MINIMIZING EXPOSURE RISK AND TRAVEL TIMES OF HAZARDOUS MATERIAL TRANSPORTATION IN URBAN AREAS

Rojee Pradhananga**, Eiichi Taniguchi*** and Tadashi Yamada****

1. Introduction

Industrialization and urbanization are aspiration of every country at present state of world. While substantial economic growth is a direct outcome of industrialization, accomplishment of the process is directly related with the use of huge quantity of hazardous material. Consequently, reliance on hazardous material has become a fact of life to one living in industrialized societies and thousands of different hazardous materials are in use at present. Huge demands of hazardous material, subsequent shipments and their potential adverse conditions are the main problems in hazardous material transportation. Despite the continuous effort to mitigate the adverse effects of hazardous materials, accidents do happen during their use, loading/unloading, transport and disposal [1)].

Hazardous material (Hazmat) transportation accidents are perceived as low probability-high consequence (LPHC) events [2)] and this is the reason that Hazmat transportation has become an active area of research since last twenty years. A number of studies related to Hazmat in the area of risk management, operation research, and decision making are available. The core concept of Hazmat routing is similar to the one used in Vehicle Routing Problem with Time Window (VRPTW), a common application of mathematical programming in business logistics [3)]. However, Hazmat routing process is a multi-objectives activity in which multiple numbers of stakeholder are involved and most importantly risk and travel time are the two major aspects that cannot be neglected. A number of multiple objective problems exist in both Hazmat case and normal VRPTW however almost all of the problem carry out routing and route choice process in two independent steps. While the vehicle routing process is carried out with consideration of multiple objectives, the route choice is done using shortest path approach keeping only one objective in consideration that is travel time in case of normal VRPTW and either risk or time in case of Hazmat routing.

This paper presents a combined multi-objective optimization model for Hazmat transportation where both risk and travel time objectives are equally considered for both routing and route choice process. Furthermore, the model proceeds with a single step process for routing and route choice. The optimized solution is expected to have a set of pareto-optimal paths thus creating a set of alternative path choices for decision making process thereby integrating concept of equity consideration.

2. Literature review

Hazmat transportation routing is a commonly faced issue in logistical decision making and considerable works have been done in the areas of risk assessment; routing; combined facility location and routing; and in network design. An extensive bibliography on these topics is available in Erkut et al. [2)]. A local routing problem, related with particular Hazmat type explosive material for road network being focus of this study, let us limit our search to the literatures on Hazmat transportation studies for local routing.

A number of local route planning models are available in literatures basically focused on the transport modes that is on road system (Kara et al. [4)], Erkut and Ingolfsson [5)]), on railway system (McClure et al. [6)], Verma and Verter [7)]) and on marine system (Iakovou [8)]).

* Key words: Hazardous material, VRPTW, multi-objective optimization

** Student member of JSCE (Applied), M.E., Doctoral Student, Graduate School of Engineering, Kyoto University.
C-1 Kyotodaigaku Katsura, Nishikyo, Kyoto 615-8540, Tel. 075-383-3231, Fax. 075-950-3800.
*** Fellow Member of JSCE, Dr. Eng.,Graduate School of Engineering, Kyoto University.
C-1 Kyotodaigaku Katsura, Nishikyo, Kyoto 615-8540, Tel. 075-383-3229, Fax. 075-950-3800.
**** Full Member of JSCE, Dr. Eng., Graduate School of Engineering, Kyoto University.
C-1 Kyotodaigaku Katsura, Nishikyo, Kyoto 615-8540, Tel. 075-383-3230, Fax. 075-950-3800.

While some studies seem to be centered on single objective models with risk as key aspect; a number of studies present multi-objective model and the procedures to determine set of pareto-optimal paths. Current et al.[9] formulated a minimum covering shortest path problem with multiple number of objectives. McCord and Leu [10] used multi attribute utility theory to resolve their multi-objective model to single objective to determine a set of pareto-optimal solutions. Public sensitivity to hazmat transport is rooted not only in public risk perception, but also in equity concerns. Many authors tried many approaches to their multi-objective models to clear out the problem of equity consideration; Zografos and Davis [11] used a pre-emptive goal programming approach, Gopalan et. al [12] used integer programming with risk equity constraints, List and Mirchandani[13] in their formulation used one of objective as minimizing risk equity. Besides many authors reported the fact that prediction of risk is a stochastic issue that is known in priori with certain uncertainty only and developed stochastic models (Turnquist[14]). With the advancement in technology and the ease it has created in the field of data collection, the recent trend in modeling is to incorporate stochastic and time varying nature (Miller – Hooks and Mahmassani [15], Chang et al. [16]).

Almost all the models in literature are for routing process and use route choice results, carried out in a separate phase as a single objective shortest path problem. However, this research study aims to address the fact that for multi-objective problems like Hazmat routing both routing and route choice process are multi-objective in nature and should be performed in a single step rather than two independent steps.

3. Hazmat Transportation Problem

Hazmat transportation problem is an extension of VRPTW which is mathematically formulated as:

Minimize an objective function Z

Given a network (V, A), where $V = \{v_1, v_2, v_3, \ldots\ldots, v_k\}$ is a finite set of vertices. The set of customer nodes to be visited $\{n_1, n_2, n_3, \ldots\ldots n_N\}$ is subset of this set V. Since each vehicle l in use has to start from depot node, it is considered as a temporary customer node n_0 to be visited by all vehicles. $A = \{a_1, a_2, a_3, \ldots\ldots, a_k\}$ is a finite set of arcs that includes all the connected links from vertex v_i to vertex v_j. $\overline{T}_{n(i)n(j)}$ is the average travel time from node n_i to n_j and $[e_{n(j)}, f_{n(j)}]$, the time window representing earliest and latest possible service time at node n_j. $D_{n(i)}$ is demand at node n_i and $W_{c,l}$, the capacity of vehicle l in use, m being the maximum number of vehicles used for transportation process.

In order to integrate the multi-objective nature of Hazmat transportation problem, the objective function here is defined as a 3 dimensional vector for minimizing $Z_1 \rightarrow$ total fixed cost, $Z_2 \rightarrow$ total transportation cost and $Z_3 \rightarrow$ the total risk exposure associated with transportation process, the detail formulation for objective function being shown here:

$$Min, Z(X, Y) = [Z_1(X, Y) \quad Z_2(X, Y) \quad Z_3(X, Y)]^T$$

Here,

$$Z_1(X, Y) = m.C_{f,l}$$

$$Z_2(X, Y) = \sum_{l=1}^{m} C_{tl}(x_l, y^p_{n(i),n(j)}) \qquad \text{for } n(i) \in x_l$$

$$C_{tl}(x_l, y^p_{n(i),n(j)}) = \sum_{\substack{i=0 \\ j=i+1}}^{N_l} C_t$$

$$C_t = C_{t,l}(\overline{T}^p_{n(i),n(j)} + t_{c,n(j)}) + C_{e,n(j)}(e_{n(j)} - t_{l,n(j)})$$
$$if\ t_{l,n(j)} < e_{n(j)}$$

$$C_t = C_{t,l}(\overline{T}^p_{n(i),n(j)} + t_{c,n(j)})$$
$$if\ e_{n(j)} < t_{l,n(j)} < l_{n(j)}$$

$$C_t = C_{t,l}(\overline{T}^p_{n(i),n(j)} + t_{c,n(j)}) + C_{d,n(j)}(l_{n(j)} - t_{l,n(j)})$$

$$if\ t_{l,n(j)} < l_{n(j)}$$

$$Z_3(X, Y) = \sum_{l=1}^{m} R_l(x_l, y^p_{n(i),n(j)}) \quad \text{for } n(i) \in x_l$$

$$R_l(x_l, y^p_{n(i),n(j)}) = \sum_{\substack{i=0 \\ j=i+1}}^{N_l} R^p_{n(i),n(j)}$$

$$R^p_{n(i),n(j)} = \sum_{v(i)v(j)\in p} AR_{v(i)v(j)}.EP_{v(i)v(j)}$$

In order to carry out the routing decision and route choice decision simultaneously, a new decision variable *Y,* order of paths to be visited by all vehicles is introduced, X being the traditional decision variable, order of visiting customer nodes for all vehicles. Both of these decision variables are superset of their respective decision variables for vehicle l that is x_l and $y^p_{n(i),n(j)}$ respectively. Here $p \in P$ represents a path, an ordered series of nodes to be visited by vehicle l while moving from node n_i to n_j, P being set of all the possible paths between these two nodes. The expression for C_t shows the detail transportation cost calculation same as in traditional method of VRPTW, however the travel time value and hence the penalty costs to move from each customer node to the next customer node to be visited vary with variable p. Terms $C_{e,n(j)}$, $C_{d,n(j)}$ are the early and delay penalty costs respectively and $t_{c,n(j)}$, $t_{l,n(j)}$ are the service time and service start time of vehicle l at node n_j respectively. Same is the case while calculating risk associated with transportation process of vehicle l, R_l the value being dependent upon the accident rate *AR* and the exposure population *EP* for links connecting nodes in path p.

The model is subjected to demand, capacity and customer number constraints as in traditional VRPTW, the mathematical expressions are available below respectively. It should be noted that these constraints hold true only during routing process and selection of nodes within path p is not subjected to these constraints. Moreover, both customer and non customer nodes of network can be selected while selecting p.

$$\sum D(n(i)) = W_l(x_l) \quad \text{for } n(i) \in x_l$$

$$W_l(x_l) = W_{c,l}$$

$$\sum_{l=1}^{m} N_l = N$$

4. Heuristic Technique for Problem Solution

VRPTW is a NP (Non –deterministic Polynomial –hard) problem and heuristic techniques must be used to achieve better solution in effective manner. The multiple number of objectives involved and requirement of getting pareto-optimal solutions in Hazmat case makes the problem much more complicated. Further, the attempt of carrying out routing and route choice decisions simultaneously excessively enlarge the possible solution space since there is network addition at each node during path selection process to reach to the next destination for delivery. Accordingly, use of heuristics is necessary to get possible better solution for this particular study also. Numbers of heuristics are used for solving routing problems; similarly numbers are used for route choice. However for this particular study, selection of appropriate heuristics that can be extended to solve both routing and route choice problem is crucial.

Considering this fact in vision, Ant Systems (AS) heuristic has been chosen to solve the problem. The reason for selection of this technique is it's appropriateness for both routing and route choice process. The concept of AS has been already applied for routing multi-objective VRPTW (Gambardella and Tailllard[17)], Baran and Schaerer[18)]). An extension of AS for multi-objective VRPTW used by Baran and Schaerer will be used in this research study.

5. Expected Results

The presented model is expected to be applied for routing gasoline vehicles within a test network with 25 nodes and 80 links. A set of dominant pareto-optimal solutions are expected to be obtained. The paths obtained are expected to cover a greater solution space than the optimal paths obtained based on only one criteria that is either the travel time or risk exposure during route choice process thereby neglecting the necessity of a single step optimization procedure. The probability of overburden that might be posed to some specific links in the network due to repetitive use of same paths for multiple shipments is expected to be greatly reduced by making use of alternative path choices from the obtained dominant paths sets. A comparison between objective values that are risk exposure, travel time and number of vehicles associated with all pareto-optimal paths will be made in order to visualize the effect of variation in one objective value with the slight variation in another objective at the state of optimality.

References:

1) Erkut, E., & Verter, V.: Hazardous materials logistics. In: Drezner, Z. (Ed.), Facility Location: A Survey of Application and Methods. Springer-Verlag, New York, chapter 20, pp. 467-506, 1995.
2) Erkut, E., Tjandra, S.A., & Verter, V.: Hazardous material transportation. In G. Laporte, & C. Barnhart(Eds.), Handbooks in Operations Research and Management Science, Elsevier Science, chapter 9, pp. 539-621, 2007.
3) Taniguchi, E., Thompson, R.G, Yamada, T., & Duin, R.V.: City Logistics. Network Modeling and Intelligent Transport Systems, Pergamon, Oxford, 2001.
4) Kara, B.Y., & Verter, V.: Designing a road network for hazardous materials transportation. Transportation Science, vol. 38(2), pp. 188-196, 2004.
5) Erkut, E., and Ingolfsson, A.: Transport risk models for hazardous materials: Revisited. Operations Research Letters, vol. 33(1), pp. 81-89, 2005.
6) McClure, T.A., Brentlinger, L.A., Drago, V.J., Kerr, D.C.: Considerations in rail routing of radioactive materials. Technical report, Office of Transport Systems and Planning, Battelle Memorial Institute, Columbus, OH, 1988.
7) Verma, M., Verter, V.: Rail transportation of hazardous materials: Population exposure to airborne toxins. Computers & Operations Research, vol. 34(5), pp 1287-1303, 2007.
8) Iakovou, E.T.: An interactive multiobjective model for the strategic maritime transportation of petroleum products: Risk analysis and routing. Safety Science, vol. 39(1-2), pp 19-29, 2001.
9) Current, J., Revell, C., & Cohon, J.: The minimum-covering/shortest-path Problem. Decision Sciences*,* vol. 19, pp. 490-503, 1988.
10) McCord, M., & Leu, L.: Sensitivity of optimal hazmat routes to limited preference specification, INFOR, vol. (33), pp. 68-83, 1995.
11) Zografos, K., & Davis, C.,: Multi-objective programming approach for routing hazardous materials. Journal of Transportation Engineering 115, pp. 661-673, 1989.
12) Gopalan, R., Kolluri, K., Batta, R., & Karwan, M.: Modeling equity of risk in the transportation of hazardous materials. Operations Research, vol. 38, pp. 961-973, 1990.
13) List, G., & Mirchandani, P.: An integrated network/planar multiobjective model for routing and siting for hazardous materials and wastes. Transportation Science, vol. 25, pp. 146-156, 1991.
14) Turnquist, M.: Multiple objectives, uncertainty and routing decisions for hazardous materials shipments. Proceedings of the 5th International Conference on Computing in Civil and Building Engineering, ASCE, New York, pp. 357-364, 1993.
15) Miller-Hooks, E.D., & Mahmassani, H.S.: Optimal routing of hazardous materials in stochastic, time-varying transportation networks. Transportation Research Record, 1645, pp. 143-151, 1998.
16) Chang, T.S., Nozick, L.K., & Turnquist, M.A.: Multi-objective path finding in stochastic dynamic networks, with application to routing hazardous materials shipments. Transportation Science, 39(3), pp. 383-399, 2005.
17) Gambardella,L., & Taillard, E., & Agazzi, G.: MACS- VRPTW: A multiple ant colony system for vehicle routing problem with time windows. Technical Report, IDSIA, Lugano, Switzerland, 1999.
18) Baran, B., & Schaerer, M.: A multiple ant colony system for vehicle routing problem with time windows. Proceeding of 21st IASTED International Conference. Applied Informatics, Austria, pp. 97-102, 2003.