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Original Paper

How do the Risk Equity Techniques Affect on Intercity Road Network Accessibility? An Empirical Study

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Abstract

Due to existing risk on hazardous materials transportation, it is essential to avoid risk agglomeration over the specific edges which are frequently used on the intercity road network. Therefore, local and/or national authorities are dealing with distributing risk over the network while risk distribution may affect on the network accessibility. The aim of this study is to propose a procedure and develop mathematical models to distribute Hazmat transport risk, named risk equity, on the intercity road network and investigate the effects on the network accessibility. Accessibility is defined as dividing transport demand by distance, where the Min (Max) risk distribution technique is utilized for risk equity over the network. The effects have been investigated on a medium size of intercity road network in Guilan province, at the north of Iran. The proposed procedure and mathematical models have been run using experimental data including 46 nodes and 126 two-way edges including Hazmat Origin-Destination matrix. The results revealed that risk distribution technique has significant effects on network accessibility in which nodes' accessibilities are statistically affected by risk equity models.

Keywords

hazardous material transportation, risk distribution and equity, network accessibility, intercity road network, mathematical modeling

1. Introduction

1.1 Hazardous Materials

According to US Department of Transportation, hazardous materials (Hazmat for short) include any material or substance that is capable of damaging humans, property, and environment. The European convention for carrying dangerous goods by road classifies hazardous materials (dangerous goods) into nine classes of explosives, gases, flammable liquids and solids, oxidizing materials, toxic substances, radioactive materials, corrosive substances and miscellaneous (UNECE, 2017). Since, reducing fatalities and property losses as well as increasing the reliability and promoting transport safety have become the main goals of transport industries; hazardous materials transportation is now being the main concern due to existing possible harms to humans and the environment. Given the catastrophic consequences of Hazmat transport accidents, using proper means to cut the resulting losses is very essential. The existing various hydrocarbon products such as types of petrochemicals along with exporting these items and the neighboring countries make Hazmat transport is more important. Finally, the geographical location of Iran, as one of the most suitable transit routes for goods, makes Hazmat transport should be safer and more sustainable in the above country (Yousefi et al., 2017).

1.2 Hazmat Transport Risk and Modelling

There is a very important issue in Hazmat transportation known as "transport risk". By definition, risk represents the relationship between the hazards and the vulnerability factors for one or more components. The high risk component is also defined based on the chance of occurrence and its consequences (Yousefi et al., 2017). Transport risks, in transporting hazardous materials, include four main components of accident severity and frequency, affected population, environment and road infrastructures (Mahmoudabadi & Seyedhosseini, 2014). So, risk reduction techniques should be applied together with considering transportation costs as an important measure in Hazmat transport procedures. The well-known method of risk management is to determine the safest path on Hazmat transportation which known as the term of "Hazmat routing problem". Routing means finding the best route in Hazmat transportation but it does not necessarily mean the shortest path. Different approaches have been examined for solving these models while the most frequented techniques are based on mathematical modeling (Seyedhosseini & Mahmoudabdi, 2010).

In modeling Hazmat routing problems, the objective function is mainly defined in three categories: two-level, two-stage, and sometimes utility function. In two-level objective function, the mathematical model has two consequent objectives in which one is usually used as a constraint for the other. In two-stage model, the first step is to solve the routing problem and determine a set of paths followed by selecting the best route by local or national experts. Through the utility objective function, the main issues such as environmental effects and transportation costs are measured based on the weighted utilities. Apart from the above mentioned, the relevant studies showed that network size and attributes have significant effect on selecting the solution approach to solve Hazmat routing problem (Seyedhosseini & Mahmoudabdi, 2010). Researches on the above problem are generally focused on two areas of determining the transportation risk to cross a particular route and determining the route with the minimum risk and cost for Hazmat transport (Carotenuto et al., 2007).

In 2004, Zografos and Androutopoulos (2004) presented a heuristic algorithm to solve the problem of hazardous materials' distribution. From their points of view, the routing of hazardous material distribution is developed as a two-objective model formulation with a time window in which risk and cost are simultaneously minimized. Risk has been also considered as a main concern in chaotic pattern of Hazmat routing problem under emergency conditions (Mahmoudabadi & Seyedhosseini, 2014) where transport authorities are dealing with finding the safest path over a damaged network together with the considering transport time in emergency situation. An iterative procedure has been further made to follow the concept of chaos theory in Hazmat routing problem where each path is selected by combining risk and cost (time). In the background of locating hazardous materials in the network, Alamur and Kara (2007) presented a new multi-objective model as well as many limitations in which the management of wastes involves the transportation and waste disposals. In their research, the goal was to find the hazardous waste disposal centers and determine the type of technology for waste disposal followed by determining the routes for each waste type. They have successfully decreased 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.

Regarding the calculated risk, Tavakkoli-Moghaddam et al. (2015) focused on developing a model for finding routes and locations of hazardous materials transportation. They determined the ideal least risk routes at the first stage followed by reducing total cost at the second stage. To validate the model together with validating the outputs, a model had been developed and implemented in a network and concluded that the model has enough credibility to locate distribution centers and to find routes hazardous materials transportation. While routing is an important issue that should be considered in Hazmat transport (Mohammadi et al., 2015), but in practice, routing is perceived as one of the best subjects for operation research (Kheirkhah et al., 2016) into two perspectives. The first is a practical problem and finding the best solution can lead to economic saving and the second is that the solution is challenging because the problem is so difficult to be solved (Mester et al., 2007). Following the above, it is concluded that the routing in Hazmat transportation does not necessarily mean finding the shortest route, but it should be attempted to determine the safest route and considering other transport attributes as well (Carotenuto et al., 2007).

1.3 Hazmat Risk Equity

It is time to define another concept in Hazmat transportation known as "risk equity". 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 agglomerated in a few links and have a fair, logical and partly balanced distribution of risk to all links (Boyer et al., 2013). There are several methods for risk distribution in Hazmat transportation where different policies can be made on distribution of probable risk in the network and equity in risk allocation as well as a series of predetermined factors is prioritized (Alumur & Kara, 2007). For example, among these policies, it is possible to highlight the safety of the most used network paths, which aims to minimize the risk in the network where the economic indicator is traveled distance which should be minimized over the network (Alumur & Kara, 2007).

1.4 Accessibility

Accessibility, a key concept in transport planning, is defined as the extent to which the land-use and transportation systems enable (groups of) individuals to reach their activities or destinations (Thomas et al., 2003). In freight transport; regional accessibility is an important factor which promotes economic growth of the region (Bowen et al., 2008). Variation of travel time or distance in transport network causes unreliability that may lead to more shipping cost and inefficient operation of manufacturing in industries. Because of the importance of accessibility, it has been studied in many ways and defining and applying different transport indicators in the relevant areas (Lim & Till, 2008). In practice, accessibility is evaluated by its measures which are used as metrics for evaluating transport performance especially to indicate the vulnerability of network where they concentrate on increasing the accessibility of regions. Several measures have been proposed to evaluate freight accessibility while most of them use average travel time (distance or cost) between origin and destination (Lim & Till, 2008).

One of the well-known equations for evaluating accessibility is gravity model in which accessibility receives direct effects from weight and in reverse from distance or cost. Gravity based models (also called potential accessibility) measure weight opportunities, usually the quantity of an activity in a certain area, by impedance which is mainly defined by a function of distance, travel time, or travel cost (Verhetsel et al., 2015). Equation (1) formulates the potential accessibility where A_j is the accessibility of zone j; w_j is the weight representing the attractiveness of zone j; t_{ij} is a measure of separation or impedance between zone i and j, and; $f(t_{ij})$ is an impedance function between zones i and j.

$$A_j = \sum_i w_j . f(t_{ij}) \tag{1}$$

1.5 Vision Statement

Following the above mentioned, risk equity is a very important concern in Hazmat transportation which is achieved by selecting low risk paths over the network. On the other hand, selecting the low risk paths may cause imposing long distance or highly cost paths and affects on the network accessibility. Therefore, the effects of risk distribution techniques on the road network accessibility should be investigated by mathematical models and experimental data. In order to compare results, a statistical method of two-sample test is utilized. In this case, analyze of variance is performed to check the differences between two cases of considering, and not considering risk equity constraint for solving Hazmat routing problem. Checking the results in a real network will also help decision makers to rationally decide on considering Hazmat transport risk equity in Hazmat transport planning.

2. Mathematical Modeling

There are two policies regarding risk distribution method and accessibility. The first is to determine Hazmat routes according to the lengths of links named here as distance based method. The shortest paths are determined according to each origin-destination pairs abbreviated as OD. The second model is to determine paths in which the maximum risk associated to the network links is minimized. It is now called the Min (Max) risk method, where all OD pairs are simultaneously satisfied over the intercity road network. From now on, models' developing procedures will be discussed in detail.

2.1 Indices

G: Intercity road network including nodes and edges (links);

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) , $(j,i) \in G$;

o : Origin node in the set of OD pairs;

d : Destination node in the set of OD pairs;

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

2.2 Parameters

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

R_{ij} : Associated risk to edge (i, j) ; In this research work it is assumed that for each two-way links $R_{ij} = R_{ji}$;

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

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

The first objective function is formulated by equation (2) in which total traveled distance is minimized. Total traveled distance also represents the total cost as a measure to optimize routes. The results are obtained for all OD pairs including assigned links for each.

$$\text{Min } Z_1 = \sum_{(o,d)\in OD} \sum_{(i,j)\in G} N_{od} \times L_{ij} \times X_{ij}^{od} \tag{2}$$

The first constraint is to keep continuous path for each OD pairs. This constraint is formulated by equation (3) where Ex is the set of exiting links and En is the set of entering links to node "j". This equation guarantees that the path assigned to each OD pairs is seamless. More detail on this formulation is available at (Taha, 2008) in general modeling and at (Mahmoudabadi & Seyedhosseini, 2014) in Hazmat transport routing problems and practice.

$$\sum_{i\in E_x(j)} X_{ji}^{od} - \sum_{i\in E_n(j)} X_{ij}^{od} = \begin{Bmatrix} 1 \text{ if } j = o \\ -1 \text{ if } j = d \\ 0 \quad O.W. \end{Bmatrix} \forall\, j \in G \,\&\, (o,d) \in OD \tag{3}$$

This model determines the shortest paths for all OD pairs without considering the risk equity over the network. The second objective function is to determine the paths for all OD pairs while risk equity is applied. In this model, the maximum risk associated to the network links is minimized by equation (4).

$$\text{Min } Z_2 = \text{Max}\left\{\sum_{(o,d)\in OD} N_{od} \times L_{ij} \times R_{ij} \times X_{ij}^{od} \quad \forall\,(i,j) \in G\right\} \tag{4}$$

Because Min-Max approach, formulated by equation (4) is a nonlinear equation, a simple linearization technique is used to simplify the model where the new variable U is defined to be assigned by the maximum value of risk associated to all selected links. The objective function is formulated as equation (5), while equation (6) is necessarily formulated to assign the maximum risk associated to link to variable U.

$$\text{Min } Z_3 = U \tag{5}$$

$$\sum_{(o,d)\in OD} N_{od} \times L_{ij} \times R_{ij} \times X_{ij}^{od} \le U \quad \forall\,(i,j) \in G \tag{6}$$

In both models, the shortest paths' distances determined for OD pairs are obtained by equation (7) where TS_{od} is the distance between the origin "o" to destination "d". Noticeably, the above mentioned parameter is obtained after solving mathematical models.

$$TS_{od} = \sum_{(i,j)\in G} L_{ij} \times X_{ij}^{od} \quad \forall\,(o,d) \in G \tag{7}$$

Accessibilities for destination nodes are now calculated by equation (8) where ACC_d is the accessibility measure for destination node "d".

$$ACC_d = \sum_{o\in G} \frac{N_{od}}{TS_{od}} \quad \forall\, d \in G \tag{8}$$

The final stage is to statistically compare the accessibilities calculated after running the proposed models. The well-known statistical measure of paired samples for means is now utilized for comparing the results. In this case, the null and alternative hypotheses are defined as follow:

H_0: Destinations' accessibilities are equal for both routing models.

H_1: Destinations' accessibilities are significantly different.

The t-student stat is now calculated by equation (9) where $\overline{X_d}$ is the mean of changes on accessibilities, σ_d their standard deviation and n is the number of destinations. T-stat is compared to t-student table with the defined criteria.

$$t = \frac{\overline{X_d} - 0}{\sigma_d / \sqrt{n}} \tag{9}$$

3. Case Study and Experimental Analysis

3.1 Case Study

The intercity road network of Guilan province, which has been selected as the case study, is a node-arc network. It means that the nodes represent cities or intersections and links connect them over the road network. The road intercity network includes 46 nodes and 126 two-way edges. Two-way edge means that two opposite directions of movement are available. The risk level for each link has been estimated in another study conducted by a student in MehrAstan university published in Persian language (Mahmoudabadi & Abouhashemi, 2016). The ranges of distance and the risk assessed at each return link are assumed equal to the main link. The length of each edge in the network is also available and derived by the map depicted in Figure 1.

Figure 1. Guilan Intercity Road Network Map

3.2 Experimental Analysis

Two proposed models have been run through the experimental data and results are tabulated in Table 1. The first and the second columns are respectively destination code and its name followed by total demand received at destination in the third column. The fourth and fifth columns are accessibility measures obtained by equation (8) in the cases of without and with the considering risk equity, respectively. The last column shows the difference of potential accessibilities. For instance, destination name for code 3 is "Amlash" with total Hazmat received of 217 Thousand tons per year. If risk equity is not considered in modeling, potential accessibility measure is equal to 3.56. In the other case where risk equity is considered, accessibility measure will fall down to 2.09. Accessibility measures for all destinations, depicted in Figure 2, help decision makers to understand the existing differences between the results of two approaches where the accessibility graph while constraining risk equity is always under the other one. As shown, potential accessibility measures are always decreased when risk equity is considered as a constraint. Therefore, it can be sensibly concluded that adding the risk equity constraint distributes risk over the network, but it makes to select the paths with longer distances on Hazmat transport which eventually decrease nodes' accessibilities over the network. It is time to check the statistical differences of accessibility of two approaches. Since difference for both approaches should be investigated, the well-known statistical technique of paired two sample means, available at Excel, has been utilized and results tabulated in Table 2. As observed, the mean of accessibility measure from 27.04 is decreased to 18.80 in the case of constraining risk equity. Assuming the null hypothesis of zero for mean revealed that t-Stat calculated by equation (9) is equal to 3.1378. It is greater than one-tail critical value of 1.7531, so the null hypothesis is rejected showing that considering risk equity has significant effect on intercity road network accessibility.

Table 1. Accessibility Measures Obtained by Mathematical Models

Row/Code	Destination Name	Total Received Demand (1000Ton)	Accessibility measure without risk equity	Accessibility measure with risk equity	Difference
1/3	Amlash	217	3.56	2.09	1.47
2/5	Astara	2059	10.01	8.52	1.48
3/6	Astaneh	474	14.79	8.44	6.34
4/9	Anzali	2625	67.31	27.34	39.96
5/11	Talesh	2384	18.77	17.94	0.83
6/22	Rasht	94	1.53	1.45	0.08
7/23	Rezvanshahr	2669	37.59	24.26	13.33
8/24	Rudbar	3622	51.65	51.57	0.08
9/26	Rudsar	2357	34.16	18.33	15.83
10/28	Siahkal	502	15.50	6.84	8.66
11/29	Shaft	356	14.17	14.17	0.00
12/31	Somehsara	1239	36.37	21.32	15.05
13/32	Fouman	805	25.37	12.95	12.42
14/38	Lahijan	2479	74.23	74.23	0.00
15/40	Langrood	1161	22.44	7.89	14.55
16/44	Masal	276	5.15	3.42	1.74

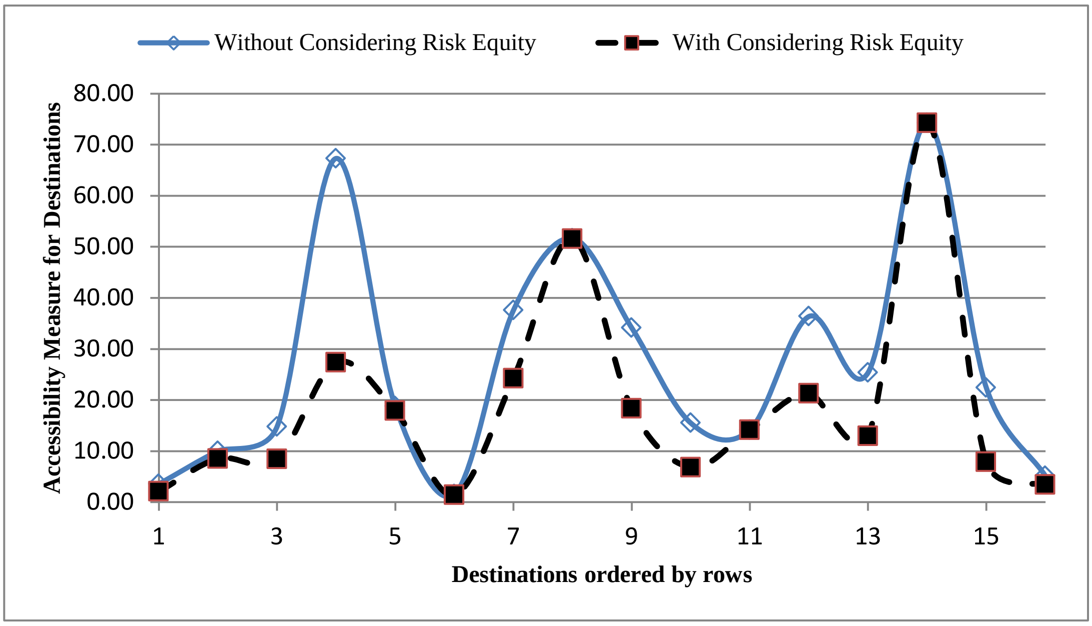

Figure 2. Accessibility Measures for All Destinations with and without Considering Risk Equity

Table 2. Results of Paired Two Sample Test for Means of Accessibilities with and without Risk Equity

	Without considering risk equity	With considering risk equity
Mean	27.037	18.797
Variance	481.028	373.568
Observations	16	16
Pearson Correlation	0.878	
Hypothesized Mean Difference	0	
Degree of Freedom	15	
t Stat	3.1378	
P(T<=t) one-tail	0.0034	
t Critical one-tail	1.7531	
P(T<=t) two-tail	0.0068	
t Critical two-tail	2.1314	

4. Summary and Conclusion

In this research work, two different mathematical models on Hazmat routing problem have been developed and their effects on road network accessibility investigated. The first model is to determine the routes for carrying hazardous materials over the network in which no concern assumed for risk equity over the links. But the second is to determine the routes through considering risk equity which means that the model distributes Hazmat transport risk over the road network. One of the northern-west provinces of Iran, named Guilan, has been selected as the case study where the network specifications and attributes as well as and risk associated with links were available. Running model by using experimental data revealed that considering risk equity has significant effects on network accessibility.

Further researches who are interested in this area are recommended to extend the current research work to a larger, nationwide scale, or to distribute risk for specific categories of hazardous materials. More studies can also be conducted on other methods of risk distribution in the network, changing hypothesis test method or parameter.

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