Bicriterion Routing Scheme for Nuclear Spent Fuel Transportation

SHIH-MIAO CHIN AND PAUL DER-MING CHENG

A new approach has been formulated to consider both cost and population at risk in hazardous material transportation. The approach involves the use of bicriterion path-finding methodology that minimizes the distance traversed and population at risk within a fixed-band width along the path. Examples using U.S. Interstate highway network and population information from the 1980 U.S. census are presented. Preliminary results indicate that the minimum distance path is significantly different from minimum population within a fixed-band width path. In addition, the minimum population paths are sensitive to the width of the band along the path. Finally, the trade-off between cost and risk varies significantly among alternative storage sites. This new approach provides decision makers with an efficient method of generating alternatives that completely describe the best options available. By combining sophisticated algorithms with graphical representation of the network, the methodology allows the trade-offs among noninferior paths to be understood more quickly and more fully.

In the transportation industry, much effort has been devoted to finding the least cost routes for shipping goods from their production sites to the market areas. In addition to cost, the decision maker must also consider the possibility of an incident when transporting hazardous materials. Transporting spent nuclear fuel from reactor sites to repositories is a conspicuous example.

Given suitable network information, existing routing methods can readily determine least-cost or least-risk routes for any shipment. These two solutions, however, represent the extremes of a large number of alternatives with different combinations of risk and cost. When selecting routes and evaluating alternative storage sites, it is not enough to know which is the lowest cost or lowest risk. Intelligent decision making requires knowledge of how much it will cost to lower risk by a certain amount.

The objective of this study is to develop an automated system to evaluate the trade-off between transportation cost and potential population at risk under different nuclear spent fuel transportation strategies. The nuclear spent fuel transportation routing problem, therefore, is formulated as a bicriterion network minimum path problem.

BICRITERION ROUTING PROBLEM

Despite of the potential applications of bicriterion shortest path problems (BSPP), this topic has been rarely studied. An approach is presented here for the bicriterion routing problem, which generates a set of noninferior (among two objectives) paths between origin and destination nodes. The characteristic of a noninferior path is that one cannot find an alternative path that can improve the performance of one objective without worsening the other. In this study, the noninferior path for a nuclear spent fuel shipment is a path such that no other paths can be found to reduce the distance traversed without increasing the population at risk along the path or vice versa.

Consider a directed network **G**(**N**,**A**), consisting of a finite set |**N**| of n nodes and a finite set |**A**| of m directed links. Each link is defined in terms of an ordered pair (i,j), where i denotes the starting node and j denotes the ending node. In this study, two criteria are associated with each link (i,j): C_{ij} (length) and P_{ij} (impacted population).

Therefore, BSPP can be stated as

Minimize

$$F_1(X) = \sum_{(i,j)\,\varepsilon\,\mathbf{A}} C_{ij} * X_{ij}$$

$$F_2(X) = \sum_{(i,j)\,\varepsilon\,\mathbf{A}} P_{ij} * X_{ij}$$

Subject to

$$\sum_{j} X_{ij} - \sum_{1} X_{1i} = 1 \qquad i = s$$

$$\sum_{j} X_{ij} - \sum_{1} X_{1i} = 0 \qquad i \neq s,t$$

$$\sum_{j} X_{ij} - \sum_{1} X_{1i} = -1 \qquad i = t$$

$$X_{ij} = 0 \text{ or } 1 \qquad \forall\,(i, j)\ \varepsilon\ \mathbf{A}$$

where

- s = designated origin node,
- t = designated destination node, and
- Σ = the simple summation over the applicable links in **G**(**N**, **A**).

A brief review of existing approaches for BSPP is provided by Henig (*1*). Two major approaches to solving this problem currently exist. One approach is the labeling approach (or the dynamic programming approach) (*2–7*); the other is the kth shortest path approach (*8–16*).

In this study, an approach for determining the extreme points of the noninferior set in the solution space instead of in the decision space (*17*) is presented. In general, not all

S. M. Chin, Energy Division, Oak Ridge National Laboratory, Oak Ridge, Tenn. 37831. P. D. M. Cheng, Department of Civil and Environmental Engineering, Vanderbilt University, Nashville, Tenn. 37235.

extreme points in the decision space correspond to the noninferior paths in the solution space. Usually, more extreme points exist in the decision space than the noninferior solutions in the solution space. Therefore, it is more efficient in computation to search noninferior paths in the solution space.

The method involves solving the same routing problem repeatedly. The routing problem involves invoking a standard shortest path routine with respect to a parametric objective function with weighted cost and population at risk. Each iteration gives either a new, efficient extreme point or changes the direction of search (by changing the weights on two objective functions) in the solution space. The algorithm terminates when no new efficient extreme point is available.

POPULATION DATA

Population data are an important parameter in risk assessment of routing nuclear spent fuel. Simply stated, if more people are around a shipment for a greater amount of time, then the risk from transport will be greater. Population data used in this study are based on information collected by the Census Bureau in 1980. Among the 1980 census data, the lowest geographical level information, such as the enumeration districts and enumeration district centroids, is used.

To accumulate the population within a fixed-distance band along the selected routes, a methodology developed by E. L. Hillsman at ORNL was used (*18*). The method involves overlaying the route on a population grid. (A population grid is the grid of predetermined resolution that overlays the enumeration district centroids map.) A bisection method is used to approximate the enumeration district boundaries on the grid. The population is then evenly distributed within each enumeration district.

By using approximated population and enumeration district boundaries, the population of each cell of the grid can be interpolated. The population within any given impact distance of a route is accumulated by counting the population of those cells that fall within the distance. This procedure processes each link separately and then sorts the cells, identifying those that had been counted more than once and discarding the duplicates before counting. To determine the sensitivity of using the population at risk as a criterion in routing, this study computes the population at risk within one-mile, three-mile, and five-mile impact distances along the whole interstate highway network.

HIGHWAY NETWORK

The digital highway network used for this study is based on the Oak Ridge National Laboratory (ORNL) Highway Network Data Base. The ORNL Highway Network Data Base, which is continuously enhanced, currently consists of 380,000 miles of U.S. roadways, including Interstate, state, U.S., and local highways. This network was constructed originally from the 1:2,000,000 scale digital line graphs produced by the U.S. Geological Survey (USGS). Geographical accuracy on this network averages 1,000 meters, with a root mean square error on the order of 1,200 meters.

To reduce the computation requirement, it is necessary to reduce the complexity of the ORNL data base. This is accomplished in two steps. The first step is to eliminate all but the Interstate highways from the ORNL data base, thus reducing the data base to a more manageable size to permit calculating alternative routes on a personal computer. The second step is to consolidate the Interstate links into *superlinks*—a *superlink* is a link with all intermediate links combined into one, longer link. This is accomplished by using special criteria for choosing certain nodes to become the end points of the new superlinks. Only those nodes that meet at least one of the following requirements become end points:

1. The node is an intersection of two or more Interstate highways,
2. The node is a location where an Interstate highway crosses a state border, or
3. The node is the beginning or ending point of a numbered interstate highway.

SENSITIVITY OF POPULATION AT RISK

Little research has been performed involving minimum population exposure within fixed distances around a network. In particular, no prior experience is available to indicate how the width of the impact band will affect the choice of route. If choice of impact distance has a major effect of route selection, then impact distances must be chosen carefully to represent appropriately the kinds of accidents that might occur and the kinds of hazardous materials being transported.

A example run was carried out to find the paths between San Diego, California, and Hoboken, New Jersey, that minimize (a) distance traversed, (b) population within a one-mile band, (c) population within a three-mile band, and (d) population within a five-mile band. The results are presented in Figure 1.

The minimum distance route is as expected and is intuitively clear. The minimum population within the one-mile band path goes north, avoiding populated cities in the Midwest and clearly routed around the Chicago area. The minimum population within the three-mile band path coincides halfway with the minimum distance path, then goes south (avoiding St. Louis) and north (avoiding Pittsburgh and Philadelphia). The minimum population within the five-mile band path coincides mostly with minimum population within three-mile band path. However, this path goes south to avoid St. Louis, Pittsburgh, and Philadelphia.

This example clearly shows that the minimum population paths are significantly different from the minimum distance paths, and that minimum population paths vary depending on the width of the band along the path. These results suggest that (a) it is necessary to consider carefully the population at risk when routing hazardous materials and (b) for different types of hazardous materials, impact areas may be different and consequently require different routing strategies.

BICRITERION ROUTING CASE STUDY

To demonstrate the bicriterion routing scheme, a case study was undertaken to find a set of noninferior paths ranging from minimum distance path to minimum population within a three-mile band. The paths originate from the Oyster Creek, New

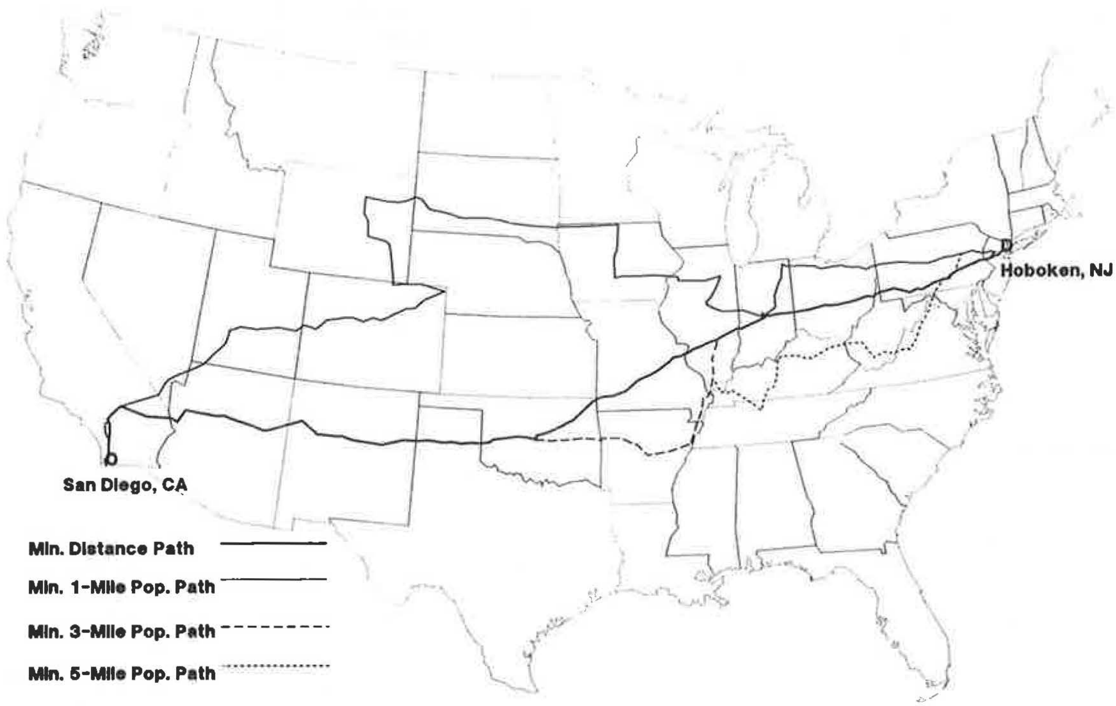

FIGURE 1 Shortest paths on Interstate highway from San Diego, California, to Hoboken, New Jersey.

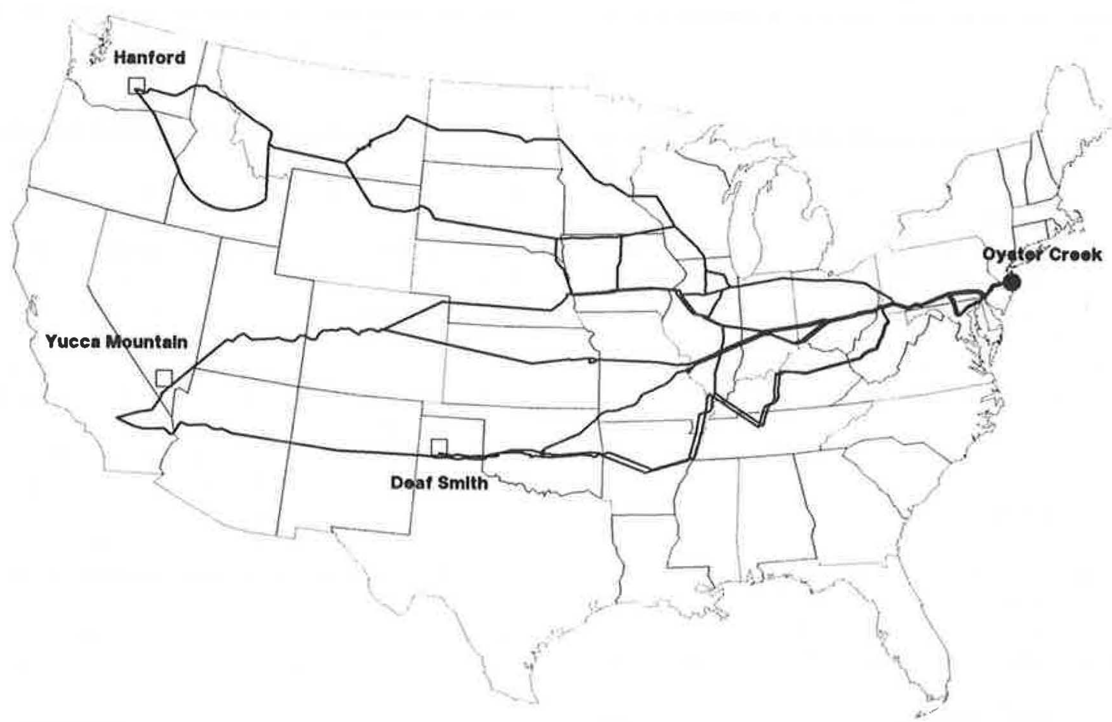

FIGURE 2 Noninferior routes for all cases.

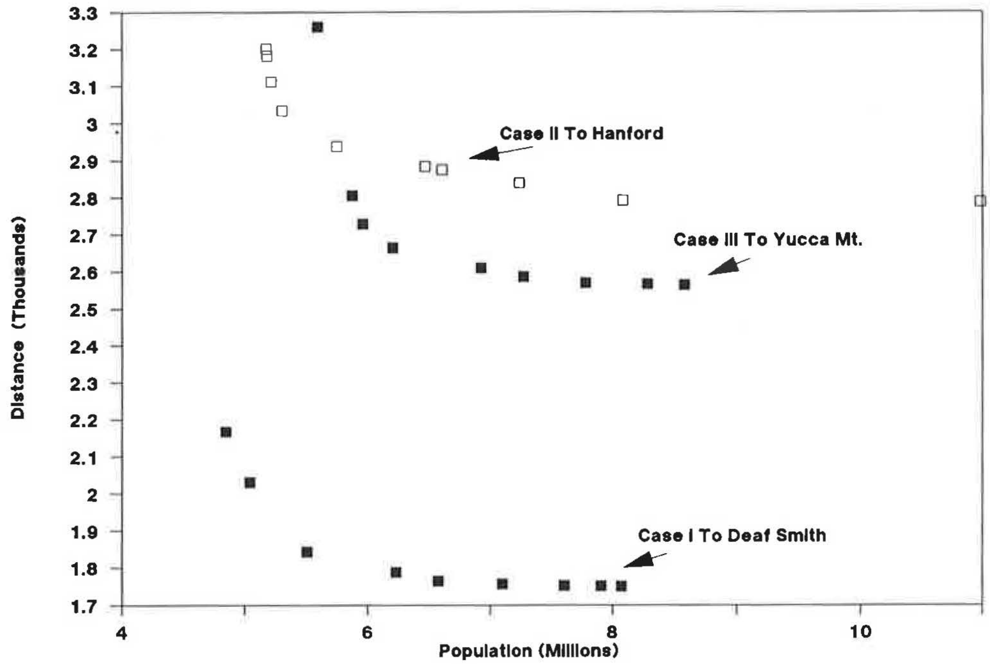

FIGURE 3 Trade-off of noninferior routes for all cases.

Jersey, nuclear power plant to three potential candidate nuclear spent fuel repository sites at Deaf Smith, Texas; Hanford, Washington; and Yucca Mountain, Nevada. There are three sets of noninferior paths from the Oyster Creek nuclear power plant to the three potential repository sites. There are nine, ten, and ten noninferior paths for Deaf Smith, Hanford, and Yucca Mountain, respectively. These routes are presented in Figure 2. The noninferior paths overlap each other somewhat.

Trade-offs between distance (costs) and population at risk among alternatives are presented in Figure 3. The distance and population at risk associated with the corresponding noninferior paths are grouped according to the potential repository sites. Within each group, the distance and population at risk associated with each noninferior path are depicted in an ascending distance and descending population at risk order. It can be seen clearly that distances for the Deaf Smith site are significantly lower than the other two sites, while the population exposures vary more or less in the same range. In addition, the trade-off patterns between the Hanford site and the Deaf Smith site are different. For the Hanford site, distance only increases about 15 percent from the minimum distance path to minimum population at risk path, while the population at risk increases about 110 percent from the minimum population at risk path to minimum distance path. However, the distance increases about 25 percent, while population at risk only increases 65 percent as the noninferior paths goes from one extreme to the other for the Deaf Smith site.

SUMMARY

A new approach has been formulated to consider both cost and population at risk in hazardous material transportation. The approach involves the use of bicriterion path-finding methodology that minimizes the distance traversed and population at risk within a fixed-band width along the path. Examples using U.S. Interstate highway network and population information from the 1980 census are presented. Preliminary results indicate that the minimum distance path is significantly different from minimum population within a fixed-band width path. In addition, the minimum population paths are sensitive to the width of the band along the path. Finally, the trade-off between cost and risk varies significantly among alternative storage sites.

This new approach provides decision makers with an efficient method of generating alternatives that completely describe the best options available. By combining sophisticated algorithms with graphical representation of the network, the methodology allows the trade-offs among noninferior paths to be understood more quickly and more fully.

REFERENCES

1. M. I. Henig. The Shortest Path Problem with Two Objectives. *European Journal of Operational Research*, Vol. 25, pp. 281–291, 1985.
2. T. A. Brown and R. E. Strauch. Dynamic Programming in Multiplicative Lattices. *Journal of Mathematical Analysis and Applications*, Vol. 12, 1985, pp. 364–370.
3. P. Vincke. Problems Multicriteres. *Cahiers du Centre d'Etudes de Recherche Operationnelle*, Vol. 16, 1974, pp. 425–439.
4. R. Hartley. Dynamic Programming in Vector Networks. *Notes in Decision Theory*, Note 86, University of Manchester, Manchester, England, 1979.
5. H. G. Daellenbach and C. A. Dekluyver. Note on Multiple Objective Dynamic Programming. *Journal of the Operational Research Society*, Vol. 31, 1980, pp. 591–594.
6. P. Hensen. Bicriterion Path Problems. In *Multiple Criteria Decision Making: Theory and Applications*, G. Fandel and T. Gal (Eds.), 1980, pp. 109–127.
7. E. Dijkstra. A Note on Two Problems in Connection with Graphs. *Numerical Mathematics*, Vol. 1, 1959, pp. 269–271.
8. J. C. N. Climaco and E. Q. V. Martins. A Bicriterion Shortest Path Algorithm. *European Journal of Operational Research*, Vol. 11, 1982, pp. 399–404.

9. S. Clarke, R. Krikorian, and J. Rausen. Computing the *N* Best Loopless Paths in a Network. *Journal of Social Industrial Applied Mathematics*, Vol. 11, 1963, pp. 1096–1102.
10. E. L. Lawler. A Procedure for Computing the *K* Best Solutions to Discrete Optimization Problems and Its Applications to the Shortest Path Problem. *Management Science*, Vol. 18, 1972, pp. 401–405.
11. E. L. Lawler. *Combinatorial Optimization: Network and Matroids*. Holt, Rinehart and Winston, New York, 1976.
12. E. L. Lawler. Comment on Computing the *K* Shortest Path in a Graph. *Communications of the ACM*, Vol. 20, 1977, pp. 603–604.
13. A. Wongseelashote. An Algebra for Determining All Path-Values in a Network with Application to *K*-Shortest-Paths Problems. *Networks*, Vol. 6, 1976, pp. 307–344.
14. J. Y. Yen. Finding the *K* Shortest Loopless Paths in a Network. *Management Science*, Vol. 17, 1971, pp. 712–716.
15. J. Y. Yen. Shortest Path Network Problems. *Mathematical Systems in Economics*, Vol. 18, 1975.
16. G. Y. Handler and I. Zang. A Dual Algorithm for the Constrained Shortest Path Problem. *Networks*, Vol. 10, 1980, pp. 293–310.
17. R. B. Dial. A Model and Algorithm for Multicritera Route-Mode Choice. *Transportation Research*, Vol. 13B, 1979, pp. 311–316.
18. E. L. Hillsman. *Estimating Population at Risk from Release of Hazardous Materials*. Oak Ridge National Laboratory, Oak Ridge, Tenn., 1986.