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Research on Risk Assessment Method of Long-Tube Trailer Road Transportation

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Abstract

Road transport safety has always been paid attention to by the safety production managers of enterprises. In this study, cloud model and analytic hierarchy process were applied to the safety of long-tube trailer transport. The opinions of 30 experts were analyzed, from which 29 key parameters were selected. The study addressed the relevance of the parameters and the possibility of automatic collection and transmission to obtain 12 core risk factors. The macro-safety risk indicator system for long-tube trailers was established based on the identified risk indicators. Finally, a risk assessment model for road transport of long tube trailers consisting of 3 dimensions of likelihood, severity and sensitivity was constructed. This model provides a technical method for strengthening the risk control of road transport of long-tube trailers.

Keywords

Cloud Model, Analytic Hierarchy Process, Long-Tube Trailer, Risk Factors, Risk Assessment Model

1. Introduction

Long tube trailers are mainly used for inter-regional short and medium distance industrial gas transportation, and are typical mobile pressurized special equipment [1]. With the widespread use of new energy sources such as natural gas, the number of long tube trailers, which are the main means of transportation, is gradually rising. Compared to traditional gas cylinders, long-tube trailer has the advantages of high efficiency, convenience and wide coverage [2]. According to statistics, the number of long tube trailers in China has increased from more than 2000 in 2005 to about 15,000 in 2020. However, long tube trailers are mainly used for storing and transporting flammable, explosive, toxic or corrosive gases such as natural gas and hydrogen [3]. Gas cylinder pressure is generally more than 20 MPa belongs to the high-pressure environment. In this environment, in case of fire, overfilling and other accidents, the pressure inside the cylinder will rise rapidly, which will easily lead to overpressure explosion [4]. The technical conditions for long tube trailers are already relatively mature. From filling to transport, they are equipped with suitable safety devices and standardized operating practices. The danger of storing and transporting long tube trailers has been effectively reduced. But the vehicle driving process is vulnerable to road conditions, traffic accidents, driving operations and other factors, if the use of improper management may occur serious special equipment accidents or special equipment-related accidents, will cause serious harm to people's lives and property [5].

The main research object of this study is long tube trailer. Aiming at the problem of lack of dynamic data and insufficient monitoring means during the operation of long tube trailers, cloud modeling, hierarchical analysis and other methods are adopted. Firstly, the safety status parameters are determined and screened by combining qualitative and quantitative methods. Then the macro safety risk indicator system of long-tube trailers is established and the weights of the indicators are determined. Finally, the macro safety risk early warning model of long tube trailer is constructed, with a view to improving the effectiveness of safety supervision of pressurized equipment.

2. Research Methods

Cloud model [6] is an uncertainty conversion model between a certain qualitative concept represented by natural language values. And its quantitative representation proposed by Academician Deyi Li to reflect the uncertainty of concepts in natural language, especially the vagueness and randomness, and to achieve a natural conversion between qualitative language values and quantitative values [7].

Cloud model [8] is mainly implemented by the forward cloud generator and the backward cloud generator.

1) Forward cloud generator

The forward cloud generator is a mapping from qualitative to quantitative with the input of three numerical characteristics of the cloud—expectation Ex, entropy En and superentropy He, and the number of cloud droplets N. The output is the quantitative position of N cloud droplets in the number field space and the degree of certainty of the concept represented by each cloud drop. Since normal clouds have universal applicability, the screening is mainly based on the application of normal clouds. The specific algorithm for the one-dimensional forward cloud generator is:

Input: Digital features (Ex, En, He) reflecting the qualitative concept of weight and the number of cloud drops N.

Output: N cloud drops X_i and affiliation of each cloud drop to the concept.

a) In the first step, a normal random number Eni' is generated with *En* as the expected value and *He* as the standard deviation.

b) In the second step, generate a normal random number *X* with *Ex* as the expected value and Eni' as the standard deviation.

c) In the third step, calculate the affiliation of X_i to the concept:

$$\mu_i = \exp\left[-\frac{(x-Ex)^2}{2En_i^2}\right] \tag{1}$$

In the fourth step, repeat a)-c) until *N* cloud droplets were generated.

2) Backward cloud generator

The function of the reverse cloud generator is to find the three digital eigenvalues (*Ex*, *En*, *He*) of the forward cloud generator from some given cloud drops. The specific algorithm of the reverse cloud generator is as follows:

Input: Take the weight value given by the expert as the sample value, $X = X_i$, among them, $i = 1, 2, \cdots, n$.

Output: Digital features reflecting the qualitative concept of parameter weights (*Ex*, *En*, *He*).

Calculation of sample means from X_i:

$$Ex = \bar{X} = \frac{1}{N}\sum_{i=1}^{n} X_i \tag{2}$$

$$En = \sqrt{\frac{\pi}{2}} \times \frac{1}{N}\sum_{i=1}^{N}\left|X_i - Ex\right| \tag{3}$$

$$He = \sqrt{S^2 - En^2}\text{, among them, } S^2 = \frac{1}{N-1}\sum_{i=1}^{N}\left(X_i - \bar{X}\right)^2 \tag{4}$$

The Analytic Hierarchy Process [9] (AHP for short) is a multi-level, multi-objective, multi-program comprehensive comparison method proposed by Professor Say in the early 1980s.

The basic principle of Analytic Hierarchy Process can be described as follows: first, find out the various factors affecting the decision of the problem, and arrange these factors into several levels from high to low according to their membership, this process is the construction of a recursive hierarchy. Then ask the authority to compare the importance of the factors in each level in pairs, and then use the mathematical method to find out the weight of the factors in each layer and sort them. Each factor is scored in the actual problem, and the final score is obtained according to the calculated weights. Finally, the results are analyzed to assist in the decision-making [10].

3. Determination of the Risk Assessment Indicators

3.1. Determine the Initial Safety State Parameters

In order to ensure the scientific, comprehensive and effectiveness of the safety state parameters, the initial parameters are selected first. The initial parameters include three sources: first, to analyze 32 national and local standards, norms and regulations concerning equipment safety, such as the Measures for the Safe

Management of Road Transportation of Dangerous Goods, TSGR005-2011 Safety Technical Supervision Regulations for Mobile Pressure Vessels, GB7258-2017 Safety Technical Conditions for Motor Vehicle Operation, etc. second, to collect and sort out the relevant accident data occurring in China [11]. Third, the experience of many experts. Finally, 56 initial parameters of the safety risk of mobile pressure equipment were determined, among which the regulatory sources accounted for 75.0%, the accident statistics sources accounted for 23.3%, and the expert experience sources accounted for 1.8%. The 56 initial parameters were divided into vehicle and tank factors, road factors, human factors and environmental factors [12]. The various initial parameters are shown in **Table 1**.

Table 1. Initial screening results of macro safety risk parameters of mobile pressure equipment.

Class	Safety risk parameters		
Equipment factor (Vehicle and tank factors)	1) Speed	14) Liquid level	27) Property of the filling media
	2) Newness of the vehicle	15) Internal diameter	28) Container corrosion allow-
	3) Operating status of the indicator lamp	16) Total length of tank	29) Cylinder material
	4) Closed condition of pipe fittings	17 Weight	30) Internal temperature
	5) Tire pressure status	18) Length	31) Pressure
	6) Chassis and mobile equipment reliability	19) Wall thickness	32) Filling situation
	7) Appearance	20) Quantity	33) Hydrogen sulfide concentration
	8) Carrying documents and tools with the car	21) Model	34) Mezzanine vacuum level
	9) Design service life	22) Filling capacity (medium storage capacity)	35) Inherent reliability of safety release devices
	10) Chassis type	23) Total volume	36) Reliability of pipeline use
	11) Design the speed limits	24) Reliability of safety accessories for use	37) Reliability of container use
	12) Pipeline materials	25) Reliability of loading and unloading accessories	—
	13) Vehicle posture	26) Charging station compliance	—
Road factor	38) Road segment accident susceptibility	40) Number of lanes	42) Road surface friction coefficient
	39) Slope	41) Visual distance	43) Turning radius
Demic factor	44) Continuous driving hours	46) Personnel qualification	47) Driving experience
	45) Fatigue level	—	—
Environment factor	48) Sensitive date	51) Visibility	54) Functional areas
	49) Traffic congestion index	52) Lighting conditions	55) Geographic conditions
	50) Environmental humidity	53) Population density	56) Hydrological conditions

In the next step, 56 initial parameters will be screened by the cloud modeling method based on the preliminary selection.

3.2. Safety Status Parameter Screening

1) First of all, 30 experts familiar with and understand the connotation of the parameters will evaluate the importance of the parameters. The language scale of the evaluation is divided into 9 levels, namely: {extremely unimportant, very unimportant, not important, not very important, generally, a bit important, important, very important, extremely important} [13]. The linguistic scales of the expert evaluations were transformed into the corresponding number of intervals, and the number of intervals corresponding to the nine levels were: {[1, 2], [1, 3], [2, 4], [3, 5], [4, 6], [5, 7], [6, 8], [7, 9], [8, 9]}. The number of intervals of the 9 uncertain language evaluation scale on the theoretical domain [1, 9] is transformed into 9 one-dimensional normal clouds, specifically as follows (set He_0 = 0.01):

a) Transforms the number of central intervals $[a_0, b_0] = [4, 6]$ into an approximately one-dimensional normal cloud, we get from formula: $a = \mu - k\sigma$, $b = \mu + k\sigma$ ($x \sim N(\mu, \sigma^2)$, $k = 2$)

$$\mu_0 = \frac{a_0 + b_0}{2} = 5$$

$$\sigma_0 = \frac{b_0 - a_0}{4} = 0.5$$

Therefore, there is: $Ex_0 = 5$, $En_0 = 0.5$, $He_0 = 0.01$, the one-dimensional forward cloud corresponding to the interval number [4, 6] is $C_0(5, 0.5, 0.01)$.

b) Similarly, there is $Ex_{+1} = 6$, $En_{+1} = 0.5$, by the golden split rate approximate method:

$$He_{+1} = \frac{He_0}{0.618} = 0.016$$

That is, the one-dimensional forward cloud corresponding to the interval number [5, 7] is $C_{+1}(6, 0.5, 0.016)$.

c) It is calculated that the nine one-dimensional forward clouds are

$$C_{-4}(Ex_{-4}, En_{-4}, He_{-4}) = C_{-4}(1.5, 0.25, 0.068)$$

$$C_{-3}(Ex_{-3}, En_{-3}, He_{-3}) = C_{-3}(2, 0.5, 0.042)$$

$$C_{-2}(Ex_{-2}, En_{-2}, He_{-2}) = C_{-2}(3, 0.5, 0.026)$$

$$C_{-1}(Ex_{-1}, En_{-1}, He_{-1}) = C_{-1}(4, 0.5, 0.016)$$

$$C_0(Ex_0, En_0, He_0) = C_0(5, 0.5, 0.01)$$

$$C_{+1}(Ex_{+1}, En_{+1}, He_{+1}) = C_{+1}(6, 0.5, 0.016)$$

$$C_{+2}(Ex_{+2}, En_{+2}, He_{+2}) = C_{+2}(7, 0.5, 0.026)$$

$$C_{+3}(Ex_{+3}, En_{+3}, He_{+3}) = C_{+3}(8, 0.5, 0.042)$$

$$C_{+4}(Ex_{+4}, En_{+4}, He_{+4}) = C_{+4}(8.5, 0.25, 0.068)$$

Nine one-dimensional, normal clouds, the cloud map as shown in **Figure 1**.

2) The set of 30 experts' ratings of the importance of parameter u_1 is $\{V_1, V_2, \cdots, V_{10}\}$. The score set of parameters is used as the evaluation sample, and the backward cloud generator generates the weight factor evaluation set $C_1'(Ex, En, He)$. Then, the forward cloud generator is used to obtain the evaluation cloud map of this parameter [12].

3) Repeat the steps (2) to obtain the evaluation cloud model of all the parameters. The cloud characteristics of the 56 safe state parameters are shown in **Table 2**.

4) The nine one-dimensional normal clouds generated by the evaluation language scale are used as the evaluation standard, and the evaluation clouds of the parameters are compared with them one by one. Since the evaluation cloud model reflects the importance of the parameters for the evaluation objectives and there may be differences in experts' perceptions of the importance of the parameters, it may lead to poor cohesion of the cloud map and show a fog distribution. Therefore, $Ex \geq 5$ is taken in the order of importance from highest to lowest, and the appropriate parameters are selected as safety state parameters in the evaluation cloud model of all factors by combining the cohesive distribution of the cloud diagram. After the calculation to obtain the cloud diagram of each parameter, and observe the cloud diagram and cloud droplet form of each parameter, if the cloud droplet dispersion is small, the cloud diagram as a whole shows a line shape, as shown in **Figure 2**, which indicates that the experts have a more unified understanding of the importance of the parameter; if the cloud droplet dispersion is larger, the cloud diagram as a whole shows a foggy shape,

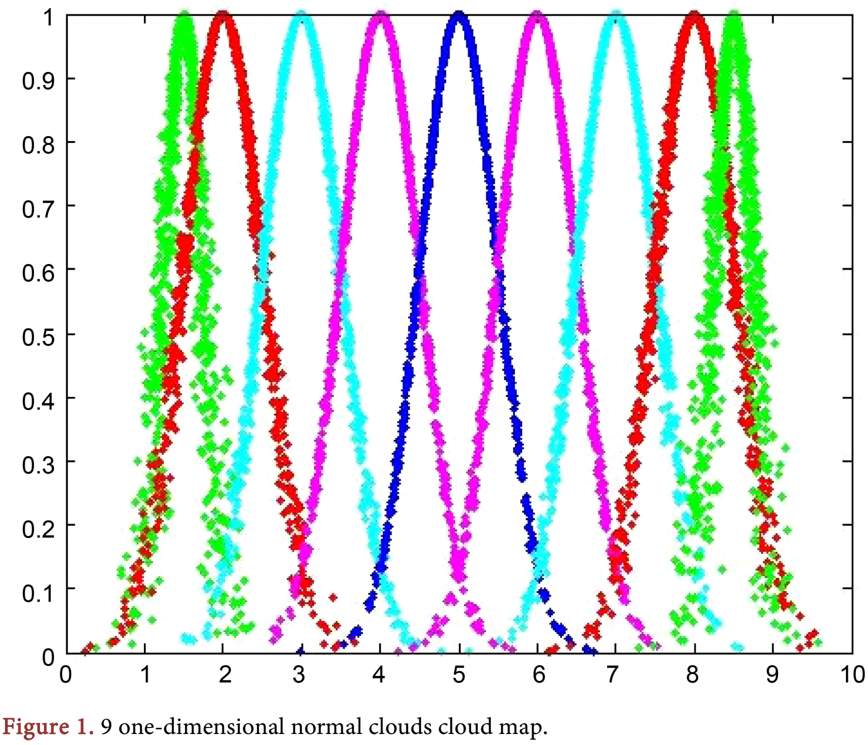

Figure 1. 9 one-dimensional normal clouds cloud map.

Table 2. Cloud characteristics of 56 safety state parameters of mobile pressure equipment.

Parameter	Digital features	Parameter	Digital features
1) Speed	(7.300, 1.512, 0.261)	29) Cylinder material	(1.757, 1.851, 0.534)
2) Newness of the vehicle	(3.567, 1.589, 0.424)	30) Internal temperature	(7.977, 0.901, 0.154)
3) Operating status of the indicator lamp	(1.647, 2.046, 0.798)	31) Pressure	(5.207, 1.953, 0.541)
4) Closed condition of pipe fittings	(7.462, 1.816, 0.437)	32) Filling situation	(4.137, 1.064, 0.380)
5) Tire pressure status	(4.271, 1.451, 0.312)	33) Hydrogen sulfide concentration	(8.313, 1.126, 0.454)
6) Chassis and mobile equipment reliability	(8.759, 2.417, 0.376)	34) Mezzanine vacuum level	(7.939, 1.061, 0.323)
7) Appearance	(2.803, 1.246, 0.103)	35) Inherent reliability of safety release devices	(7.239, 1.405, 0.320)
8) Carrying documents and tools with the car	(2.371, 0.909, 0.149)	36) Reliability of pipeline use	(6.299, 1.818, 0.339)
9) Design service life	(3.066, 3.411, 0.889)	37) Reliability of container use	(8.019, 1.279, 0.214)
10) Chassis type	(6.158, 1.584, 0.533)	38) Road segment accident susceptibility	(4.925, 3.091, 1.555)
11) Design the speed limits	(3.798, 2.324, 0.501)	39) Slope	(5.709, 1.154, 0.220)
12) Pipeline materials	(4.046, 1.253, 0.158)	40) Number of lanes	(6.664, 1.012, 0.370)
13) Vehicle posture	(2.753, 0.777, 0.023)	41) Visual distance	(6.286, 1.026, 0.099)
14) Liquid level	(4.517, 2.303, 0.403)	42) Road surface friction coefficient	(6.424, 0.928, 0.367)
15) Internal diameter	(3.909, 1.966, 0.527)	43) Turning radius	(6.603, 1.424, 0.587)
16) Total length of tank	(4.125, 1.511, 0.054)	44) Continuous driving hours	(8.557, 0.692, 0.091)
17 Weight	(3.668, 1.360, 0.324)	45) Fatigue level	(7.257, 1.260, 0.545)
18) Length	(3.848, 1.323, 0.518)	46) Personnel qualification	(3.151, 0.980, 0.346)
19) Wall thickness	(4.352, 1.205, 0.573)	47) Driving experience	(4.024, 2.039, 0.357)
20) Quantity	(4.334, 3.301, 0.813)	48) Sensitive date	(6.336, 1.887, 0.250)
21) Model	(2.674, 0.665, 0.069)	49) Traffic congestion index	(3.606, 3.061, 1.376)
22) Filling capacity (medium storage capacity)	(8.466, 1.625, 0.107)	50) Environmental humidity	(3.296, 1.006, 0.505)
23) Total volume	(3.841, 4.089, 0.818)	51) Visibility	(5.659, 1.349, 0.446))
24) Reliability of safety accessories for use	(7.537, 0.969, 0.414)	52) Lighting conditions	(5.888, 1.035, 0.692)
25) Reliability of loading and unloading accessories	(7.119, 1.748, 0.374)	53) Population density	(7.841, 0.884, 0.276)
26) Charging station compliance	(4.907, 0.920, 0.242)	54) Functional areas	(7.129, 1.637, 0.314)
27) Property of the filling media	(7.407, 1.356, 0.349)	55) Geographic conditions	(5.843, 1.678, 0.695)
28) Container corrosion allowance	(4.619, 2.993, 1.285)	56) Hydrological conditions	(5.357, 1.786, 0.570)

as shown in **Figure 3**, which indicates that the experts have not yet formed a unified understanding of the importance of the parameter.

5) Finally, 29 safety status parameters were selected, as shown in **Table 3**.

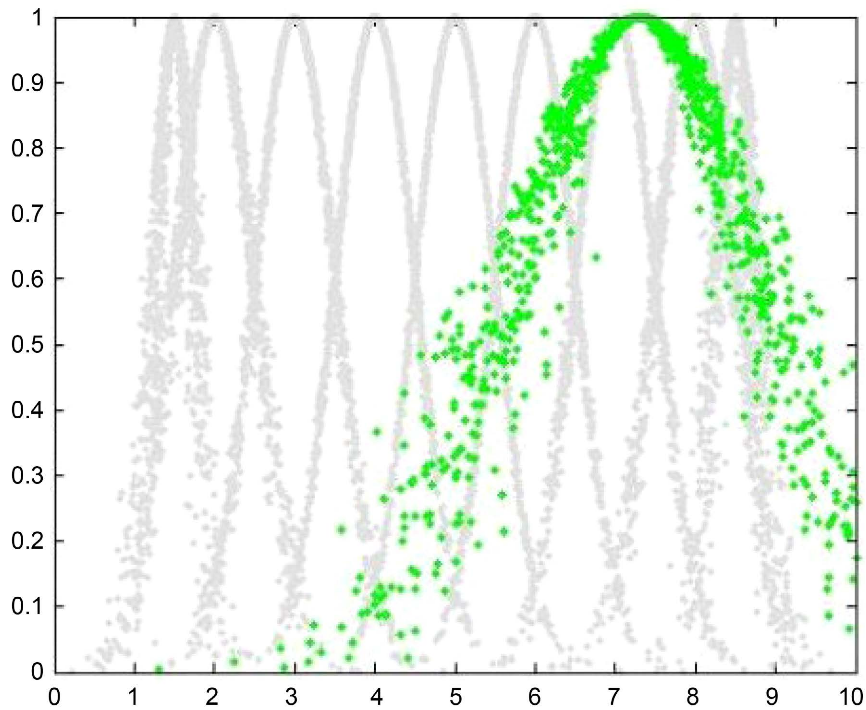

Figure 2. Cloud diagram of vehicle speed parameters.

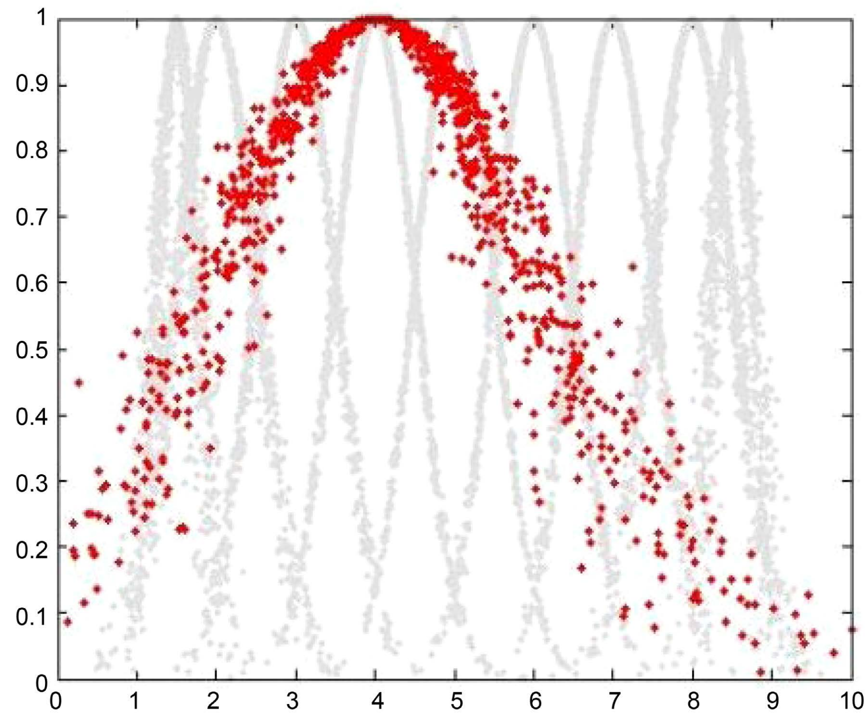

Figure 3. Cloud diagram of driving age parameters.

Table 3. 29 safety status parameters of mobile pressure-bearing equipment.

Parameter		
1) Speed	11) Hydrogen sulfide concentration	21) Continuous driving hours
2) Closed condition of pipe fittings	12) Mezzanine vacuum level	22) Fatigue level
3) Chassis and mobile equipment reliability	13) Inherent reliability of safety release devices	23) Sensitive date
4) Chassis type	14) Reliability of pipeline use	24) Visibility
5) Filling capacity (medium storage capacity)	15) Reliability of container use	25) Lighting conditions
6) Reliability of safety accessories for use	16) Slope	26) Population density
7) Reliability of loading and unloading accessories	17) Number of lanes	27) Functional areas
8) Property of the filling medium	18) Visual distance	28) Geographic conditions
9) Internal temperature	19) Road surface friction coefficient	29) Hydrological conditions
10) Pressure	20) Turning radius	—

4. Research on the Macro-Safety Risk Early Warning Index System of Long-Tube Trailer

4.1. Handling of Macro-Safety Risk Early-Warning Indicators

First of all, the principle that should be followed for the construction of the indicator system are clarified SMART principles [14], namely S-Specific, M-Measurable, A-Attainable, R-Relevant, T-Trackable.

Secondly, according to the principles that should be followed, the safety state parameters are transformed into measurable and meaningful indicators, and the selected 29 safety state parameters are analyzed, and appropriately modified or combined to form the real-time risk warning index of mobile pressure equipment [15].

Then, the importance of the indicators was further tested. Use the risk importance evaluation method to test the index and design the expert opinion scoring table of the index to evaluate the importance of the index [16], and assigning values to the importance according to **Table 4**.

70 expert scoring forms were distributed, and the survey experts included the Special Inspection Institute, equipment operation units, Lanke High-Tech, Shougang Group, and scientific research institutes such as the Academy of Safety Sciences and universities, a total of 66 valid questionnaires were recovered. Process the recovered data and calculate the importance coefficient according to

Table 4. Importance of risk warning indicators.

Indicator importance	Very important	Important	General	Unimportant	Very unimportant
value	9	7	5	3	1

the following formula:

$$RF_i = \frac{\sum_{j=1}^{m} a_{ij}}{m} \left(i = 1, 2, \cdots, n; j = 1, 2, \cdots, m \right) \tag{5}$$

$$\sigma_i = \sqrt{\frac{\sum_{j=1}^{m} \left(a_{ij} - RF_i \right)^2}{m-1}} \tag{6}$$

$$CV_i = \frac{\sigma_i}{RF_I} \left(i = 1, 2, \cdots, n \right) \tag{7}$$

m Among them, for the total number of survey experts;

a_{ij} is the evaluation score of the j-th expert for the i-th indicator;

RF_i is the importance coefficient of the i-th index;

CV_i is the coefficient of variation of the i-th index;

σ_i is the sample standard deviation for the i-th indicator.

The importance coefficient of each indicator (4.5 is the 50% grade value of the 9-point scoring scale) is specified and the coefficient of variation $CV_i \le 25\%$, and the indicators that do not meet the requirements are removed [17]. The index processing process and results are shown in **Table 5**, and are finally merged into 12 indicators.

4.2. Establish the Macro-Safety Risk Index System of Long-Tube Trailer

Macro safety risk refers to the systematic, comprehensive and social safety risks measured from a large time scale and spatial scope [18], can be expressed as a combination of likelihood, severity, and sensitivity.

1) Likelihood: the possibility of unsafe events or accidents;

2) Severity: the severity of the possible consequences of unsafe events or accidents;

3) Spatiotemporal sensitivity: the time, space, or system sensitivity of unsafe events or accidents.

Based on the concept of the three dimensions of macro safety risk to determine the pressure-bearing equipment macro safety risk index system is shown in **Figure 4**.

4.3. Risk Warning Indicator Grading Standard

Some indicators grading description:

1) Equipment inspection status: In accordance with *Pressure Vessels Periodical Inspection Regulation* (TSG R7001-2013), the vehicle should be inspected

Table 5. Processing results and index screening and optimization process of mobile pressure-bearing equipment.

Type	Safety status parameters	Index processing	Primary index	*RF*	*CV*	Result of handling
Equipment	Reliability of safety accessories for use Chassis and mobile equipment reliability Reliability of container use Hydrogen sulfide content Reliability of pipeline use Reliability of loading and unloading accessories	Merge	Equipment inspection status	7.05	15.94%	Continue to have
	Chassis type Inherent reliability of safety release devices	Merge	Inherent equipment reliability	6.16	18.87%	Continue to have
	Internal temperature Pressure Mezzanine vacuum level Closed condition of pipe fittings	Merge	Vessel operating parameters	7.69	23.54%	Continue to have
	Property of the filling medium	—	Property of the filling medium	8.00	17.53%	Continue to have
	Filling capacity (medium storage capacity)	—	Filling capacity (medium storage capacity)	6.95	18.76%	Continue to have
Human being	Continuous driving time	—	Continuous driving time	7.46	22.79%	Continue to have
	Fatigue degree	Delete: Indicator cannot be measured, reflected by continuous driving hours	—	—	—	—
	Speed	—	Speed	6.85	14.35%	Continue to have
Road	Road surface friction coefficient Visibility	Merge	Local weather	6.90	19.88%	Continue to have
	Turning radius Slope	Merge	Current road type	6.31	20.46%	Continue to have

Continued

	Number of lanes Visual distance lighting condition					
Environment	Sensitive date	—	Sensitive date	6.59	23.54%	Continue to have
	Density of population Functional areas	Merge	The surrounding social environment	7.72	14.47%	Continue to have
	Geographical conditions Hydrological conditions	Merge	Surrounding natural environment	6.18	21.83%	Continue to have

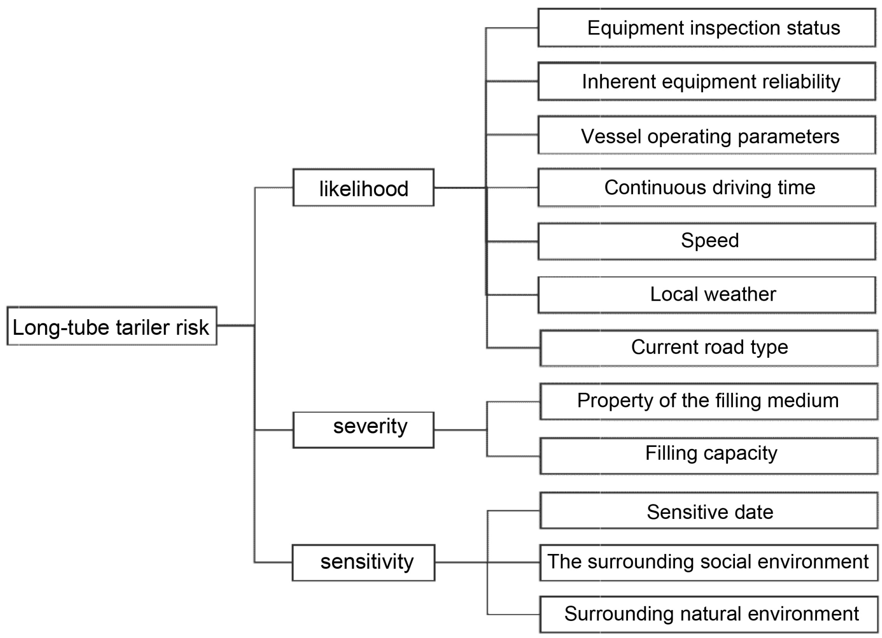

Figure 4. Pressure-bearing equipment macro-safety risk index system.

regularly. In line with the provisions and in the inspection period, according to the distance to the overdue time is divided into three levels, to the overdue time of 3 months and more assigned a value of 1 point; to the overdue time of 2 to 3 months assigned a value of 2 points; to the overdue time of 1 to 2 months assigned a value of 3 points; late inspection is assigned a value of 4 points.

2) Current road type: Considering the actual situation, the system divides the road types into ordinary roads and expressways in the data processing process. Because the speed is slow on the ordinary road, the risk value is low; driving on the highway, high speed, high risk value. The curve road is classified as a special road, with a value of 4 points.

3) Sensitive date: Multiple sensitive dates are saved in the system database, and the current date is compared to the sensitive date in the database during the vehicle driving. If it overlaps, it is high risk; otherwise, it is low risk.

4) Surrounding natural environment: In the process of vehicle driving, the natural environment is more complex than the social environment, with plains, mountains, rivers, which is not easy to classify in detail. The system compares the current position coordinates of the vehicle with the coordinates of rivers and lakes in the database. If the coordinates overlap, the vehicle travels to the sensitive place, the risk value is high, and 4 points are assigned; while the risk value is low, and the risk value is assigned 1 point.

The grading criteria for the 12 indicators are shown in Table 6.

Table 6. Guidelines for grading risk warning indicators for pressure-bearing equipment.

Data type	Number	Indicators	Evaluation criterion				According to
			Level IV (1 Points)	Level III (2 Points)	Level II (3 Points)	Level I (4 Points)	
Likelihood	1	**Equipment inspection status**	During the inspection period, distance to the overdue time is 3 months or more	During the inspection period, distance to the overdue time is between 2 and 3 months	During the inspection period, distance to the overdue time is between 1 and 2 months	Overdue inspection	Measures for the Safety Management of Road Transport of Dangerous Goods
	2	**Inherent equipment reliability**	The long pipe trailer is three rows of wheels and the combination of blasting sheet and safety valve	—	The long pipe trailer is three rows of wheels with only safety valve, or two rows of wheels and blasting sheet and safety valve combination	The long pipe trailer is two rows of wheels with only safety valves	Expert opinion, TSG R0005-2011, Gas station long tube trailer rupture disc abnormal detonation accident analysis and countermeasures
	3	**Vessel operating parameters**	1) The internal temperature of the long-tube trailer is less than 40˚C 2) The natural gas leakage concentration shall not exceed 10% LEL	1) Internal temperature of the long tube trailer is 40˚C - 50˚C 2) Natural gas leakage concentration is greater than 10% LEL and not more than 20% LEL	1) Internal temperature of the long tube trailer is 50˚C - 60˚C 2) Natural gas leakage concentration is greater than 20% LEL and not more than 30% LEL	1) The internal temperature of the long-tube trailer is greater than 60˚C 2) Natural gas leakage concentration is greater than 30% LEL	TSG R0005-2011 Safety Technical Supervision Regulations for Mobile Pressure Vessels, NB/T 47058-2017, Code for Design of Combustible and Toxic Gas Alarms

Continued

4	**Continuous driving time**	1) Drive for less than 4 hours continuously during the day; 2) Drive for less than 2 hours continuously at night	1) Drive continuously for 4 to 4.5 consecutive hours during the day; 2) Drive continuously for 2 to 2.5 hours at night	1) Drive continuously for 4.5 to 5 consecutive hours during the day; 2) Drive continuously for 2.5 to 3 hours at night	1) Driving continuously for more than 5 hours during the day; 2) Drive for more than 3 consecutive hours at night	The Regulations on the Implementation of the Road Traffic Safety Law and the Opinions of The State Council on Strengthening the Road Safety Work
5	**Speed**	1) The speed do not exceed the prescribed speed on the highway 2) Other roads do not exceed the prescribed speed	1) On the highway, exceeding the prescribed speed, but not up to 10% 2) Other roads exceed the prescribed speed but not up to 20%	1) Over 10% - 20% of the prescribed speed on the highway 2) Other roads exceed 20%-50% of the prescribed speed	1) More than 20% of the prescribed speed on the highway 2) Other roads exceed 50% of the prescribed speed	Article 45 of road Transport Safety Management Measures of Dangerous Goods, 2018
6	**Local weather**	1) Fog 2) Light to moderate rain (rainfall of 10 - 14.9 mm) 3) Average wind force 5 - 6 or gusts force 7 (8.0 m/s - 13.8 m/s or 13.9 m/s - 17.1 m/s); 4) Light snow or sleet 5) Normal weather	1) Fog 2) Moderate rain (precipitation: 15 - 29.9 mm) 3) Average wind force 7 or gusts force 8 (13.9 m/s - 17.1 m/s or 17.2 m/s - 20.7 m/s); 4) Middle snow;	1) Heavy fog 2) Heavy rain (precipitation: 30.0 - 49.9 mm) 3) Average wind force 8 or gusts force 9 - 10 (17.2 m/s - 20.7 m/s or 20.8 m/s - 28.4 m/s); 4) Heavy snow;	1) Heavy fog 2) Rainstorm/ heavy rainstorm/ extremely heavy rainstorm (precipitation of 50.0 - 99.9 mm/100 - 250.0 mm/exceeds 250 mm) 3) Average wind force 9 or gusts force 11 (20.8 m/s or 28.5 m/s) 4) Blizzard;	Grade of Highway Traffic Weather Conditions Rating
7	**Current road type**	Ordinary road section (1 points)		Special road section (4 points)		Accident Statistical Analysis and Code for Setting Up Highway Traffic Signs and Line Markings

Continued

severity	8	**Property of the filling medium**	Non-toxic		Highly toxic		The European Convention on the International Road Transport of Dangerous Goods (ADR), Article 7 of the Regular Inspection Rules of Pressure Vessels, TSG R0005-2011, GB 6944-2012, Dangerous Goods Classification and Name Number
	9	**Filling capacity**	0 < P 125 MPa·m^3	125 < P ≤ 250 MPa·m^3	250 < P ≤ 375 MPa·m^3	P > 375 MPa·m^3	Technical parameters of long-tube trailers, TSG R0005-2011
			PV value: 0 < V ≤ 9.6 MPa·m^3	PV value: 9.6 < V 12 MPa·m^3	PV value: 12 < V ≤ 14.4 MPa·m^3	PV value: V > 14.4125 MPa·m^3	The Guiding Opinions on Developing the Supervision and Management of Major Hazard Sources
sensitivity	10	**Sensitive date**	Not in the peak period of holidays and major activities (1 points)		During the peak period of holidays and major events (4 points)		Study on Road Speed Limit Design Method Based on Risk Classification
	11	**The surrounding social environment**	Industrial zones exist within every kilometer	Agricultural areas and commercial areas	Residential areas, administrative office area, transportation hub area	Science and technology and cultural areas, cultural relics protection areas, kindergartens, nursing homes and other elderly and children gathering areas	Measures for the Safety Management of Road Transport of Dangerous Goods Research on the Real-time Risk Early Warning Method of Road Dangerous Goods Transport Vehicles
	12	**Surrounding natural environment**	1) There is no water source protection area or nature reserve within each kilometer (1 points) 2) There are water source protection areas or nature reserves within each kilometer, but the transport medium is not strongly oxidized, corrosive or toxic (1 Points)		There are water source reserves and nature reserves within each kilometer, and the transport medium is highly oxidative, corrosive or toxic (4 Points)		Research on the Real-time Risk Early Warning Method of Road Dangerous Goods Transport Vehicles

5. Construction of Macro-Safety Risk Early Warning Model for Long-Tube Trailer

5.1. Determining Indicator Weights

1) Build a judgment matrix

Based on the relationship between risk and likelihood, severity, and sensitivity, constructed a risk model $R = P \times L \times S$, among them, R as risk, P as likelihood, L as severity, and S as spatiotemporal sensitivity. To determine the weights of the secondary indicators using hierarchical analysis, there are seven secondary indicators that have an impact on the likelihood, and to determine their impact ratios, the pairwise comparison method is chosen, two indicators (set as C_i and C_j) are taken at a time, and the ratio of the impact of C_i and C_j on the upper-level indicators is expressed by a_{ij} [19]. The results of all comparisons were represented by the matrix of $\boldsymbol{A} = \left(a_{ij}\right)_{n \times n} \left(a_{ij} > 0\right)$.

$$\boldsymbol{A} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{8}$$

$a_{ii} = 1, a_{ji} = \frac{1}{a_{ij}} \left(i, j = 1, 2, \cdots, n\right)$, So $\boldsymbol{A}$ is an inverse matrix of order n.

The value of RF is obtained according to the importance evaluation method of risk indicators [20], Calculate the $\Delta RF = RF_i - RF_j$ $(-8 \le \Delta RF \le 8)$, compare the value of ΔRF to the 9-quantile scale method (as shown in Table 7) to determine the value of each element in the matrix.

The following three judgment matrices can be obtained by comparing the importance data of "likelihood" and "sensitivity" and all secondary indicators at the lower level pairwise by the above method [21], Among them, matrix $\boldsymbol{A}_1$ is the judgment matrix of "likelihood" indicators, matrix $\boldsymbol{A}_2$ is the judgment matrix of "severity" indicators, and matrix $\boldsymbol{A}_3$ is the judgment matrix of "sensitivity" indicators.

$$\boldsymbol{A}_1 = \begin{bmatrix} 1 & 2 & 1/2 & 1/2 & 2 & 2 & 2 \\ & 1 & 1/3 & 1/3 & 1/2 & 1/2 & 1/2 \\ & & 1 & 2 & 2 & 2 & 3 \\ & & & 1 & 2 & 2 & 3 \\ & & & & 1 & 1/2 & 2 \\ & & & & & 1 & 2 \\ & & & & & & 1 \end{bmatrix}$$

Table 7. The ΔRF and the 9-quantile scale correspondence table.

ΔRF	0	(0, 1]	(1, 2]	(2, 3]	(3, 4]	(4, 5]	(5, 6]	(6, 7]	(7, 8]
scale	1	2	3	4	5	6	7	8	9
ΔRF	0	[−1, 0)	[−2, −1)	[−3, −2)	[−4, −3)	[−5, −4)	[−6, −5)	[−7, −6)	[−8, −7)
scale	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9

$$\boldsymbol{A}_2 = \begin{bmatrix} 1 & 3 \\ & 1 \end{bmatrix}$$

$$\boldsymbol{A}_3 = \begin{bmatrix} 1 & 1/3 & 2 \\ & 1 & 3 \\ & & 1 \end{bmatrix}$$

2) Determine the weight coefficient

The steps to determine the index weight coefficient by using the sum-product method are as follows [22]:

a) The elements of the judgment matrix $\boldsymbol{A}$ are normalized by columns to obtain the matrix $\boldsymbol{B} = \left(b_{ij}\right)_{n \times n}$

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}, \left(i, j = 1, 2, \cdots, n\right) \tag{9}$$

b) Summing the elements of matrix $\boldsymbol{B}$ by rows gives the vector $\boldsymbol{Z} = \left(z_1, z_2, \cdots, z_n\right)^{\mathrm{T}}$, among them,

$$z_i = \sum_{j=1}^{n} b_{ij}, \left(i, j = 1, 2, \cdots, n\right) \tag{10}$$

c) The vector $\boldsymbol{Z}$ is normalized to obtain the feature vector $\boldsymbol{W} = \left(w_1, w_2, \cdots, w_n\right)^{\mathrm{T}}$, among them,

$$w_i = \frac{z_i}{\sum_{k=1}^{n} z_k}, \left(i = 1, 2, \cdots, n\right) \tag{11}$$

To calculate $\boldsymbol{A}_1$, $\boldsymbol{A}_2$ and $\boldsymbol{A}_3$ Using the above method, we obtained the weights of "equipment inspection status, Inherent equipment reliability, vessel operating parameters, continuous driving time, speed, local weather, current road type "to the 'likelihood' indicators are: 0.1527, 0.0605, 0.2441, 0.2037, 0.1030, 0.1571, 0.0788. The weights of 'the property of the filling medium, filling capacity'" to the "severity" indicators are: 0.7500 and 0.2500. The weights of the "sensitive date, surrounding social environment and surrounding natural environment" to the "sensitivity" indicators are: 0.2519, 0.5889, and 0.1592.

3) Consistency check

For the consistency test of the judgment matrix, the maximum eigenvalue of the judgment matrix is calculated first, and then calculated the consistency index, n denotes the order of the judgment matrix.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{12}$$

If $CI = 0$, it indicates that the judgment matrix has full consistency; if $CI \neq 0$, the calculation of stochastic consistency ratio is required [23]

$$CR = \frac{CI}{RI} \tag{13}$$

where, RI is the average stochastic consistency index of the judgment matrix, and its value is related to the order of the matrix. If, $CR < 0.1$, then the consistency of the judgment matrix and the single-level ranking results is considered acceptable. The RI corresponding to the matrices of order 1 to 10 is shown in Table 8.

After calculation, the judgment matrix $\boldsymbol{A}_1$ corresponding to $CR = 0.0811 < 0.1$, the judgment matrix $\boldsymbol{A}_2$ corresponding to $CR = 0.0000 < 0.1$, the judgement matrix $\boldsymbol{A}_3$ corresponding to $CR = 0.0465 < 0.1$. All passed the consistency test.

Finally get:

1) Likelihood impact factor indicator weights $\omega_P = (0.1527, 0.0605, 0.2441, 0.2037, 0.1030, 0.1571, 0.0788)$.

2) Severity impact factorindicator weights $\omega_L = (0.7500, 0.2500)$.

3) Sensitivity impact factor index indicator weights $\omega_S = (0.2519, 0.5889, 0.1592)$.

5.2. Building a Risk Warning Model

Based on the equipment risk early warning theory model, index system and weights [24], the equipment risk early warning grading model can be obtained as shown below:

$$R = \sum_{i=1}^{n} d_i \omega_i \cdot \sum_{j=1}^{m} d_j \omega_j \cdot \sum_{k=1}^{l} d_k \omega_k$$

$$= \left[d_{P1}, d_{P2}, d_{P3}, d_{P4}, d_{P5}, d_{P6}, d_{P7}\right] \begin{bmatrix} 0.1527 \\ 0.0605 \\ 0.2441 \\ 0.2037 \\ 0.1030 \\ 0.1571 \\ 0.0788 \end{bmatrix} \cdot \left[d_{L1}, d_{L2}\right] \begin{bmatrix} 0.7500 \\ 0.2500 \end{bmatrix}$$

$$\cdot \left[d_{S1}, d_{S2}, d_{S3}\right] \begin{bmatrix} 0.2519 \\ 0.5889 \\ 0.1592 \end{bmatrix}$$

where: R—risk score value;

d—index score;

ω—indicators correspond to the weights.

After the risk value R is obtained through the risk model, the risk classification standard (Table 9) is determined according to the "80/20 rule", and the risk level of the equipment can be obtained [25].

6. Project Demonstration

The study used a long tube trailer as a case study for engineering justification

Table 8. The RI corresponding to the matrix of order 1 to 10.

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49

Table 9. Real-time risk warning classification standard for long-tube trailer.

Risk grade	Risk level IV (average risk)	Risk level III (Greater risk)	Risk level II (Significant risk)	Risk level I (Extraordinary risk)
Risk value R	1.0 - 8.0	8.0 - 15.6	15.6 - 27.0	27.0 - 64.0
Scale	20%	30%	30%	20%

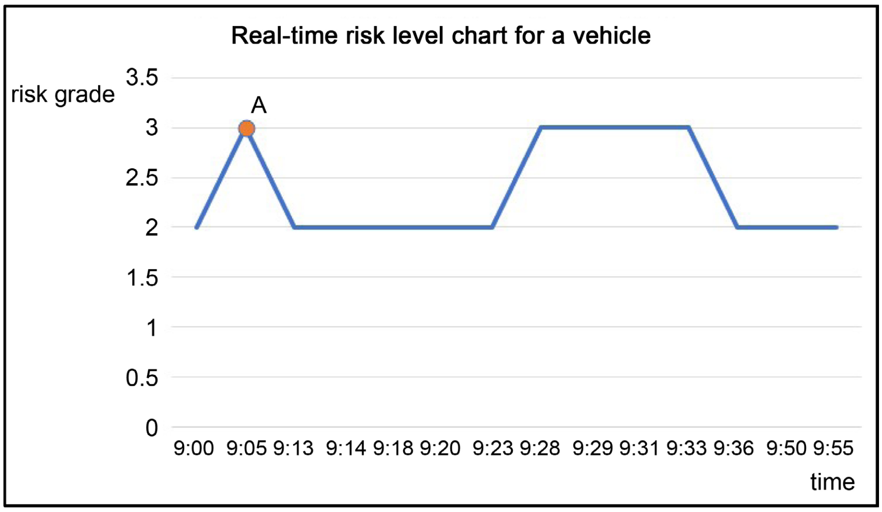

Figure 5. Real-time risk level diagram of a long tube trailer.

and obtained the real-time risk level of this long tube trailer as shown in Figure 5.

From the risk statistics chart we can see that the risk level of this long tube trailer increases at point A when it passes through the school area and decreases after leaving, so the risk level of the long-tube trailer during driving changes with the state of the long tube trailer itself, the driver's driving hours, the road conditions and the environment and so on.

7. Conclusions

1) Macro-safety risk index system was established from three dimensions: probability, severity and sensitivity by using cloud model methods, including 12 indicators: equipment inspection status, Inherent equipment reliability, vessel operating parameters, continuous driving time, speed, local weather, current road type, the property of the filling medium, filling capacity, sensitive date, surrounding social environment and surrounding natural environment.

2) The weight of the macro safety risk index of the long-tube trailer is determined, the macro safety risk calculation model is established, and a more comprehensive risk evaluation model and grading criteria with 12 evaluation indicators and 4 risk levels were obtained. It provides the theoretical basis and method

guidance for giving the safety risk management and response plan of pressure equipment from the perspective of supervision and realizing the precise and dynamic supervision of special equipment.

3) Automation and visualization are inevitable requirements for achieving precise supervision, and future research can incorporate safety state parameters such as driver fatigue that are not easy to obtain automatically into the model to improve the scientific of risk assessment.

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Declarations

Ethics Approval and Consent to Participate

This article does not contain any studies with human or animal subjects performed by any of the authors. All authors consent to participate.

Consent for Publication

All authors consent for publication.

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Authors' Contributions

Wenkun Wang: Literature review, Data collection and collation, Experiment, Indicator system and early warning model construction. Ming Xu: Data curation, Formal analysis, Guidance and modification. CaiYan Dai, ChengLong Ma, LianQing Yang: Data collection and collation, Experiment. All authors reviewed the manuscript.

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Competing Interests

There is no competing interest in this article.

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