.934	3	Result

Table 4. Calculated results of DEMATEL method

It can be seen from Table 4 that a_3, a_9, and a_1 show high causality, and they easily influence other risk factors in the system. They are key preventive factors in risk control. Moreover, a_2, a_4 and a_{10} show great centrality, indicating their great influences on heavy-cargo transportation risk system accidents.

According to Step (8), it determines λ =0.43 according to experts' opinions. The calculated K is shown in Table 5. According to Step (9), K was divided into several levels and a hierarchical structural model of heavy-cargo transportation risk factors was plotted (Figure 4).

It can be seen from Figure 4 that in the heavy-cargo transportation safety system, a_9 is an intrinsic cause. a_1, a_3 and a_{10} are transition causes. a_2, a_4, a_5, a_7 and a_8 are neighbour causes, and they are factors that influence heavy-cargo transportation safety directly. Therefore, the analysis results of the action mechanism among risk factors based on the integrated DEMATEL-ISM method basically conform to the "2-4 accident model" (Chen et al., 2017). In other words, the lack of a safety culture

	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}
a_1	1	1	0	1	0	0	0	0	0	0
a_2	0	1	0	0	0	0	0	0	0	0
a_3	0	1	1	1	0	0	0	0	0	0
a_4	0	0	0	1	0	0	0	0	0	0
a_5	0	0	0	0	1	0	0	0	0	0
a_6	0	0	0	0	0	1	0	0	0	0
a_7	0	0	0	0	0	0	1	0	0	0
a_8	0	0	0	0	0	0	0	1	0	0
a_9	1	1	0	1	0	0	0	0	0	0
a_{10}	0	1	0	0	0	0	0	0	0	0

Table 5. Reachability matrix *K* at λ = 0.43

and safety management system on the organization level is the fundamental cause. The habitual behaviors of individuals, as well as one-time behaviors and state of matters, are direct or indirect causes. Influenced by organizational and individual behaviours together, the behavioural consequence of "accident and loss" occurs.

According to the observation of the action mechanism of factors, a_9 and a_{10} cause a_2 and finally lead to accidents. Moreover, a_1, a_3 and a_9 can all influence a_2 and a_4, thus causing accidents. a_5, a_6, a_7 and a_8 influence accidents independently.

5. Conclusions and Management Enlightenment

Through literature review, field survey, and discussion with experts, a risk factor system of heavy-cargo transportation accidents is formed in this study according to three stages and five aspects of risk recognition. The mutual influencing degrees among risk factors are analyzed by the integrated DEMATEL-ISM method. Moreover, the hierarchical structural model of risk factors is constructed. It is found that inadequate professional knowledge is the essential cause of accidents. Weak safety consciousness is a cause with great centrality. The dual prevention mechanism of risk ranking control and hidden danger checking shall be adopted in risk control. Attention shall be

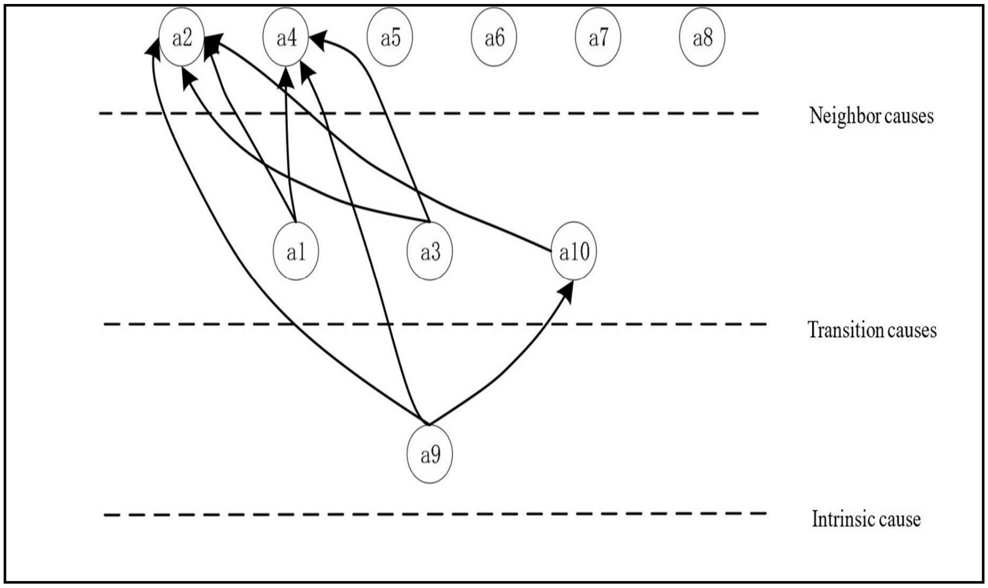

Figure 4. Hierarchical structural model of accident risk factors in the heavy-cargo transportation system

paid to not only deep-level causes but also risk factors to control safety risks before the occurrence of hidden danger and recognize hidden danger before the occurrence of accidents. The safety risk control of heavy-cargo transportation accidents shall focus on the following three aspects:

(1) Perfect the safety management system. *Management is the overall management of involved parties, vehicles, cargo, road and natural environmental conditions during heavy-cargo transportation. It is the baton of the successful heavy-cargo transpiration. On the one hand, enterprises shall pay great attention to training in the safety culture and create a cultural atmosphere in which all workers are concerned with safety prevention and participate in safety management. On the other hand, management quality determines the effect and efficiency of heavy-cargo transportation directly. The management layer shall strengthen the learning of professional knowledge to realize targeted, professional and reasonable management, thus improving the management level.*

(2) Strengthen the safety consciousness of workers. *Guide behaviours with consciousness. It can avoid risks during operation behaviours as long as safety culture is concerned highly with ideology. Enterprises shall pay attention to training safety consciousness and responsibility consciousness, risk cognition ability and responses of workers, train and approve qualification and technical level of operators strictly, and formulate and improve operation standards of workers to make workers meet standard operation conditions ideologically and thereby avoid risk behaviours.*

(3) Prevent vehicle, cargo and environmental risks. *Risk factors that may cause accidents directly are checked and prevented, which can achieve effects in a short period. Concerning vehicles, it shall ensure that the technical performances of vehicles conform to requirements. Moreover, it is suggested to make real-time monitoring of state in vehicle transportation and perfect the safety early warning mechanism. For cargo, it shall check cargo information, load cargo reasonably, and make real-time monitoring of the state and positions of cargo. For the environment, it is suggested to investigate roads and bridges and clear barriers, comprehend traffic and weather conditions in passing regions during transportation in advance, and formulate emergency schemes.*

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