# A survey on hazardous materials accidents during road transport in China from 2000 to 2008

Jie Yang[a,b], Fengying Li[a,c], Jingbo Zhou[b], Ling Zhang[a], Lei Huang[a,*], Jun Bi[a,*]

[a] State Key Laboratory of Pollution Control & Resources Reuse, School of the Environment, Nanjing University, Nanjing 210093, China
[b] School of Environmental Science and Engineering, Suzhou University of Science and Technology, Suzhou 215011, China
[c] School of Environment Science and Engineering, Nanjing University of Information Science & Technology, Nanjing 210044, China

## ARTICLE INFO

## ABSTRACT

A study of 322 accidents that occurred during the road transport of hazardous materials (hazmat) in China from 2000 to 2008 was carried out. The results showed an increase in the frequency of accidents from 2000 to 2007 and a decline in 2008. More than 63% of the accidents occurred in the eastern coastal areas, 25.5% in the central inland areas, and only 10.9% in the western remote areas. The most frequent types of accident were releases (84.5%), followed by gas clouds (13.0%), fires (10.2%), no substance released due to timely measures (9.9%), and explosions (5.9%). The spatial distribution, the causes and consequences of the accidents related to the population (e.g., number of people killed, injured, evacuated, or poisoned), and environment elements were analyzed. Finally, conclusions are drawn concerning the need to improve certain safety measures in the road transport of hazmat in China.

## 1. Introduction

In recent years, many accidents involving hazardous materials(hazmat) transport by road have caused catastrophic losses to humans and the environment in China. Such accidents have attracted increasing attention from the Chinese public, the government, and NGOs. Based on latest statistics, more attention should be given to the possibility of accidents. In addition, their potential severe consequences must be studied due to the dangerous properties of some chemicals transported by road, the high volume of road traffic, and the presence of populous residential areas in the vicinity of the accident site. Therefore, it is necessary to clarify the use of accident investigation practices among public safety authorities and organizations involved in this kind of high-risk activities. However, little extensive research has been carried out to depict the overall situation in China.

Road transport of hazmat has been a very active research area during the last 20 years, and there are three research areas related to the problem. First, several historical surveys of accidents have been carried out, revealing their features, such as distribution, origin, consequences, severity, and frequency, among others [1]. More researchers compared these features with those occurring in industrial installations [2–6], marine transportation [7,8], and seaports [9], to name a few. The results can help identifying main risk sources and most probable accidents, so as to reduce accident probabilities and mitigate the potential consequences. However, only few quantitative analyses on this kind of accident have been done in China. Second, in the context of hazmat transport by road, risk is taken as a measure of the probability and severity of harm from exposed receptors due to potential undesired events involving hazmat. Many related studies have focused on calculating probabilities [10] and risk magnitudes [11–13] or on minimizing transport risk in quantitative risk assessment (QRA) studies. Given that hazmat transport is a typical multi-objective problem involving different stakeholders, some scholars have discussed social and cultural influences on risk magnitude. For example, the concept of social amplification of risk [14,15], the individual and social perceptions of risk [16], and risk perception playing a role in emergency management [17] inaccuracies and inconsistencies in the communication process that lead to rumors and speculations on risk magnitude [18]. Finally, the prioritization of transportation routes has been widely investigated. Different path optimization models have been designed with consideration to the impact of different risk factors [19–22]. In addition, GIS map algebra techniques have been applied to the road network [23].

According to statistics, there is an annual average of 36 serious and social-impact accidents involving the road transport of hazmat in China. In order to reveal accident features and avoid damage as efficiently as possible, a study of 322 accidents from 2000 to 2008 in China was carried out. This paper aims to provide an updated survey on the situation in this field in China by analyzing road accidents, including their causes, consequences, severity,

* Corresponding authors at: No. 163 Xianlin Road, Room B308, School of Environment, Nanjing University, Xianlin Campus, Jiangsu 210046, China.
Tel.: +86 25 89680566; fax: +86 25 89680566.
E-mail addresses: huanglei@nju.edu.cn (L. Huang), jbi@nju.edu.cn (J. Bi).

and frequency. Based on the analysis of these data, preventive measures to reduce this frequency are also recommended.

## 2. Methodology

### 2.1. Accident information source

There are no public databases about major hazard incidents in China, unlike in the UK, which has the Major Hazard Incident Data Service (MHIDAS) managed by the Safety and Reliability Directorate (SRD); this is an agency under the control of the British Health and Safety Executive (HSE). Nevertheless, preliminary accident information (e.g., time, brief incidents, and source) in China, published in the *Journal of Safety and Environment* from 2000 to 2008, was used in this study. In addition, detailed information was gathered from the newspapers and the Internet. However, some accidents without sufficient information were excluded. Finally, 322 accidents were screened out as research subjects and stored in the database. For each accident, the following pieces of information were placed in the fields: source (i.e., name of the newspaper, internet web site, or other sources used), time, location, type of road, immediate causes of the accident (sequence of events that led to the accident), classification of substances (e.g., explosive, toxic, flammable, etc.) in accordance with the Chinese classification system [24], type of accident (time sequence of phenomena after the accident), type of pollution eventually caused, and severity.

### 2.2. Method

Statistical analysis was performed using two interrelated methods.

#### 2.2.1. Descriptive analysis

Descriptive analysis is the determination of conditional probability. In this method, the probability of the occurrence of an event is defined as the number of ways an event can occur, divided by the number of all possible results of observations.

#### 2.2.2. Societal risk and f–N curves

Accident fatality statistics can be used to obtain social risk curves using accumulated frequency/number of death (*f–N*) graphs; these *f–N* graphs [25] relate the number of deaths in a particular accident to the relative probability of that number. It is not possible to calculate the frequency (deaths/year) because information is not always available on all accidents that occurred. It must be assumed that the sample used is representative. As reported in previous studies [1,3,4,9,10], relative frequency can be estimated by assigning the value "1" to all accidents involving one death on the *y*-axis of the *f–N* representation. According to this analysis, we grouped
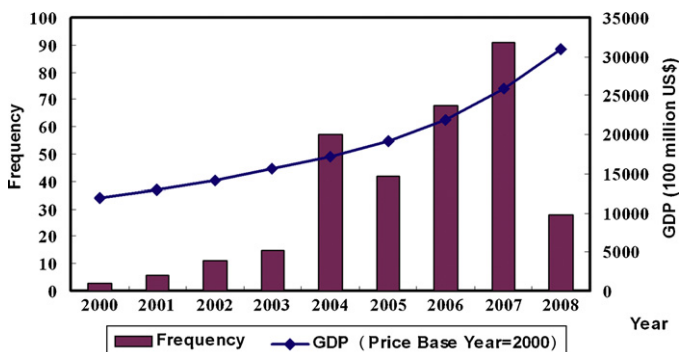
all accidents based on the number of fatalities and calculated the cumulative probability or frequency using the following equation:

$$P_{(x \geq N)} = F_j = \frac{\sum_{i=j}^{n} N_i}{\sum_{i=1}^{n} N_i}. \tag{1}$$

In the above, *N* is the number of deaths (*x*-axis), $P(x \geq N) = F_j$ is the probability of an accident with more than *N* deaths (*y*-axis), *n* represents the total amount of categories or rankings, and $N_i$ is the number of accidents in a given category *i*.

This method was also used to estimate the risk severity of people injured, evacuated, and poisoned.

## 3. Results and discussion

### 3.1. Distribution of the accidents over time

The accident frequencies increased from 2000 to 2007, with a significant rise in 2004 (Fig. 1). In addition, the road transport of hazmat increased significantly with GDP growth, which explains partly the current situation described in the preceding section. In the past, there were fewer accidents probably due to less coverage; at present, however, the number of accidents has increased, and this could be attributed to increasing number of reports. In relation to this, more efficient and comprehensive practices related to accident reporting should be taken into account because they could affect the aforementioned trend. A significant decline in 2008 has also been noted in terms of frequency. However, according to statistics, the number of hazmat-laden vehicles on highways increased every year from 2000 to 2008 with an average annual growth rate of 18.1% [26]. It indicated that safety measures were already taken and proved to be successful in China. In fact, China has experienced in several major environmental pollution accidents since 2004, the government has taken numerous measures to prevent and control such accidents.

### 3.2. Accident location

The locations of the accidents were characterized in terms of province, economic belt, and the type of road on which an accident occurred. Mainland China is usually divided into three areas in terms of geography and degree of development: the eastern coastal, central inland, and western remote areas. As can be seen, more than 63% of the accidents belong to the first category, 25.5% to the second, and only 10.9% to the third. Obviously, the greater volume of road transport of hazmat in more industrialized areas resulted in this kind of spatial distribution. Zhejiang (19.3%), Jiangsu (12.7%), and Guangdong (9.6%) are the provinces with the highest percentages of such accidents, while Chongqing is the province with the least number of road accidents (Fig. 2). Guizhou, Gansu, Ningxia, and Xinjiang also show lower accident frequencies, owing to the smaller scales of chemical industries found in these provinces. Meanwhile, no accidents occurred in the Hainan, Tibet and Qinghai Provinces, owing to the smaller scales of industries and freight road traffic existing in these regions. The spatial distribution of accident frequency and the average annual GDP (at 2000 prices) of the different provinces are shown in Fig. 2.

More than half of the accidents occurred on general roads (52.2%), followed by highways (39.4%), city roads (8.1%), and others (0.3%). However, the survey on accidents in 95 countries throughout the world indicated that most road accidents occur on highways (81.4%), followed by level crossings and minor roads (both with 7.6%), and tunnels (3.3%) [1]. Factors such as road condition, tolls, regulatory standards, and national regulations on the road transport of dangerous goods play roles in the different countries.
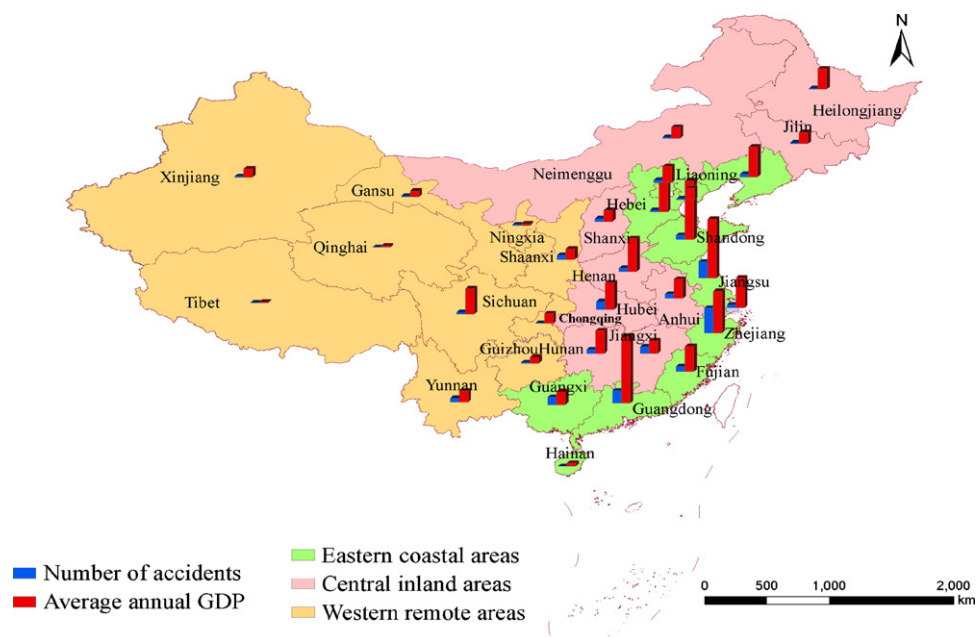


**Fig. 1.** Distribution of accidents as a function of time and GDP growth.

**Fig. 2.** Distribution of accidents and economic development in provinces.

## 3.3. Types of materials

The types of materials involved in the accident, based on the classification given by the National Institute of Standards-Classification and the Code of Dangerous Goods (GB 6944-2005) [24], were identified for 321 cases (99.7%). The distribution among the different categories is shown in Table 1.

To determine the type of hazard associated with a particular feature of a substance (e.g., toxicity, corrosion, flammability, etc.), a statistical analysis of incidents that involved at least one of the hazards was carried out. Since more than one of the hazards considered may be present in any given accident (e.g., 'flammable' and 'toxic' simultaneously), the sum of all these hazards could be higher than the number of entries (i.e., the sum of the percentages will be greater than 100). The values thus obtained are shown in Table 1. One of the hazards, toxicity, was present in 12.1% of the cases; flammable substances were involved in almost 53.3% of the accidents; corrosive substances were in 29.6% of cases, and oxidation in 1.9%. The table thus shows that flammable substances and corrosive materials account for the majority of hazmat accidents in China.

## 3.4. Causes of accidents

Four categories of possible causes were taken into consideration (i.e., external events, management factors, mechanical and equipment failure, driver error). According to the analysis, 60.6% of road accidents were caused by some driver error (which often shows an impact or collision between vehicles). The next set of most common causes consisted of various types of mechanical and equipment failure (31.4%) and management factors (20.2%), comprising up to 40% of the listed road accidents. The percentages of the remaining causes show that the latter are quite relevant (12.4%). As seen in Table 2, one or several specific causes can be identified among the majority of the general categories. A great variety of causes is present in the mechanical failure category, which is why the "Others" section has a high percentage (13.2%). Finally, for the management factor category, the percentage for "communication" (16.1%) is also quite high, indicating that there is a great variety of specific problems in the process of risk communication among stockholders.

Of the total of 322 accidents, the most frequent initial event (general cause and specific cause) is driver error-road accident, which has a frequency of 46.6%, followed by driver error-improper emergency response (13.7%) and management failure-overloading (9.0%).

According to the statistics, human-related causes account for 72.7%, followed by vehicles and equipment-related causes (31.4%), road conditions-related causes (5.6%), and weather-related causes (6.8%). Hence, human factors are the most common causes of accidents.

A country or region's social, political, economic, cultural, educational, as well as scientific and technical factors lead to human errors that cause road accidents. In addition, poor supervision of social factors (e.g., laws and regulations, educational training, management organization, infrastructures, and so on) leads to the occurrence of road accidents involving hazmat in China mainly.

Based on the previous analysis, 60.6% of accidents were initiated by driver errors (i.e., traffic accidents) and that most hazmat accidents occurred in general roads were caused by traffic accidents. Therefore, improving the maintenance of lorries and equipment, road conditions, and training of relevant staff must be done to minimize the occurrence of road accidents.

Management factors are the more significant causes of road accidents, with overloading (29 accidents) and illegal transport (28 accidents) contributing greatly to the management failure factor. These should be given more attention in future studies. A critical step is to strengthen law enforcement and supervision, and improve risk management. Another recommendation is for stakeholders, such as the government, transport companies and drivers,

**Table 1**
Risks associated with the types of materials.

| Hazmat | Number of accidents related to the types of materials | % of known risks |
|---|---|---|
| Toxic | 39 | 12.1 |
| Flammable | 171 | 53.3 |
| Oxidizing | 6 | 1.9 |
| Corrosive | 95 | 29.6 |
| Other | 17 | 5.3 |

**Table 2**
Specific causes of accidents.

| General cause | Specific cause | Number of accidents | Percentage of category (%) | Percentage of total accidents (%) |
|---|---|---|---|---|
| External (12.4%) | Poor road conditions | 18 | 45.0 | 5.6 |
| | Bad weather conditions | 22 | 55.0 | 6.8 |
| Management failure (20.2%) | Overloading | 29 | 33.3 | 9.0 |
| | Illegal transport | 28 | 32.2 | 8.7 |
| | Storage equipment failure | 11 | 12.6 | 3.4 |
| | Entering into an area where passage of vehicles with dangerous goods is forbidden | 3 | 3.4 | 0.9 |
| | Communication failure | 14 | 16.1 | 4.3 |
| | Others | 2 | 2.3 | 0.6 |
| Mechanical and equipment failure (31.4%) | Burst tires | 19 | 17.9 | 5.9 |
| | Brake system failure | 16 | 15.1 | 5.0 |
| | Barrels or cans cracking or dumping | 24 | 22.6 | 7.5 |
| | Tank valve failure | 16 | 15.1 | 5.0 |
| | Illegal use (e.g., no special qualifications or legal formality, failure to undergo annual check-up, etc.) | 11 | 10.4 | 3.4 |
| | Wheel failure | 6 | 5.7 | 1.9 |
| | Others | 14 | 13.2 | 4.3 |
| Driver error (60.6%) | Speeding | 19 | 7.7 | 5.9 |
| | Misoperation | 20 | 8.1 | 6.2 |
| | Road accident | 150 | 60.5 | 46.6 |
| | Fatigued driving | 12 | 4.8 | 3.7 |
| | Improper emergency response | 44 | 17.7 | 13.7 |
| | Others | 3 | 1.2 | 0.9 |

to consolidate their efforts in organizing, planning, implementing, and monitoring the road transport of hazmat in order to minimize the environmental risks of such accidents. It should be emphasized that the establishment of an effective emergency planning and optimisation are very essential, based on the risk assessment, to minimize the magnitude and to prevent escalation of the accident. In case of accident in hazmat transportation and subsequent release into the environment, it is very important to have at one's disposal information on each chemical hazardous product involved, trained and skilful personnel, and suitable 'prompt action vehicles', properly equipped to be employed if the hazardous release would happen [27].

### 3.5. Types of accidents

Accidents are classified into five different incidence types: no substance released due to timely measures, release, fire, explosion, and gas cloud. Each accident may fall under one or more of these types (Table 3). The total percentages add up to more than 100% because a particular accident may, strictly speaking, be placed under more than one category. For example, an accident might consist of a release that then causes an explosion, or a release might give rise to an explosion followed by a fire. As a matter of fact, most accidents do start with release.

Based on the data, the general event tree shown in Fig. 3 was obtained. The figures in square brackets represent the probability

**Table 3**
Types of accidents.

| Type | Number of entries | % of total |
|---|---|---|
| Releases | 272 | 84.5 |
| Gas cloud | 42 | 13.0 |
| Fire | 33 | 10.2 |
| No substance released due to timely measures | 32 | 9.9 |
| Explosions | 19 | 5.9 |
| Total | 398 | 123.6 |

that a particular type is involved in an accident, in comparison with the one at the level immediately above it (the probability refers to the ratio of the number of accidents at the lower level to that at the higher level). The figures at the end of each branch show the overall probability of occurrence of each specific accident compared with the entire set sequences [1].

With reference to the results, the following observations can be made. These are listed below.

(1) The percentage of release cases without further events (fire, explosion) is highest at 64.3%; this is followed by release-gas cloud sequences (12.1%), release-fire sequences (4.35%), and release-fire-explosion sequences (1.24%). Immediate explosions after a release occur in 1.55% of cases. Therefore, 1 out of every 19.4 releases results in a fire, 1 out of every 4.5 release-fire events causes an explosion, and 1 out of every 7.0 releases results in a gas cloud. The release-gas cloud-fire sequence occurs once for every 14 times that a release-gas cloud sequence occurs.
(2) Fires (all types and sequences) exist in 10.2% of cases. However, in the general set of accidents, only 1 out of every 6 fires results in an explosion.
(3) Considering all the events in Fig. 3, 1 out of every 16.9 accidents leads to an explosion; 1 out of every 9.8 accidents results in a fire; and more specifically, 1 out of every 40.2 accidents results in a fire-explosion.

Comparing these results with the findings obtained by Oggero et al. in a previous study on road transport accidents [1], the probabilities of accidents leading to an explosion, fire, and fire-explosion are found to be much lower in China, although flammable substances are the most common features of road accidents involving hazmat. In addition, driver error-road accident is the most common event, often resulting in damaged tanks (Table 2). As a result of the implementation of appropriate emergency measures (e.g., timely stalling and plugging a leak), hazardous materials are released without leading to fires or explosions.
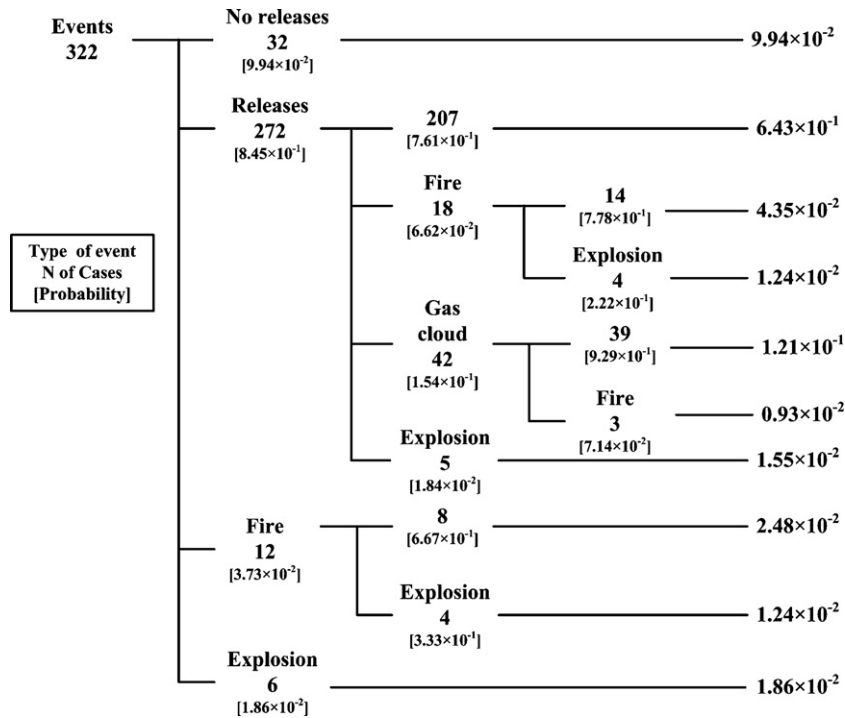
**Fig. 3.** General event tree and relative probabilities of occurrence.

### 3.6. Population affected by road accidents

The populations affected by the road accidents were expressed by four variables according to the scale of the consequences: number of deaths, number of the injured, number of the evacuated and number of the poisoned.

#### 3.6.1. Number of deaths

Most road accidents (>86%) are not considered fatal, with the total number of deaths reaching 127. Of those that did cause fatalities, a very high percentage (almost 91.1%) involved 1–5 deaths; 6.67% involved 6–25 deaths; and only 1 involved more than 25 deaths.

We used Eq. (1) to calculate the cumulative probability or frequency of the number of deaths. The probability obtained can be seen in Fig. 4. For $1 < N < 30$, the best fit (minimum square method) for a curve of type $P = N^b$ gave $b = -0.988$. A straight line with a slope of $-0.988$ was obtained by plotting the data on a log–log axis system. This indicates that the probability of an accident involving 10 or more deaths is 3.0 times greater than that of an accident involving 30 or more deaths.
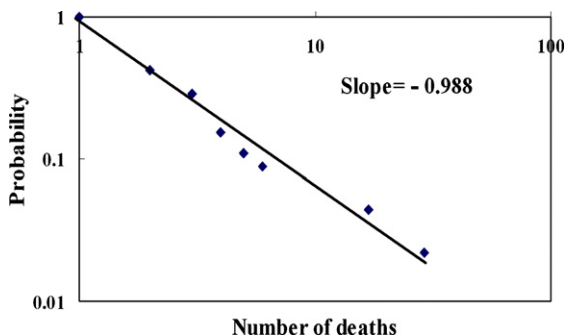
The same plot for accidents in the transport of hazmat gave a lower value of $-0.81$ [1]. Fryer and Griffiths obtained lower gradient values of between $-0.4$ and $-0.7$ for natural disasters (e.g., earthquakes, floods, etc.), and higher slopes ranging between $-1.0$ and $-1.1$ for explosions, fires, and marine and mining accidents between 1946 and 1975 [28].

#### 3.6.2. Number of people injured

As in the previous section, the number of people injured (287) was grouped into several categories (*no injuries*, *1–5*, *6–40*, and *over 40*). Injuries were not involved in 67.4% of the accidents; in 95.2% of the remaining cases, between 1 and 5 people were injured. Only one accident caused more than 40 injuries.

The cumulative probability of the number of injuries was derived using Eq. (1). The results are shown in Fig. 5. For $1 < N < 50$, the best fit (minimum square method) for a curve of type $P = N^b$ gave $b = -0.974$. A straight line with a slope of $-0.974$ was obtained by plotting the data on a log–log axis system. This indicates that the probability of an accident involving 10 or more injuries is 4.8 times greater than that of an accident involving 50 or more injuries.
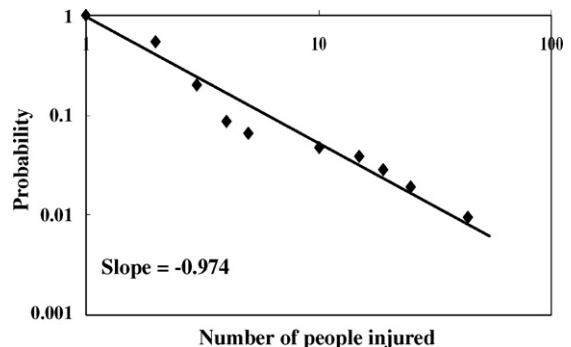


**Fig. 4.** Accumulated probability of an accident with $N$ deaths.



**Fig. 5.** Accumulated probability of an accident with $N$ injuries.

**Table 4**
Environmental elements affected by the accidents.

| Environmental elements | Water pollution | Air pollution | Soil pollution | Biological damage |
| --- | --- | --- | --- | --- |
| Number of accidents | 89 | 228 | 41 | 87 |
| % of total | 27.6 | 70.8 | 12.7 | 27.0 |

### 3.6.3. Number of people evacuated

Of the 322 accidents, 290 involved no evacuations; 3 involved the evacuation of 1 to10 people; 7 involved between 11 and 100 people; 10 involved between 101 and 1000 people; 8 accidents involved between 1001 and 7000 people; and 4 involved more than 10,000 people. A total of 79,802 people were evacuated.

The cumulative probability of the number of evacuees obtained for the accidents can be seen in Fig. 6. For $1 < N < 10,000$, the best fit (minimum square method) for a curve of type $P = N^b$ gave $b = -0.928$. A straight line with a slope of $-0.928$ was obtained by plotting the data on a log–log axis system. This indicates that the probability of an accident involving 100 or more evacuees was 8.5 times greater than that of an accident involving 1000 or more evacuees.

### 3.6.4. Number of people poisoned

In all, 556 people were affected by significant symptoms of poisoning in 322 accidents. A huge majority (97.2%) of the accidents did not involve symptoms of poisoning; in 2.2% of the accidents, between 1 and 15 people were poisoned. In only one accident was more than 300 people poisoned. The cumulative probability of the number of people who have been poisoned can be seen in Fig. 7. For $1 < N < 400$, the best fit (minimum square method) for a curve of type $P = N^b$ gave $b = -0.944$. A straight line with a slope of $-0.944$ was obtained by plotting the data on a log–log axis system. This indicates that the probability of an accident involving 10 or more people poisoned is 8.8 times greater than that of an accident involving 100 or more people poisoned.
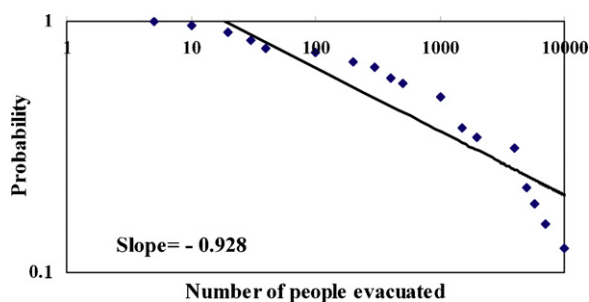


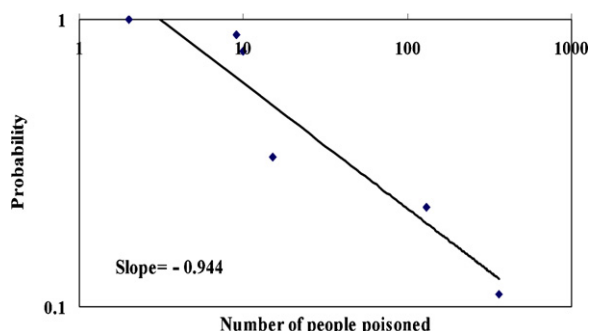**Fig. 6.** Accumulated probability of an accident with $N$ evacuees.



**Fig. 7.** Accumulated probability of an accident with $N$ people poisoned.

### 3.7. Environmental elements affected by the accidents

The environmental effects of road accidents were divided among four categories based on the type of environmental element affected: water pollution, air pollution, soil pollution, and biological damage. Given that more than one of the environmental elements may be affected in one accident (e.g., 'water pollution' and 'air pollution' simultaneously), the sum of all the environmental elements may be higher than the number of entries (i.e., the sum of the percentages will be greater than 100). The values thus obtained are shown in Table 4. Of the total number of accidents, 27.6% involve water pollution, and among these, 18 accidents involve the pollution of drinking water sources. The figure also shows that air pollution accounts for the bulk of the negative environmental effects of road accidents in China, followed by water pollution and biological damage.

## 4. Conclusions

Of the total number of accidents found, more than 63% of road accidents occurred in the eastern coastal areas, 25.5% in the central inland areas, and only 10.9% in the western remote areas. Zhejiang (19.3%), Jiangsu (12.7%), and Guangdong (9.6%) had the highest percentages of accidents.

According to the event tree, the most frequent phenomenon without further consequences is release, which is observed in 64.3% of cases, followed by gas cloud without further consequences (12.1%). However, as one phenomenon is often followed by another, the following pieces of information are probably more significant: the most frequent sequence is a release followed by a gas cloud (15.4%), a fire (6.6%) and an explosion (1.8%). Approximately 1 out of every 16.9 accidents leads to an explosion, 1 out of every 9.8 accidents leads to a fire, and 1 out of every 40.2 accidents leads to a fire and an explosion.

Of the total 322 accidents, the most frequent initial event (general cause and specific cause) is driver error-road accident (46.6%), followed by driver error-improper emergency response (13.7%), and then by management failure-overloading at 9.0%.

Road accidents can be analyzed in terms of the number of deaths and injuries, as well as the number of people who were evacuated and poisoned. First, more than 86% of the accidents did not lead to any fatality, and majority of those accidents causing fatalities involve 1–5 deaths. The probability/frequency curve has a gradient of −0.988 for accidents involving fatalities. Second, more than 67% of the accidents did not involve any injury, while most of the remaining accidents involve 1–5 injuries. The probability/frequency curve has a gradient of –0.974 for accidents leading to injury. Third, in the case of an evacuation (which would have been rather unusual), the number of people involved would usually be less than 1000 (62.5%). Only in four cases are there more than 10,000 evacuees. The probability/frequency curve in this case has a gradient of −0.928. Finally, in the case of poisoning, the number of people involved is usually between 1 and 15 (77.8%). The probability/frequency curve in this scenario has a gradient of −0.944.

Finally, air pollution accounts for the majority of accidents of road transport of hazmat in China, followed by water pollution and biological damage. Thus, the consequences of the road accidents are more serious for the environment than on humans.

It must be explained that there were some difficulties in carrying out the survey, mainly due to the subpar quality of available information. For the statistical studies to be more reliable, a more selective and perfect database is required. This database should be built and managed by public safety authorities. It should perform the function of recording data pertaining to the fields, such as risk source, failure of control and preventive measures, receptor sensitivity parameters, and consequence data (i.e., type and magnitude of impact of population and environmental quality). And there is clearly a need to improve the statistical analysis.

## Acknowledgements

## References

[1] A. Oggero, R.M. Darbra, M. Muñoz, E. Planas, J. Casal, A survey of accidents occurring during the transport of hazardous substances by road and rail, J. Hazard. Mater. A133 (2006) 1–7.

[2] P. Haastrup, H. Rømer, An analysis of the database coverage of industrial accidents involving hazardous materials in Europe, J. Loss Prey. Process Ind. 8 (1995) 79–86.

[3] J.A. Vilchez, S. Sevilla, H. Montiel, J. Casal, Historical analysis of accidents in chemical plants and in the transportation of hazardous materials, J. Loss Prey. Process Ind. 8 (1995) 87–96.

[4] E. Planas-Cuchi, H. Montiel, J. Casal, A Survey of the origin, type and consequences of fire accidents in process plants and in the transportation of hazardous materials, Process Saf. Environ. Prot. 75 (1997) 3–8.

[5] T. Sverre Roed-Larsen, L. Valvisto, C. Harms-Ringdahl, Kirchsteiger, Accident investigation practices in Europe—main responses from a recent study of accidents in industry and transport, J. Hazard. Mater. 111 (2004) 7–12.

[6] S.-E. Andersson, Safe transport of dangerous goods: road, rail or sea? A screening of technical and administrative factors, Eur. J. Oper. Res. 75 (1994) 499–507.

[7] H Rømer, P. Haastrup, H.J. Styhr Petersen, Accidents during marine transport of dangerous goods. Distribution of fatalities, J. Loss Prev. Process Ind. 8 (1995) 29–34.

[8] H. Rømer, L. Brockhoff, P. Haastrup, H.J. Styhr Petersen, Marine transport of dangerous goods. Risks assessment based on historical accident data, J. Loss Prev. Process Ind. 6 (1993) 219–225.

[9] R.M. Darbra, J. Casal, Historical analysis of accidents in seaports, Saf. Sci. 42 (2004) 85–98.

[10] A. Ronza, J.A. Vïlchez, J. Casal, Using transportation accident databases to investigate ignition and explosion probabilities of flammable spills, J. Hazard. Mater. 146 (2007) 106–123.

[11] E. Erkut, V. Verter, A framework for hazardous materials transport risk assessment, Risk Anal. 15 (1995) 589–601.

[12] T.S. Glickman, M.A. Sontag, The tradeoffs associated with re-routing highway shipments of hazardous materials to minimize risk, Risk Anal. 15 (1995) 61–67.

[13] E. Erkut, T. Glickman, Minimax population exposure in routing highway shipments of hazardous materials, J. Transport. Res. Board 1602 (1997) 93–100.

[14] R.E. Kasperson, O. Renn, P. Slovic, H.S. Brown, J. Emel, R. Goble, J.S. Kasperson, S. Ratick, The social amplification of risk: a conceptual framework, Risk Anal. 8 (1988) 177–187.

[15] O. Renn, W.J. Burns, J.X. Kasperson, R.E. Kasperson, P. Slovic, The social amplification of risk: theoretical foundations and empirical applications, J. Soc. Issues 48 (1992) 137–160.

[16] T. Horlick-Jones, Modern disasters as outrage and betrayal, Int. J. Mass Emerg. Disasters 13 (1995) 305–315.

[17] L. Pezzullo, R. De Filippo, Perceptions of industrial risk and emergency management procedures in Hazmat Logistics: a qualitative mental model approach, Saf. Sci. 47 (2009) 537–541.

[18] P. Barnes, Regulating safety in an unsafe world (risk reduction for and with communities), J. Hazard. Mater. 86 (2001) 25–37.

[19] P. Leonelli, S. Bonvicini, G. Spadoni, Hazardous materials transportation: a risk-analysis-based routing methodology, J. Hazard. Mater. 71 (2000) 283–300.

[20] B. Fabiano, F. Currò, E. Palazzi, R. Pastorino, A framework for risk assessment and decision-making strategies in dangerous good transportation, J. Hazard. Mater. 93 (2002) 1–15.

[21] E. Erkut, A. Ingolfsson, Transport risk models for hazardous materials: revisited, Oper. Res. Lett. 33 (2005) 81–89.

[22] V. Akgün, A. Parekh, R. Batta, C.M. Rump, Routing of a hazmat truck in the presence of weather systems, Comput. Oper. Res. 34 (2007) 1351–1373.

[23] J. Zhang, J. Hodgsen, E. Erkut, Using GIS to assess the risks of hazardous materials transport in networks, Eur. J. Oper. Res. 121 (2000) 316–329.

[24] Classification and code of dangerous goods (GB 6944-2005), Implementation Date: November 1, 2005.

[25] P. Haastrup, L. Brockhoff, Severity of accidents with hazardous materials: a comparison between transportation and fixed installations, J. Loss Prev. Process Ind. 3 (1990) 395–405.

[26] National Bureau of Statistics of China, China Statistical Yearbook (2001–2009), China Statistics Press, Beijing, 2001–2009.

[27] B. Fabiano, F. Currò, A.P. Reverberi, R. Pastorino, Dangerous good transportation by road: from risk analysis to emergency planning, J. Loss Prev. Process Ind. 18 (2005) 403–413.

[28] L.S. Fryer, R.F. Griffiths, Worldwide data on the incidence of multiple fatalities accidents, Saf. Reliability Directorate 149 (1979).