How to Distribute Hazmat Transport Risk over the Intercity Network? An Empirical Study

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Abstract

Due to the existing transport risk on hazardous materials transportation, it is very essential to prevent risk agglomeration over the most frequently used edges of the intercity road network. Although, there are many approaches for risk distribution over the network, but the main concern is to select the best approach. Therefore, three different techniques including bounded proportional risk, minimizing the maximum loaded risk, and minimizing risk absolute errors have been investigated through developing their proposed risk distribution models. After developing corresponding models, the well-known criterion of risk variation (total variance) has been selected for comparing the performances of three techniques. In order to check the proposed models' validities, the medium size of Guilan intercity road network, located at the northern part of Iran, including 46 nodes and 126 two-way edges has been selected as case study. Three mathematical models have been run using experimental data of network structure as well as Hazmat Origin-Destination matrix and results revealed that the minimizing the maximum loaded risk technique is the best one for risk distribution over the intercity road network in Hazmat transportation.

Keywords: Hazardous Material Transportation, Risk Distribution, Intercity Road Network, Mathematical Modeling

1. Introduction

Hazardous Materials: Hazardous materials, as defined by the US Department of Transportation, include any material or substance that is capable of damaging humans, property, and environment. According to the dangerous goods transport convention by road, hazardous materials are classified into nine main classes, consisting of: explosives, gases, flammable liquids and solids, oxidizing materials, toxic substances, radioactive materials, corrosive substances and waste (Environmental Health & Safety, 2011). Since, reducing fatalities and financial losses, increasing the reliability as well as promoting transport safety have become the main objectives of transport industries not only by roads and even railways; transport of hazardous materials (Hazmat for short) is always a concern with possible harm to humans and the environment. Given the catastrophic consequences of accidents involving the transport of hazardous materials as well as the growing transport of these materials, the study of the transportation of hazardous materials and the use of appropriate means to reduce the resulting losses is of particular importance. In addition, the existence of various hydrocarbon reserves and products derived from them, such as: types of petrochemicals that are in turn considered as hazardous materials; on the other hand, the importance of Iran as the country exporting these items and the request of neighboring countries from Iran to receive these materials in different border areas, and finally, the geographical location of Iran as one of the most suitable transit routes for goods transit among the countries of the region, shows the need for these materials for transportation, and the importance of the safety of the transfer of these materials (Yousefi et al., 2017).

Hazmat Transport Risk: There is a very important issue in Hazmat transportation known as "risk". In the definition of risk, it can be said that risk represents the relationship between the hazards and the vulnerability factors of one or more components of risk, and that most often risk is defined based on the probability of occurrence and its consequences (Yousefi et al., 2017). The risk involved in transporting hazardous materials includes four main components: accident information, population, environment and infrastructure aspects (Mahmoudabadi & Seyedhosseini, 2014). So, risk reduction techniques should be applied together with transportation costs as an important measure at all stages of material transfers. The well-known method of risk management over the network is solving Hazmat Routing Problem. Routing, means as finding the best route, in the transport of hazardous materials does not necessarily determine the shortest path. It strives to determine the safest route for Hazmat transportation. Different approaches have been examined for solving these models by studying mathematical models of hazardous materials routing.

Hazmat Transport Modeling: For modeling Hazmat routing problems, the objective functions are also investigated in three categories: two-level, two-step, and utility. In the two-level objective function, the mathematical model has two levels of objective functions, one of which is the constraint for the other objective functions. In the two-step one, the first step is to solve the routing problem and determine a set of paths. In the next step, the expert finds the best route from this set. In the utility objective function, considerations such as environmental considerations and transportation costs are considered as a weighted utility function. The results of these studies show that both network size and type of variables have an important influence on the model solution approach (Seyedhosseini & Mahmoudabdi, 2010). Researches on the routing problem of Hazmat transportation generally focus on two general areas, including determining the transportation risk to cross a particular route and determining the route that has the least risk and cost for the transportation of hazardous cargo (Carotenuto et al., 2007).

In 2004, Zografos and Androutopoulos (2004) presented a heuristic algorithm to solve the problem of hazardous materials distribution. From their point of view, the routing of hazardous material distribution can be a two-objective problem with a time window in which risk and cost are minimized together. Risk has been also considered as a main concern in chaotic pattern of Hazmat Routing problem under emergency conditions (Mahmoudabadi & Seyedhosseini, 2014) when transport authorities are dealing with finding the safest path over a damaged network. An iterative procedure has been made to follow the concept of chaos theory in Hazmat routing problem as well as each path is selected by a combination of risk and cost. In the context of locating hazardous materials in the network, Alamur and Kara, in an article, presented a new multi-objective model that included some limitations. The management of hazardous waste involves the transportation and disposal of the waste. In their research, the goal was to determine the centers of hazardous waste disposal and determine the type of technology needed for disposal as well as to determine different routes for hazardous waste types and the route for combining different waste and how disposal of waste is left to its disposal centers in order to minimize the total cost and risk of transportation and examined them by the implementation of a large-scale model in the central Anatolian region of Turkey (Alumur & Kara, 2007).

In another study, Tavakkoli-Moghaddam et al. (2015) focused on developing an idealized planning model for routing the location of hazardous materials transportation, which in the first stage, with regard to the calculated risk, they determined the optimal route for the least risk, and the results were used in the second stage, which aimed to reduce the total costs. In the second stage of the developed model, using the results of the first step and evaluating the optimal route in terms of having the least cost, as well as locating the distribution sites of the fuel, taking into account the cost of making optimal distribution sites, they introduced the passing arcs from these places to destinations with high levels of hazardous transfer materials. Finally, to validate the model as well as to examine the status of the outputs of the model, the model developed in a network was implemented and it was determined that the model had sufficient credibility to locate distribution centers and routing hazardous materials transportation.

Routing is an important issue that should be considered in the provisions for Hazmat (Mohammadi et al., 2015). Due to the practical concerns and considerable problems, routing is perceived as one of the best subject matters for research in operation (Kheirkhah et al., 2016). This issue is important to researchers from two perspectives. The first perspective is that it is a practical problem and finding an optimum solution can lead to economic saving and the second is that its solution is challenging because the problem is so difficult to be solved (Mester et al., 2007).

Routing in the transportation of Hazmat is not necessarily concerned with finding the shortest route, but it should be attempted to determine the safest route (Carotenuto et al., 2007).

Hazmat Risk Distribution: It is time to define another concept known as risk distribution in Hazmat transport system. In order to transport hazardous materials from the origin to other destinations, routes should be determined in such a way that the risk of transporting hazardous materials is not concentrated in just one section (edge) of the network and have a fair, logical and partially balanced distribution of risk to all parts (Boyer et al., 2013). There are several methods for risk distribution in Hazmat transportation. In these methods, different policies can be made in relation to the distribution of probable risk in the network and equity in risk allocation, so that a series of predetermined factors are prioritized (Alumur & Kara, 2007). For example, among these policies, it is possible to highlight the safety of the most used networks' paths, which aims to minimize the risk in the entire study network and not going beyond the specified risk or economic pathways in which economic indicator is the amount of distance traveled and the goal is to minimize the total distance traveled. Another policy with a risk minimization approach for all transit materials and all existing routes can be adopted, which is in fact impossible, but if we reach it, we will be at the lowest risk (Alumur & Kara, 2007).

Vision: In this research, we strived to develop a model by which to locate the distribution centers of hazardous materials in the network of roads based on three risk assessment methods, which include minimizing bounded proportional risk and minimizing the maximum risk and absolute error model. It can be argued that in the transport system of hazardous materials, there is a concept known as risk distribution that, for the transport of hazardous materials from the origin to other destinations, the routes should be determined in such a way that there is no centralization of the risk in parts of the network. In the context of risk analysis, there is a concept called risk distribution that includes three general structures called bounded proportional risk, maximum risk and absolute magnitude of error. In describing bounded proportional risk, it can be said that for the transport of hazardous materials in the network, the amount of transit load may designate a large percentage of the total load of the network in one of the network axes. This is called being loaded. Using the concept of bounded proportional risk, it is possible to consider other routes for cargo that does not exceed the specified limits for the transportation of hazardous materials in each axis which is called so-called bounded proportional risk. Also, in another approach, the target function can be defined in such a way that the maximum risk associated with that axis is minimized, which the mathematical programming system to some extent does this and distributes the load on other parts of the network.
The criteria for the most appropriate risk in the network for these three modes is the variance of the risk allocated to the network axes in different scenarios, and the more appropriate method would be the one which has less variance.

2. Mathematical Modeling

There are several ways to distribute risk in the transport of hazardous materials in a given network. In this study, three basic methods i.e. distributing bounded proportional risk, maximum risk as well as the absolute magnitude error in the network are investigated. There are several policies in relation to risk distribution methods, including those policies that have been addressed in this research work. For example, the safety of most of the network paths can be pointed out which is aimed at minimizing risk in the entire network of the study route and not going beyond the risk of a certain amount, or the economy of routes that the economy index in this case is the amount of distance traveled and the goal is to minimize the total distance traveled. After examining the mentioned models as well as studying the distance traveled by the network by a criterion of variance which is a suitable measure for distribution of risk in the network, each of the three models will be compared with each other and to ensure the accuracy of the proposed model, all of these steps in the given network will be examined and solved by the well-known software of general algebraic modeling system (GAMS).
Indices, parameters and decision variables are as follow:

Indices:

G: Transportation network, including nodes, edges and origin-destination pairs;

i : Start node for each edge in the network;

j : End node for each edge in the network;

(i, j) , (j,i) : Set of two-way edges in the network; (i, j) , $(j,i) \in G$ & (j,i) , $(i, j) \in G$;

o : Origin node in the set of OD pairs;

d : Destination node in the set of OD pairs;

OD: Set of origin-destination pairs; $od \in OD$.

Parameters:

N_{OD} : Number of vehicles that are dispatched from origin "o" to destination "d";

R_{ij} : Associated risk of edge (i, j) ; in this research work we assume that for two-way links we have $R_{ij} = R_{ji}$;

L_{ij} : Length of link (i, j) ; for two-way links we have $L_{ij} = L_{ji}$;

X_{ij}^{od} : 1 If link (i, j) is on a route from origin o to destination d; 0 otherwise;

As it previously discussed, in Hazmat transportation, sometimes, a large part of total network load may be allocated to few routes. For solving this problem, we proposed a mathematical model with an aim to the amount of Hazmat shipment on each link should not exceed a set value ($\alpha\%$).
Objective function is now formulated by equation (1).

$$MinZ = \sum_{od \in OD} \sum_{(i,j) \in G} N_{OD} \times R_{ij} \times L_{ij} \times X_{ij}^{od} \tag{1}$$

The first constraint is to keep continuous path over the network for each OD pairs. This constraint can be satisfied by equation (2) where Ex is the set of exiting arcs and En is the set of entering arcs for node "j". More details are available at (Taha, 20808) in general modeling and (Mahmoudabadi & Seyedhosseini, 2014) in Hazmat transport routing problems.

$$\sum_{i \in E_x(j)} X_{ji}^{od} - \sum_{i \in E_n(j)} X_{ij}^{od} = \begin{Bmatrix} 1\ if\ j = o \\ -1\ if\ j = d \\ 0 \quad O.W. \end{Bmatrix} \forall\, j \in G\ \&\ (o, d) \in CN$$

Another concept is the tolerance of risk which is a proportion of total transport risk loaded in the network. Symbol α is a percent of total risk loaded over the network in the best situation can be considered by equation (3) in which the loaded risk on each link should be less than the loaded risk on all links multiplied by α .

$$\sum_{od \in OD} N_{OD} \times R_{ij} \times L_{ij} \times X_{ij}^{od} \le \alpha \times \sum_{od \in OD} \sum_{(i,j) \in G} N_{OD} \times R_{ij} \times L_{ij} \times X_{ij}^{od} \tag{3}$$

To obtain maximum loaded risk over the network, the model is that the maximum loaded risk on each link can be formulated as equation (4), so the objective function of this mathematical model is as follow:

$$MIN\ (MAX \sum_{od \in OD} N_{OD} \times R_{ij} \times L_{ij} \times X_{ij}^{od}) \tag{4}$$

Let us use a change of variable in order to minimizing the maximum value of loaded risk on each link. Equation (5) satisfies the above consideration where U is obtained by solving the model. In this case, objective function and corresponding constraint are changed as equation (5), (6) and (7).

$$U = MAX \sum_{od \in OD} N_{OD} \times R_{ij} \times L_{ij} \times X_{ij}^{od} \tag{5}$$

$$MIN\ \ Z=U \tag{6}$$

$$\sum_{od \in OD} N_{OD} \times R_{ij} \times L_{ij} \times X_{ij}^{od} \le U \tag{7}$$

To obtain minimizing absolute errors the model can be formulated as equation (8) in which absolute loaded risk on each link with the average loaded risk on all links should be minimized.

$$MIN\ \ Z= \frac{1}{n} \sum_{i,j \in G} \Big| \sum_{od \in OD} N_{OD} \times R_{ij} \times L_{ij} \times X_{ij}^{od} - MR \Big| \tag{8}$$

Actually, the positive and negative deviations of loaded risk on the network should be investigated than to the average of total loaded risk on the network. In other words, we can minimize the absolute error when its deviations have their minimum values. For this purpose, equation 8 ensures that the sum of deviations can have its minimum value. In this case, objective function and corresponding constraints can be formulated as equations (9) to (12).

$$MIN\ \ Z= \sum_{i,j \in G} PR_{ij} + NR_{ij} \tag{9}$$

$$\sum_{od \in OD} N_{OD} \times R_{ij} \times L_{ij} \times X_{ij}^{od} - MR - PR_{ij} + NR_{ij} = 0 \tag{10}$$

$$MR = \beta \sum_{od \in OD} \sum_{(i,j) \in G} N_{OD} \times R_{ij} \times L_{ij} \times X_{ij}^{od} \tag{11}$$

$$\sum_{od \in OD} N_{OD} \times R_{ij} \times L_{ij} \times X_{ij}^{od} \leq G \tag{12}$$

Where PR_{ij} and NR_{ij} are positive and negative deviations respectively, MR is average risk, n is the number of links in the network. Also, it is noteworthy that in this model $\frac{1}{n}$ has been shown as β. The third constraint ensures that the network risk is less than a specific value (G). Other parameters are as previously mentioned.

To obtain minimum distance approach, objective functions those are investigated in previous models for developing minimum distance model. The proposed model is formulated as a multi-objective programming model with two objections: 1) minimizing the amount of risk in the network and 2) minimizing total distance. In this part of our research, we measure the minimum distance that is obtained from previous models as well as calculating the minimum risk. If the output of the equation (13) is greater than or equal to the loaded risk on each link, and if the output of the minimizing the maximum loaded risk model is less than a specific value (G), we can ensure that the minimum distance is measured by adding the equation (14) to the model. Objective function of the minimum distance model is given by equation (15). Constraint of the minimum distance model is now formulated by equation (16).

$$MIN \;\; Z=U \tag{13}$$

$$\sum_{od \in OD} N_{OD} \times R_{ij} \times L_{ij} \times X_{ij}^{od} \leq U \tag{14}$$

$$Z = \sum_{(i,j) \in G} \sum_{od \in OD} N_{OD} \times L_{ij} \times X_{ij}^{od} \tag{15}$$

$$\sum_{od \in OD} N_{OD} \times R_{ij} \times L_{ij} \times X_{ij}^{od} \leq GOAL \tag{16}$$

Following the stage of developing three different mathematical models for the above mentioned techniques, the well-known criterion of risk variation (total variance) has been selected for comparing distribution performances on three above mentioned techniques. Equations (17), (18) and (19) are defined to calculate total risk, average and variance of risk distributed over the network, respectively, where M is the average risk, R is the total loaded risk on each link and NL is the number of links in the network.

$$R = \sum_{od \in OD} N_{OD} \times R_{ij} \times L_{ij} \times X_{ij}^{od} \tag{17}$$

$$M = \sum_{i,j} \frac{R}{NL} \tag{18}$$

$$\text{var} = \sum_{i,j} \frac{\left|(\text{R} - \text{M})^2\right|}{NL} \tag{19}$$

3. Illustrative Example

In order to check the validity of models, an illustrative road network including 8 nodes connecting with 10 two-way links and 2 pairs of origin-destination nodes has been selected. The amount of hazardous material shipped from node 1 to node 8 (No.1 O-D pair) is equal to 200 and from node 3 to node 7 (No.2 O-D pair) is equal to 300. In addition, all links considered as two-way links and as stated earlier, the length and the loaded risk of each two-way link is equal to each other. In the next step, mathematical models including bounded proportional risk, minimizing the maximum risk and minimizing absolute errors of risk models was run through the use of well-known software of General Algebraic Modeling System (GAMS). More details for network specifications are available at table 1 as well as figure 1 depicts the overall view of illustrative network.

Table 1. Network specification on illustrative example

Link	**Two-way link** (i,j) , (j,i)	R_{ij}	L_{ij}	**Link**	**Two-way link** (i,j) , (j,i)	R_{ij}	L_{ij}
1	1-2 , 2-1	50	30	**6**	4-7 , 7-4	30	85
2	2-3 , 3-2	75	80	**7**	5-6 , 6-5	62	115
3	2-4 , 4-2	35	75	**8**	5-7 , 7-5	42	50
4	3-5 , 5-3	28	110	**9**	6-8 , 8-6	15	40
5	4-5 , 5-4	52	90	**10**	7-8 , 8-7	23	55

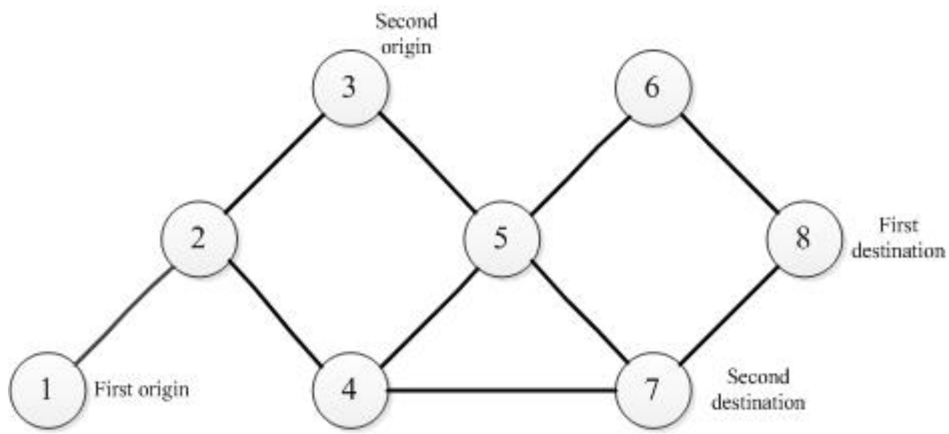

Figure 1. An overall view of illustrative example network

Table 2 shows the results of running models in GAMS. As shown in Table 2, the values of the risk distribution and the minimum distance for the above mentioned techniques were obtained. It is noteworthy that the amount of minimum distance for the proposed network has an equal value in all three models. Additionally, because of running these models over a small size network, the results show that all three developed techniques have a same variance. The obtained variance for these models is equal to 697000,000. So, in order to have a better investigation, an experimental road network will be checked at the next stage of the paper.

Table 2. Models' risk values and corresponding traveled distances over the network

Model	**Total Risk**	**Traveled Distance**
Bounded proportional risk	3556144	97000
Maximum risk	708589	97000
Minimizing absolute error	92400	97000

4. Case Study and Experimental Analysis

The network of Guilan province, which has been selected as a case study for this research, is a node-arc type, meaning that the nodes represent cities, trinkets, towns in the network, and the links connecting the nodes represent the connecting paths between the points which is shown as an arc. The network has 46 nodes and 126 bilateral links. The risk level in each of the communication axes of the studied network is determined. Also, the amount of relocating hazardous deliveries from the destination to certain and unchangeable destinations and the risk of changes to the transfer of hazardous materials in the network are negligible. Ranges of distance and risk assessed at each return link are equal. Also, the distance of each edge in the network is also known. By solving the problem model, the value of the bounded proportional risk model is determined, which is 1.023243×10^7. It should be noted that in the bounded proportional risk model, the value of $\alpha\%$ is assumed to be 0.2%. The degree of variance with the changes in the value of $\alpha\%$ is a generally stable trend, as shown in Figure 2. However, by increasing the value of $\alpha\%$ to the values above 0.2, the value of the objective function will not change. As shown in the graph, the value of the objective function is downward trend and is declining along with an increase in the value of $\alpha\%$. Also, by comparing the two graphs and the point of their collision, which, according to what is visible in Figure 2, cut off each other at a point in the range of [0.04,0.05]. Therefore, it can be concluded that the appropriate $\alpha\%$ value for a bounded proportional risk model is a value within this interval.

Table 3. Bounded proportional risk model analysis

α	**Model Output ($\times 10^7$)**	**Variance ($\times 10^8$)**
1%	8.052938	2.072134
2%	4.026469	2.072193
3%	2.684313	2.072134
4%	1.342156	2.072134
5%	1.026861	2.093338
10%	1.024748	2.093338
20%	1.023243	2.093338

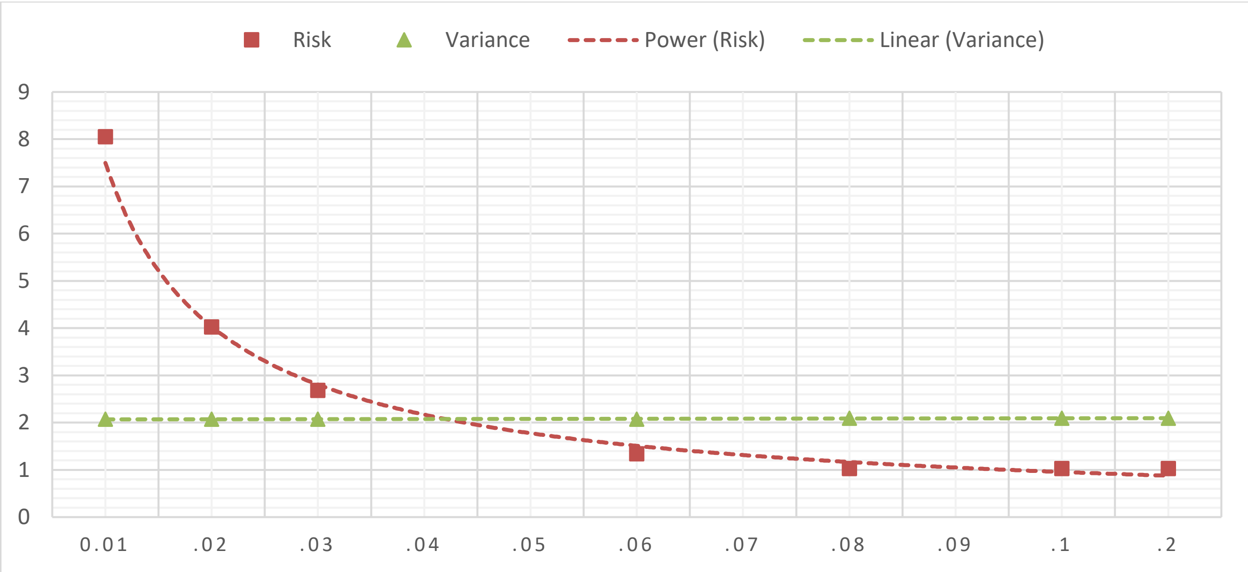

Figure 2. Bounded proportional risk model values

Solving the model revealed that the value of objective function model in the maximum risk model is determined as 805294 and 1488875 for minimizing the absolute value. As can be observed in Table 4, by examining the variance level of each of the three main models that include bounded proportional risk, maximum risk, and absolute magnitude error model, and according to the considered criterion for decision making, for the main problem of this research, which is the proper distribution of risk in the network, the maximum risk model has less variance than the other two models, so it can be said that a more appropriate model for optimal and equitable distribution of risk in the network will be investigated. The values for the least distance traveled by each of the three models under consideration with respect to the objective functions and the constraints of each one of them and calculations by the corresponding software are given in Table 4. It can be said that the differences are relatively small.

Table 4. Variance and minimum traveled distances for three risk distribution approaches

Model	**Variance (10^8)**	**Minimum Traveled Distance**
Bounded proportional risk	2.093	1748706
Maximum risk	1.555	1783266
Minimizing absolute error	2.058	1749012

5. Summary and Conclusion

In this research work, three different approaches of distributing bounded proportional risk, maximum risk as well as the absolute magnitude error have been developed and investigated for Hazmat risk distribution over the road network. Three approaches have been utilized in the case study of intercity road network in Guilan province located at the north of Iran. Results obtained for the risk values and variance of each model and the analysis of the results, it is observed that the maximum risk model has the less variance compared to the other two models. Therefore, it will be selected as the selected model to meet the main goal of the research, which is the proper distribution of risk in the network. Then, the absolute value error model and the bounded proportional risk model will be known as the best approach for Hazmat transport risk distribution over the intercity network.

Further researches in this area are recommended to extend the current research to a larger, nationwide scale, or to distribute risk for a specific category of hazardous materials that are present more than other materials in the road network of Guilan province and are of higher importance for the safe delivery. Further studies can be also focused on other methods for distributing risk in the network, changing the studied parameter or changing the decision criteria for distribution of risk in the network, minimizing variance, and turning the nonlinear model into a linear model.

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Biographies

Mahdieh Mahmoudabadi was born in 1990, received the BSc. in Civil Engineering from Iranian University of Science and technology, in 2014 and MSc. in Transportation Engineering from Sharif University of Technology in 2017. Since 2016, she has been working as transport research assistant in Parseh in the field of road safety transport planning. As a researcher, she focuses on operation management techniques, and Hazmat transportation. In addition to her roles as a research assistant at Sharif University of Technology, she has also published many national and international conference papers in the field of optimization and transportation.

Abbas Mahmoudabadi is faculty member in Industrial Engineering at MehrAstan University, Guilan, Iran. He received Ph.D. degree in January 2014 in the field of optimization in Hazmat transportation and received Thesis Dissertation Award from IEOM society in 2015 as well as many others in the recent years. He has published near 75 journal or international conference papers published in the field of industrial engineering, transportation and traffic safety and e-commerce. He teaches transport, industrial engineering and electronic commerce courses at universities including supervision rules for MSc. students who study in the fields of transportation, industrial engineering, e-commerce and construction engineering. He has around 24 years of experiences on traffic and road safety planning in developing countries working on the field of transport planning as a national authority and advisory cooperation on making Iranian road safety action plan. He has also strong cooperation with national and international agencies on traffic safety and industrial engineering.

Nillofar Afifi Kisomi was born in 1991 received the BSc. in Industrial Engineering in 2014 and MSc. in 2017 from MehrAstan University, Guilan, Iran. As a researcher, she focuses on operation management techniques such as location allocation, routing problem and hazardous material transportation. She has been working as an industrial engineer expert in Guilan industries and has also published some national conference papers in the field of optimization and location allocation problems.

Arash Gholami received MSc. in Electrical engineering in 2014 and is currently Ph.D. student in electrical Engineering at Islamic Azad University, Science and Research Branch, Tehran, Iran. Since 2015, he has been working as an expert in Tehran Chamber of Commerce, Industry, Mines and Agriculture. He has also published many national and international conference papers in the field of electrical engineering.