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A ROUTING METHODOLOGY FOR HAZARDOUS MATERIALS TRANSPORTATION TO REDUCE THE RISK OF ROAD NETWORK

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Abstract*: The shipments of hazardous materials (HAZMATs) induce various risks to the road network. Today, one of the major considerations of transportation system managers is HAZMATs shipments, due to the increasing demand of these goods (because it is more used in industry, agriculture, medicine, etc.), and the rising number of incidents that are associated to hazardous materials.*

This paper presents a tool for HAZMATs transportation authorities and planners that would reduce the risk of the road network by identifying safe and economic routes for HM transshipment. Using the proposed linear integer programming model, the HM management system could determine an optimal assignment for all origin–destination pairs for various hazardous materials in a transportation network and so reduce the vulnerability due to HAZMATs releases such as population and environmental vulnerability. The model is implemented and evaluated for the hazardous materials routing within Fars, Yazd, Isfahan, and Chaharmaha-o-Bakhtiyari provinces of Iran. The branch-and-bound algorithm is applied to solve the model using the Lingo software package.

Keywords*: Transportation network, Hazardous materials, Risk index, Routing, Network optimization.*

1. Introduction

Today, hazardous materials (HM) such as explosives, flammable liquids, toxic gases and infectious substances are being widely used in different fields such as industry, agriculture and medicine. In most cases, the production site is far from the consumption site and so the goods must be transported to the consumption site from the production site. Due to the hazardous nature of these substances, safety measures must be provided for them during all production, storage and transportation process. The history of HM accidents and their release emphasizes the importance of this subject. Risk analysis, the location of facilities, routing and scheduling are the main problems in transportation of such substances. In routing problem, on one hand, HAZMATs shipment must be economic enough to have the potential to attract investment and on the other hand, some safety measures must be provided to reduce the risk of HAZMATs transportation.

Since 1980, many researchers have undertaken studies in this field and many methods have been presented for routing the shipment of these substances. Routing of these materials is a tradeoff between cost and risk for each O-D pair. These studies can be categorized based on the dependency of their networks on time (time-independent or time-dependent networks) or the objective functions of their models (one-objective or multi-objective models).

In time-independent (time-invariant) networks, it is assumed that the features of network links such as travel time and risk are constant. But in time-dependent (time-varying) networks, these features are variable. For instance, in time-dependent networks, the travel time on the link depends on the length of link and the time of day due to the variation of the traffic conditions of the network. Therefore, in such networks, risk and travel time are random variables with a probability distribution function.

In one-objective models, the shortest path algorithm has been used. In these models, depending on the objective function, the intended attribute is considered to be the label of links. For example, Kara & Verter (2004)

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[1], presented a two-phased model in which the objective of the first phase (public sector) is to minimize the population risk and that of second phase (private sector) is to minimize the travel length. Similarly Carotenuto et al. (2007) [2] have used population risk as the link label.

The difference between multi-objective models proposed in the literature is that whether or not a utility function has been used to combine the objectives. In the models where a utility function has been used, the multi-objective model reduces to a one-objective model which could be solved by the shortest path algorithm.

In this case, the selected path is very sensitive to the change in parameters of the utility function. For example, Ashtakala & Eno (1996) [3] have included in the objective function, the weighted combination of normalized population and environmental risk. Likewise, the utility function based on a model introduced by Haghani and Chen (2003) [4] is to minimize the weighted combination of three objectives: O-D travel time, vulnerable population on the route and that on intermediate nodes. However, models that have not used utility function provide a set of pareto-optimal paths (non-dominated paths). Non-dominated paths are a set of paths that none of them have any advantage or preference over others based on all the objectives. In such cases, it is up to the decision maker to select the preferred alternative. For example, the model proposed by Penwahr et al. (2000) [5] considers optimal non-dominated paths based on the least special population risk and least travel time. The objectives that have been used in the pareto-optimal solutions as reflected in the Huang and Ferry method [6] include travel time, probability of release accidents, population risk, special population risk, environmental risk, private sector cost, damages resulting from delayed emergency response teams, and security risk. The objective of Meng's model is to identify non-dominated paths between an origin-destination pair in a time-varying network based on travel time and other criteria such as vulnerable population [7].

The Attributes of the model proposed by Miller-Hooks & Mahmassani (1998) [8] are travel time and vulnerable population and its objective is to determine the optimal path in a time-varying network based on a tradeoff between cost and risk. In the model devised by Nozick and Turnquit, the number of objectives is optional [9]. In this study the travel time and vulnerable population have been considered as random variables.

In general, the factors that affect the routing of hazardous materials can be categorized into two parts; the first category are those related to the risk considerations and depends on vulnerable elements including population risk, special population risk, environmental risk and property risk.

The second part is related to the economic considerations and includes travel cost, travel length and travel time. Special populations groups such as schools, hospitals and shopping centers are groups that may be particularly sensitive to hazardous materials releases, may be difficult to evacuate, and are highly concentrated, or are outdoors [10]. It is clear that economic measures are dependent upon each other and because of this, only one of them is applied in the optimization problem, while several risk measures from the first category may be applied.

2. Risk Consideration

This paper uses Eq. (1) for risk assessment:

$$R_i = P_i\, C_i \tag{1}$$

Where R_i is the risk of link i, P_i is the occurrence probability of the release accident on link i and C_i is the measure of release accident consequence on link i.
Since risk on the whole route is equal to the sum of the risks of its contributing links, the risk of a route is specified as follows [11]:

$$TR(r) = \sum_i P_i.C_i \qquad ;\forall i \in r \tag{2}$$

Where $TR(r)$ is the risk on route r.

In addition, according to Eq. (3), HM incident probability has been used to calculate the occurrence probability of a HM accident. (More details can be found in [12].)

$$P_i = P(A)_i = Rate(A)_i.l_i \tag{3}$$

Where P_i is the occurrence probability of a HM accident on link i, $P(A)_i$ is the HM incident probability, $Rate(A)_i$ is the rate of HM incident on link i (for per million vehicle-km) and l_i is the length of link i (km).

The vulnerable components that have been considered in this study include those of population and environment (C_i). To determine the amount of population and environment exposure, the impact radius method is used as follows [10]:

$$IA_{i,c} = 2\,d_c\,.l_i \tag{4}$$

$$PV_{i,c} = IA_{i,c}\,.PD_i \tag{5}$$

$$EV_{i,c} = IA_{i,c}\,.ED_i \tag{6}$$

Where $IA_{i,c}$ is the impact area along link i due to shipment of HM class c on link i (km^2), d_c is the impact distance of HM class c (km), l_i is the length of link i (km), $PV_{i,c}$ is the population exposure on link i for the shipment of HM class c (people), PD_i is the population density on link i (people/km^2), EV_i is the environmental resource exposure on link i for the shipment of HM class c (km^2) and ED_i is the density of environmental resource on link i for the shipment of HM class c (km^2/km^2).

In order to improve the capabilities of the model, some simplifying assumptions have been used based on available data. The application of these hypothesis results in the calculation of relative risk rather than absolute risk. As the aim of this study is to determine the

optimal assignment of HM trucks and in other words the aim is to compare some alternative routes and find a preferable option, the application of relative risk would be acceptable.

3. Cost Considerations

There is another criterion that matters in HAZMATs routing other than safety criteria (risk criteria), and that is the cost of transportation. It is obvious that risk and cost measures are two competitive and opposite criteria. Abkowitz et al. (1991) [13] showed that if routing model is only based on risk factor, the length of the obtained route would be at least twice the shortest route, which can not be accepted from an economical point of view. In earlier studies, travel cost, travel time and travel length have been considered as the cost of transportation in HAZMATs routing models.

In this study, travel time has been considered as transportation cost. It is assumed that this measure is a time-independent variable. It is obvious that when the length and average travel speed on each link is specified, the travel time on that link can be calculated.

4. Problem Formulation

Consider a transportation network *N(V,A)* where *V* is the set of network nodes and *A* is the set of network links such that the links ($i \in A$) posses population and environmental risk limitations. This network has three different types of nodes: origin nodes, destination nodes and intermediate nodes.

The aim is to ship a definite quantity of various HAZMATs between several O-D pairs. In other words, O-D matrix for different kinds of HAZMATs is definite and specified.

There are some alternative routes to transport these materials from origins to destinations. The problem is to determine the optimal assignment of truck flow within this transportation network that minimizes the weighted combination of objectives.

The linear integer programming problem is expressed by Eq. (7). Where, u_{PR}, u_{ER} and u_T are respectively the utility of objectives; population risk, environmental risk and travel time in the network ($0 \le u_i \le 1$), Z_{PR}, Z_{ER} and Z_T are respectively population risk, environmental risk and travel time of the network, Z_{PR}^{max} and Z_{PR}^{min} are respectively the maximum and minimum population risk in the network, Z_{ER}^{max} and Z_{ER}^{min} are respectively maximum and minimum environmental risk, Z_T^{max} and Z_T^{min} are respectively maximum and minimum travel time, $N_{i,c}^{k,r}$ is the number of trucks carrying HM class *c* on link *i* in route *r* from O-D pair *k* (decision variable), $N_{.,c}^{k,r}$ is the number of trucks carrying HM class *c* on route *r* from O-D pair *k*, $N_{.,c}^{k,.}$ is the demand of (number of trucks carrying) HM class *c* from O-D pair *k*, $PR_{i,c}$ and $ER_{i,c}$ are respectively the base population and environmental risk on link *i* due to passing HM class *c* on that link (or the population and environmental risk on link *i* due to passing a truck of HM class *c* on that link), $T_{i,.}$ is the travel time on link *i*, ER_{max} and PR_{max} are respectively the maximum allowable (upper-bound) population and environmental risk on unit-length links, l_i is the length of link *i* and $\delta_{i,.}^{k,r}$ is the binary parameter of link-incidence.

The decision variable that is the number of trucks carrying HM class *c* on link *i* on route *r* from O-D pair *k* and ($N_{i,c}^{k,r}$) is therefore an integer variable.

$$
\begin{aligned}
&(S)\ Max\ \{u_{PR}, u_{ER}, u_T\}\\
&subject\ to:\\
&1)\quad u_{PR} = \frac{Z_{PR}^{max} - Z_{PR}}{Z_{PR}^{max} - Z_{PR}^{min}}\\
&2)\quad u_{ER} = \frac{Z_{ER}^{max} - Z_{ER}}{Z_{ER}^{max} - Z_{ER}^{min}}\\
&3)\quad u_T = \frac{Z_T^{max} - Z_T}{Z_T^{max} - Z_T^{min}}\\
&4)\quad Z_{PR} = \sum_i \sum_c \sum_k \sum_r N_{i,c}^{k,r} . PR_{i,c}\\
&5)\quad Z_{ER} = \sum_i \sum_c \sum_k \sum_r N_{i,c}^{k,r} . ER_{i,c}\\
&6)\quad Z_T = \sum_i \sum_c \sum_k \sum_r N_{i,c}^{k,r} . T_{i,.}\\
&7)\quad \sum_r N_{.,c}^{k,r} = N_{.,c}^{k,.} \qquad ;\forall c, k\\
&8)\quad \sum_c \sum_k \sum_r N_{i,c}^{k,r} . PR_{i,c} \le PR_{\max} . l_i \qquad ;\forall i\\
&9)\quad \sum_c \sum_k \sum_r N_{i,c}^{k,r} . ER_{i,c} \le ER_{\max} . l_i \qquad ;\forall i\\
&10)\quad N_{i,c}^{k,r} = \begin{cases} N_{.,c}^{k,r} & d_{i,.}^{k,r} = 1 \\ 0 & d_{i,.}^{k,r} = 0 \end{cases} \qquad ;\forall i, c, k, r\\
&\qquad N_{i,c}^{k,r} \quad Integer \qquad ;\forall i, c, k, r
\end{aligned}
\tag{7}
$$

Equation (8) has been used to combine all three objectives into a utility function and convert the multi-objective function into a single-objective function.

$$Max \quad U = w_{PR} u_{PR} + w_{ER} u_{ER} + w_T u_T \tag{8}$$

Where *U* is the total network utility ($0 \le U \le 1$), u_{PR}, u_{ER} and u_T are respectively the utility of objectives; population risk, environmental risk and travel time in the network ($0 \le u_i \le 1$) and w_{PR}, w_{ER} and w_T are respectively the weight of objectives.

Therefore, the objective function model has been defined as the maximization of the total network's utility (*U*). This measure is made up of a weighted combination

of utilities of population risk, environmental risk and travel time at the network level. Equation (9) has been used to calculate any one of those utilities [14].

$$u_i = \frac{Z_i^{\max} - Z_i}{Z_i^{\max} - Z_i^{\min}} \tag{9}$$

Where u_i is the utility of objective i, Z_i, Z_i^{max} and Z_i^{min} are respectively current, minimum and maximum values of objective i.

The values of utility measures are between 0 and 1. Also, the weighting system has two characteristics; the sum of these weights is equal to 1 and each weight is between 0 and 1. Therefore, the total utility measure value will be between 0 and 1.

$$0 \le u_i \le 1 \ , \ 0 \le w_i \le 1 \ , \ \sum_{i=1}^{3} w_i = 1 \Rightarrow 0 \le U \le 1 \tag{10}$$

Weighting systems are determinate by decision makers. The upper and lower limits of the utility function will help the analyst to interpret the model's results. This advantage of utility functions in the form of Eq. (9) is the reason of its application.

Constraints 1, 2 and 3 are the utility of different objectives. Constraints 4, 5 and 6 are the three objectives at the network level. The risk of the network is the sum of the risks of all links. Constraint 7 represents the fact that there are several paths between every O-D pair to which the O-D truck demand should be assigned.

Constraints 8 and 9 are respectively the allowed population and environmental risk limitations for links. These limitations are determined by the decision makers. These limitations together with minimizing related risks at the network level may raise the question on whether they overlap one another. It can be noted that principally they are neither opposite to each other nor synthetic or overlapped by each other.

In other words, optimizing a measure does not necessarily mean considering the limits of that allowed measure. On the other hand, in this model, a combination of objectives is used as the utility function, and the model does not minimize each single objective. It is therefore necessary to enter constraints in the model to consider these limits.

Constraint 10 defines the flow in the route. It is obvious that the flow on each link that belongs to a route connecting any O-D pair is equal to the flow in that route. In other words, if link i belongs to route r connecting O-D pair k ($\delta_{i,.}^{k,r}=1$), all the flow in route r is assigned to that link.

In addition, if the decision-maker is interested in adding a constraint as the minimum link flow (truck), a constraint as $N_{i,c}^{k,r} \le N'^{k,r}_{i,c}$ could be added to the model in which $N'^{k,r}_{i,c}$ is the minimum allowed number of passing trucks carrying HM class c on link i in route r connecting O-D pair k. It is obvious that such constraint would put a further limit to the feasible region or in other words it decreases the feasibility of solving the problem.

To calculate the maximum and minimum values of each objective, a model with the following general form must be solved:

(M) *Objective Function*

subject to:

1) $\sum_r N_{.,c}^{k,r} = N_{.,c}^{k,.} \quad ;\forall c, k$

2) $\sum_c \sum_k \sum_r N_{i,c}^{k,r} . PR_{i,c} \le PR_{\max} . l_i \quad ;\forall i$

3) $\sum_c \sum_k \sum_r N_{i,c}^{k,r} . ER_{i,c} \le ER_{\max} . l_i \quad ;\forall i$

4) $N_{i,c}^{k,r} = \begin{cases} N_{.,c}^{k,r} & d_{i,.}^{k,r} = 1 \\ 0 & d_{i,.}^{k,r} = 0 \end{cases} \quad ;\forall i, c, k, r$

$N_{i,c}^{k,r}$ *Integer* $\quad ;\forall i, c, k, r \qquad (11)$

Problem M is divided into six sub-models that are presented in table 1, based on objective functions.

5. Application Flowchart

In general, the application flowchart of the HAZMATs transportation routing problem that is shown in Fig. 1 consists of three sections:

5.1. Inputs

This part concerns the model input data and consists of data about the transportation network, population distribution, environmental resources distribution, HAZMATs information and decision maker information.

5.2. Calculations

Three operations are conducted in this section. First, the feasible paths between every O-D pair are identified based on the transportation network, so $\delta_{i,.}^{k,r}$ is obtained and the link labels are determined. The six sub-models are solved using this data so that all other required data for the solution of the major problem are in hand.

Tab. 1. Six sub-models

No.	Sub-model	Objective function
1	Maximization network population risk	$(M1)\ Max\ Z_{PR}$
2	Minimization network population risk	$(M2)\ Min\ Z_{PR}$
3	Maximization network environmental risk	$(M3)\ Max\ Z_{ER}$
4	Minimization network environmental risk	$(M4)\ Min\ Z_{ER}$
5	Maximization network travel time	$(M5)\ Max\ Z_T$
6	Minimization network travel time	$(M6)\ Min\ Z_T$

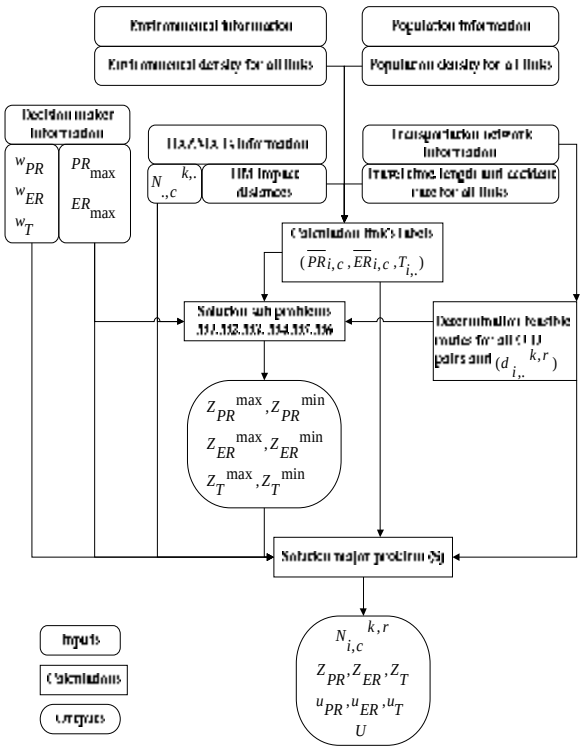

Fig 1. Problem solution algorithm

5.3. Outputs

Ultimately, the main output of the problem, which is the decision variable $N_{i,c}^{k,r}$ is obtained by solving the major problem. In addition, other outputs such as population risk, environmental risk and travel time at the network level or link level and utilities are calculated.

Also it is necessary to explain the two following items:

5.4. Link's label

Based on the population risk, environmental risk and travel time in the objective function, the vector label of any link of the network that consists of three elements can be defined as follows:

$$(\overline{PR}_{i,c}, \overline{ER}_{i,c}, T_{i,.}) = \left(\begin{bmatrix} PR_{i,1} \\ PR_{i,2} \\ . \\ . \\ . \\ PR_{i,c} \end{bmatrix}, \begin{bmatrix} ER_{i,1} \\ ER_{i,2} \\ . \\ . \\ . \\ ER_{i,c} \end{bmatrix}, T_{i,.} \right) \quad (12)$$

The first and second elements of the link label are a vector with *c* elements. All elements of the link label are fixed. To determine first and second elements of this label, data such as accident rate, link length, impact distance of HAZMATs, population density and environmental resources density for all network links are required.

5.5. Link-incidence matrix

Every route is a chain of links that connect two nodes. To define the feasible routes, a binary parameter $\delta_{i,.}^{k,r}$ was used.

$$d_{i,.}^{k,r} = \begin{cases} 1 & \text{If link } i \text{ belongs to route } r \text{ from O-D pair } k \\ 0 & \text{Otherwise} \end{cases} \quad ;\forall i, k, r \quad (13)$$

6. Case Study

The case study network is shown in Fig. 2. This study was undertaken in Fars, Yazd, Isfahan, and Chaharmahal-o-Bakhtiyari provinces. This network has 73 links and 66 nodes, three nodes of which are origins and destinations and other 70 nodes are intermediate nodes. The network links are numbered from 10 to 82.

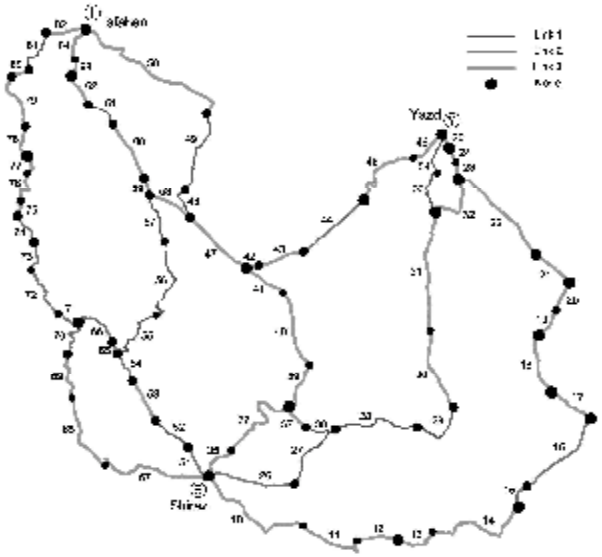

Fig 2. Case study Network

The network nodes have been chosen in such a way that the attributes of any link are constant. These attributes include link type (speed), population density [15] and environmental resource density [16]. Therefore, the nodes shown in Fig. 2 do not indicate a population center but indeed predominates as at least one of the mentioned attributes. The network links have been divided into types 1, 2 and 3; and travel speeds of trucks in these links are 40, 60 and 70 km/h, respectively.

O-D pairs, as specified in this study, are Shiraz-Yazd (SY) and Isfahan-Shiraz (IS). Therefore, the origins are Shiraz (S) and Isfahan (I) and the destinations are Yazd (Y) and Shiraz (S). Two considered kinds of hazardous materials are HM1 and HM2 with impact distance of 0.8 and 0.5 km, respectively. The demand matrix is shown in table 2. This matrix shows the demand of O-D pairs in terms of the number of trucks for both kinds of HAZMATs.

Tab. 2. Demand matrix (number of trucks)

HAZMAT	SY	IS
HM1	41	62
HM2	54	36

Table 3 shows some of the links' information in the network. In this table, it is assumed that the dimension of

accident rate on each link is accident numbers/billion vehicles-km. The level of available information was at the provincial and municipal levels. Due to this, the information about population density which was at the municipal level is shown in more details than that of environmental resource density.

There are 12 feasible paths in the network such that there are six paths between every O-D pair (R1, R2… R12). The routes between SY and IS are shown in Fig. 3. In the next step, it is necessary to calculate the impact area, vulnerable population, vulnerable environment and accident probability of all network links for two HAZMATs. Since these HAZMATs are in prospect, for each link two quantities are obtained for vulnerable population and vulnerable environment.

Then, population base risk and environmental base risk of all network links must be calculated. The base risk of a link is associated to the passage of a single truck with a certain class of HAZMAT and it is calculated using link accident probability (link accident rate multiplied by link length) multiplied by the vulnerable area (population and environmental vulnerability).

Population and environmental base risks on a link show respectively the expected values of vulnerable population and environment due to the passage of a truck. Also, since the length (hr) and speed (km/hr) of links are known, their travel time (hr) is calculable. Therefore, by far three attributes of the network links that are required as model inputs have been calculated; population base risk, environmental base risk and travel time of network links.

Tab. 3. Details of links in network

Link No.	Link type	L	Accident rate	Pop. density	Env. density
		km	10^{-9} /veh-km	pop/km^2	km^2/km^2
10	3	96.6	0.65	146.05	13.7
11	3	56.8	1.185	47.05	13.7
16	2	71.8	0.316	19.05	2.85
17	3	34.1	1.331	5.55	2.85
22	3	85.1	0.287	5.55	13.7
23	3	13.1	1.058	5.55	13.7
49	1	67	0.261	146.05	2.85
50	3	127	0.582	146.05	2.85
65	2	10.3	2.472	31.55	13.7
66	2	36.3	0.709	31.55	13.7
74	2	24.8	1.05	47.05	13.7

The values of travel time, population risk and environmental risk at two levels of the network links and the whole network are a part of model outputs. The travel time of a link or network correspondingly indicates the truck-hours traveled in a link or network. Population risk of a link or network correspondingly indicates the expected number of dead people or those of injured due to one billion trucks along the link or network. Environmental risk of a link or network correspondingly indicates the expected environmental vulnerability (km^2) due to the passage of one billion trucks along the link or network. It is obvious that by the division of link risk by the length of the link, the unit length risk of the link is obtained. In order to solve a model, it is necessary to include the data offered by the decision-maker. This data consists of the weighting system and risk limitations. In this case study, we consider the decision-maker data according to table 4.

Tab. 4. Decision-maker data

PR_{max}	ER_{max}	w_{PR}	w_{ER}	w_T
250000	40000	0.33	0.33	0.33

First, it is primarily necessary to solve the six sub-models for decision-maker data. At this stage, weighting systems have no effect and only the risk limitation must be considered (table 4).Table 5 shows the solution results of the six sub-models.

Tab. 5. Results of six sub-models

Z_{PR}^{max}	Z_{ER}^{max}	Z_T^{max}
228471500	49836020	1840
Z_{PR}^{min}	Z_{ER}^{min}	Z_T^{min}
161057400	43140350	1612

Based on the inputs, the results of the implemented model are shown in Fig. 4 to Fig. 6. The LINGO software package is used to solve problem (S) and sub-problems (M). The solver employs the branch-and-bound algorithm to solve those. Branch-and-bound is a systematic method for implicitly enumerating all possible combinations of the integer variables. To analyse the above-mentioned optimizing case, two cases have been considered:

Case I. The travel time based shortest path assignment; In this case, the total demand of each O-D pair is passed through its shortest path. In other words, in this case, risk limitation has not been considered and the shortest path between each pair has been used for the shipment of HAZMATs.

Case II. Uniform assignment; In this case, the total demand of each O-D pair is distributed equally between the feasible paths. Similarly in this case, no risk limitation is applied.

The values of population risk, environmental risk and travel time in the network in any of these three cases have been shown in table 6 and Fig. 7. Likewise table 7 shows the used paths in any of three cases.

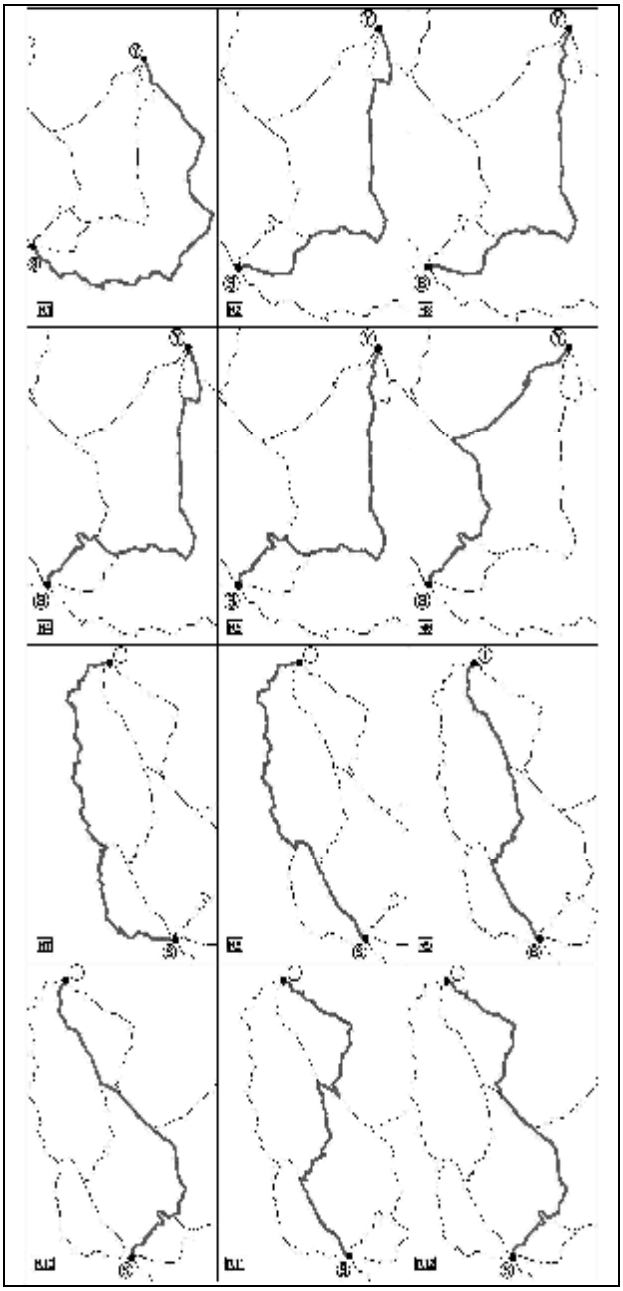

Fig 3. Feasible routes Shiraz-Yazd and Isfahan-Shiraz

Tab. 6. Values of three attributes in the network in any of the three cases

Assignment	Network population risk	Network environmental risk	Network travel time
Travel time shortest path	157035186	48552800	1352
Uniform	238157326	46771022	1692
Optimal	162830500	43305790	1614

In general, it could be said that as the allowable level of risk has not been considered in the shortest path assignment, the whole demand has been assigned to these shortest paths; so the flow of HM trucks is high on these paths and the resultant risk on links belonging to these paths is increased.

In uniform assignment, the network travel time increases but the severity of population and environmental risks on links decreases. In uniform assignment, the number of critical links is fewer than that of travel time shortest path assignment. In the optimal assignment (proposed in this article), there is no critical link but the network travel time is more than that of shortest path assignment. Although, it is still less than the travel time in uniform assignment.

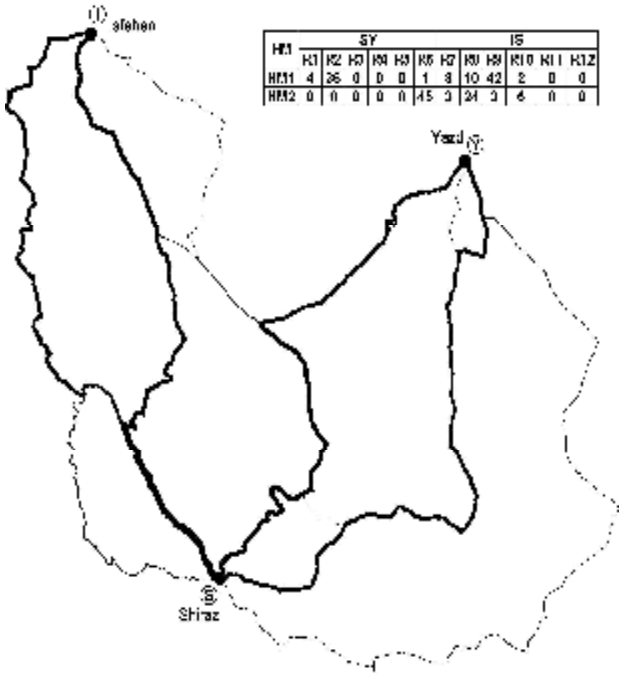

Fig 4. Routing of HAZMATs in the network

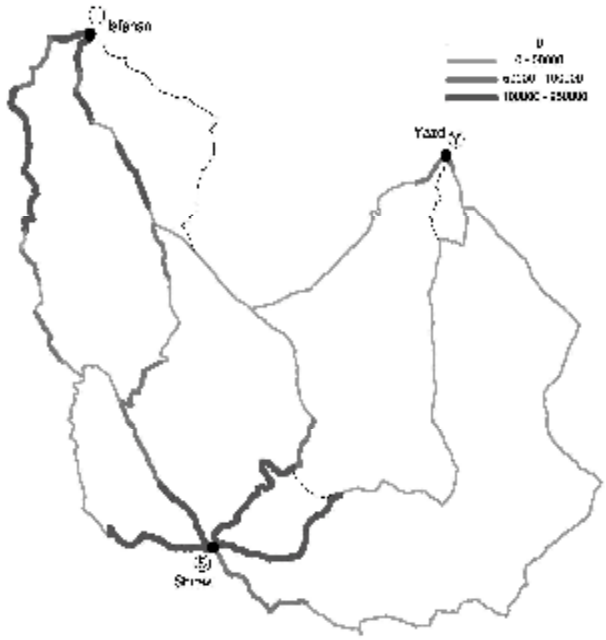

Fig 5. Population risk of unit length of link

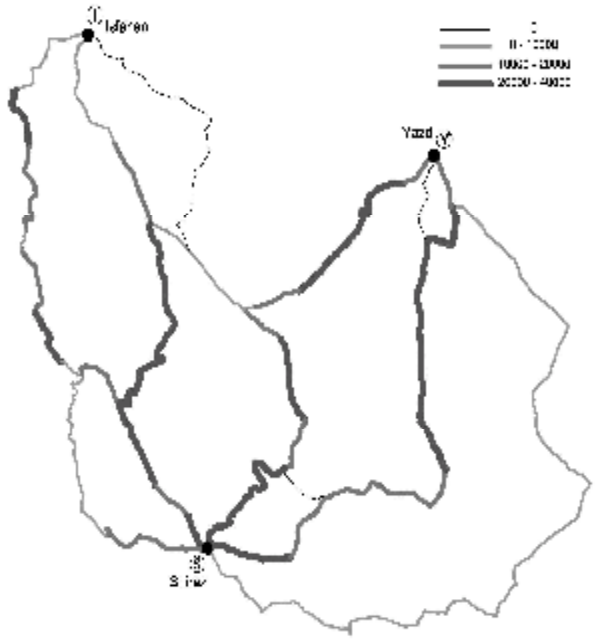

Fig 6. Environmental risk of unit length of links

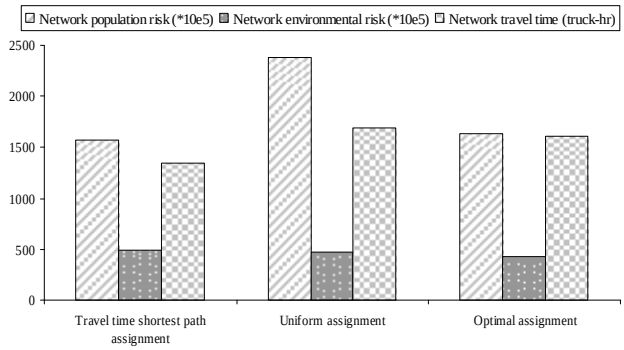

Fig 7. Network population risk, Network environmental risk and Network travel time at any of three cases

Tab. 7. The used network Paths at three cases

Assignment	Shiraz-Yazd (SY)	Isfahan-Shiraz (IS)
Travel time shortest path	R6	R10
Uniform	All routes	All routes
Optimal	R1 ,R2 , R6	R7 , R8 , R9 , R10

Using this comparison, the capability of this model in minimizing the weighted combination of all three objectives; population risk, environmental risk and travel time of network has been clearly shown.

7. Conclusion

Based on this research, it is evident that the transportation of HM trucks in road networks could be optimized. The application of optimal routes contributes to the risk minimization and maximizes the safety. In the previous studies, the main objective was to find the shortest path for the shipment of demand between just one O-D pair. In addition, some other differences between this study and other researches could be pointed out as the following:

A. Since the aim of these problems is to transport HAZMATs from one origin to one destination, the directions of links on the network have been assumed based on origin-destination direction. Therefore, the model is introduced in a directional network.

B. As the shortest path algorithm has been used in these researches, the demand does not affect the selection of the option.

C. As the demand has not been considered in these models, no limitation has been applied to the network links in the models. Therefore, the whole demand is transferred on the first shortest path and it is not necessary to find next paths.

D. Several risk and cost attributes have been assigned to the network links based on objectives of the model that some of them could vary with time of day.

In comparison with the previous studies, in this research, the demand matrix consists of several O-D pairs and different classes of HAZMATs. In this network, some links operate bidirectional and therefore the network is not a directional network. Furthermore, it is assumed that the attributes of network links are time independent.

The application of the proposed model makes assessment of the current HM flow patterns on road networks possible. This can be accomplished by both comparing risk measures of network links in the existing situation and the allowed risk and by comparing them with the optimal flow pattern. Furthermore, by optimizing the HAZMATs assignment, the critical links in the network can be determined. The term “critical links” means those links which have approached their specified allowed risk. This model also allows the assessment of the rule and importance of any link and the alternative routes for flow of HM trucks in network reliability.

This model, therefore, contributes considerably to the present decision-making and future planning undertaken by authorities to improve the operation of the road network based on HAZMATs transportation.

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