Routing Hazardous Materials in Order to Minimize Risk in Urban Transportation Network

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Abstract

Hazardous materials have been extensively used in industry, agriculture and medicine such that its essential role in human's lives is inevitable. If an incident occurs during the shipment of these hazardous materials and in the case of leak due to these incidents, many environmental, social and financial losses will be sustained. In particular, these accidents can be happened in a large populated urban area.

Thus the routing of hazardous materials has been an interest to many urban transportation network management organizations in order to minimize the risks that have been induced to the people who live in urban area. This article presents a method that minimizes the risk of the urban transportation network with respect to the origins and destinations of these materials, their types and quantities. In this method a programming model has been used to optimize the transportation network risk based on measures such as the social risk index and travel length in the network. This method estimates the optimal assignment of these materials on the network and consequently reduces the probability of damages and harm to a city.

Keyword: *Hazardous materials, Transportation network, Risk analysis, Network optimization*

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1. Introduction

Nowadays, hazardous materials (HAZMAT or HM) are being widely used in different fields such as industry, agriculture and medicine. For HAZMAT routing problem, in one hand, HAZMAT shipment must be economic to allow us to attract investment in it and on the other hand, some safety measures must be provided to reduce the risk of HAZMAT transportation.

Since 1980, many researchers have undertaken studies in this field. Kara & Verter (2004) [1] presented a two-phased model that the objectives are to minimize the population risk and the travel length. Similarly Carotenuto et al. (2007) [2] have used population risk as the link label. The utility function based on a model introduced by Haghani and Chen (2003) [3] is to minimize the weighted combination of three objectives: O-D travel time, vulnerable population on the route and that on intermediate nodes. The model proposed by Penwahr et al. (2000) [4] considers optimal non-dominated paths based on the least special population risk and least travel time. The objective of Meng's model (2005) is to identify non-dominated paths between an origin-destination pair in a time-varying network based on travel time and other criteria's such as vulnerable population [5]. The Attributes of the model proposed by Miller-Hooks & Mahmassani (1998) [6] are travel time and vulnerable population and its objective is to determine the optimal path in a time-varying network based on a trade off between cost and risk.

2. HAZMAT Routing Considerations

This paper uses Eq. (1) for risk assessment [7]:

$$R_i = P_i . C_i = (Rate(A)_i . l_i).((2 d_c . l_i).PD_i) \tag{1}$$

Where R_i is the risk of link *i*, P_i is the occurrence probability of the release accident on link *i*, C_i is the measure of release accident consequence on link *i* (the vulnerable components that have been considered in this study include population), $Rate(A)_i$ is the rate of HM incident on link *i* (for per million vehicle-km), l_i is the length of link *i* (km), d_c is the impact distance of HAZMAT class *c* (km) and PD_i is the population density on link *i* (people/km^2). (For more details refer to [8].)

Other then safety criteria's (risk criteria's), there is another criterion that matters in HAZMAT routing that is the cost of transportation. In earlier studies, travel cost, travel time and travel length have been considered as the cost of transportation in HAZAMAT routing model. In This study, travel length (truck-km) has been considered as transportation cost.

3. Problem Formulation

Consider a urban transportation network *N(V,A)* such that the links ($i \in A$) posses population risk limitation. The aim is to ship a definite quantity of various HAZMAT between several O-D pairs. The problem is to determine the optimal assignment of truck flow within this urban transportation network that minimizes the weighted combination of objectives. The linear integer programming problem is expressed by Eq. (2).

$$
\begin{aligned}
&(S)\quad Max \quad U = w_{PR}\,u_{PR} + w_{TL}\,u_{TL} \\
&\quad subject\ to: \\
&\quad 1)\ u_{PR} = \frac{Z_{PR}^{\max} - Z_{PR}}{Z_{PR}^{\max} - Z_{PR}^{\min}} && 5)\ \sum_{r} N_{.,c}^{\ k,r} = N_{.,c}^{\ k,.} \qquad ;\forall c,\, k \\
&\quad 2)\ u_{TL} = \frac{Z_{TL}^{\max} - Z_{TL}}{Z_{TL}^{\max} - Z_{TL}^{\min}} && 6)\ \sum_{c}\sum_{k}\sum_{r} N_{i,c}^{\ k,r}\,.PR_{i,c} \le PR_{\max}\,.l_i \quad ;\forall i \\
&\quad 3)\ Z_{PR} = \sum_{i}\sum_{c}\sum_{k}\sum_{r} N_{i,c}^{\ k,r}\,.PR_{i,c} && 7)\ N_{i,c}^{\ k,r} = \begin{cases} N_{.,c}^{\ k,r} & \delta_{i,.}^{\ k,r} = 1 \\ 0 & \delta_{i,.}^{\ k,r} = 0 \end{cases} \quad ;\forall i, c, k, r \\
&\quad 4)\ Z_{TL} = \sum_{i}\sum_{c}\sum_{k}\sum_{r} N_{i,c}^{\ k,r}\,.TL_{i,.} && 8)\ N_{i,c}^{\ k,r} \quad Integer \qquad ;\forall i, c, k, r
\end{aligned}
\tag{2}
$$

Where, U is the total network utility ($0 \le U \le 1$), u_{PR} and u_{TL} are respectively the utility of objectives; population risk and travel length in the network ($0 \le u_i \le 1$) and w_{PR} and w_{TL} are respectively the weight of objectives (weighting system), Z_{PR} and Z_{TL} are respectively population risk and travel length of the network, Z_{PR}^{max} and Z_{PR}^{min} are respectively the maximum and minimum population risk in the network, Z_{TL}^{max} and Z_{TL}^{min} are respectively maximum and minimum travel length, $N_{i,c}^{k,r}$ is the number of trucks carrying HAZMAT c on link i in route r from O-D pair k (decision variable), $N_{.,c}^{k,r}$ is the number of trucks carrying HAZMAT c on route r from O-D pair k, $N_{.,c}^{k,.}$ is the demand of (number of trucks carrying) HAZMAT c from O-D pair k, $PR_{i,c}$ is the base population risk on link i due to passing a truck of HAZMAT c on that link, $TL_{i,.}$ is the travel length on link i, PR_{max} is the maximum allowable (upper-bound) population 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.

Constraints 1 and 2 are the utility of different objectives. Constraints 3 and 4 are the two objectives at network level. The value of each links risk index is equal to the sum of the product of the base risk associated to the passage of a single truck with a certain class of HAZMAT, with the volume of trucks passing that link. The risk of the network is the sum of the risks of all links. The constraint 5 represents the fact that there are several paths between every O-D pair which the O-D truck demand should be assigned to these paths. Constraint 6 is allowed population risk limitation for links. This limitation is determined by the decision makers. Constraint 10 defines the flow in the route. If link i belongs to route r from O-D pair k ($\delta_{i,.}^{k,r}=1$), all the flow in route r is assigned to that link.

To calculate the maximum and minimum of any objectives, a model with the following general from must be solved. Problem M is divided into four sub-models based on objective functions that are presented in table 1.

$$
\begin{aligned}
&(M)\quad Objective\,Function\\
&\quad subject\ to:\\
&1)\ \sum_r N_{.,c}^{\ k,r} = N_{.,c}^{\ k,.}\ ;\forall c,k \qquad 3)\ N_{i,c}^{\ k,r} = \begin{cases} N_{.,c}^{\ k,r} & \delta_{i,.}^{\ k,r}=1 \\ 0 & \delta_{i,.}^{\ k,r}=0 \end{cases} \ ;\forall i,c,k,r \\
&2)\ \sum_c\sum_k\sum_r N_{i,c}^{\ k,r}.PR_{i,c} \le PR_{\max}.l_i\ ;\forall i \qquad 4)\ N_{i,c}^{\ k,r}\quad Integer\ ;\forall i,c,k,r
\end{aligned}
\tag{3}
$$

Table (1) Four sub-models

1	Max. network population risk	$(M1)\,Max\,Z_{PR}$	3	Max. network travel length	$(M3)\,Max\,Z_{TL}$
2	Min. network population risk	$(M2)\,Min\,Z_{PR}$	4	Min. network travel length	$(M4)\,Min\,Z_{TL}$

4. Solution Algorithm

In general, the solution algorithm of the HAZMAT transportation routing problem that is shown in Fig. 1 consists of three sections; inputs, calculations and outputs.

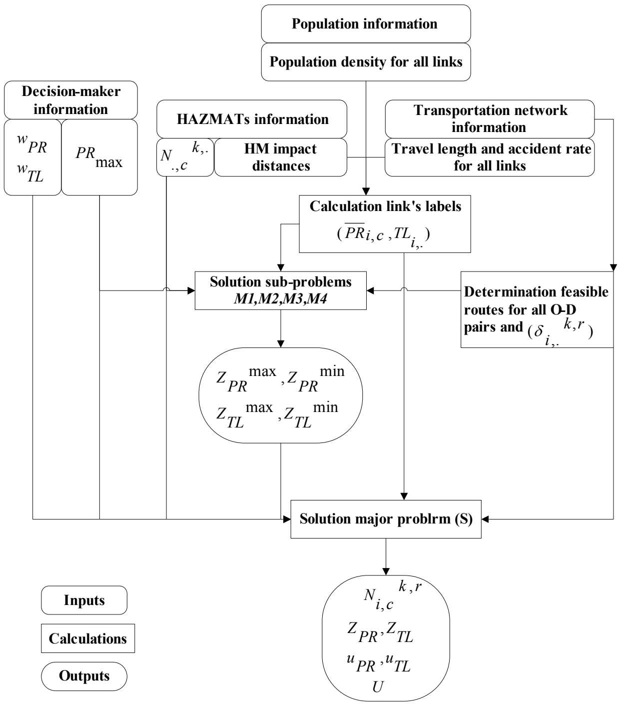

Figure (1) Problem solution algorithm

5. Implementation on a Hypothetical Network

The hypothetical network and the demand matrix have been shown in Fig. 2. It should be noted that the population density has been assumed to be constant within each link and the nodes are not population centers. O-D pairs as specified in this study are A-D and B-C. Two kinds of hazardous materials such as HM1 and HM2 respectively with impact distance of 0.8 and 0.5 km are transferred between origins and destinations. The demand matrix shows the demand of O-D pairs according to the number of truck for both kinds of HAZMAT. There are six feasible paths in the network such that there are three paths between every O-D pair (Fig. 3). Also PR_{max} = 800000, w_{PR} = 0.50 and w_{TL} = 0.50. Based on these inputs, the results of the model were shown in Fig. 4.

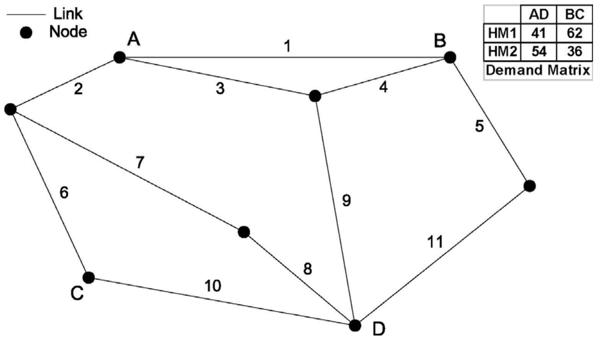

Figure (2) Hypothetical network

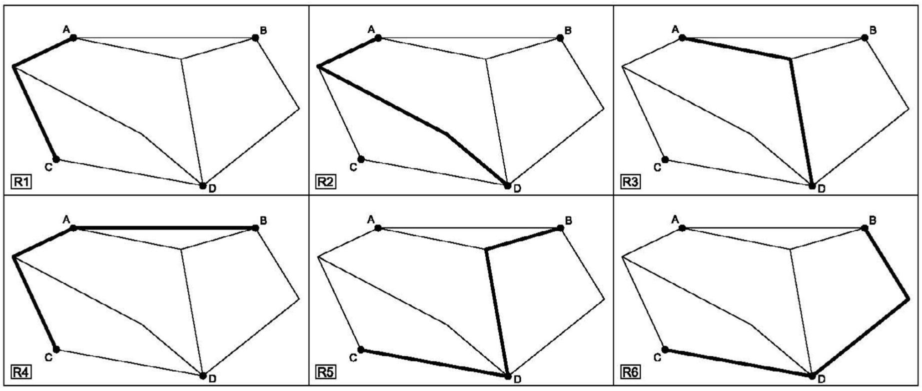

Figure (3) Feasible routes A-D and B-C

It is obvious that in stance of considering risk limitation in optimal routing, the network travel length is more and less than the travel length shortest path assignment and the uniform assignment respectively.

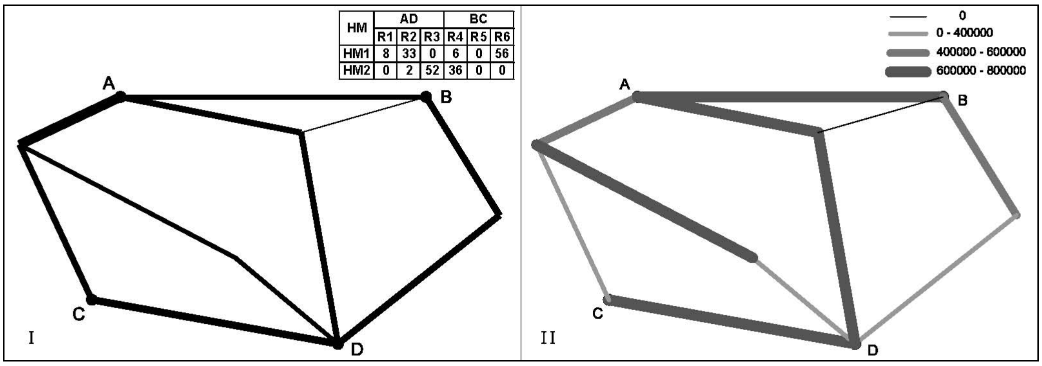

Figure (4) I. Routing of HAZMAT in the network, II. Population risk of unit length of link

6. Conclusion

Based on this research, it is evident that the transportation of HAZMAT trucks in urban transportation networks could be optimized. The application of optimal routes contributes to the risk minimization and maximizes the safety. For this purpose, we must first determine intended indices and how to calculate them specially population risk on links. Then by modeling the problem in the form of a multi-objective integer problem, the optimal routes for HAZMAT shipment of various O-D pairs could be obtained. It is clear that the indices should be selected such that economic and risk considerations could be met. In the previous researches, the problem rose as transportation of HAZMAT from one origin to one destination and the main objective was to find the first shortest path. Therefore these models have been introduced in a directional network and no limitation has been applied to the network links in the models. But in this research, the urban transportation network consists of several O-D pairs such that each of them contains demands of several of HAZMAT. In such a network, some links have operated bidirectional (the non-directional network).

By using the proposed model, we can assess the current HAZMAT flow pattern on road networks. 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. This model, therefore, contributes considerably to the present decision-making and future planning as undertaken by authorities to improve the operation of the network based on HAZMAT transportation.

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