Hindawi
Mathematical Problems in Engineering
Volume 2022, Article ID 6162829, 14 pages
https://doi.org/10.1155/2022/6162829

Research Article

Quantitative Risk Analysis on Rail Transportation of Hazardous Materials

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Received 19 May 2021; Revised 11 September 2021; Accepted 24 December 2021; Published 8 March 2022

Academic Editor: Alessandro Della Corte

The hazardous nature of the chemical materials is of significant concern in the economic viability of rail transportation globally. The potential risks of these materials to cause severe health impairments and catastrophic accidents have been widely studied and reported. Moreover, several models have been employed for assessing the risks associated with transporting hazardous materials by rail. However, a more holistic, quantitative, and robust model should incorporate more potential risk-triggered criteria, especially those causing severe health loss and devastating consequences like vapor cloud explosion. This study develops a risk assessment model by incorporating potential health risk factors and the obstacle circumstances. The potential risk factors are population density, route distance from residential areas, and the availability of sensitive third parties for health consequences. The proposed model utilizes Bayesian networks for causality modeling of the material release scenarios and fuzzy set theory for estimating the health effects and severity impact coefficient. Finally, individual risk curves and safe distances from the railway are developed. A real rail system for gasoline transportation in Tehran is investigated to evaluate the model's effectiveness. The study provides panoramic leverages for risk-managed decision-making for safely transporting hazardous material by rail.

1. Introduction

Rail transport is an effective mode for transporting materials, with an estimate of about a million shipments conducted annually in the USA [1]. Statistical data show that 10% of all materials were transported via a railway network in 2014 in Iran [2]. Despite the lower share of the rail network in materials' transportation, statistical data show that a significant percentage of hazardous chemicals is transported using this network [3, 4].

Annually, consignments consisting of petroleum products and other hazardous materials result in accidents at localities whose level of emergency preparedness is next to nothing [5, 6]. Although rail accidents rarely occur, they are more severe than road accidents, mainly due to the high volume of the hazardous materials transported [7]. For example, a postcollision train crash of Graniteville, USA, in January 2005 resulted in over 100 casualties, displacement of about 5400 populated a residential area, and loss of $ 6.9 million worth of economic ventures [8]. Also, the Neyshabur accident in Iran in 2004 is one of the biggest railway accidents related to the transportation of chemicals, in which railway wagons carrying a load of dangerous goods exploded. The accident killed more than 720 people and destroyed residential areas within a radius of 10 km [9].

A practical and effective technique of managing accidents in railway networks globally should involve timely identification, assessment, and evaluation of potential hazards and the attendant risks [1]. In addition, such a technique should have the capability to effectively reduce the probability of occurrence [7]. The Federal Railroad Administration (FRA) has attempted to categorize rail accidents according to the significant causative factors such as the track, equipment, human, signals, and other causes [10]. Several techniques such as the conventional risk assessment [10–12], human error analysis [13], optimal routing [14], economic impact assessment [15], environmental impacts [16], and accident statistical analysis [10, 17, 18] have been deployed through various studies to identify the major causative factors of rail accidents.

Previous studies have shown that the quantitative risk analysis (QRA) approach can be used as a reliable and high-precision technique for determining safety zones on transportation routes [19–21] and hazardous material storages [22, 23]. For example, Ahmadi et al. used the new Fuzzy-Bayesian network approach for risk assessment in the process industries [24]. The work of Gooijer et al. also used a new quantitative risk assessment approach to determine the safe construction distance around the process industries [25]. Gonzalez Dan et al. used the Monte Carlo simulation method to assess the quantitative risk of human error in the process industries [26]. Moreover, Guo et al. used the Copula-based Bayesian network (BN) technique to investigate the fault tree analysis (FT) uncertainty for the examination of quantitative risk in process systems [27]. In addition, the new fuzzy approach was used by Miri Lavasani et al. to assess the oil and gas industries [28]. Dormohammadi et al. used the QRA approach to model the potential safety risks and consequences of LPG [23]. Other recent QRA studies were on hydrogen release [29, 30] and the dynamic QRA on hydrogen infrastructure [31].

However, new fuzzy-based approaches have shown enhanced integrity and support for various aspects of risk assessment. For instance, Li et al. used the Fuzzy-BN approach to assess the risk of road transport conveying combustible materials [32]. Moreover, in the field of fuzzy inferences and fuzzy analytical hierarchy process (FAHP), An et al. [33] evaluated the quantitative risk of the railway network. Furthermore, a quantitative risk assessment approach was employed by Hassan et al. to assess the risk of ammonium transportation in the rail network [34]. Leitner assessed the risk of rail transportation in the field of scenario-based assessment [35]. However, for the modeling-based risk assessment approach, Paltrinieri et al. assessed the quantitative risk of the dangerous goods transported through railway routes [36]. Furthermore, Zhang et al. used a quantitative approach to determine critical nodes in railway routes [37].

Generally, both the semiquantitative and qualitative methods have been widely applied; however, they are plagued by a poor level of accuracy [38]. Conversely, quantitative methods are more valid due to the low level of uncertainty [39–43]. More often than none for accurate modeling [20, 37], the quantitative risk assessment of the rail network is usually based on equipment failures [33, 44] and human error [45–47]. The Bayesian network is one of the new methods in risk assessment, which is widely used due to its ability to interrelate the nonlinear relationships between parameters and, as a result, enhance the level of computational accuracy [48]. Meanwhile, conventional applications of BN have been criticized for employing crisp probabilities in assessing uncertainty; assigning fuzzy probabilities in BN has been found to produce more accurate findings in risk and safety analysis of critical systems [49, 50]. Providentially, a robust assessment of the potential health hazards with the attendant risks could be reliably achieved with high accuracy by imbibing in the assessment tool the effects of the causative agents viz-a-viz population density, distance from residential zones, and the critical points. Therefore, this current study presents a comprehensive and quantitative BN-fuzzy set theory (BN-FST) risk assessment tool for modeling the transportation of petroleum via railway networks under uncertainty. The specific research objectives are fashioned as follows: (i) determining the probability of chemical leakage from trucks, (ii) describing the leakage process and emission of materials using equations, and (iii) modeling the health and safety effects of chemical leakage.

The paper proceeds as follows. In Section 2, the proposed methodology and the case study are fully described and demonstrated, findings are presented in Section 3, and, finally, the discussion and conclusion are provided in Sections 4 and 5, respectively.

2. Materials and Methods

The proposed methodology in the present study is illustrated in Figure 1. The occurrence probability of chemical material release and the potential consequences are predicted under uncertainty in the first step. Concurrently, the severity of the latter is being estimated as described in the next step. After that a severity impact coefficient (SIC) is defined to modify the estimated health risk for the critical points in the case study. Finally, individual health and explosion risks are estimated. Each of these steps is explained in the following sections.

2.1. Estimating the Probability of Consequences

2.1.1. The Causes-Consequences Modeling. The cause-consequences analysis of material leakage from rail cars is performed at the initial step using the Bowtie (BT) method. This method is suitable for identifying the effects of causes on the occurrence of events and how events turn into consequences by considering the effects of safety barriers [51]. This method is closely linked to Event Tree Analysis (ET) and FT methods [52]. At the onset, the views of safety experts on specific issues about the history of by rail accidents with chemical materials consignments are collected and collated. These views help identify primary and intermediate events causing the leakage from the rail cars. It also provides some data on the possibility of each event per year. In this process, the opinions of 20 safety and railway experts are employed, and finally, the quantitative probabilities are

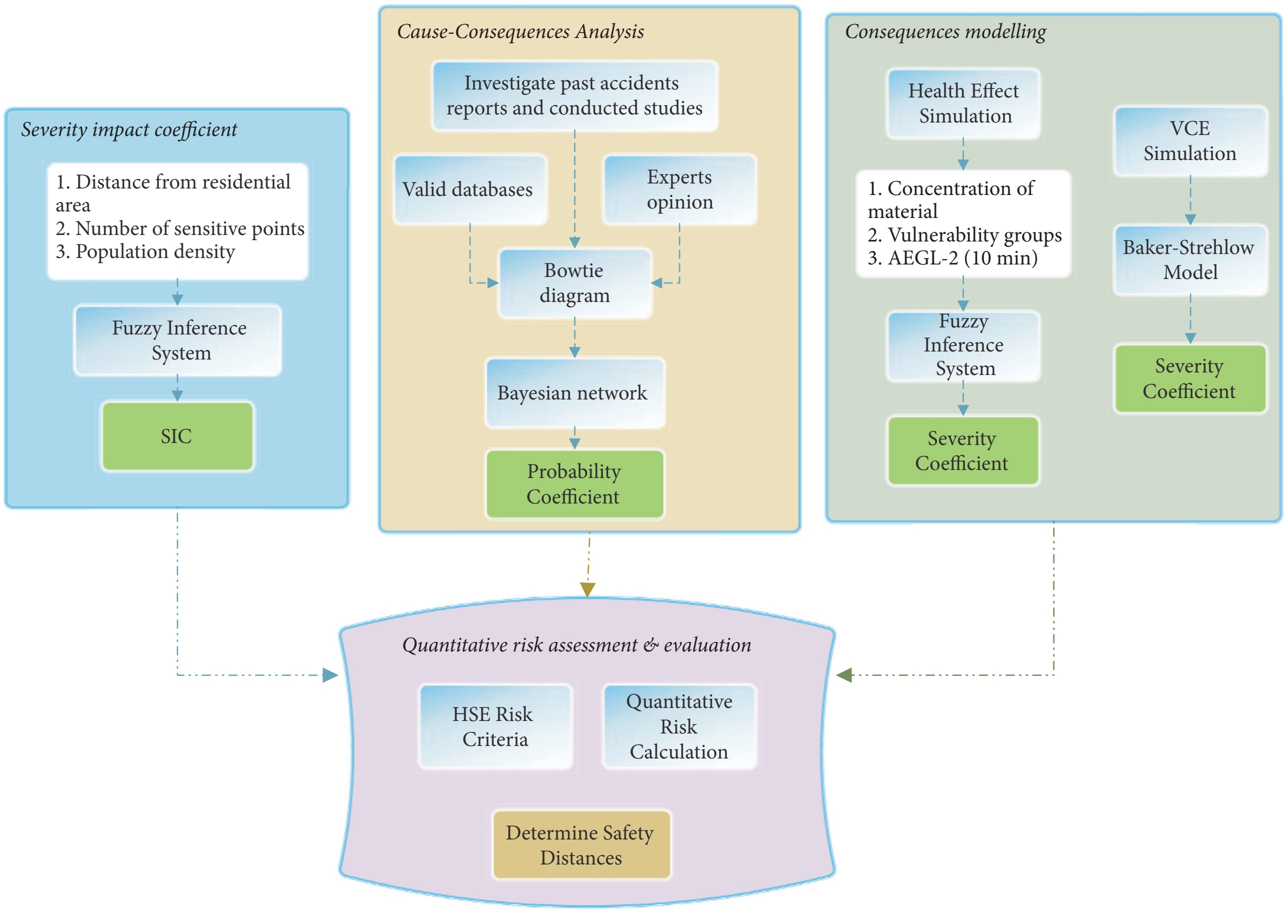

Figure 1: The proposed framework to quantitative risk analysis of hazardous material transportation.

calculated using the FAHP method. Given the prevalent conditions of time and location of the incidence, the probable factors of occurrence, types, and probability of consequences can be deduced. Figure 1 depicts the causes of events on the left and the outcomes on the right [53, 54].

2.1.2. Bayesian Network Modeling. BN was applied to quantitative modeling of cause-effect scenarios under uncertainty [6]. This study performed the BN analysis because it provides a noncyclic graph that presents a set of random variables. The associations between them are assessed using conditional probability tables (CPT). Nodes (random variables) and arcs (possible relationships) form the basis of this network, whose main task is to display nonlinear relationships between parameters. Bayes theory is the main foundation of this network, and it is presented in Equation (1). In this equation, A and B are events and $P(B) \neq 0$; moreover, $P(A|B)$ is the probability of A occurring when B is true, and also, $P(B|A)$ is the probability of B occurring when A is true. In the same vein, $P(A)$ and $P(B)$ are likelihood of A and B, which is known as marginal probability. In addition, this network is applied to determine the most concrete outcomes of leakage; and to this end, material leakage (TE) as the evidence node and the essential items influencing leakage are selected [43, 55–57]:

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}. \tag{1}$$

2.2. Estimating the Severity of Consequences

2.2.1. Modeling of VCE. The Baker-Strehlow (BS) method simulated vapor cloud explosion (VCE) of petroleum products' leakage from the rail cars. The BS method was first introduced in a 1996 paper by Baker et al. [58] and was developed based on obstructed regions. According to recent studies, this method is more accurate than other models (such as multienergy and TNT methods) [59]. The main reason for selecting BS is its capability to assess the explosion pressure using all the factors influencing overpressure and flame propagation speed [4]. This consequently leads to the determination of the explosion blast intensity by assessing the propagating of the flame front, fuel reactivity, and obstacle density. Accordingly, the BS method can determine cloud dimensions and evaluate the energy of the explosion. This method is applied in the next step to measure the overpressure as a function of the scaled distance using flame speed as an effective parameter as suggested by [60].

The vapor cloud can be estimated from the leaked liquid state (flammable liquid pool). The quantity of vapor forming the vapor cloud is the product of the liquid's evaporation rate and the time of inflammable, which is the time span between the leakages and the explosion. It should be noted that the simulation calculations are performed based on 80% leakage. First, taking into account the weight of the material leaking from the reservoir, the density of the vapor of the material, and the material to oxygen molecular ratio (based on the chemical reaction of combustion), the volume of vapor of the leaked material is calculated using the following equation:

$$V\left(m^3\right) = \left(\frac{m}{\rho}\right)R, \tag{2}$$

where m is the weight of the material leaked from the reservoir (kg), ρ is the density of the vapor of the material (kg/m$^{\text{vl}}$), and R is the material to molecular oxygen ratio. The cloud radius, R (m), is obtained from the cloud volume V (m^3), considered that a hemisphere is calculated using the following equation:

$$R = \left(\frac{3v}{2\pi}\right)^{1/3}. \tag{3}$$

From the reference tables [60], the flame speed (Mj) is calculated based on the flame expansion (1D, 2D, or 3D), fuel reactivity (high, medium, or low reactivity), and obstacle density. For example, when the flame is free to expand in three dimensions, the reactivity of the material is considered to be high, and the density of obstacles is medium. The flame speed is then equal to 0.153 Mj. Conversely, the scaled distance (r′) is calculated using the following equation:

$$r' = x\left(\frac{E}{P_a}\right)^{-\left(\frac{1}{3}\right)}, \tag{4}$$

where P_a (MP$_a$) is the ambient pressure (= 0.1 MPa), and x (m) is the distance from the center of the explosion. Using combustion heat ΔHc (MJ/kg), cloud volume V (m^3), density ρ_{m} (kg/m^3), and reaction stoichiometry ratio of material to oxygen (R), the energy of the explosion E (MJ) is E (MJ) is the total energy of the explosion is calculated using the following equation:

$$E = V\left[\Delta H_c \times \rho \times \left(\frac{1}{R}\right)\right]. \tag{5}$$

Finally, considering the scaled distance (r′), flame speed (Mj), and reference diagrams, the size of explosion pressure (bar) is determined.

Then, using Equation (6), the fatality probit of the VCE is estimated as [61]

$$Y = -77.1 + 6.91 \ln P, \tag{6}$$

where Y is the fatality probit of the VCE, and P is the overpressure (N/m^2). Finally, the probability of VCE fatality or the severity coefficient is estimated using equation (7) (based on the probit model):

$$\Pr(Y = 1lX) = \phi\left(X^T\beta\right), \tag{7}$$

where φ was the distribution function.

2.2.2. Modeling the Toxicological Consequences. In the fuzzy set theory, verbal expressions (linguistic terms) introduce numerical intervals. The output of the fuzzy set is a numerical index, but to design it, the numerical intervals must first be specified as verbal codes in the fuzzy toolbox. From a verbal expression, L represented by a numerical interval {0.0, 0.5, 1.0}, the numerical output is estimated according to the fuzzy inference rules. The philosophy of using a fuzzy set in quantifying experts' opinions is based on this principle [62]. To model the potential health consequences, a fuzzy set theory is applied. Accordingly, crisp linguistic variables are changed into fuzzy numbers through the fuzzy rules, and defuzzification operations are applied to obtain the fuzzy output numbers [63].

The system used three input parameters, including the concentration of the leaked chemicals, the rate of vulnerability in population, and toxicological characteristics of the released material. This system was first used by Gholamizadeh et al. [64, 65] to assess the toxicological consequences of chemical road transport. The desired output is the severity exposure coefficient calculated using the parameters above. Equation (8) is used to determine the airborne concentration of the substance [66]:

$$c(x, y, z) = \frac{Q}{2\pi u\sigma_y\sigma_z}e^{-y^2/2\sigma_y^2}\left\{e^{-(z-H)^2/2\sigma_z^2} + e^{-(z-H)^2/2\sigma_z^2}\right\}, \tag{8}$$

where C is the airborne concentration (g/m^3), Q is the output flow rate at the moment of leakage (g/s), U is the local wind speed (m/s), H is the respiratory point height (m), Z is the substance leakage height (m), σ_y is the dispersion in the y-axis (m), and σ_z is the dispersion in the z-axis (m). The relationships and the classification of materials stability are used to assess the last two parameters σ_y and σ_z. Then, based on the opinions of toxicology and safety experts, age, lifestyle, and specific situations (such as pregnancy), the levels of exposure are categorized into several groups.

Acute exposure is considered an essential item in evaluating accidents and chemicals' leakage. For this purpose, the AEGL-2 (10 min) parameter is selected as an item representing all the features of the hazardous material (HM) in both mild and acute exposures [67]. Eighty if-then rules are set and applied with the three input variables and experts' opinions. Therefore, a Mamdani set (fuzzy inputs and outputs) was designed, and a defuzzification technique based on the "center of area" was used. Researchers have used this fuzzy technique for risk assessment [68, 69].

2.3. SIC Estimation. The extent of exposure is determined by the region's population density where the hazards are released. The severity of the effects of the accident is expected to be lower for a sparsely populated region than for a densely populated region. Therefore, a new item SIC is added to Equation (9) and used for normalization. Accordingly, a standard questionnaire is designed to estimate the average number of people in 2500 m^2 during peak times when a significant number of people are present, and the route distance to residential points is measured. The sensitive points are determined based on the experts' opinions. Considering all parameters, the quantitative input and output items are evaluated using the Sugeno set (fuzzy inputs but numerical outputs) [70]. This system helps to determine this coefficient related to the nodes. Tables 1 and 2 illustrate the fuzzy system developed to assess the toxicological effects and SIC, respectively.

2.4. Quantitative Risk Assessment and Evaluation. In this step, the quantitative risk is calculated based on the probability of the specified parameter (P), severity (S), and SCI using Equation (9). It is noteworthy that safety distances are calculated based on the geometric average of the SIC on the railway route, and the node with the highest geometric mean of SIC is considered in the following equation:

$$\text{Risk} = P \times [SIC \times SS]. \tag{9}$$

The individual risk (IR) levels are evaluated according to the UK's health and safety executive (HSE) that divides the risk at the border of three levels of "broadly acceptable" (1.00E-6/year), "tolerable" (1.00E-5/year), and "unacceptable" (1.00E-4/year) [71] using Equation (9) [5]. The safe construction distances are determined based on these criteria. Safety philosophy tells us that when assessing and evaluating risk and determining safe distances, the most severe condition should be considered a criterion [65]. Accordingly, the safe distances are calculated based on the most severe cases, the most dangerous study node, and the "high obstacles" state.

2.5. Case Study Description. In consultation with the experts working in Tehran Petroleum Products Distribution Company, the route of gasoline fuel transportation from Tehran Railway to "Shahr-e-Ray" Railway is selected for the stu11111111 dy. The selected transport route is presented in Figure 2. This route is 8.5 km long and passes through residential areas in the south of Tehran. High traffic points, high accident areas, and critical and congested areas are selected. The specifications of the gasoline carriage are presented in Table 3. This fuel does not damage the health of exposed people [72]. The case study assumed that the atmospheric conditions are stable with a wind speed of 360 m/h.

3. Results

3.1. The Results of Probability Prediction

3.1.1. Bowtie Results. BT results show that defects in rail car compartments and packaging (containers, etc.) are identified as some of the main causes of HM release. Finally, 29 root causes (BE) and 19 intermediate causes (IE) for material release are identified. The specifications of each of the causes and their classical probabilities are presented in Table 3. Moreover, Figure 3 shows the general ET regarding HM leakage. If the flammable HM is released, a pool of fire occurs when there is an immediate ignition source; in addition, if the emergency response team does not respond at the right time, and given the right conditions, continuous material leakage could lead to dispersion. The dispersion of any chemical product can cause vapor cloud and health damage in the absence of ignition.

Moreover, if being a delay in the ignition and the environment congested, VCE is expected to occur due to inhalation of the vapor. On the other hand, flash fire is expected if there are no sources of delayed ignition in the open-space environment. In this regard, Table 4 shows the probabilities (per calendar year) of the parameters related to this diagram.

3.1.2. BN Results. Figure 4 demonstrates the ET diagram related to the HM leakage. In addition, the numerical results are presented in Table 5. Accordingly, the probability of Hazmat leakage is 1.18E-2 or once every 84 years (Table 5). The railway line studied has been operated for 11 years without any significant leakages; accurate statistics of rail accidents in the study area are scarce. Mirabadi et al. [6] regarding the influencing causes of rail accidents between 1994 and 2005 revealed that human error, locomotive defects, and defects in rail cars had the most significant impact on rail accidents in Tehran. This existing study corroborates the results of the present study. Moreover, the quantitative probabilities of health damage (per working year), VCE, flash fire, and pool fire are 2.40E-3, 3.80E-2, 2.50E-3, and 2.50E-3, respectively. In addition, the probability of successful containment is obtained as a 6.00E-4/working year.

3.2. The Results of Severity Estimation

3.2.1. VCE Modeling Results. The radii of the rail car's explosion are calculated as shown in Figure 5. This further reveals the overpressure is caused by VCE in three states of obstacles in retrospect of the distance from the point of explosion. The chart shows that VCE pressure in the "high obstacles" state is significantly different from other states. Under the mentioned conditions, VCE pressure is 3.72 bar (372500 N/m2) when it is three meters away from the leakage point, and it is 1.20 bar (12000 N/m2) and 0.10 bar (10000 N/m2), respectively, in the "medium obstacles" and "low obstacles" conditions.

The severity coefficient of VCE is presented in Figure 6. As shown in this figure, the probability of fatality for the population exposed to VCE in the "high obstacles" state is 100% (severity coefficient = 1) at a distance up to 37 meters away from the explosion point. In the "medium obstacles" state, at a distance of 3 meters away from the leakage point, the probability of fatality for the exposed population is coming 10% (severity coefficient = 0.1). In the "low obstacles" state, the probability of fatality at all distances becomes zero (severity coefficient = 0).

Table 1: The details of fuzzy set system related to toxicological effects.

Level of factor	Airborne concentration of the substance	LT*	Vulnerability groups (age)	LT	AEGL-2 (10 min) (ppm)	LT	Toxicological effect	LT
1	<NOAEL of material	L	18 to 34	L	>1000	L	Low	L
2	<IDLH of material	LM	34 to 54	LM	500 to 100	LM	Low-moderate	LM
3	<LC50 of material	M	11 to 18 and 54 to74	MH	100 to 500	MH	Moderate	M
4	<Lethal dose of material	MH	Sensitive group<11>74	H	<100	H	Moderate-high	MH
5	>Lethal dose of material	H					High	H

*LT: linguistic term, L: low, LM: low-moderate, M: moderate, MH: moderate-high, H: high.

Table 2: The details of fuzzy set system related to severity impact coefficient (SIC).

Level of factor	Number of people in 2500 m^2 (person)	LT*	Route distance to residential points (m)	LT	Number of critical points	LT	SIC**	LT
1	<10	L	>40	L	0	L	Low	L
2	10 to 50	LM	30 to 40	LM	1	LM	Low-moderate	LM
3	50 to 100	MH	20 to30	MH	2 and 3	MH	Moderate-high	MH
4	>100	H	<20	H	3>	H	High	H

*LT: linguistic term, **SIC: severity impact coefficient, L: low, LM: low-moderate, M: moderate, MH: moderate-high, H: high.

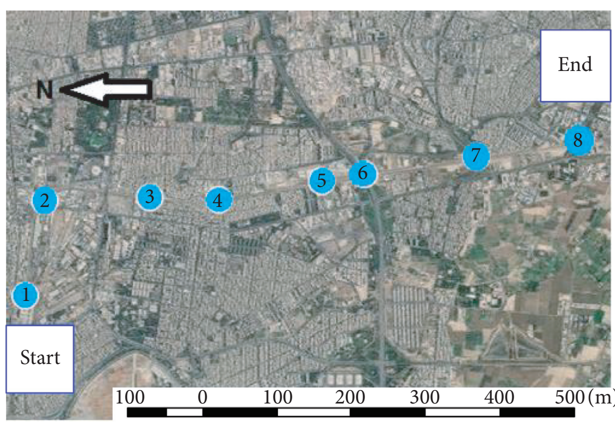

Figure 2: Study nodes in the selected rail system.

Table 3: The properties of transported material.

Material	Volume (m^3)	Stability class	AEGL-2 10 min (mg/m3)	Lc50 (g/m3)	IDLH (g/m3)	Reactivity level	Heat combustion (mj/kg)
Gasoline	65	Relatively stable		300	38.24	High	45.5

IDLH: immediately dangerous to life or health, AEGL-2: acute exposure guideline levels, LC: lethal concentration.

3.2.2. Toxicological Modeling Results. Based on the dispersion and the classifications in the fuzzy set, the airborne concentration of gasoline vapor at the dispersion area is 0.07 g/m^3. It should be noted that this amount is meager; thus, it is classified as the *L* level of the fuzzy system. This concentration is well below the toxicological indices of gasoline. Other cases are analyzed via the FL based on the ages of the population and the toxicological characteristics of gasoline. Table 6 shows the results of the case study using this system.

It is observed that no information is available on AEGL-2 *e* or the NOAEL (no observed adverse effect level) of gasoline, and the level of AEGL-2 gasoline *L* is taken into account. Going by the results, if gasoline is released, the concentration of gasoline vapor will be lower than the NOAEL. Consequently, the radius is not affected by different parts due to the concentration deficit at the leakage point. The graph reveals that the exposure severity decreases as it moves away from the leakage point. Hence, the vulnerability of any individual will be determined by the exposure coefficient.

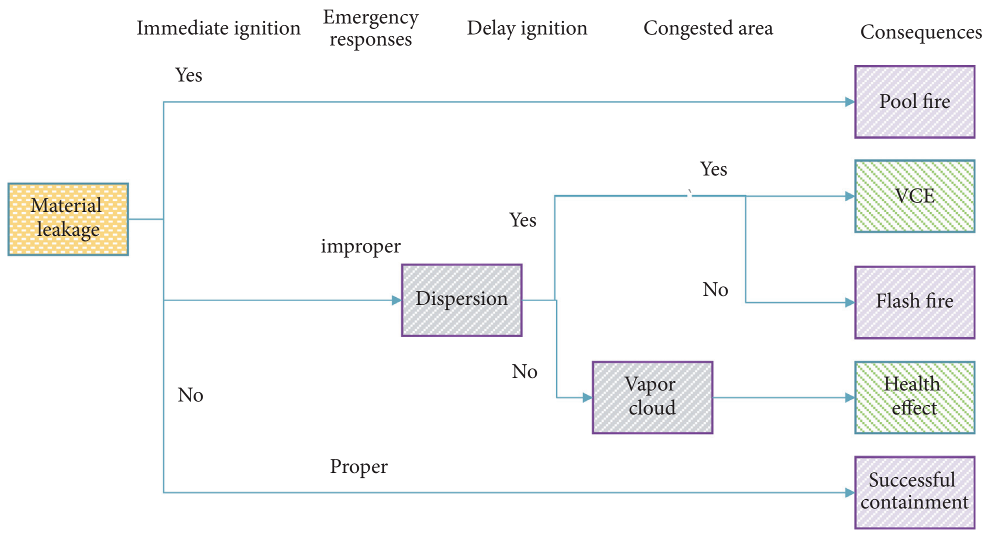

Figure 3: Event tree (ET) diagram related to the hazardous material (HM) leakage.

Table 4: Basic and intermediate causes in BT and BN diagram and the corresponding probability.

Event	BT probability (calendar year)	BN probability (calendar year)	Event	BT probability (calendar year)	BN probability (calendar year)
Basic event			Failure to connect rail cars	7.00E-3	6.00E-2
Defects in radio communication signals	1.00E-2	8.60E-2	Malfunction in terminal monitoring system	4.00E-3	4.00E-3
Fault in the emergency brake system	6.00E-3	1.00E-4	Burnout of material containers	3.00E-3	3.00E-3
Wheels broken	8.00E-4	6.00E-3	Holes in the body of the container	3.00E-3	3.00E-3
Intentional error in leaving the train	2.00E-3	1.70E-2	Intermediate event		
Operator inexperience	8.00E-3	6.90E-2	Accident	1.07E-1	8.84E-1
High-speed train	1.00E-2	8.60E-2	Defect in rail car body	1.50E-2	1.29E-1
Lack of familiarity with the route of transport of materials	1.00E-4	1.00E-4	Defects in packaging materials	2.40E-5	1.00E-4
Fault in rail connections	2.00E-3	1.70E-2	Exit train from rails	3.61E-2	3.07E-1
Rail fracture	4.00E-3	3.40E-2	Train collision with another train	7.17E-2	5.99E-1
Error in the route monitoring system	5.50E-3	4.70E-2	Planning error	2.35E-2	2.01E-1
Error in line adjustment by the operator	3.00E-3	2.60E-2	Operator error	1.82E-2	1.56E-1
Error in the route monitoring system	8.00E-3	3.90E-2	Inappropriate weather conditions	8.00E-3	6.9E-2
Operator error in timing	7.00E-3	6.00E-2	A technical defect in train	1.60E-2	1.37E-1
Operator inexperience	8.00E-3	6.90E-2	Railway defect	6.00E-3	1.05E-2
Operator fatigue	1.00E-3	8.06E-2	Error in setting lines	8.50E-3	7.30E-2
Lack of familiarity with the route of transport of materials	2.00E-4	2.00E-3	Error in scheduling	1.50E-2	1.29E-1
Intentional error in train collision with another train	1.00E-5	1.00E-5	A technical defect in train	1.00E-2	8.60E-2
Dusty railway	6.00E-3	5.00E-2	Operator error	2.01E-2	1.72E-2
Foggy railway	2.00E-3	1.70E-2	Railway defect	6.00E-3	5.20E-2
Defects in radio communication signals	1.00E-2	8.60E-2	Defects in train wheels	4.80E-6	1.00E-6
Fault in the emergency brake system	6.00E-3	5.20E-2	Unintentional error in leaving the train	1.81E-2	1.55E-1

Table 4: Continued.

Event	BT probability (calendar year)	BN probability (calendar year)	Event	BT probability (calendar year)	BN probability (calendar year)
Fault in rail connections	2.00E-3	1.70E-2	Unintentional crash on the train with another train	1.82E-2	1.56E-2
Rail fracture	4.00E-3	3.40E-2	Defects in the body of containers carrying materials	6.00E-3	6.00E-3
Leakage of the rail car body	3.00E-3	2.60E-2	Top event		
Wreckage of rail car body	5.00E-3	4.30E-2	Material leakage	1.225E-1	1.16E-1

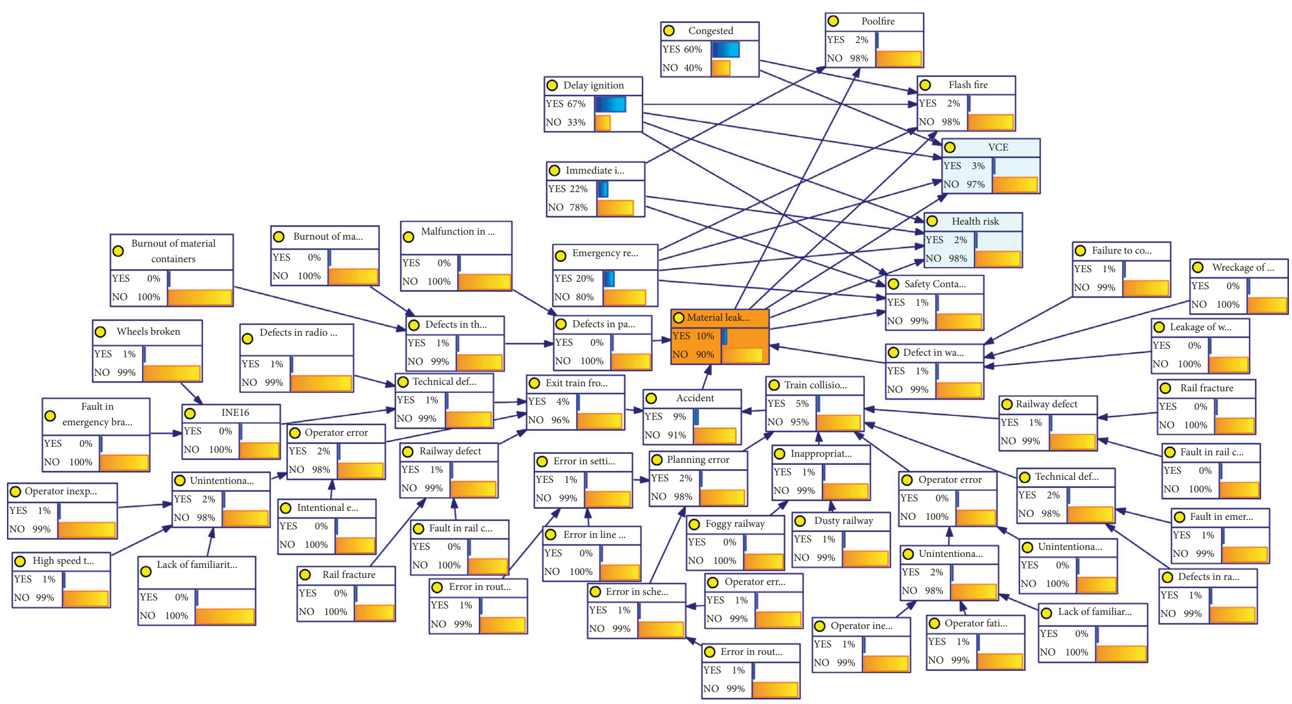

Figure 4: Bayesian network model of gasoline leakage.

Table 5: The barriers and consequences related to material leakage from rail cars.

Barrier	Probability (working year)*	Consequences	BT probability (working year)	BN probability (working year)
Material leakage	1.18E-2	Pool fire	7.90E-3	2.50E-3
Immediate ignition	6.70E-1	Flash fire	1.00E-3	2.50E-3
Delay ignition	2.20E-1	VCE	1.50E-3	3.80E-2
Proper emergency responses	2.00E-1	Health risk	4.70E-3	2.40E-3
Congested area	6.00E-1	Safe containment	3.80E-3	6.00E-4

*Working year = calendar year×0.119.

3.3. SIC Estimation Results. In this section, eight study nodes are evaluated. The final scores (rank) of all the selected nodes are presented in Figure 7. Based on the results, node 5, with a coefficient of 1.50, has the highest, and node 6, with a SIC of 1.15, has the lowest coefficient. So, node 5 is considered a basic node in calculating QRA.

3.4. QRA Results. Based on the BN results, the health and safety simulations, and the determined SICs, the individual quantitative risks in the health and safety consequences are calculated using Equation (8). Figures 8–10 show the final findings of the quantitative VCE and toxicology risk assessment. The risk also approached zero at 55 m. Therefore, safe construction distance should be determined based on node 5 and age group 4. As presented in Figure 8, the individual risk of fatality due to VCE at a distance of 3 meters away from the leakage point is 8.49E-3 per working year. Figure 9 also shows that the individual risk of fatality from a VCE at a distance of 3 meters away from the leakage point is 8.49E-2 per working year. The trend of decreasing risk relative to the distance in the “medium density” state is abnormal due

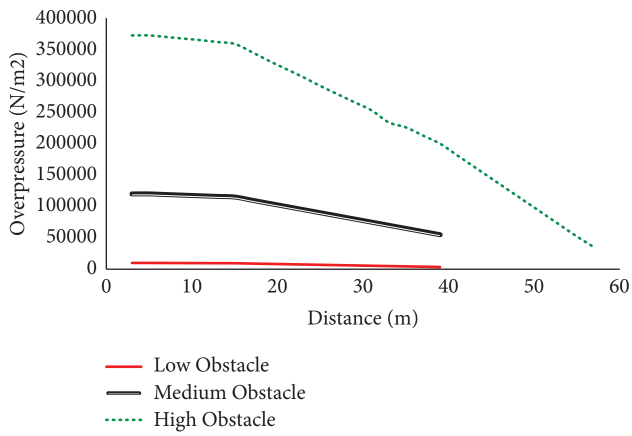

Figure 5: VCE overpressure at different distances from the leakage point.

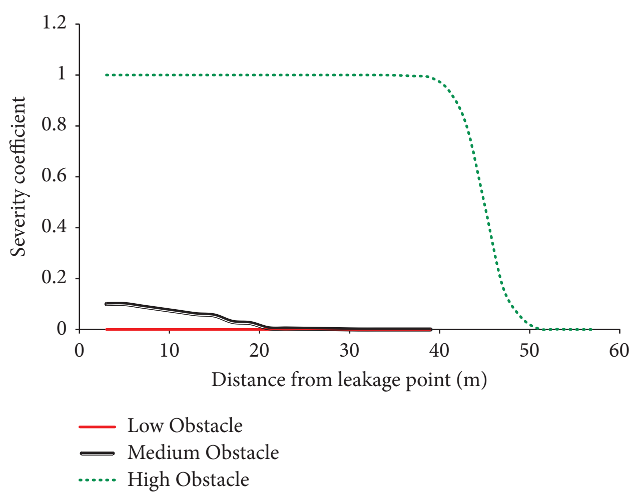

Figure 6: VCE severity at different distances from the leakage point.

Table 6: Severity coefficient of exposure to gasoline vapor in different age groups using FIS.

Groups	Vulnerability class	Severity coefficient
1	Age range: 18–34	0.08
2	Age range: 35–54	0.12
3	Age range: 11–17 and 55–74	0.2
4	Pregnant women, persons with underlying illness, age range: ≥75 and ≤10	0.5

to reference diagrams adopted for the BS method. Conversely, Figure 10 shows a significant difference between the risk of irreversible health damage between age group 4 and other groups. Based on this, it was found that the risk faced by group 4 is 1.78E-3 and group 1 is 2.85E-4 per working year. These risks were calculated based on the SIC of node 5.

The risk map is plotted based on the results of Equation (8) (see Figure 11, considering the most severe cases = node 5

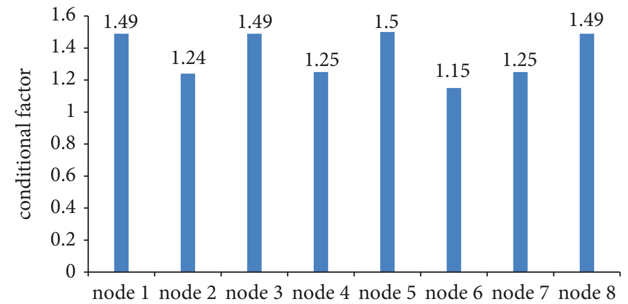

Figure 7: Severity impact coefficient (SIC) in the studied nodes.

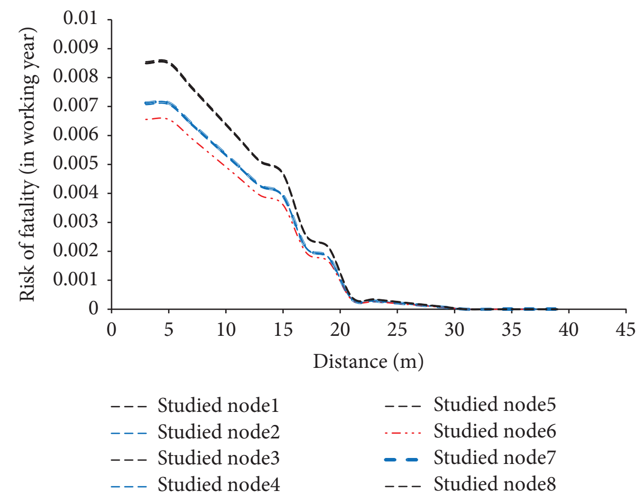

Figure 8: Individual severity of VCE based on the “medium obstacles” level.

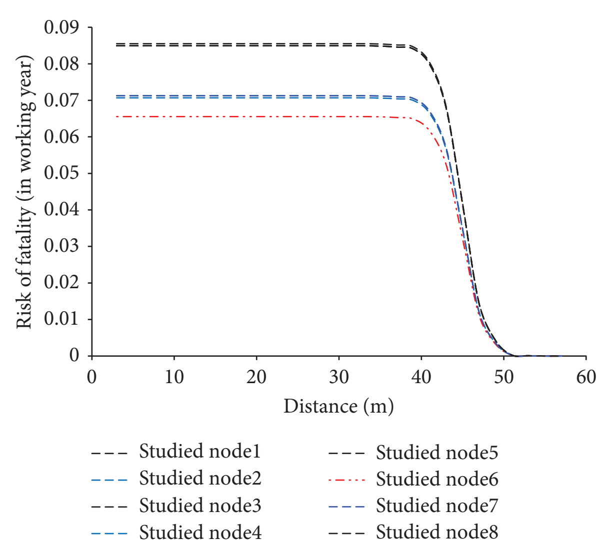

Figure 9: Individual risk of VCE based on the “medium obstacles” level.

and the “high obstacles” state in the BS method). Based on the three criteria mentioned above, at 50.00, 53.00, and 54.50 meters away from the leakage point, the individual

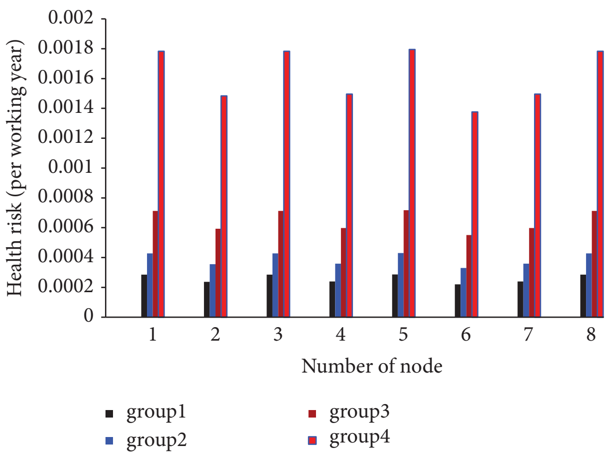

Figure 10: Health risk in different age groups in the selected study nodes.

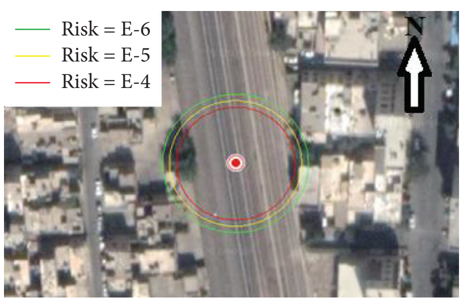

Figure 11: Explosion risk map based on the three criteria in node 5.

risks (per working year) are obtained as 1.00E-4, 1.00E-5, and 1.00E-6, respectively. It should be noted that given the low amount of health risk in the case studied, the risk map is plotted based on the risk of VCE.

4. Discussion

In the present study, the QRA related to the consequences of the leakage of petroleum products in railway transport is conducted using BN and FL systems. The BN is used to estimate the quantitative probability of gasoline release and possible consequences such as toxicological effects and VCE. In addition, a combination of equations is used to simulate the VCE. Furthermore, a fuzzy set is applied to simulate and evaluate the severity of toxicological consequences and estimate the SIC of the studied nodes.

The proposed model indicates that BN can be used as a proper tool in improving the accuracy of the probabilistic findings related to cause-consequences analysis. This assertion has been posited by Khakzad et al. [51]. The present study shows that considering the nonlinear relationships between influential parameters produced higher accuracy than the BT method; this is also in conformity with the previous work of Zarei et al. [43] and Aliabadi et al. [6]. In addition, the present study corroborates the findings of Papazoglou et al. [73] that a direct relationship exists between the heat of combustion and overpressure. Moreover, our findings proved that a direct relationship between the distance from the point of explosion and the probability of mortality is consistent with Azhar et al. [61]. The proposed hybrid equation can also simulate explosions in petroleum liquids. Thus, the results indicate that the probit (the probit function is the quantitative function associated with the standard normal distribution) of mortality must be used to determine the recommended safe distances. Nevertheless, a different approach by Chakrabarti [21] where pressure from the explosion point was used to determine safe distances is used as the basis for comparing the proposed study.

On the other hand, in the study of Jahangiri et al. [74], the factor of "National Fire Protection Association (NFPA) 704" [75] was considered as the only influential factor in transportation risk. However, in the present study, the equations related to estimating airborne concentration and the fuzzy set theory based on the vulnerability of community groups are used. In designing the fuzzy system for simulating the toxicological effects, we were tried to consider all the influencing factors. For instance, in compiling the approach by Azar et al. [76] in designing this system, the main factor of acute exposure, namely AEGL-2 (10 min), is considered as one of the systems' inputs. In line with Milovanović et al.' [77], chemical characteristics and the sensitivity class of the exposed peoples are equally considered. The findings show that group 4 should be considered the base group in determining the safe distance. Our approach in this regard is in line with the approach of Huang et al. [78].

In analyzing technical and human factors, the results obtained can be compared with similar studies. Our results show inexperience as one of the major causes of rail accidents. This is consistent with the findings of Kyriakidis et al. [79] who reported that familiarity was one of the main causes (15.4% of accidents) of rail accidents. The ability to properly monitor the system and skills required for performing routine settings and repairs are identified as the most vital parts of the human factor. It is found that the level of monitoring and accuracy in repairs and detection of defects with a failure rate = 8.00E-3 is higher than what was reported by Singh et al. [80] with a failure rate = 1.00E-2. In line with the study conducted by Rose et al. [45], Baysari et al. [81], as well as Kim et al. [47], BT analysis of the proposed study shows that human factors directly impacted the technical failure rate of the equipment. Therefore, the defects in the maintenance of the equipment directly impact the defect rate of the brake and wheel systems of the rail cars. These systems are identified as the safest technical part of the rail cars because of the good level of monitoring and maintenance. This level is higher than the level calculated by Kumar et al. [82] with a Brake system failure rate = 0.20 and Singh et al. [80] study with a wheel failure rate = 0.039.

Contrary to Oggero et al. [12], BN is used instead of ET to estimate the consequence probability. This improved the accuracy of probability calculations. Although Marsh et al. [83] used the Bayesian network to model rail events, root causes and possible BN consequences are further considered in this study. Contrary to the study conducted by Liu et al. [10], who cited railroad fractures as the main cause of accidents (from 2001 to 2010), this study identified radio communication defects and unauthorized speeds as the main causes of accidents in rail cars. The divergent results can be attributed to Iran's other monitoring and surveillance systems and other countries.

The study of Andrew and Dunnett [84] on the statistics of rail accidents in Europe showed that radio communication failure is one of the significant causes of rail accidents. However, the present study adopts a new approach for quantitative risk assessment of petroleum products transport in the rail network. It, therefore, shows that gasoline could not cause health damage in healthy groups of the community. Adequate preventive measures should be taken to protect the vulnerable group 4, as stated in this study. The authors suggest that moving residential areas out of the dangerous zones can be a beneficial sure in this regard.

Although the radius of health effects on gasoline leakage was not obtained, the authors strongly believe that in the transportation of all liquid HM, the approach of this study can be used to assess the risk of toxicological effects. The findings show that residential areas, roads, and pedestrian crossings should be constructed over 54 meters away from railway networks. In addition, our findings show that Hazmat transportation during the day when there is less pedestrian or vehicle traffic (00 : 00 to 05 : 00 am) is the more appropriate option to decrease the risk of hazardous incidents. Moreover, looking at the equations used in VCE simulation, it can be seen that the volume of the reservoirs has the most significant impact on the overpressure. Therefore, the authors suggest that the reservoirs' volume should be reduced as much as conceivable. For example, if the volume of the tanks decreases by 50 percent, at 11 meters from the center of the explosion, we can see a 25% reduction in the radius of the vapor cloud and a reduction of 1,000 N/m^2 in the overpressure. This reduction can decrease the risk significantly by 18%. Future studies can focus on optimizing the routes based on the proposed method and utilizing other simulation systems such as genetic algorithms and dynamic analysis.

5. Conclusion

Rail transporting of hazardous materials has led to severe accident occurrences. These potential accidents pose severe risks to humans and the environment. Therefore, a risk assessment should be conducted to ensure that potential hazards are adequately identified and controlled. To this end, the present research has developed a concerted model to assess the safety and health risks of Hazmat transporting in railway systems. The proposed model used the BNs to develop a quantitative cause-consequences modeling beginning from the root events. Several factors contributing to health and safety risks are included in the risk function developed using the fuzzy set theory. This operation deals with the epistemic uncertainty in estimating the severity parameter and provides a precise risk prediction. The proposed risk model can analyze the possible risks and safely design transporting routes and third parts such as transporting rules. This research focuses on VCE as the worst safety consequence, while other types of fire and explosion, such as pool fire and flash fire, occur only when released into the atmosphere.

Moreover, the health concerns and safety characteristics of other hazards that may be different from gasoline are investigated in the present study. Finally, domino effects in rail transportation of chemical materials in terms of VCE and BLEVE can impose significant risks. These are not modeled in the current research. Hence, this can be posed as new opportunities for future investigations.

Data Availability

In this study, the data used in the Bayesian network were obtained through the fuzzy hierarchical analysis (FHA) and using the opinions of safety and rail experts. Parameters affecting material leakage as well as parameters affecting the fuzzy systems used were identified and classified by reviewing past studies and using the opinions of experts. This content is described in the text of the article quite clearly. All of these data can be found in the text of the study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors would like to thank the Tehran Petroleum Products Distribution Company for their cooperation and HUMS for financial support. This study has been supported by Hamadan University of Medical Sciences, grant no. 9803282465.

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