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Improving Transportation of Hazardous Materials Through Risk Assessment and Routing

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Addresses of Authors

Brogan, James D., Department of Civil Engineering, University of New Mexico, Albuquerque, N.Mex. 87131
Cantilli, Edmund J., Department of Transportation and Industrial Engineering, Polytechnic Institute of New York, 333 Jay Street, Brooklyn, N.Y. 11201
Cashwell, Jonathan W., Transportation Systems Development Department, Division 6321, Sandia National Laboratories, Albuquerque, N.Mex. 87185
Foote, Steve, Department of Geography, Arizona State University, Tempe, Ariz. 85287
Judd, Charles A., Department of Civil Engineering, University of Utah, Salt Lake City, Utah 84112
Pijawka, K. David, Center for Environmental Studies and School for Public Affairs, Arizona State University, Tempe, Ariz. 85287
F. Frank Saccomanno, Department of Civil Engineering, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada
Scanlon, Raymond D., Department of Transportation and Safety Engineering, Polytechnic Institute of New York, 333 Jay Street, Brooklyn, N.Y. 11201
Soesilo, Andy, Department of Geography, Arizona State University, Tempe, Ariz. 85287
Yu, Jason C., Department of Civil Engineering, University of Utah, Salt Lake City, Utah 84112

Risk Assessment of Transporting Hazardous Material: Route Analysis and Hazard Management

K. DAVID PIJAWKA, STEVE FOOTE, and ANDY SOESILO

ABSTRACT

The transportation of hazardous materials is a growing national problem. The percentage of highway and rail accidents that involve hazardous materials is increasing, the amount of damages per accident is escalating, and compliance with transportation regulations is eroding. A model for hazardous materials risk management is developed in this paper wherein vulnerability is a product of risk reduction (mitigation) and preparedness. Various risk assessment approaches to shipping hazardous materials along major routes were presented and applied to the state of Arizona so that transportation routes could be comparatively evaluated. Type and volume of flow were determined from a survey of commercial trucks that permitted an analysis of hazardous materials accident probabilities for individual routes. By using evacuation distances for chemical spills, a population risk factor was defined as the multiplicative product of hazardous materials accident probabilities and population-at-risk. The risk score for individual routes reflected the interaction of four variables: (a) the number of hazardous events that have occurred on the route, (b) hazardous materials accident probability, (c) population-at-risk and the potential hazard rating--a composite index incorporating potential incident severity, and (d) volume of hazardous materials by class.

The transportation of hazardous material or materials (HM) is a growing national problem. The number of highway accidents that involve HM has steadily increased since 1976, and HM rail accidents continue to increase as well as the costs per accident (1,2). Despite these trends, recent studies have found that management activities directed at reducing vulnerability to HM accidents are insufficient (3,4). Effective management to reduce risk and improve the level of preparedness to mitigate the adverse consequences of HM releases is contingent on understanding the magnitude and nature of the threat to local communities that reside near transport routes.

Risk assessments of HM transport have recently emerged as a critical need and several models and approaches have appeared (5-9). Risk assessment of HM transport can be conceptualized as consisting of the following activities: (a) identification of the type and volume of HM transported; (b) the nature of the threat to the environment and populace of potential release; (c) the estimation of probabilities of HM accidents and chemical release, and (d) the consequences of release (10).

The first section of this paper contains data on national trends of HM accidents and the identifications of several national policy issues in regulating HM transportation. This is followed by a description of a model of the HM risk management system, in which community vulnerability to HM accidents is defined in terms of the interaction between the level of risk and hazard preparedness. Also presented in this paper is an approach for assessing the risks of transporting HM. The approach is applied to the transport of HM along the major highway routes in Arizona.

TRENDS IN THE TRANSPORTATION OF HM

HM--their manufacture, use, proliferation, transportation, and disposal, and the consequent risks to public safety--present many planning and management opportunities at both the state and national levels. HM concerns include definition; designation; regulatory action in material use, manufacture, transportation safety, and disposal; emergency response to accidents; and involvement in cleanup of chronic problems.

There are thousands of materials classified as "hazardous materials," "hazardous substances," and "hazardous wastes" that depend on their destination and material nature. HM are defined as "those [materials] the Secretary of Transportation has found to be in a quantity and form that may pose an unreasonable risk to health and safety or property when transported in commerce" (11). Explosives, flammables, oxidizing materials, organic peroxides, corrosives, gases, poisons, radioactive substances, and etiologic (human disease-causing) agents are included in this definition. Hazardous substances are defined differently by the Environmental Protection Agency (EPA) under two distinct statutes--the Clean Water Act; and the Comprehensive Environmental Response, Compensation, and Liability Act (Superfund). The "hazardous" designation is based on the threat to waterways and the environment in the event of spillage. To date, over 300 specific hazardous chemicals have been identified by the EPA (12). Obviously, there is considerable overlap between the two hazardous classes: most EPA-designated hazardous chemicals are already regulated in transit as a result of the potential threat unrelated to pollution. In addition, hazardous wastes are designated by the EPA under the authority of the Resource Conservation and Recovery Act, and are regulated by the EPA from their origin through disposal and treatment--a cradle-to-grave approach.

The HM situation in the United States is serious, as indicated by the following statistics. As of 1980, more than 55,000 toxic substances, whose sales approach $146 billion, were manufactured and processed for commercial use in the United States (13).

At least 250,000 shipments of HM are made daily which totals at least 4 billion tons per year, and this volume is expected to double in 10 years.

As the volume of HM transport is expected to increase, so is the amount of concern over violations of safety regulations. For example, nearly 95 percent of the HM carriers surveyed in a 1978 study by the Bureau of Motor Carrier Safety had violated the driver hours-of-service rules, and as a group had "the worst record for preventable accident frequency...20 percent more involvement than expected" (1). Moreover, of the 621 most severe commercial carrier accidents investigated by FHWA between 1973 and 1976, those that involve HM accounted for 24.9 percent of the accidents and 57.3 percent of the property damage (2).

The conclusions to be drawn from these statistics are that hazardous substances are in wide use, the volume transported will increase, and accidents that involve HM are costly. The overall national commercial accident trend shows that the number of total commercial accidents in transit has decreased since 1978. The incidence of transit accidents in which HM were carried was fairly constant. However, as a percentage of total vehicular accidents, these are increasing. More specifically, the percent of HM rail accidents to the total number of rail accidents has continued to increase from 7.5 percent in 1978 to 11 percent in 1982. HM highway accidents to all highway accidents has fluctuated between 5 and 6 percent.

Property damage per accident for both hazardous and nonhazardous material carriers has continued to increase as well. Damage per accident for HM carriers indicates the comparative severity of HM-involved accidents. In 1982 the cost per accident of HM carriers averaged $24,000 and the average for nonhazardous accidents was approximately $13,000.

THE HM RISK MANAGEMENT SYSTEM

The growing incidence of HM accidents and chemical releases, which includes a few major evacuations, has resulted in increased interest in "vulnerability assessment." Vulnerability assessment refers to the determination of the level of danger that is posed to a community or area because of HM transport, and the capabilities of the community to reduce the consequences of HM releases. Understanding communities' vulnerability to the hazards of shipping HM is the first step toward mitigation planning. ("Vulnerability" is defined as the degree to which HM threaten a particular population and also represents the interaction of two critical hazard dimensions--risk and preparedness.)

Risk refers to both the probability of occurrence of a hazardous event (an accident with potential for HM release through a breach in containment or the release of HM that necessitates emergency response) and the probability that certain consequences will result from the event (injury and chronic health effects or property damage). The measurement of the level of risk associated with HM in transit can consider three possibilities: (a) the probability of an accident to occur, (b) the probability of containment breach and consequent release of HM into the environment, and (c) the consequences of the release in terms of the population-at-risk. The latter estimation--is the most difficult to quantify. Assessment of the consequence domain requires estimates of the extent and characteristics of the population-at-risk and incorporates (a) type of HM in transit (hazard class) and hazard properties (toxicity, nature of effects to human safety and health, and impacts on environmental quality), (b) population at risk (evacuation distance by chemical type, population density), and (c) prevailing local geographical factors.

Alarmingly little is known about amounts and destination of HM in transit, shippers and carriers involved in their handling, and the number and severity of accidents that directly involve HM and the subsequent risks and costs to society. The Hazardous Material Transportation Act (HMTA), Title I of the Transportation Safety Act of 1974, represented an attempt to alleviate this lack of information and systematic control. It was an expression of congressional concern with the lack of enforcement of earlier legislation (14). The HMTA authorizes the U.S. Department of Transportation (DOT) to regulate transportation safety in the commerce of HM. Thus, all safety aspects of HM handling in transportation, including packaging, labeling, placarding, and routing, fall under DOT regulatory control.

The risk of hazardous materials can be reduced through mitigative planning. At the federal level, promulgation of regulation and enforcement actions is directed at the reduction of accidents and the resulting consequences. Stringent national standards for containers of hazardous materials, driver training, and educational programs are intended to reduce the frequency of accident occurrence and release of hazardous substances. At the local level, risk reduction measures such as rerouting, industry safety inspections, and zoning are difficult because they are contingent on community norms over private versus public roles. Vulnerability to HM hazards is not merely a function of risk. Counterbalancing risk is the level of community preparedness.

Preparedness is defined as measures taken to reduce the consequences that result from chemical release. Preparedness characteristically includes such activities as preventing the siting of facilities with special populations (homes for the elderly, schools) near routes with large volumes of HM flow, specialized training of first-on-scene emergency responders, preparation of emergency and evacuation plans, and the establishment of community mutual-aid relationships. Although some communities may face high levels of risk from HM transportation, equally high levels of preparedness will have the effect of reducing the adverse consequences of HM events, and thereby overall vulnerability.

The relationship between costs and vulnerability is shown in Figure 1. The larger the risks faced by a community, the more investment one would want to place in mitigative planning to reduce the consequences of risk. However, the relationship between costs of preparedness and reduction of vulnerability may not be linear. The theoretical cost curve for reducing vulnerability is based on an assumption that the first unit of investment in preparedness represents a high variable cost (the first purchase of equipment or the first preparation of an emergency plan). There are high initial costs for the amount of safety gained at first. Between A and B the return per unit invested in preparedness is large, and maximized at the 40 percent reduction level in vulnerability. Reducing the level of a community's vulnerability above 40 percent will result in increasingly greater costs per unit of safety gained until point C is reached. At point C, cost per unit of preparedness will not buy an equal unit of safety gained. Thus, on the basis of risk-benefit management criteria, theoretically acceptable risk for this community may be reached with an 80 percent reduction in vulnerability.

There are a number of gradations in the magnitude of the HM threat. At one level, the event may present a situation where potential hazard exists in that an accident has occurred but containment has

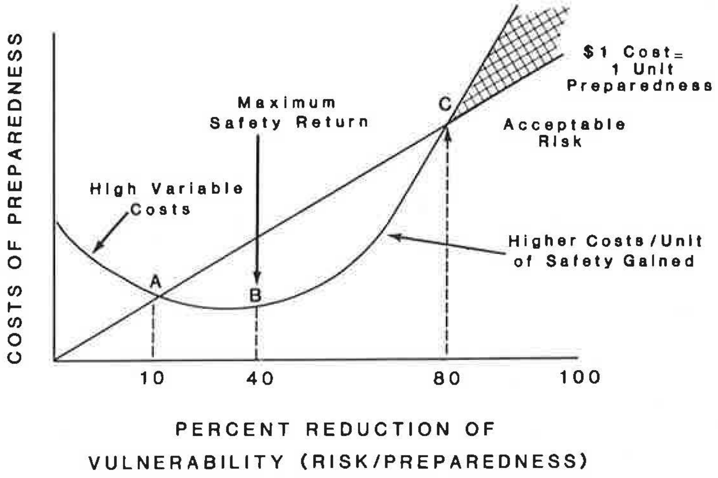

FIGURE 1 Theoretical cost curve of reducing vulnerability.

not been breached. In such cases, emergency response is directed at (a) prevention of release of the hazardous material, (b) removal or containment of the source of threat from the population, and (c) evacuation of potentially exposed population in the event of release. Although the magnitude of effects is expressed in the potentiality of release, the threat may be severe and contingent on the nature of the chemical and proximity of the threat to the population. Response to potential release, however, may be significant and result in large costs to communities' fiscal resources. For example, the potential of release of chlorine gas following a derailment in Toronto, Canada, resulted in an evacuation of about 250,000 people and substantial secondary costs.

Response refers to measures taken to

1. Contain or suppress the release of HM or their hazard manifestation (fire, toxic fumes);
2. Protect the public from the released material through warnings, aid, or evacuation;
3. Monitor and assess secondary and long-term impacts to health and the environment; and
4. Clean up spilled material.

Much of the literature on HM incidents has dealt with emergency response and evacuation behavior. The evidence indicates that whereas the transportation of HM is a growing concern, there are serious problems in local preparedness and effective response to chemical hazards (2). A major problem in the recovery of HM spills is the level of technology that is currently available for detection and neutralization of the contaminant.

RISK ASSESSMENT OF TRANSPORTING HM

Response planning and community preparedness must be directed toward meeting particular threats. The development of an effective HM transportation management system is contingent on an understanding of the nature and degree of risk. Therefore, risk assessment consists of three vital activities: identification of hazard, estimation of risk, and evaluation of possible consequences. When the threats posed by HM transport accidents are considered, identification includes type and volume of HM transported in the area under study and the routes over which the HM are carried. Through estimation, the question is raised of how often (frequency) one can expect transit-related accidents along the identified routes. Evaluation of consequences refers to the population-at-risk from a potential HM release and the nature of the threat.

Risk assessment involves the measurement of the probability and severity of harm in exposure to a hazardous object or event. Risk assessment is a scientific empirical activity and is to be distinguished from judging safety, which involves determination of the acceptability of various levels of measured risk, and is a normative, subjective, or political activity (16). By providing objectives measures or rankings of risks, it is the purpose of a risk assessment to provide empirical scientific data so that the subjective process of judging the relative safety of various options can be performed on an informed basis.

RISK ASSESSMENT OF TRANSPORTING HM IN ARIZONA

This section of the paper contains an empirically based risk analysis of transporting hazardous material on major highway routes in Arizona. In addition, it provides an approach for the determination of HM transportation risk where risk comparisons of alternative routes can be analyzed. The objective is to determine risk "scores" for routes under study so that transportation routes can be comparatively evaluated.

STEPS IN THE RISK ANALYSIS (15)

Identification of HM and Transport Flow Pattern

Hazard identification is the first step in the risk assessment. The HM are identified by hazard class and volume transported by route. The data were based on a sample of commercial motor vehicles at four inspection points along major Arizona highways. Of the 4,438 vehicles, 263 (5.92 percent) transported HM. Table 1 shows the volume of hazardous material by hazard class at each inspection point. The next step in the risk analysis allocated the total volume flow of HM at each inspection point to 10 major routes in Arizona over which HM are carried. The flow pattern is based on average annual trends and does not describe shifts in seasonal patterns, which are substantial.

Determination of Exposure-Miles

The survey provided data on total volume of HM in pounds by hazard class. For assessment of accident

TABLE 1 Total HM and Hazard Class

Inspection Point	Explosives (lb) Class A	Explosives (lb) Class B	Explosives (lb) Class C	Flammable (lb) Liquid	Flammable (lb) Solid	Flammable (lb) Gas	Combustible Liquid (lb)	Nonflammable Gas (lb)	Poison B (lb)	Corrosive Material (lb)	Oxidizer (lb)
Yuma	150	6,507	798	440,236	165	285,171	15,233	48,910	NA	106,062	101,820
Ehrenberg	0	46	248	195,993	700	13,294	23,847	95,476	4,009	227,121	60,048
Kingman	NA	890	NA	10,533	42,136	NA	NA	216	NA	64,540	95,020
Williams	50,788	NA	3,524	143,828	92,591	40,274	2,079	68,606	41,190	79,592	1,019
Total	50,938	7,443	4,570	790,580	135,592	338,739	41,159	213,208	45,199	477,315	257,907

Note: NA = not applicable.
Source: Arizona Department of Transportation.

probabilities, it is important to determine the total number of trips per hazard class for individual routes. Each hazard class poses particular risks to populations that are unique for that class. To estimate the number of trips per hazard class, the HM volume carried per vehicle for each class was first determined.

Exposure-miles is defined as the total number of miles traversed annually by vehicles carrying HM on a route-by-route basis. The load-per-vehicle factors are applied to the weight of HM transported by hazard class to determine the number of trips by class. These are then summed for an entire route. The number of trips are subsequently multiplied by real travel miles along individual routes to yield exposure-miles. These data are shown in Table 2 for each of the 10 routes.

TABLE 2 Exposure-Miles of HM in Arizona

Route Designation	Travel Miles	Estimated No. of Trips	Exposure-Miles
1	30.16	1,240	37,398
2	32.11	422	13,550
3	115.14	8,423	969,824
4	63.19	8,821	557,399
5	129.70	4,094	530,992
6	6.34	3,277	20,776
7	44.18	658	29,070
8	61.28	8,056	493,672
9	132.79	1,348	179,000
10	141.70	4,305	610,018

HM Accident Probability

Accident probability measures the chance that one accident could occur to a commercial vehicle that carries HM on a particular route. For each route, the prevailing accident rate (number of accidents per 1,000 vehicle-miles) was estimated. The number of accidents by an HM carrier expected per year was obtained by multiplying the accident rate by the number of total miles of exposure of HM transport on each route.

Population-at-Risk Factor

Risk assessment of HM transportation must not only derive the probability of an HM incident, but must estimate the degree to which populations are at risk from such events. In fact, risk can be defined as the multiplicative product of the probability of an accident and the exposure to population if it does occur. Thus, the risk analysis utilized the evaluation-of-distances and population-at-risk factors that were likely to be affected by chemical incidents. Population-at-risk estimates were based on evacuation distances. Evacuation distances for chemical spills have been determined for HM once entry into the environment has occurred. Population estimates on either side of a route and along the route (to include vehicular traffic at risk) were estimated. The population risk factor is defined as the HM accident probability multiplied by the population-at-risk for each route. On this basis, routes can be compared and risks balanced. Table 3 shows the population risk factors for the 10 routes as the product of accident probabilities and population-at-risk.

TABLE 3 Risk Comparison of Transporting HM in Arizona

Route	Population at Risk/Mile	HM Accident Probability	Population Risk Factor
1	5.9	.0002	.0012
2	784.3	.001	.784
3	94.8	.067	6.3516
4	135.3	.0223	3.0172
5	39.1	.053	2.0723
6	2,510.4	.0002	.5021
7	381.1	.00087	.3316
8	813.8	.197	160.32
9	29.8	.0358	1.067
10	85.1	.244	20.764

USE OF POTENTIAL HAZARD RATING IN ALTERNATIVE RISK ASSESSMENT APPROACH

An alternative method for assessment of transportation risks involves the use of the potential hazard rating (PHR). The PHR is a measure of potential hazard posed by HM transport that utilizes two risk factors: volume of HM transported by hazard class and evacuation distance by hazard class. The PHR is the product of the volume of HM transported along a route and the average evacuation distance by hazard class. Table 4 illustrates the PHR for the Gila Bend-to-Buckeye route in the Arizona case study. Table 5 shows the PHRs for the 10 routes. The summed products for each route were normalized so that comparisons could be made with the route characterized by the largest PHR. The principal advantage of including the PHR in a risk assessment methodology is its ability to inject a more sensitive measure of incident severity into any risk equation. Because the PHR contains a component that measures the mean minimum evacuation distance for each class of hazardous materials as an indicator of potential incident severity, it becomes possible to consider the degree of hazard posed by the types of materials transported on a particular route as part of a final risk assessment.

The PHR is but one factor in the determination of the risks of HM transport. The risk analysis for individual routes involves use of the following equation:

$$R = H \cdot PHR \cdot AR \cdot PR \qquad (1)$$

where

R = the composite risk rating of HM transport on an individual route,
H = the number of incidents (releases of HM) that have occurred on the route,
AR = the accident rate for the route, and
PR = the population-at-risk from any release along the route.

TABLE 4 Derivation of PHR for the Gila Bend-to-Buckeye Route in Arizona

HM Class	Volume Transported (lb/hr)	Average Evacuation Distance (miles)	Potential Hazard Rating
Class A explosive	.25	0.5	.125
Class B explosive	11.15	0.5	5.58
Class C explosive	3.05	0.3	.915
Flammable liquid	2,040.35	1.3	2,652.45
Combustible liquid	184.4	2.2	405.68
Flammable gas	563.9	0.97	546.98
Flammable solid	5.0	0.8	4.0
Nonflammable gas	718.0	2.1	1,507.8
Poison A	NA	NA	NA
Poison B	26.7	1.95	52.0
Corrosive	1,690.95	1.3	2,198.24
Oxidizer	569.70	1.95	1,110.92
Total			8,484.69

Note: Evacuation distances for each HM class were determined by using the Table of Isolation and Evacuation Distances in the DOT Emergency Response Guidebook *(17)*. NA = not applicable.

TABLE 5 Potential Hazard Ratings for 10 Arizona Routes

Route	PHR Summed Product	PHR Normalized
1	8,484.69	.18
2	2,208.85	.05
3	44,176.60	.92
4	48,243.95	1.0
5	31,382.16	.65
6	25,105.67	.52
7	5,021.45	.11
8	45,275.30	.94
9	10,582.87	.22
10	22,033.16	.46

A score was assigned for each variable. Based on the Federal Emergency Management Agency's criteria, the variables were weighted to reflect the differing importance they hold in risk determination. The population-at-risk variable was weighted most heavily (multiplied by 9) because of the importance placed in protecting those populations. A relatively high weight (multiplied by 7) was given to the "incident" variable. The PHR variable was weighted moderately (multiplied by 5) because the variable itself does not measure values that in themselves result in incidents, but instead provides a measure of the severity of an incident after it occurs. The "accident rate" variable was given a moderately high rating (multiplied by 6). Once the variable scores were weighted, the composite risk rating for each route was obtained. The results of this analysis are given in Table 6.

TABLE 6 Composite Risk Ratings for HM Transportation in Arizona

Route Designation	Incidence Factor	PHR	Accident Rate	Population at Risk	Risk Rating
1	.11	.18	.00001	.0036	1.70
2	.33	.05	.00008	.5051	7.11
3	.11	.92	.00007	.2188	7.34
4	.11	1.00	.00004	.1714	7.31
5	.55	.65	.00010	.1018	8.02
6	.11	.52	.00001	.3191	6.24
7	.11	.11	.00003	.3375	4.36
8	.66	.94	.00040	1.0000	18.32
9	.11	.22	.00020	.0793	2.58
10	1.00	.46	.00040	.2419	11.48

Note: The following variable scores have been normalized for route comparison purposes: incidence, PHR, population-at-risk.

FINDINGS AND SUMMARY

Increasing awareness of HM incidents and potential catastrophic consequences has lead to concern over risk mitigation and activities that are directed toward preparedness planning. Vulnerability was presented as the interaction of risk and preparedness factors. Reduction of vulnerability implies an improvement and expansion in preparedness or a reduction in risk. Both activities necessitate understanding of the level and nature of the HM threat. Developed in the paper was an operational model for assessment of the risks of HM transport that has wide applicability. Further, the approach was applied to a risk analysis of routes in Arizona. Two approaches were employed--the population risk factor method and a composite risk rating technique that utilized the PHR. Comparison of the results revealed some differences, although they were not significant, in final risk scores for individual transport routes. The ability to define and compare routes on the basis of risk has strong relevance for planning and hazard management.

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Assessing the Risk and Safety in the Transportation of Hazardous Materials

RAYMOND D. SCANLON and EDMUND J. CANTILLI

ABSTRACT

The transportation of hazardous materials is a broad and complex topic, which is made unmanageable by a morass of regulatory measures at several levels of government. Risk assessment methodologies provide the best means of helping community-level practitioners come to grips with local fears and perceptions. Current approaches to the development of risk assessment methods tend toward the relative rather than the absolute formulations needed by local authorities. The differences between these approaches are discussed. Although it is impractical to achieve a truly absolute risk- or safety-assessment model, an approach is suggested for a more realistic manner of determining an overall safety situation rather than simply risk-of-incident. By concentrating on the highway transportation mode for simplicity of analysis, a set of model formulations is developed that leads to a community safety assessment index. This index is, in turn, made up of a community preparedness index and a community risk index. The argument is made that risk assessment techniques as presently offered provide no distinction between these two means of measuring current safety (preparedness and risk), and do not distinguish between those variables within the control of communities and those beyond that control. A case study is presented for a hypothetical city, Newtown, New Guernsey, which illustrates how such a community assessment index might be calculated and how its results might be interpreted.

The transportation of hazardous materials is a broad and complex topic as a result of the varied legal and physical conditions that surround the subject and the many hazards to be encountered by moving vehicles. This complexity is increased appreciably by the many regulatory measures at the several levels of government and among sovereign countries. The lack of proper controls over hazardous materials transportation has created unreasonable risks to life, health, private and public property, and the natural environment--risks that can and do lead to catastrophic results, including the widespread dispersion of toxic gases, fire, and explosion.

All modes of transportation have been affected, and, in contrast to most other technological activities, hazardous materials transportation portends a greater risk for a greater number of persons. Given the volumes and frequencies with which hazardous materials are transported, risk assessment applications can provide both valuable insights into the solution of these problems and substantial safety improvements in regulations and management.

Government and industry have long recognized that U.S. economic and technical resources have limits; therefore, the application of risk assessment within the context of hazardous materials transportation is recommended to the regulator, the policymaker, and the entrepreneur.

MODAL CONSIDERATIONS

Although all transport modes have hazardous materials safety problems, bulk movements by highway are the most numerous, thereby creating the greatest exposure of populations to risk, on a general basis. Figure 1 shows that the highway mode accounted for most injuries caused by hazardous materials (except sulfuric acid) than did the rail mode; Figure 2 shows that, except for 1976, gasoline carried by the highway mode accounted for the most deaths per year than any other hazardous material.

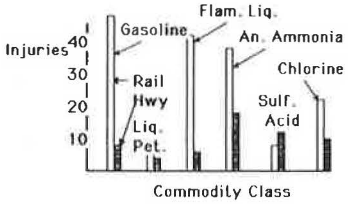

FIGURE 1 Bulk movements of hazardous materials: 1980-1981.

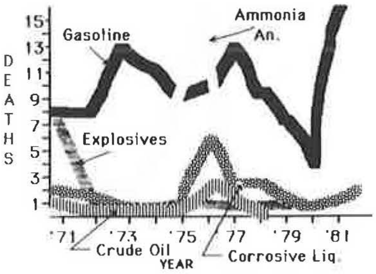

FIGURE 2 Deaths due to five highest commodities, highway mode.

In 1977, of the 653 billion ton-miles of freight transported by trucks both inter-city and local, 74 billion ton-miles, or 11 percent, carried hazardous materials. Of the 5.7 million trucks in the United States, 6 percent, or 351,000, were in the service of hazardous materials. The typical 5-ton, single-unit truck traveled an average of 28 miles per trip, which accounted for 1.5 billion ton-miles in 56 million trips. The typical 18-ton tractor-trailer traveled an average of 98 miles per trip, this accounted for 3.6 billion ton-miles in 37 million trips, which represents 2.3 times more exposure to incidents. For these reasons, the following discussion relates chiefly to the highway mode, although conclusions are fully applicable to all modes.

ESTIMATION OF RISKS

Risk can be estimated quantitatively if it is possible to assign quantitative values to the probability of an occurrence and the consequences of that occurrence. The probability of unlikely events can be estimated in a number of ways. In some cases the event results from a combination of other events that occur with greater frequency; then the subject event can be estimated statistically by combining the probabilities of the subevents that contribute to its occurrence. In other cases statistical extrapolation techniques permit the estimation of the probability of unlikely events on the basis of the largest values of such events previously experienced. In the procedure proposed in this paper, the known relationships between hazardous conditions (e.g., on highways) and hazardous materials transportation incidents are used.

Relative and Absolute Risk

Most approaches to risk assessment today are of the relative variety, that is, a numerical assessment by which one route or even one mode can be evaluated against another. The end result of such an assessment is that Route A can only be stated as being better or worse than Route B or safer or less safe than Route B.

Absolute risk is a direct measure of hazard, that is, an estimate of the numbers of persons who might be killed or injured, the dollar amount of potential economic loss, or the physical extent (quantitatively expressed) of possible environmental and ecologic damage. Although this approach is the most desirable one--it is the most useful and comprehensible to nonacademic, nonstatistically oriented persons--it is difficult to achieve. Nevertheless, a risk measure that tends toward the absolute is desirable, one that provides the practitioner with a feel for the condition of safety in which the community finds itself as a result of exposure to potential catastrophe.

A recent survey (1) of attitudes among those practitioners who have the greatest need for a usable means of assessing risk (including 400 municipal administrators, 2,500 fire and police chiefs, and 100 drivers of highway tank vehicles revealed not only the dearth of information, knowledge, and training among such interested parties, but the overwhelming need, expressed as interest and desire, for a usable means of assessing local community risk or levels of safety in relation to the movement of hazardous materials vehicles in or near those communities.

Current Practice and Definitions

Risk is defined as "the chance of injury, damage, or loss." The word "chance" can be translated as "probability," which can be turned into a numerical value. Risk is also defined as "hazard."

Previous definitions of risk and earlier risk models are described in a Kansas State University Study (2) in the section entitled, Risk--The Threat to a Community. The model in this case then becomes a series of logical steps to follow, which are intended to lead to better decision making. Risk level is subjectively categorized as high, medium, and low.

The definition of risk in hazardous materials transportation safety considerations has been accepted as the product of the probability of a hazardous materials accident and the consequences of that accident. Consequences are usually expressed as effects on either population or property. Then population risk plus property risk equals total risk. The probability that an accident will occur has usually been defined as the accident history of the roadway segment under study.

Another study (3) includes in its calculations "traffic density, proximity of transportation route to population density, environment, property, and manufacturing and storage establishments," and "forms of threat," defined as fire, explosion, and toxic release.

EVALUATING PROBABILITY

An evaluation of the "probability of injury, damage, or loss" in hazardous materials transportation should not, however, be based entirely on past accident figures or rates. Instead, the evaluation should be based on (a) the current, identifiable hazards and conditions presented to the hazardous materials vehicles on any given facility, (b) hazards inherent in the vehicles used to transport hazardous materials, and (c) hazards reflected in the condition and capability of specific drivers.

Researchers have consistently attempted to approximate true probability (i.e., in terms of percent of a whole) and this requires the use of previous accident data. However, previous accident data do not help in predicting future accident experience. This is an "incorrect assumption" (3) about unchanging conditions of roadway environment; vehicle characteristics; capabilities and conditions; and driver qualifications, training, and temperament. Therefore, the best estimate of probability of occurrence is a subjective assessment of real and apparent hazards.

This method has been approached in a study (3) in which the "fault tree" methodology (from systems-safety engineering) is proposed. In this regard, the number of potential faults in the system would have to be assessed. If faults are equated with hazards, this approach provides a more realistic method of assessing probability, and one that relates more directly to the capabilities and knowledge of practitioners in local communities.

The systems engineering approach requires that hazards be identified not only in the roadway environment element of the human-machine-environment system, but also in the driver (the human) and the vehicle aspects. Severity, or consequences, should be a separate aspect of risk.

COMMUNITY VULNERABILITY

The vulnerability of the community to potential explosion, fire, or other release of hazardous materials has recently come into consideration. Vulnerable is defined as that which is capable of being wounded or physically injured. In one risk study (2), vulnerability is used as the status of community preparedness. This definition requires that preparedness itself be suitably defined, but it is reasonable to assume that vulnerability relates directly to preparedness, among other factors.

Risk calculations must be separated from preparedness assessments, however. The purpose of assessing risk is, appropriately, for the selection of corridors of transport of hazardous materials and the selection of routes within those corridors. The definition of vulnerability does not equate entirely with preparedness. Preparedness should be defined in terms not included in the risk model, so that a community can assess its preparedness quite apart from the assessment of risk made by itself or, more probably, by some external agency.

The value of a community that assesses its state of overall safety lies in (a) the recognition of the degree to which it is, as a community, exposed to the hazard of catastrophe on a daily or weekly basis; and (b) the determination of its needs for improvement in preparation for a hazardous materials incident, from the emergency-response and evacuation standpoints.

In this regard, vulnerability cannot be set equal to, simply, Risk · Preparedness. Vulnerability (the capability of being wounded) should be evaluated in terms of variables such as state of emergency preparedness, public awareness, preparation for evacuation, readiness for evacuation, numbers of persons liable to be evacuated, and similar terms. The only justification for using the term "preparedness" in lieu of "vulnerability" is that "vulnerability" is a negative term that has shock value and therefore would not find support (or use) among grass-roots practitioners, whereas "preparedness" is a positive term and can be perceived as having clearer meaning.

A Proposed Community Safety Assessment Model

The two elements of an overall Community Safety Assessment model are community risk (CR) and community preparedness (CP).

CR is developed from a formulation of the risk level of a motor vehicle incident [RL (mvi)], the risk level of a hazardous materials incident [RL (hmi)], traffic volume level (Ltv), and community risk factors (traffic volume levels are given in Table 1.)

TABLE 1 Traffic Volume Levels

Level	Annual Average Daily Traffic
1	0–5,000
2	5–10,000
3	10–15,000
4	15–20,000
5	20–30,000
6	30–40,000
7	40–50,000
8	50–60,000
9	60–70,000
10	70,000+

$$\mathrm{RL(mvi)} = \mathrm{Ltv} \cdot (\mathrm{Ni\ or\ Nr} + \mathrm{Nhc} + \mathrm{Nvc} + \mathrm{Cp} + \mathrm{Cm} + \mathrm{Nrh} + \mathrm{Ctc}) \quad (1)$$

where

Ni = number of intersections per mile,
Nr = number of on and off ramps per mile,
Nhc = number of horizontal curves per mile,
Nvc = number of vertical curves per mile,
Cp = condition of pavement (e.g., a Pavement Serviceability Index, to be based on AASHTO's Present Serviceability Index),
Cm = condition of median (e.g., a scale of 1 to 10, with 1 = positive barrier, correctly chosen, correctly installed, and maintained; and 10 = no barrier, median width of 20 ft or less),
Nrh = number of roadside hazards per mi (e.g., a scale of 1 to 10, with 1 = no roadside

hazards, 30-ft clear zone or smooth walls per barriers, and 10 = 20 primary hazards or 30 secondary hazards or a combination of the two), and

Ctc = condition of traffic control devices (signs, signals, markings) (e.g., a scale of 1 to 10, with 1 = excellent, and 10 = great number of devices in poor condition).

Then, the RL(hmi) can be expressed as follows:

$$RL(hmi) = RL(mvi) \cdot \{P(ex) \cdot 5.5 + P(fl) \cdot 2.5 + P(cg) \cdot 4.0 + P(c) \cdot 1.0 + P(p) \cdot 1.0\} \cdot Lv \cdot Ld \tag{2}$$

where

P(ex) = proportion of explosives vehicles in AADT (e.g., use percentage derived from random surveys; random surveys should cover 24 hr, each day of week, four seasons of year);
P(fl) = proportion of flammable liquids vehicles in AADT;
P(cg) = proportion of compressed gas vehicles in AADT;
P(c) = proportion of corrosives vehicles in AADT;
P(p) = proportion of poisons vehicles in AADT [the multipliers (5.5, 2.5, 4.0, 1.0, 1.0) were based on the approximate comparative impact of an incident];
Lv = vehicle level, including physical condition, how material is loaded, braking system, age of vehicle, condition of tires, and type of container--evaluation of the container is to be based on criteria of Bureau of Motor Carrier Safety, Federal Highway Administration, U.S. Department of Transportation. This evaluation is related also to available gauges and instruments within or on specific vehicles; and
Ld = driver level (including driver experience, accidents/violations history, training, awareness of regulations, awareness of emergency response actions, and knowledge of potential of material carried).

Then

$$CR = RL(hmi) \cdot \{Pd = Na + V\$ + Ns\} \tag{3}$$

where

Dp = population density of impacted areas (e.g., from Census Bureau classifications in specific tracts, available to community representatives, on a scale from rural to heavily urbanized);
Na = number of hazardous materials actors (generators, receivers, storers); this requires a land-use survey--available records should not be relied upon;
V$ = dollar value of property affected; and
Ns = number of sensitive facilities (e.g., schools, hospitals, churches, nursing/old age homes, libraries, manufacturing facilities, and area of public concentration).

The CP element is formulated in the following manner:

$$CP = Ler + Lec \tag{4}$$

where Ler is the level of emergency response capability (e.g., training, equipment, communication, transportation, manpower, evacuation capability, response time, planning, and exercises). Public awareness and preparedness emergency services include fire services, police, health and hospitals, public works, and contract personnel. Lec is the enforcement and compliance level, including training level of personnel (police and fire); number of inspections, both fixed-facility and on highways; history of violations; history of releases and incidents; and penalty structure.

CP, when combined with CR, provides an overall community safety assessment (CSA) as can be seen in Equation 5.

$$CSA = CP/CR \tag{5}$$

The eventual value of CSA, as a product of CP and CR, will reflect the overall community safety situation relative to hazardous materials transportation. For instance, values between 1 and 5 for CP, with 5 as "best" condition, or highest CP level, and between 0.1 and 1.0 for CR, with 1.0 as "worst" condition, or highest CR level, offer the following CSA values: in the worst-case condition, CP = 1, CR = 1.0: CSA = 1; and in the best-case condition, CP = 5, CR = 0.1: CSA = 50.

If the variables introduced in the three elements of the CSA are given values that result in a CSA index of this configuration, the significance of CSA can be shown graphically, as in Figure 3. A "criticality value" would be chosen to represent unacceptable levels (to the community) of death, injury, and/or destruction in the event of an incident. If, for example, we set the criticality value of the CSA at 25, it is clear that a reduction of risk has a much greater effect on overall safety than does an increase in preparedness.

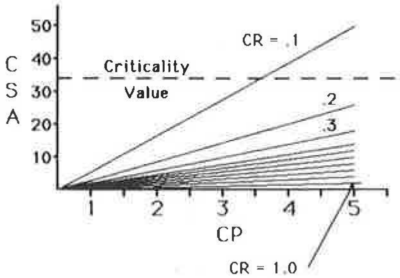

FIGURE 3 Community safety assessment (CSA = CP/CR).

CASE STUDY: HYPOTHETICAL CITY OF NEWTOWN, NEW GUERNSEY

Newtown, N.G. (Figure 4), is a suburban town in a northeastern state, with a population of 15,000. It is bisected by an Interstate route (I-88), a U.S. route (US-44), and two state routes (NG-20 and NG-55). A railroad (P and G) also bisects the town and branches off into two lines close to the central business district (CBD).

Figure 4 shows the general hazardous materials risk situation of Newtown. Hazardous-materials-carrying vehicles in large numbers pass through the town close to the CBD, churches, schools, hospitals, and other sensitive facilities, and close to industry, much of which itself produces, stores, and/or utilizes hazardous materials. Thus, residential, commercial, industrial, institutional, govern-

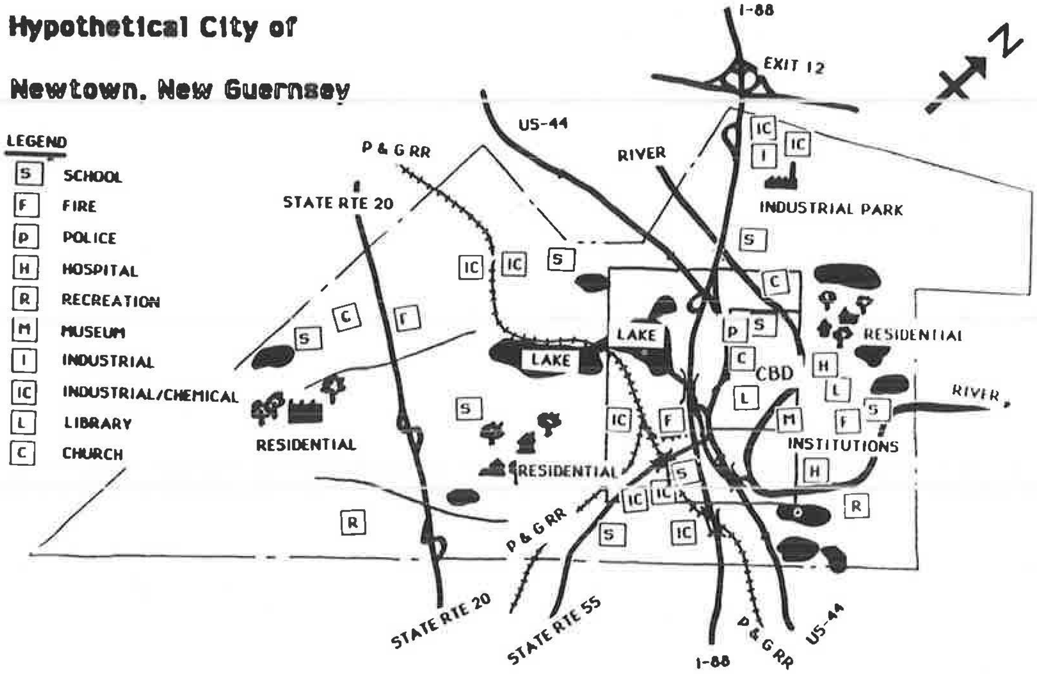

FIGURE 4 Map of Newtown, New Guernsey.

ment, and recreational (note streams and bodies of water) properties are exposed to risk.

Information from Observation

The following observations are made:

1. Newtown has a volunteer fire department, which does as well as it can to keep ready for emergencies. However, emergencies related to hazardous materials, (for which there is great potential in Newtown) are not easily confronted by volunteers. Training can never be adequate under such conditions; knowledge of the effects of and proper countermeasures for each of the many toxic chemicals is difficult to impart to part-time personnel. The Fire Chief has developed a more than adequate emergency plan, but his efforts are hampered by lack of personnel, appropriate equipment, and hydrants in strategic locations (such as within a reasonable distance of segments of I-88, which carries most of the hazardous materials vehicles).
2. Roads are heavily traveled by hazardous-materials-carrying vehicles (up to 119 tankers and 53 nontankers in a single 24-hour period). Thirty-six of these vehicles were carrying gasoline. The others ran the gamut of hazardous materials, including corrosives, flammable liquids and gases, poisons, combustible materials, oxidizers, and radioactive materials.
3. The industries within the city of Newtown use, receive, store, and ship materials such as oils, acetone and ethyl alcohol, pesticides, pigments and resins, lacquer, thinners, freon, antimony oxide, oxybisphenoxarsine, ketone, trichloroethane, toluene, and methylene chloride.
4. Accident information reveals that on I-88 alone some 25 commercial-vehicle accidents occur per year.
5. A major danger is that of hazardous materials spills that run off roads into the river, which interconnects with the many lakes and ponds seen in Figure 4. The P and G railroad has been asked by the Fire Chief not to park tanker cars on the overpasses precisely for this reason.
6. There is "incredibly heavy" traffic on the indicated roads--all of which (except for I-88) enter the city at street grade in the a.m. and p.m. peak hours. Tanker trucks thread through city streets and stop at diners.
7. There is a lack of hydrants and water lines along certain stretches of the highways.
8. An existing, continuing hazard that raises the risk factor considerably is the climbing lane on northbound I-88, which ends at the top of the upgrade. Just beyond that upgrade summit, out of sight of climbing trucks, other trucks pull off the road for repairs or rest periods. The area they pull off onto is in the shoulder--precisely in line with climbing trucks.
9. Since the state of New Guernsey has not adopted CFR 49, the Code of Federal Regulations rule that concerns the transportation of hazardous materials, no state, county, or city officials have any authority to control the movement of hazardous materials vehicles through Newtown.

Application of the CSA Model

Risk, Preparedness, and Safety Assessment Methodology

To assess the risk, preparedness, and safety values, it is necessary to recall Equation 1. As examples, traffic volumes and a simplified volume-level rating system are given as follows:

Road	AADT	Level
I-88	75,000	10
US-44	30,000	6
NG-20	24,000	5
NG-55	24,000	5

Estimated hazard values (Ni through Ctc), are given in Table 2. By normalizing all values to retain a span of 1 to 10, RL(mvi) is calculated to have a

TABLE 2 Hazard Values for Roads, Newtown, New Guernsey

Road	Ni-Nr	Nhc	Nvc	Cp	Cm	Nrh	Ctc
I-88	3	3	3	5	8	10	8
US 44	2	3	2	4	10	10	8
NG 20	2	5	2	3	10	10	6
NG 55	2	4	3	4	10	10	7

value between 8 and 4.5. Then CR = 0.7 (on a scale of 0.1 to 1.0), and CP = 2.5 (on a scale of 1 to 5). Then, the CSA = 2.5/0.7 = 3.6. If the CSA value is located on Figure 4, as shown in Figure 5, it is found to be well below the criticality value.

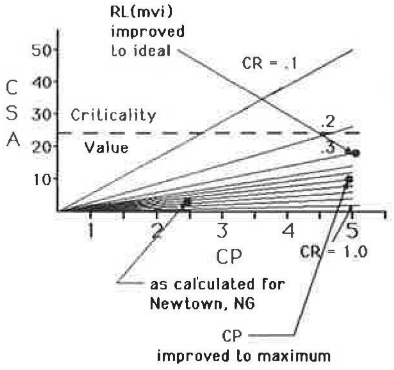

FIGURE 5 Newtown, New Guernsey: CP, CR, and CSA values.

Evaluation

The CSA value, at 3.6, is clearly below the agreed-upon criticality value of CSA = 25. The CSA value can be increased by increasing the CP value, decreasing the CR value, or both.

If it is assumed that CP can be improved to its maximum value (CP = 5), it is found that (as shown in Figure 5) it remains, at 7.14, well below the criticality value.

If it is then assumed that the RL(mvi) will be reduced by reducing the value of each of the hazard factors to 1, CR is reduced to .3.

This improves CSA to a value of 16.7, still well below the agreed-upon criticality value. Some options for added improvement can be considered, such as

- Rerouting all traffic;
- Rerouting hazardous materials vehicles;
- Shifting population;
- Shifting hazardous materials actors;
- Moving sensitive facilities;
- Reducing speed of traffic;
- Escorting (convoy) hazardous materials vehicles;
- Restricting hazardous materials vehicles to I-88, specific lanes, lower speeds, under escort, etc.; and
- Erecting protective walls, etc.

Other remedies may be available, but it is clear that preparedness in and of itself cannot reduce vulnerability, and therefore cannot significantly improve safety, yet, a high level of preparedness is absolutely essential.

The variables that are most difficult to improve in any existing situation are precisely those that can be avoided, prevented, or ameliorated in the planning stage: proximity of hazardous materials transport facilities and routes to concentrations of population, sensitive facilities, and hazardous materials industrial sites.

CONCLUSIONS

Risk/safety assessment methods that tend toward the acceptable, understandable (to community-level practitioners), absolute type can and must be developed. Theoretical, relative methods are neither comprehensible to nor usable by grass-roots practitioners. In addition, the need to separate risk assessments from vulnerability (or preparedness) assessments is quite clear.

Although greater detail and calibration of the method discussed here are necessary and desirable, the expressed needs are met for a usable methodology, and the desirability of improving community preparedness while at the same time improving the risk exposure situation of individual communities.

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Economic Evaluation of Routing Strategies for Hazardous Road Shipments

F. FRANK SACCOMANNO and A. Y.-W. CHAN

ABSTRACT

Potential risks from hazardous materials spills can be reduced by restricting shipments to designated safe routes. Several criteria can be used for designating safe truck routes with widely varying results. Three distinctive routing strategies for the road transportation of hazardous materials are discussed: minimum risk, minimum accident likelihood, and minimum truck operating costs. Each routing strategy is applied to the Toronto road network, on the basis of 1981 truck accident profiles. Recommended safe routes are analyzed for cost-effectiveness for a wide range of environmental conditions. Two important aspects emerge from this cost-effectiveness analysis: (a) the minimum risk routing strategy produces net economic gains in the form of enhanced safety, and (b) significant trade-offs occur between truck operating costs and safety benefits. These trade-offs are of fundamental concern to the implementation of this type of safety enhancement strategy for the transportation of hazardous materials.

The transportation of hazardous materials on congested urban roads is becoming an important concern. Several strategies for reducing the incidence of accidental spills have been considered. One such strategy is to restrict hazardous movements in urban areas to designated routes, where the potential risks are perceived to be less severe.

Ashton (1) Nemmers and Williams (2), House (3), and Wright and Glickman (4) provide an extensive review of current experience with safe routing strategies in North America and Europe. In general, recent practice has been to direct hazardous shipments to designated corridors, where land development is less intensive, and historical accident rates are less pronounced. The underlying basis of this approach is to project past accident trends into the future with a minimum assessment of the contextual factors that affect accident occurrence at specific locations in the road network at different points in time. A static assessment of past accident experience, however, may fail to effectively identify those routes that are safe under a wide range of random environmental conditions.

Three basic concerns that have not been fully addressed in the literature are examined in this paper:

1. Evaluation of alternative control strategies for restricting hazardous material traffic to specific routes. Three strategies will be assessed: minimum objective risk exposure, minimum accident likelihood, and minimum truck operating cost. Each control strategy reflects a different view of the underlying safety principle associated with this type of traffic.
2. Evaluation of the sensitivity of each designated route in the network to changes in random environmental influences.
3. Assessment of the incidence of costs and benefits associated with each control strategy for various environmental influences.

In the interest of implementation, an economic evaluation of alternative routing strategies for hazardous materials must address the incidence of costs and benefits to society in general and to the trucking industry in particular. Minimum risk routes may involve more circuitous travel patterns and, consequently, increased truck operating costs. These trade-offs are understandably of critical importance to the trucking industry and must be resolved if this type of safety enhancement program is to become more practicable.

METHODOLOGY FOR DESIGNATING SAFE TRUCK ROUTES

The three criteria under study are based on a minimization of truck operating costs, accident likelihood, and risk exposure.

Minimizing Truck Operating Costs

These costs include only time and out-of-pocket expenses borne directly by the truck operator. Accident costs occur too infrequently and too randomly to be perceived in normal route choice decisions; consequently, these costs have not been included in estimating direct operating expenses. Furthermore, although a significant portion of accident costs are borne directly by those individuals involved in the accident, the full allocation of these costs is distorted by legal and insurance settlements. A large component of the damage from specific accidents may be shared by the trucking industry as a whole through universal insurance premium increases. As a result, it is unlikely that these damages are perceived or incorporated into normal route choice decisions.

A routing strategy that is based on minimum truck operating costs is essentially an unregulated approach. Where route restrictions are not in effect, operators will likely select those routes that yield lower time and out-of-pocket expenses. Because safer routes may involve more circuitous travel paths, a control strategy that is based solely on minimizing operating costs serves as a reference for comparing the cost-effectiveness of these alternative safety strategies.

Minimizing Accident Likelihood

This routing strategy incorporates the relative frequency of truck accidents on select road links directly into the decision framework. Safety is essentially enhanced by restricting hazardous movements to routes where the potential for accident occurrence is reduced.

Because the frequency of accidents at specific locations in the road network varies from time to time depending on random environmental influences, a minimum accident likelihood strategy must be effective over a wide range of conditions. Two types of random environmental influences are considered in this paper: deterministic and stochastic. For each accident profile, deterministic influences can be controlled through specific planning and design options. Stochastic influences, however, although predictable to a degree, remain essentially unalterable in nature.

Deterministic influences are reflected in road design characteristics where these characteristics are expected to in some way affect general accident rates. For illustrative purposes, six homogeneous road classes have been selected to represent deterministic influences on truck accident rates:

- Expressways--design speed $\geq$ 100 km/hr,
- Expressways--design speed < 100 km/hr,
- Arterials and collectors--design speed > 50 km/hr,
- Arterials and collectors--design speed $\leq$ 50 km/hr,
- Major intersections, and
- Expressway ramps.

Similarly, four factors are used to represent stochastic influences at specific locations of the road network:

- Pavement surface condition--wet,
- Pavement surface condition--dry,
- Visibility--unrestricted, and
- Visibility--restricted.

In general, accident response to both deterministic and stochastic influences is expected to be random in nature, and can therefore be expressed in probabilistic terms.

In this paper, two assumptions are made concerning the interrelationships of constituent environmental factors. First, the occurrence of stochastic influences is assumed to be independent of the previous incidence of deterministic influences. For commercial traffic in urban areas, the choice of road type is not likely to be affected by random factors such as pavement surface and visibility. As noted by Saccomanno and Chan (5), observed truck movements in Toronto in 1981 substantiate this assertion. The second assumption concerns the probability of encountering certain road types along a given route. Because constituent links of a specific type are either present or absent for a given route, link probabilities of truck accident occurrence can be expressed as

$$\begin{aligned} P[A \cap E_d(i) \cap E_s(j)] &= P[A|E_d(i) \cap E_s(j)]\ P[E_d(i)|E_s(j)]\ P[E_s(j)] \\ &= P[A|E_d(i) \cap E_s(j)]\ P[E_s(j)] \end{aligned} \quad (1)$$

where

$P[A|E_d(i) \cap E_s(j)]$ = conditional probability of truck accidents given the previous joint occurrence of deterministic and stochastic factors $E_d(i)$ and $E_s(j)$, respectively;

$P[E_d(i)|E_s(j)]$ = conditional probability that factor $E_d(i)$ takes place given the previous occurrence of factor $E_s(j)$;

$P[E_s(j)]$ = probability for occurrence of stochastic factor $E_s(j)$; and

$P[A \cap E_d(i) \cap E_s(j)]$ = joint probability of a truck accident for a specific set of environmental influences.

Equation 1 is simply the truck accident rate for a specific combination of environmental influences, and can be rewritten as

$$P[A \cap E_d(i) \cap E_s(j)] = P[E_s(j)]\ (NA/TTV\text{-km}) \Big|_{\substack{E_d(i) \\ E_s(j)}} \quad (2)$$

where NA is the number of truck accidents for a given set of environmental conditions, and TTV-km is the total truck vehicle-kilometers for this same set of conditions. The distance factor in Equation 2 is used to standardize accident rates for a unit interval of roadway. Route probabilities for a single truck movement can be obtained by multiplying this standardized accident probability by the link distance and summing the result over all constituent links of the truck route.

Minimizing Objective Risk Exposure

Objective risk exposure for each link in the road network is defined simply as the product of accident likelihood and consequent damages from each material spill. Both accident liklihood and consequent damages are assumed to be affected by random environmental influences. As a result, estimates of risk exposure along specific links of the road network must account for variations induced by changes in these influences.

A number of studies have assessed the consequent damages to population and property from exposure to various hazardous materials spills (6-9). In general, these studies have recognized that certain environmental conditions present in each accident profile can affect the containment of damages to varying degrees. Again, the central concern in this literature is to suggest a context for each accident profile that relates directly to consequent damages.

Consequent damages are confined in this paper to three types of impact: (a) toxic--airborne dispersion of contaminants, (b) fire--ignition of flammable vapor cloud, and (c) explosion--blast effect of unconfined vapor cloud. As noted by Cairns (10), a realistic damage spectrum can be considerably more extensive than is implied by these three damage features. Individual damages may be augmented dramatically by process interdependencies. For example, Rose (11) has noted that an explosion can be followed by either a shock wave, a fireball, or fragmentation of material, each with a distinctive set of ramifications. The intricacies of the damage process are clearly outside the scope of this study, and have not been incorporated directly into the framework.

Three types of damages are assumed to result from the consequent impacts of hazardous materials spills:

1. Damages to individuals directly involved in each accident [this includes drivers and passengers of all vehicles (trucks and otherwise) involved];
2. Damages to individuals not directly involved in the accident but who reside in proximity to the spill site; and
3. General property damages that result directly or indirectly from a spill (this includes vehicles and other properties).

The damages associated with each spill are multiplied by the probability of accident occurrence to give an estimate of risk exposure along each link of the road network. The expression used in this study is of the following form:

$$R_i(k) = \sum_j P_{ij} \cdot D(k) \tag{3}$$

where

$R_i(k)$ = objective risk on a unit interval of class i road;
P_{ij} = joint probability of accident occurrence on road class i for stochastic event j from Equation 2...$P[A \cap E_d(i) \cap E_s(j)]$; and
$D(k)$ = likely damage associated with link k of the road network.

The minimum risk route is obtained by summing the link risk from Equation 3 over all constituent links (including intersections) for each route. Risk exposure for each route can be expressed either for a given set of stochastic environmental conditions or, if the probability of occurrence for these conditions is known, risk can be estimated for all possible stochastic conditions over a given interval. The latter is accomplished by summing link accident probabilities from Equation 3 over all events j.

ESTIMATING THE COSTS OF RISK EXPOSURE

Before evaluating the economic effectiveness of alternative routing strategies, it is desirable to express the potential damage associated with accidental spills in terms of actual costs. For the three types of impact under consideration, road link damages can be obtained from the expression

$$D(k) = \alpha^T C^T(k) + \alpha^F C^F(k) + \alpha^E C^E(k) \tag{4}$$

where

$D(k)$ = aggregate damage costs for road link k (\$);
$C^T(k)$, $C^F(k)$, and $C^E(k)$ = costs for toxic, fire, and explosion damages, respectively; and
α^T, α^F, and α^E = proportion of hazardous materials spills that result in toxic, fire, and explosion effects, respectively.

An assessment of historical accident records that involve hazardous materials provides a basic estimate of the proportion of spills in which toxic, fire, and explosion effects take place. Table 1 is a summary of the types of damage associated with various hazardous materials spills in the United States from 1973 through 1979 as documented by FHWA (6). On average, toxic, fire, and explosion effects have occurred in 0.032, 0.019, and 0.065 percent of all reported spills, respectively. Because information on prevailing environmental conditions at each spill site is not available, it is not possible to adjust these values by random environmental influences.

TABLE 1 Types of Road Accidents Involving Hazardous Materials in United States, 1973-1979 *(6)*

Material	Fire	Explosion	Toxic	Spill without Damages
Gasoline	34	11	0	49
Flammable liquids	13	5	0	28
Flammable compressed gas	4	13	12	12
Nonflammable compressed gas	0	0	0	8
Oxidizing materials	0	1	0	3
Poison, class A	1	0	1	1
Poison, class B	2	0	0	3
Explosives, class A	1	3	0	1
Expolsives, class C	1	2	0	1
Combustibles	3	2	0	5
Corrosive materials	4	1	0	10
Radioactive materials	0	0	0	2
Total	63	38	13	109

Damages that result from toxic, fire, and explosion effects can be expressed in terms of specific impacts on population and property. For toxic effects, for example, the expression is of the following form:

$$C^T(k) = (\gamma^T_{ft} C^f + \gamma^T_{it} C^i) + (\gamma_{fp} C^f + \gamma_{ip} C^i)\, A^T(k)\, p(k) + \overline{PD}^T \tag{5}$$

where

$C^T(k)$ = total cost of damage on link k from toxic impact;
γ^T_{ft}, γ^T_{it} = the proportion of fatalities and injuries to individuals directly involved in each accident where toxic impact is realized;
γ^T_{fp}, γ^T_{ip} = the proportion of fatalities and injuries to population in proximity to each spill site, where toxic impact is realized;
C_i, C^f = average real cost value of injuries and fatalities, respectively;
$A^T(k)$ = impact area for toxic damages on road link k;
$p(k)$ = population density associated with link k; and
$\overline{PD}^T$ = average damages to property where toxic impact is realized (vehicles, buildings, etc.).

Similar expressions can be obtained for fire and explosion effects.

Analysis of 140 accident profiles from FHWA records from 1973 through 1979 provides an estimate of the proportion of accidental spills that result in fatalities, injuries, and property damage. These records are used to calibrate the parameters in Equation 5. Given the accidental release of hazardous material, the additional consequences following each spill are assumed to be similar for both the U.S. and Canada.

The average costs, associated with fatalities and injuries, are based on data obtained from the National Safety Council (NSC) (12) and the National Highway Traffic Safety Administration (NHTSA) (13), U.S. Department of Transportation. These costs, expressed in 1981 Canadian dollars, are as follows. (Note: "NA" means not applicable, and 1981 Canadian dollars can be converted to 1981 U.S. dollars by multiplying by 0.72.)

	NHTSA (1981 $ Canada)	NSC (1981 $ Canada)
Fatal	617,190	230,520
Critical injury	413,156	NA
Severe injury	17,376	9,085
Moderate injury	9,349	NA
Minor injury	4,707	NA

Cost differences between the two agencies are essentially a result of different reporting procedures. The NSC records include only direct costs of fatalities and injuries whereas the NHTSA records also include indirect social costs. In general, two assumptions tend to cause distortions in these damage estimates: (a) that relocation costs have been ignored, and (b) that only major spills were reported.

The costs of relocating victims of an accidental hazardous materials spill can be significant. In many accidents, this cost component tends to dominate the damage spectrum, particularly where actual fatalities and injuries are few, but the potential risk is perceived to be severe. Relocation costs are assumed in this paper to be proportional to population levels within designated impact zones for each road link. The absence of a clear estimate of relocation costs, however, necessitates the production, by using Equation 5, of a new cost estimate that will underestimate the real damage associated with each accidental spill. In this way, the inclusion of only major spills in the data base can be compensated for, so as to yield a more realistic cost estimate.

A zone of impact can be obtained for each link in the road network by assuming a continuum of possible spill sites along its length, and a circular range of impact for each spill. The assumption of a circular range of impact may not reflect a realistic dispersal of toxic contaminants. As noted by Schulze (14), plume dispersion arcs of 20 to 40 degrees have been observed, depending on wind speed and direction. The circular dispersion formula in this study is a center line of plume estimate, with the wind blowing from all directions. As such, the impact zone estimated for each road link tends to overestimate the area that is likely to be affected in a real spill situation. The area of impact for each link depends on the nature of damage from a potential spill. As an example, for toxic damage, the zone that is likely to be affected can be obtained from the expression

$$f_k^T(w) = \begin{cases} 2w\ell_w + \pi^2 & \text{for each link} \\ \pi w^2 & \text{for each intersection} \end{cases} \qquad (6)$$

where

$f_k^T(w)$ = impact area for toxic effects on road section k,
ℓ_k = link distance (km), and
w = range (m).

Similar expressions can be established for fire and explosion effects. Several empirical relationships have been used in this study to estimate the expected range of toxic, fire, and explosion impacts along each link of the road network. These expressions are a function of material properties and environmental conditions. For example, fire can be expressed by using the amount of hydrocarbons in the spill material; explosion can be expressed by using the amount of trinitrotoluene (TNT) equivalent in the material; and toxic dispersal can be expressed by using wind direction, wind speed, and atmospheric stability. The structure of these relationships is discussed in detail by Schulze (14).

Exposure to each potential spill varies with distance from the accident site. More distant points are not contained within the range of potential damage for the same duration time as nearby points. In this paper, the range w in Equation 6 is multiplied by a factor of π/4 to standardize the range for exposure variations with distance. Within this reduced range, all locations are assumed to be equally affected by hazardous materials spills.

SENSITIVITIES OF ALTERNATIVE ROUTING STRATEGIES FOR TORONTO

An aggregation of the Toronto road network is used to study the effects of alternative routing strategies for the transportation of hazardous materials. This network consists of 255 nodes and 457 links. Eleven origin-destination (OD) zones have been selected to represent areas where the production and use of hazardous materials is likely to be more pronounced. These OD zones are coincident with major concentrations of industrial activity and with principal entry or exit gates into the urban region.

A total of 1,084 heavy truck accident profiles were extracted from Metropolitan Toronto police records for 1981. These records provide an excellent description of the contextual framework in which each accident takes place. Annual network-wide heavy truck volumes were estimated from Metro cordon counts (15), supplemented by daily vehicle traffic counts on each section of the network. Population and employment densities associated with each road link are averages of nearby 1981 census district values.

Conditional accident probabilities for heavy truck movements, as estimated from Equation 2, are summarized in Table 2 for a range of environmental conditions. These values suggest that despite environmental changes, truck accident rates remain infrequent random events. When road class is considered, truck accidents are less likely to occur on expressways than on arterials over all pavement surface and visibility restrictions. This may reflect higher design standards on expressways, with emphasis on entry and exit controls, traffic stream separation, and less abrupt alignment changes. These standards are especially important for heavy trucks, where vehicle maneuverability is appreciably reduced relative to the automobile. On arterial roads, however, restrictions imposed by wet pavement can produce higher accident rates, especially where design speeds are also higher. More significantly, accident probabilities on expressway ramps are several times greater than probabilities on discrete 1-km segments

TABLE 2 Conditional Truck Accident Probabilities

	Probability ($X10^{-6}$)					
Conditions	A	B	C	D	E	F
Dry pavement						
Unrestricted visibility	3.715	2.744	0.876	1.478	2.215	0.830
Restricted visibility	3.957	1.779	1.672	2.519	5.218	0.935
Wet pavement						
Unrestricted visibility	1.816	1.895	0.956	1.728	2.580	0.878
Restricted visibility	0.957	1.737	0.531	2.740	8.279	0.593

Note: A = arterial/collectors with speed = 50 km/hr; B = arterial/collectors with speed > 50 km/hr; C = expressways with speed < 100 km/hr; D = expressways with speed = 100 km/hr; E = ramps; and F = major intersections.

of expressway links for the same set of environmental influences. Again, because ramps are associated with more abrupt changes in direction and speed, these results attest to the maneuverability problems associated with heavy trucks. It is interesting to note that no appreciable difference in accident rates is revealed between intersections and arterial links. (Link accidents are those that occur at minor intersections along each arterial link.) Apparently, maneuverability factors are not as critical on arterial roads, where speeds are lower and response times are less restrictive. It should be noted, however, that only major intersections have been identified in this study.

In the final analysis, however, it is not possible to speculate that all intersections are safer than arterial links solely on the basis of these results because accident rates for a selected number of major intersections tend to be lower than link accident rates.

Minimum path trees were obtained for each of the 11 zones in the road network, under the three control strategies that minimize risk, accident likelihood, and truck operating cost. For illustrative purposes, the minimum path trees for the downtown industrial zone have been included in this paper in Figures 1 and 2. Minimum paths for the downtown zone represent close, network-wide sensitivities to control strategies and environmental conditions. In general, the minimum path trees for all 11 zones indicate a high sensitivity not only to underlying routing strategy, but also for each strategy for which they represent significant variations for different combinations of environmental factors. As illustrated in Figures 1 and 2, when operating costs are minimized, arterial roads comprise a greater share of the minimum paths that connect the central zone to each of the 10 outer zones. For example, when risk is minimized, expressway use is increased commensurately especially for the more restrictive environmental conditions such as wet pavement and reduced visibility. In addition, when risk is minimized, road links in the central area are avoided for all environmental influences. This does not appear to be the case for the minimum accident likelihood or minimum operating cost strategies. Essentially, the risk measure appears to be sensitive to higher population and employment densities in the central area, where the potential damage from an accidental spill of hazardous materials is expected to be more pronounced.

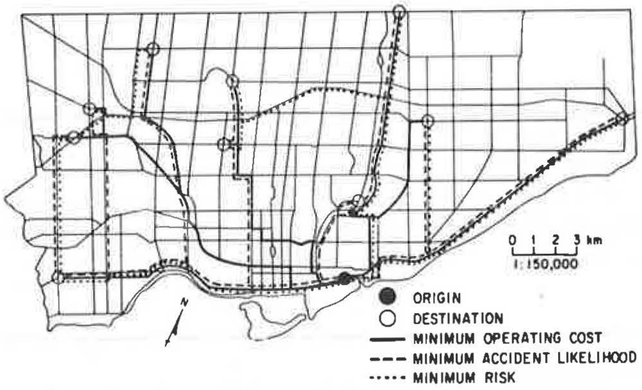

FIGURE 1 Minimum path trees for downtown zone under dry pavement and unrestricted visibility.

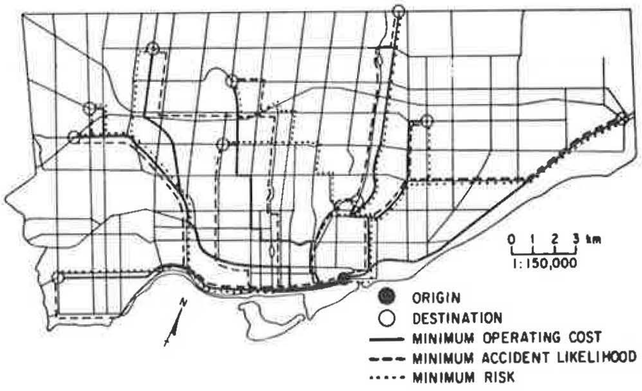

FIGURE 2 Minimum path trees for downtown zone under wet pavement and restricted visibility.

In this analysis, the Toronto road network is a simplified aggregation of reality in that minor streets and intersections have been ignored. A detailed road network with a more extensive array of links and nodes would very likely increase the choice options at each node and therefore accentuate the variations in route choice as suggested here.

EVALUATING COSTS AND BENEFITS

A true appreciation of the full incidence of costs and benefits associated with each routing strategy is not attainable without first determining the actual movements of hazardous materials over the network. Nevertheless, some insight into the relative cost-effective merits of alternative routing strategies is possible from the analysis of a single truck movement between all OD pairs in the network.

Several cost components are summarized in Table 3 for each of the three control routing strategies, and several combinations of environmental factors. All costs in this table are in terms of a single truck movement along the minimum paths joining all 11 OD zones in the Toronto road network. Total truck operating costs for constituent links are based on unit values from Table 4 for central and suburban locations where these costs are multiplied by the appropriate link distance. Expected accident costs in Table 3 are similarly obtained by multiplying estimates of direct unit damages to population and vehicles by the probability of accident occurrence associated with each constituent link of the desig-

TABLE 3 Summary of Cost Components for the Routing Strategies

	Cost Component (1981 $ Canada)		
	Minimum Operating Cost	Minimum Accident Likelihood	Minimum Risk
Dry pavement			
Unrestricted visibility			
Operating cost	1,746.17	1,939.48	2,049.35
Direct accident cost	67.96	57.50	63.70
Risk	990.23	706.47	603.58
Restricted visibility			
Operating cost	1,746.17	2,021.85	2,020.26
Direct accident cost	67.96	84.90	90.60
Risk	1,784.60	1,725.50	1,179.20
Wet pavement			
Unrestricted visibility			
Operating cost	1,746.17	1,814.73	1,919.56
Direct accident cost	67.96	67.23	71.94
Risk	811.01	772.30	647.58
Restricted visibility			
Operating cost	1,746.17	2,055.97	1,999.46
Direct accident cost	67.96	77.95	75.46
Risk	762.51	704.00	532.00

Note: To convert 1981 Canadian dollars to 1981 U.S. dollars, multiply by 0.72.

TABLE 4 Unit Truck Operating Costs *(16)*

Item	Cost (1980 $ Canada/km)
Central business district	
Crew	0.740
Fuel and oil	0.140
Tire wear	0.051
Maintenance	
Parts	0.060
Labor	0.046
Interest and depreciation	0.129
Fixed cost	0.059
Total	1.225
Other urban area	
Crew	0.446
Fuel and oil	0.101
Tire wear	0.042
Maintenance	
Parts	0.052
Labor	0.040
Interest and depreciation	0.129
Fixed cost	0.050
Total	0.860

Note: To convert 1980 Canadian dollars to 1980 U.S. dollars, multiply by 0.72.

nated minimum path. Costs that reflect risk exposure include indirect potential damages to adjacent population for each road link. Potential damages from accidental material spills are confined to toxic, fire, and explosion effects expressed in terms of fatalities, injuries, and property damages.

As expected, minimum operating cost routes produce aggregate truck operating costs that are significantly lower than either minimum risk or minimum accident likelihood options. This advantage for the minimum truck operating cost strategy is gained at the expense of higher risks. This trade-off between safety enhancement and increased truck operating costs occurs consistently for all environmental combinations without significant variations.

The inclusion of an accident cost component does not alter route patterns to any substantial degree. Accident costs are not significant in relation to either risk or truck operating costs and can thus be ignored. It is interesting to note that accident costs are not reduced for those routing strategies where safety is the primary concern. Expected accident costs are strongly influenced by exposure along selected routes, where exposure is a function of distance traveled. Because distance is minimized commensurately with a minimum truck operating cost strategy, accident costs also tend to be lower for these results.

The trade-offs between truck operating costs and risk are shown in Figures 3 and 4 for each routing strategy and two combinations of environmental influences. In general the minimum accident likelihood strategy is not cost-effective. With the exception of unrestricted environmental conditions (i.e., dry pavement and unrestricted visibility), minimum accident likelihood routes consistently yield both higher risk values and, in most cases, higher operating costs. Lower risk values associated with minimum risk routes, however, are sufficient to offset higher truck operating expenses relative to the minimum operating cost strategy. These minimum risk routes yield an average savings per vehicle-kilometer traveled of $0.22 per single truck movement.

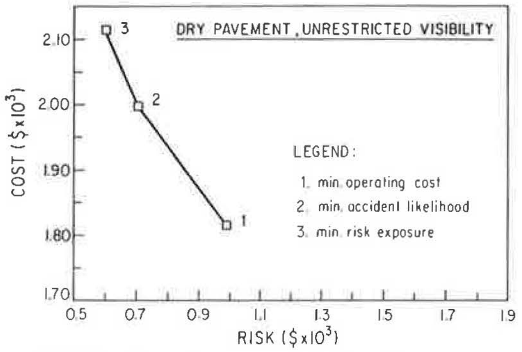

FIGURE 3 Cost-effectiveness of alternative routing strategies (dry pavement-unrestricted visibility).

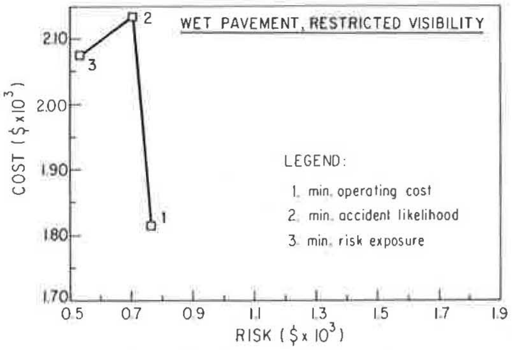

FIGURE 4 Cost-effectiveness of alternative routing strategies (wet pavement-restricted visibility).

An annual commercial traffic volume of 496.3 million vehicle-km was observed in Toronto in 1978 of which approximately 19 percent comprised some type of hazardous material (15). Restriction of this traffic to designated minimum risk routes can yield approximately $20.7 million in savings per year over the route option currently in effect that minimizes operating costs. Increased costs to the trucking industry, however, are approximately $11.8 million per year. Environmental conditions, as defined in this paper, do not generally appear to alter these cost trade-offs to any large extent.

CONCLUSIONS

The following conclusions can be drawn from this study:

1. The safe transportation of hazardous materials in large urban areas can be enhanced through effective routing strategies. Distinctive route options are suggested for each of three strategies: minimum truck operating costs, minimum accident likelihood, and minimum objective risk exposure. Within each strategy, designated routes are observed to be highly sensitive to random environmental influences. These influences can vary over time and for different locations in the road network.

2. A minimum risk routing strategy can reduce potential damages associated with hazardous materials spills, and can produce net economic gains to society. Minimum risk routes are clearly the most cost-effective means of restricting hazardous shipments on the urban road network. The effectiveness of this strategy, however, must be viewed in relation to higher truck operating costs. In the interests of implementation, any safety enhancement program for the transportation of hazardous materials based on route choice must address the problem of higher operating costs as borne by the trucking industry.

3. A routing strategy that is based solely on minimum accident likelihood does not appear to be cost-effective. Not only are operating costs higher for this strategy relative to the minimum operating cost approach, but risk benefits are also lower. The introduction of direct accident costs into the analysis fails to alter any of these conclusions. Accident costs are not significant when compared with either truck operating expenses or risk exposure, and can be neglected without altering the results to any appreciable extent.

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Routing Models for the Transportation of Hazardous Materials—State Level Enhancements and Modifications

JAMES D. BROGAN and JONATHAN W. CASHWELL

ABSTRACT

Computerized routing models for the movement of radioactive and other hazardous materials by highway exist at the national level. These models use gross estimates of distance and operating speed to select minimum paths for various origin-destination pairs. Although these models are constantly being enhanced, the coarseness of data aggregation that is necessary on a national scale has precluded their use at smaller levels of analysis such as an individual state. The purpose of this paper is to report on efforts to refine the existing models for improved operation on more limited networks. The existing highway network for New Mexico is described and additional data bases are defined and examined to identify supplementary information (such as roadway geometrics and operational parameters) that will improve model performance at the state level. The accuracy and effectiveness of detailed routing projections as well as the associated costs, benefits, and sensitivities of the use of various network parameters are also to be evaluated.

Research and development activities in the transportation of radioactive materials have been under way for several years. These efforts have been directed toward a number of areas that include the design and testing of waste-transport hardware, the development and maintenance of a number of computerized data bases that pertain to the transport of radioactive and other hazardous materials, and the development and application of several computerized routing models for the transportation of hazardous materials.

This latter activity has resulted in two nationwide routing models for the movement of radioactive materials by road (HIGHWAY) and rail (INTERLINE). In addition, a data base that contains legislative, regulatory, and operational restrictions (LRIS) on the movement of radioactive and hazardous waste is maintained; efforts are now under way to interface these restrictions with the previously developed routing models. Technical developments in these two areas have been performed primarily by Oak Ridge National Laboratory (ORNL) and have been reported previously in the technical literature (1-5).

Although the nationwide models just described are continually being enhanced, the level of data aggregation that is necessary on a nationwide scale may preclude serious consideration of detailed network geometric and operational factors appropriate at other levels of analysis. Thus, for example, application of the routing models at a more detailed level of analysis, such as a region of the country or a specific state, may require more refined network information than the gross link distances and average driving speeds used in the nationwide code.

The work on which this paper is based is an attempt to "window-in" on only a limited portion of the nationwide network--the state of New Mexico-and investigate the desirability of enhancing network descriptions through the consideration of additional link parameters that may influence the movement of highway vehicles used to transport hazardous materials. Thus, the overall project has four goals:

1. To examine the applicability of currently available nationwide network routing models,
2. To evaluate the appropriateness of such models to regional and state levels of analysis,
3. To assess the availability and applicability of additional statewide network data that are helpful in improving model performance, and
4. To conduct sensitivity analyses to determine the cost-effectiveness of more detailed model applications.

Subsequent sections of the paper contain a description of the existing highway model, its data requirements and its output, a discussion on the state-level network defined by the national model, a list and evaluation of additional data sources that are available at the state level to refine the national model as applied to New Mexico, and an outline of future activities related to improved model performance (including cost-effectiveness) at the state level.

THE HIGHWAY ROUTING MODEL

Network models that involve use of path selection criteria and vehicle trip assignment to previously selected paths have been an integral part of transportation analysis for many years. At the urban-area scale, the emphasis of these models has been on the assignment of passenger vehicles to alternative highway networks based on the selection of minimum paths as a function of distance, travel time, cost, or some general measure of trip impedance (6). More recently, traffic or trip assignment models have been applied to passenger movements at other levels of aggregation, such as regions, states, or even the entire country (7), and analysis methods have been broadened to include the assignment of freight as well as passenger movements (8,9). Conceptually, however, modeling approaches have remained basically unchanged. Thus, for example, groups of paths, or "trees," are first developed on the basis of the minimization of some measure of trip disutility through the network. Then movement volumes, or flows, are assigned to the minimum paths between an origin and all possible destinations. Individual volumes on any one link in the network may then be easily obtained by summing minimum path volumes for all paths that involve use of that link.

Procedures such as those described earlier have been used by ORNL in the development and subsequent modification of HIGHWAY, a routing program for predicting highway paths for the movement of radioactive waste nationwide. The data base used in HIGHWAY, originally the COMPU.MAP program developed by Logistic Systems, Inc. (10), is basically a computerized road atlas that contains over 240,000 miles of highway on over 15,000 roadway links defined by 10,500 nodal intersections. In terms of functional or administrative classification, all Interstate highways and all U.S. numbered highways (with the exception of those that parallel the Interstate system) are included in the HIGHWAY data base. Most principal state routes are also included, and a number of local roads and streets, particularly those that connect nuclear facilities with nearby airports, have recently been added to the network (5).

Information in the data base for each link includes link origin and destination (usually a city, town, or major street intersection), link designation (Interstate, U.S., state, or local road route number), highway functional classification (given in Table 1), estimated driving speed on the link (in miles per hour), and link length (in miles). Output from the HIGHWAY model consists of the route between an origin-destination pair chosen by minimization of the total impedance (a function of distance and travel time) between the pair.

TABLE 1 Functional Classification of the HIGHWAY Data Base

Class No.	Description
1	Multilane limited access
2	Two-lane limited access
3	Four-lane divided
4	Four-lane undivided
5	Principal highway
6	Other through highway
7	All other roads

The model is capable of reacting to several user-imposed constraints on the routing. In addition to routes based only on state and local restrictions that govern the movement of normal commerce, the model can also select routes that bypass areas of high population density--the so-called Nuclear Regulatory Commission (NRC) routes--or that maximize the use of Interstate facilities--the U.S. Department of Transportation (DOT) criteria (4,5).

Results obtained by using the different routing criteria are summarized in Table 2, which compares the three routing criteria for a shipment between Barnwell, South Carolina and Richland, Washington. As can be seen in the table, the regular route is the most direct, both in terms of distance and driving time, and uses Interstate facilities for 90 percent of the trip. By using the NRC criteria, in contrast, the route bypasses six metropolitan areas and increases the travel distance by just over 5 percent. The driving time on this route, however, is increased by almost 12 percent because of the greater percentage of use of lower-speed, non-Interstate facilities. The DOT route, which maximizes the use of Interstate facilities, results in the longest distance but, because of the greater use of high speed facilities, only a slight increase in overall travel time. The DOT route passes through eight urbanized areas. Differences among the three routes are shown in Figure 1.

TABLE 2 Comparison of Routes Between Richland, Washington and Barnwell, South Carolina *(4)*

Type	Distance (km)	Driving Time (hr)	Percent of Interstate
Regular	4312	46.2	90.0
NRC	4542	51.7	56.4
DOT	4562	47.7	96.7

The limited amount of data available from the national model, however, may limit its effectiveness when applied to regional or state levels of analysis. As the size of the analysis area decreases, the need to define network parameters in more detail increases. Link lengths of 75 to 150 miles, although appropriate for analyses at the national level, are too coarse for use in state and regional applications. Average driving speeds from road atlas time-and-distance maps, which are the basis for the national network, similarly do not consider variations in driving speed, and, hence, travel time at the state level. Finally, additional data not appropriate at the national level, such as roadway geometrics, operating speeds by time of day, and the identification of critical spot locations (rail-highway grade crossings and critical bridges, for example) need to be considered at the lower levels of aggregation. It is the availability and the use of such data that is discussed in the next section.

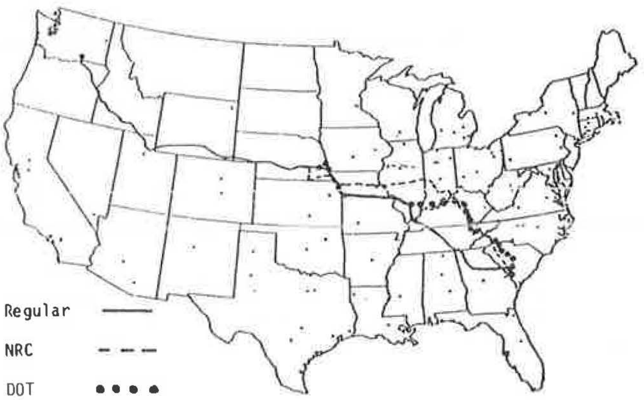
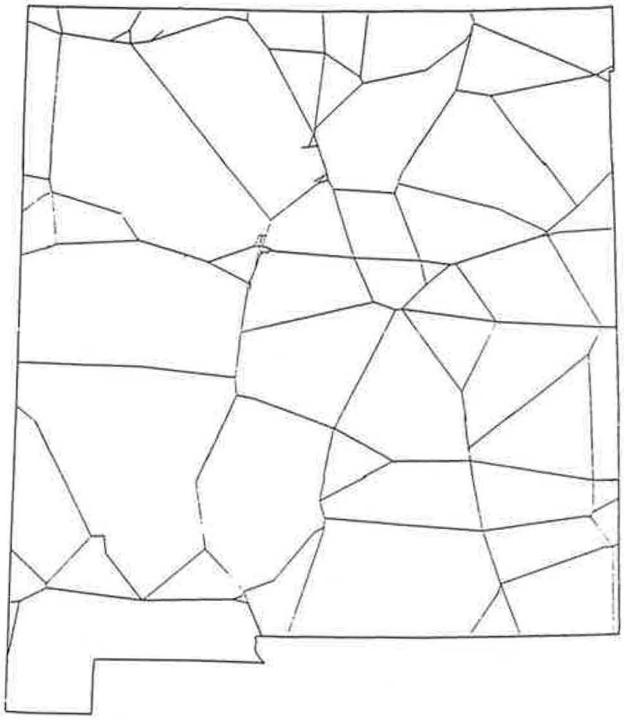


FIGURE 1 Routes between Barnwell, South Carolina and Richland, Washington *(4)*.

DATA NEEDS AT THE STATE LEVEL

The New Mexico portion of the nationwide HIGHWAY data base is shown in Figure 2. The New Mexico network shown contains a total of 207 links that range in length from 1 to 153 miles. Estimated driving speeds on the network vary from 60 mph on the state's Interstate facilities to a low of 10 mph on a number of restricted local streets. The only other information available from the national data base for the New Mexico network is functional classification.

One of this project's objectives was the consideration of additional data available at the state



Source: Oak Ridge National Laboratory, Oak Ridge, Tennessee.

FIGURE 2 ORNL HIGHWAY data base.

level to augment the state network represented in HIGHWAY. These additional data were deemed to be necessary because of the coarseness and the limited amount of information available from the national data. The process may be thought of as similar to the process that occurs in the network coding step at the urban transportation planning level where, as the size of the area decreases (or the sophistication of the analysis technique increases), the level of detail and the number of special features to be coded increases. Thus, for instance, broad region-wide planning studies have little need for detailed geometrics whereas small area studies may have to consider such network or operational features as

- Turn penalties at intersections,
- Roadway capacity,
- Directional distribution of traffic,
- Street width,
- The presence or absence of parking,
- Roadway surface type and condition, and
- The predominant land use in the area (6).

Fortunately, a great deal of inventory information on New Mexico roadways exists. This information is maintained in a standard format, for the most part, for a number of state highway offices by the Division of Government Research (DGR) at the University of New Mexico. Not all of the information is appropriate, of course, for the statewide routing issue. Data thought to be most useful have been identified by file source and are summarized in Table 3.

As the data in Table 3 indicate, a large amount of additional network information is available to refine the New Mexico roadway system for the analysis of intrastate routing of hazardous materials. A number of technical issues need to be resolved, however, before the refined network is used in model applications. The issue of the length of sections that define network links, for instance, must be addressed. Link lengths on the existing HIGHWAY network for the state, as previously mentioned, range from 1 to over 150 miles. Segment lengths on the state's Roadway Inventory file for the Interstate system, on the other hand, vary in length from only 200 ft to over 11 miles. Use of the refined state network will require section lengths somewhere between the extremes represented by the HIGHWAY and Roadway Inventory data bases.

Another issue in the use of additional state-level data to improve network model performance involves the utility of spot, or specific locational data, in conjunction with sections or links of varying lengths. For example, critical geometric factors (sharp curves, steep grades, limited sight distances) may occur at a number of locations along a previously defined network link. In order to use this spot information in the routing code, an index for the section that reflects the number and severity of such critical locations on the link must be developed. The same may be true for accident information contained in the state's computerized accident information system if it is to be used to identify locations (or links) with unusual accident characteristics.

FUTURE DEVELOPMENTS

Considerable work remains to be done to implement improved routing models for the shipment of hazardous materials at the state level of analysis. The existing state network has been defined and data sources available at the state level that will add detailed information on existing links have been identified. Work on extracting the additional variables of interest from a number of diverse data bases is under way and a single source that contains the complete set of desired information is anticipated shortly.

The refined network will then be used to examine the sensitivity of various routing alternatives to the new level of network detail. Alternative routing travel times may be relatively insensitive to roadway geometric features such as vertical alignment, for instance, but may be particularly sensitive to speed and traffic flow volumes by time of day. Regulatory or legislative restrictions that prohibit

TABLE 3 Available Data for Highway Routing—State Level

File	Variables of Interest
Roadway inventory	Average daily traffic (ADT), average highway speed, critical grade, critical sight distance, functional classification, number of lanes, segment length, left shoulder width, median width, median type, log mile of section start, roadway width, administrative route number, right shoulder width, ROW width, surface width
Roadway condition	Adjusted overall rating, capacity rating, percent heavy commercial, design speed, 30th highest hourly volume
Photolog file	Roadway gradient, horizontal curvature, average roadway roughness, vertical curvature
Highway needs	Future ADT, operating speed, passing sight distance, safe speed, terrain type, percent heavy commercial
Highway bridge file	Approach width, bridge width, functional classification, operating load, substructure condition, super-structure condition, vertical clearance

hazardous materials movement during certain hours or on certain routes may similarly add to the time and costs of scheduling such movements. Geometric and traffic operational parameters may also be related to accident experience on roadway segments, thus identifying possible high hazard locations.

SUMMARY

The research discussed in this paper concerns investigation of the highway routing of radioactive and other hazardous materials in New Mexico through the application and refinement of existing nationwide network analysis models. Truck-related data bases that detail truck movements, as well as detailed geometric and operational inventory data, have been identified at the state level and are being used to refine estimates of hazardous materials movements in the state. Results of this project will enable estimates of the probable routes of such movements to be made within New Mexico and will allow decision makers at various levels to better evaluate the impacts of such movements.

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Cost-Effectiveness Analysis of Transportation Strategies for Nuclear Waste Repository Sites

JASON C. YU and CHARLES A. JUDD

ABSTRACT

Because of the complexity involved in the evaluation of transportation strategies for nuclear wastes, a cost-effectiveness methodology is presented in this study for use in ranking the potential nuclear waste repository sites in the United States from the transportation perspective. In addition, some historical data are presented to help clarify the issue of safety in nuclear waste transportation. The basic features of the cost-effectiveness model are well-suited for the analysis of the issues addressed in this study. Based on available data, the results of two model applications indicate that the best nuclear waste repository location in the United States among five potential sites would be the Gulf Interior region in Mississippi, with a railroad connection to and from the points of waste production, and that the optimal local transportation corridor for the Gibson Dome site in Utah would be through the Colorado Canyon. It should be noted that the basic intent of this study was to illustrate how a cost-effectiveness model may be applied to resolving transportation-related issues in nuclear waste repository site selection. The tentative solutions recommended by this study need to be validated by further analysis, and to be based on a more complete data set.

One of the major issues that faces the United States today is the use of nuclear materials. With respect to public safety and health hazards, this issue becomes particularly critical when the transportation and disposal of high-level nuclear waste is required. The transportation and disposal of nuclear wastes is not only of national concern, but is of keen interest at local and state levels as well. For instance, the state of Utah has been chosen as one of the possible locations for a nuclear repository. The public seems to form its opinion without placing the issue in proper perspective, which causes undue confusion in our society. The decisions that need to be made when choosing a site for a nuclear waste repository are complex; there exist a wide range of consequences for the neighboring area. These include direct or objective impacts such as the cost and safety of transporting nuclear wastes, as well as indirect or subjective impacts, such as socioeconomic and environmental effects on the community. Therefore, the ranking of alternative nuclear waste repository sites from the transportation standpoint is a challenging task in which a variety of interests must be weighed among all parties involved. The purpose of the selection process, which involves weighing objective versus subjective factors, is to provide the public with the greatest net benefit. For coping with the complexity of the task, research is needed to develop an effective tool for use in the public decision-making process. This tool could be used to select the optimal transportation strategies under various situations. Many past studies have dealt with transportation planning methods for cost-benefit and alternative analyses. However, there are no known methodologies especially developed to evaluate and to set priorities for transportation alternatives of nuclear waste materials.

Presented first in this paper are some background data on the issue of nuclear waste transportation. Then, a cost-effectiveness model is introduced for the evaluation of alternative methods of nuclear waste transportation. Following this, the model is applied to two separate issues, one at the national level and the other at the state level. It is hoped that the information presented in this paper will be useful to the planning, programming, and project development personnel of the transportation and energy agencies. In the area of planning, the concept presented here should assist the planner in sketch planning or preliminary feasibility studies to determine whether further planning or development efforts are worthwhile for any given nuclear waste repository site. In programming, the model for ranking a set of transportation strategies should have high utility. Finally, project development staff should find the approach instrumental in the assessment of environmental impacts and other project-supporting documents, and in the design of the transportation project itself.

It should be stressed that the model application is presented for illustrative purposes, and is not meant to provide a definitive ranking of sites. In particular, a firm conclusion would require more information on projected spent-fuel shipments and associated technical data, and greater attention to the process of establishing relative weights for the various subjective factors. However, for the purpose of this study, application of the model to a restricted data set is able to fully demonstrate the potential power and range of the proposed methodology.

TRANSPORTATION OF NUCLEAR MATERIALS

A brief exposition of current methods of transporting nuclear material will enable a deeper understanding of subsequent sections. Nuclear material is one of many classes of officially designated hazardous materials. A hazardous material is defined, both by stature (the Hazardous Materials Transportation Act) and by regulation (Code of Federal Regulations, No. 49, section 171.8), to be those materials or substances in a form or quantity that has been found to pose unreasonable risks to health and safety or property in commerce. There are approximately 2,400 materials so designated (1). There are insufficient data from which to derive verifiable figures on the amount of hazardous materials that are transported; the most commonly reported estimate by the U.S. Department of Transportation is that there are about 4 billion tons shipped each year (2). Of this amount, approximately 30 percent is transported by truck and about 70 percent by rail (3). Table 1 lists different types of hazardous substances that are shipped in the United States.

TABLE 1 Hazardous Materials Shipped in the United States *(1)*

Substance	Percentage of Shipments
Gasoline and jet fuels—flammable liquid	56
Distillate fuel oil—combustible liquid	34
Anhydrous ammonia—nonflammable gas	4
LPG—flammable gas	2
Paints and allied products	2
Industrial gases	1
Other	1

Of the more than 100 million shipments per year of hazardous materials in the United States only 3 percent or some 3 million packages contain radioactive materials (4). The material of perhaps most frequent public concern (and the material under the most restrictive regulatory and safety guidelines) is spent reactor fuel (i.e., high-level waste). The few hundred shipments a year of spent fuel constitutes only a tiny fraction of the annual shipments of radioactive materials currently taking place (5).

The safety record of hazardous materials transportation, on the whole, is fairly impressive. The total number of fatalities that result from hazardous materials transportation is very small relative to other transportation-related fatalities. For example, only 19 fatalities resulted from hazardous materials accidents in 1980 (with none attributable to the radioactive nature of the cargo), whereas in the same year 51,900 lives were claimed by highway accidents and 530 in railroad accidents. This is impressive considering that up to 15 percent of the trucks on the road are carrying hazardous materials (1). Furthermore, there is a significant difference in accident risk between transporting spent fuel and transporting other energy-related commodities. In terms of the statistical likelihood of fatalities, the shipment of gasoline, propane, and chlorine is from 300 to 30,000 times riskier than the shipment of all materials that are associated with the nuclear fuel cycle. An accident that involves a chlorine-carrying train resulted in 9 fatalities; in another case, a chlorine-shipment accident caused the evacuation of 250,000 people (6). Fires resulting from accidents that involved the transportation of gasoline on the nation's highways took 480 lives and injured another 3,500 between 1976 and 1980. In a similar vein, each year there are some 100 to 150 explosions and fires that cause approximately 2 dozen fatalities as a result of the transportation of natural gas through pipelines (7).

Of course, there is always the chance for the occurrence of the first nuclear spent-fuel accident, and the possibility that the accident would be major. However, with the extreme safety precautions that are taken in transporting radioactive spent fuel, these possibilities are relatively small. One of the reasons for the relatively small chance of an accident is the design of the casks in which the nuclear wastes are encased. High-level nuclear wastes must be shipped in heavily shielded casks (Figure 1) on vehicles that conform to applicable federal regulations (8). A high-level waste shipping cask must be able to withstand severe simulated transportation accidents without losing its contents or shielding efficiency. Extensive testing of high-level nuclear waste casks that were conducted by the Transportation Technology Center of Sandia National Laboratories in New Mexico has shown that there would be no significant loss of contents or shielding if an accident did take place (5). Casks have undergone a rigorous series of crash and fire tests, which have been open to the public. In a typical test, a spent-fuel cask was mounted on a truck and crashed into a concrete wall at 60 mph. The same cask was crashed again at 80 mph. There was only superficial damage. In a third test, a locomotive crashed into a cask broadside. The 80-mph impact demolished the locomotive, but hardly dented the cask. A 150-ton railcar-cask assembly was crashed into a concrete barrier at over 80 mph, and then exposed to fire for more than 2 hr.

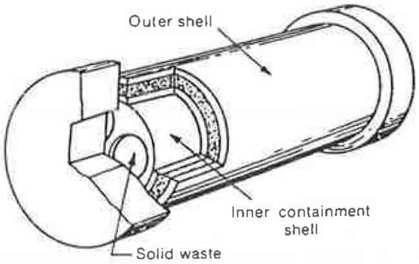

FIGURE 1 Shipping casks for nuclear wastes *(8)*.

The results of these tests indicated that there would have been no radioactive hazard had the casks actually been loaded with spent fuel or solidified high-level waste. The casks also provide protection under normal traveling conditions. There is essentially no risk from the radiation exposure during the normal transportation of spent fuel. An individual who lives 90 ft from a highway where 250 spent-fuel shipments pass each year traveling at an average speed of 30 mph would receive a radiation dose some 9,000 times less than that received from natural sources--the sun, the earth, and radioactivity that occurs naturally in the human body. For comparison, the dose would be only slightly higher than that received from an ordinary smoke alarm in 1 year's time. Most smoke alarms contain a miniscule amount of radioactive material that is used to detect smoke (9).

A COST-EFFECTIVENESS MODEL

As indicated previously, transportation of nuclear wastes demands that the cost and efficiency of the transportation strategy itself, as well as the impacts of the strategy on the community, be fully considered and analyzed. Because of the complexity of the decision-making process, there is an immediate need for a comprehensive yet simple procedure for ranking alternative transportation strategies under a given environment, subject to policy and regulatory constraints. In this context, a cost-effectiveness decision model developed by Yu and

Pang (10) offers an excellent methodological framework to deal with the issue of transportation of nuclear waste. The following is a brief description of the model.

Yu and Pang's model was originally developed for ranking alternative strategies of transportation energy conservation, with the following objectives in mind:

1. To account for all relevant impacts of transportation strategies,
2. To consider both tangible and intangible impacts on a comparable scale,
3. To link the modeling framework to the actual public decision-making process,
4. To maximize the economic return from the expenditures invested, and
5. To be computer-based to facilitate actual applications of the model.

The foregoing features are all well suited for the consideration of nuclear-waste transportation alternatives. It is believed that the basic model with minor modifications should be useful in the evaluation and decision making on alternative methods for delivering nuclear wastes to possible repository sites.

The cost-effectiveness model quantifies objective and subjective impacts into dimensionless indices and includes decision weight factors for both. A composite measure of effectiveness (CMOE) is computed for the setting of strategic priorities. The model is mathematically expressed as

$$\mathrm{CMOE}_i = W_o \cdot \mathrm{OIM}_i + W_s \cdot \mathrm{SIM}_i \qquad (1)$$

where

CMOE_i = composite measure of effectiveness of strategy i,
OIM_i = objective impact measure of strategy i ($0 < \mathrm{OIM}_i < 1$ and $\sum_i \mathrm{OIM} = 1$),
SIM_i = subjective impact measure of strategy i ($0 < \mathrm{SIM}_i < 1$ and $\sum_i \mathrm{SIM} = 1$),
W_o = objective impact decision weight ($0 < W_o < 1$), and
W_s = subjective impact decision weight ($0 < W_s < 1$ and $W_o + W_s = 1$).

The CMOE values are used as a basis for assessing the relative worth of a transportation strategy compared with all other strategies considered. Strategies with higher CMOE values are preferred over those with lower values.

All objective impacts are classified as being measurable in monetary terms. The life-cycle cost of each strategy is the basic element in the case of transportation of nuclear wastes. To ensure compatibility between objective and subjective impact measures, objective impact measures are converted to dimensionless indices. In deriving these indices, it is necessary to compute a monetary ratio for each strategy. These cost ratios are then normalized to obtain dimensionless indices (objective impact measure) for each strategy by the following equation:

$$\mathrm{OIM}_i = \mathrm{OIC} \cdot \left[\sum_i (1/\mathrm{OIC}_i)\right]^{-1} \qquad (2)$$

where OIM_i is the objective impact cost for strategy i.

Subjective impacts are usually difficult or impossible to quantify in dollar terms. The subjective impact measure for a given strategy i is a function of two quantities: (a) the relative weight of each subjective impact as compared with all of the subjective impacts, and (b) the relative weight of each strategy for a given subjective impact. The subjective impact measure of strategy i in the model is mathematically given as

$$\mathrm{SIM}_i = \sum_i (\mathrm{SIM}_k \cdot \mathrm{SW}_{ik}) \qquad (3)$$

where SIW_k is the weight of subjective impact k relative to all subjective impacts, and SW_{ik} is the weight of strategy i relative to all strategies for a given subjective impact k.

The individual subjective impact weights are determined from ratings through a decision-making body involved in nuclear waste projects. A member of a decision-making body may view one or more particular objectives as more important than others. The way for that member to express this is to attach weights to the different impacts. For each member, the sum of the weights assigned to all impacts considered may be a total of, for example, 100 points. The average rating of each subjective impact is then normalized to a number within a range of 0 to 1, which is comparable with the objective impact measure.

The subjective impacts of a specific transportation strategy vary in magnitude, intensity, scope, importance, and acceptability with each community. The strategy weights must be carefully established by the technical staff of the transportation agency so that the impact of given transportation alternatives for nuclear wastes can be assessed. This involves (a) assessing utility functions for individual subjective impacts, (b) predicting anticipated impact levels for each strategy and finding the corresponding utility associated with that level, and (c) estimating the scope of the strategy (i.e., the proportion of the population or area affected by the strategy). The value of an individual strategy weight is derived by the sum of the ratings for all transportation strategies with respect to each subjective impact.

The decision weights, W_o and W_s, measure the relative importance of objective impacts versus subjective impacts. The sum of both decision weights is equal to 1 (i.e., $W_o + W_s = 1$) and thus the value of each weight ranges between 0 and 1. The values of W_o and W_s are obtained from the decision-making body by using an approach similar to that used in determining the subjective impact weight. Each member assigns a value for W_o and W_s. The values of all members are then averaged to obtain the final value for the decision weights.

As indicated earlier, Yu and Pang's basic model and its application procedure were slightly modified to be more suitable for analyzing the transportation of nuclear wastes. The major area of modification is the determination of the objective impact measure. Instead of using the benefit-cost ratio as specified originally, only the cost-ratio factor was employed. This is because no tangible benefit related to the nuclear disposal transportation can be realized. The concept will be illustrated in the model application that is presented in the next section. To facilitate actual application, the model has been implemented as a computer package for a microcomputer.

ISSUES OF STUDY

The cost-effectiveness model was applied to two current issues associated with transportation alternatives for nuclear waste: (a) which of the five proposed nuclear repository sites in the United States would be most desirable from a standpoint of transportation (while this issue is being considered, two transportation modes, rail and highway, are compared), and (b) which of the five proposed Utah transportation routes would be the best for delivering nuclear wastes if Paradox Valley, Utah, was chosen as a repository site.

Before the cost-effectiveness model is applied to these issues, background information is given on them. Model applications will then be illustrated for both issues in a step-by-step manner.

Issue 1

At the present time, there are five proposed sites under consideration for a nuclear repository site in the United States:

- Paradox Valley, Utah,
- Hanford, Washington,
- Yucca Mountain, Nevada,
- Permian, Texas, and
- the Gulf Interior region in Mississippi (GIR).

The five sites are being considered along with two major nuclear waste producers, the West Valley Plant and the Savannah River Plant (11). The question to be addressed is which of the sites would be the best choice as far as transportation is concerned.

Issue 2

Early in 1980, it was announced that southeastern Utah was one of five potential sites for a nuclear waste repository. Since that time, the possibility of a nuclear repository in Utah has been a topic of great popular interest. There were, initially, as many as four different proposed sites in the Paradox Valley area of southeastern Utah. The four sites have presently been narrowed down to one site, the Gibson Dome area. Many citizens, especially those in southeastern Utah, support the possibility of the site because they believe that it would help their economic situation. On the other hand, there are citizens, especially environmentalists, who believe that the Utah site is too dangerous and that placement in Utah would be extremely detrimental to the natural beauty of the area. On May 4, 1984, the former governor of Utah, Scott Matheson, announced that he was strongly opposed to selection of the Utah site. Governor Matheson stated several reasons for his opposition, including the site's proximity to the Colorado River and other environmental factors. However, the major reason was that the U.S. Department of Energy had not provided enough information on the effects that a depository would have on the area (S.M. Matheson--unpublished data).

There are many unknown factors with respect to the Gibson Dome site. One that remains unanswered is the method of transporting nuclear wastes within the state. There are two options under consideration: (a) transporting nuclear wastes over existing transportation systems, or (b) building new transportation systems to be used especially for delivering nuclear wastes to the proposed repository site. According to officials of the Utah Department of Transportation, it is most likely that the nuclear wastes will arrive in Utah by rail. Possible locations for building a transfer station along the route have been considered carefully; it was found that the only feasible location would be Potash, Utah. With this in mind, the answer that is still unknown is to the question of what route would be best for the transfer of nuclear material from Potash to the proposed site.

MODEL APPLICATION

Identification of Transportation Strategies

The first step is to identify what transportation strategies are available for the evaluation of relative impacts as the result of transporting nuclear wastes.

Issue 1

There are 10 possible alternative routes (11):

1. Gulf Interior Region by truck,
2. Permian Basin by truck,
3. Paradox Valley by truck,
4. Yucca Mountain by truck,
5. Hanford by truck,
6. Gulf Interior Region by rail,
7. Permian Basin by rail,
8. Paradox Valley by rail,
9. Yucca Mountain by rail,
10. Hanford by rail.

Issue 2

Five different alignments are compared as to which is the best route for nuclear waste transportation through southeastern Utah:

1. Spanish Valley route via the low bridge,
2. Spanish Valley route via the high bridge,
3. Kane Springs route,
4. Colorado Canyon route,
5. Spanish Valley route via LaSal Junction.

The first four routes were suggested in a study performed by the Bechtel Group, Inc. (12), whereas the last route was advocated through a study by Stearns-Roger Services Inc. (13).

Determination of Objective Impact Measures

It is now necessary to determine all objective impacts that are relevant to the issues in question. As mentioned earlier, the direct costs involved in implementing individual transportation strategies are considered as objective impacts. After all of the strategy costs are determined, it then becomes necessary to determine the corresponding cost ratios for available strategies. Cost ratios may be obtained by dividing the lowest strategy's total cost into each of the resulting values. The cost ratio is then normalized to a value between 0 and 1 as the objective impact measure (OIM) for each transportation strategy.

Issue 1

The objective impact used in this issue was total cost, which consists of shipping, maintenance, and capital costs. Capital costs are specifically defined by a reference source (11) as the cost of transportation packaging and its trailer or railcar. They do not include fixed facility requirements such as highway or rail-line construction to the repository site or facility-handling equipment requirements. Maintenance costs include the money needed for system upkeep (e.g., containers and trailers or railcars). Shipping costs are expenses charged by the carrier. As would be expected, the shipping costs are closely related to the distance traveled.

TABLE 2 Costs, Cost Ratios, and OIMs for Issue 1 Transportation Alternatives *(11)*

	Transportation Alternative[a]									
	1	2	3	4	5	6	7	8	9	10
Costs ($\$ \times 10^6$)										
Capital	173	199	220	247	258	206	233	252	272	274
Maintenance	111	129	142	160	167	124	140	151	163	165
Shipping	492	662	812	984	1,040	484	595	680	779	805
Total	776	990	1,170	1,390	1,460	814	968	1,080	1,210	1,240
Cost ratio (percent)	1.00	.78	.66	.56	.53	.95	.80	.72	.64	.62
OIM	.137	.108	.091	.077	.073	.132	.110	.099	.088	.086

[a] Refer to the route numbers in the text for the 10 possible transportation alternatives.

TABLE 3 Costs, Cost Ratios, and OIMs for Issue 2 Alternative Routes *(14)*.

	Alternative Route[a]				
	1	2	3	4	5
Capital costs ($\$ \times 10^6$)	364	384	669	327	288
Cost ratio (percent)	.79	.75	.43	.88	1.00
OIM	.205	.194	.112	.228	.259

[a] Refer to the route numbers in the text for the 5 possible transportation routes.

Table 2 shows the total costs, the cost ratios, and the OIMs for Issue 1. The costs for each alternative were estimated by Sandia National Laboratories (<u>11</u>).

Issue 2

The only data available for the Utah issue was capital costs. Because the lengths of all five routes are approximately the same, it is reasonable to assume that the maintenance costs and shipping costs will be fairly equal for the five alternatives. [The data used in this study were gathered by Stearns-Roger Services Inc. (<u>13</u>).] The capital costs, cost ratios, and objective impact measures for Issue 2 are given in Table 3.

<u>Determination of Subjective Weight Matrix</u>

It is now necessary to determine the subjective impacts for each issue. After all subjective impacts are determined, ratings are assigned to each alternative for every subjective impact. For simplicity, a linear utility function is assumed, and these ratings run from -3 to 3. For positive impacts, a positive number is used with a higher positive number being a more positive impact. Conversely, a negative number means a negative effect, ranging from 0 to -3. The ratings are then normalized (NR values) and developed into strategy weights by dividing each NR value by its respective total number.

Issue 1

For Issue 1, four subjective impacts were considered:

1. Projected fatalities,
2. Environmental impacts,
3. Economic impacts, and
4. Traffic impacts.

Projected fatality weights were obtained through a study by Sandia National Laboratories (<u>11</u>). Environmental impact weights were determined by comparing railway versus highway environmental effects. Economic impacts are defined as the changes in economic base as a result of nuclear waste repository activities that take place in the area. Traffic impacts are caused by construction activities and increased traffic volumes in the area. Table 4 lists the ratings, the normalized ratings, and the strategy weights (SW_k) for the Issue 1 subjective impacts.

Issue 2

Subjective impacts for the proposed Utah routes were selected on the basis of the general transportation

TABLE 4 Ratings, Normalized Ratings, and Strategy Weights of Subjective Impacts for Issue 1 Transportation Alternatives

	Transportation Alternative[a]									
	1	2	3	4	5	6	7	8	9	10
Rating										
SI 1	−2	−2	−2	−2	−2	0	0	0	0	0
SI 2	−2	−2	−3	−3	−3	0	0	−1	−1	−1
SI 3	−2	−2	−2	−2	−2	−1	−1	−1	−1	−1
SI 4	2	2	2	2	2	1	1	1	1	1
Normalized rating										
SI 1	.16	.16	.16	.16	.16	.50	.50	.50	.50	.50
SI 2	.16	.16	0	0	0	.50	.50	.33	.33	.33
SI 3	.16	.16	.16	.16	.16	.33	.33	.33	.33	.33
SI 4	.83	.83	.83	.83	.83	.66	.66	.66	.66	.66
Strategy weight (SW_k)										
SI 1	.05	.05	.05	.05	.05	.15	.15	.15	.15	.15
SI 2	.06	.06	0	0	0	.19	.19	.12	.12	.12
SI 3	.07	.07	.07	.07	.07	.13	.13	.13	.13	.13
SI 4	.11	.11	.11	.11	.11	.09	.09	.09	.09	.09

Note: SI = subjective impact.

[a] Refer to the route numbers in the text for the 10 possible transportation alternatives.

TABLE 5 Ratings, Normalized Ratings, and Strategy Weights of Subjective Impacts for Issue 2 Alternative Routes

	Alternative Route[a]				
	1	2	3	4	5
Rating					
SI 1	0	0	−2	2	0
SI 2	−2	−3	−1	2	−2
SI 3	−1	−1	−2	0	1
SI 4	−1	−1	0	−2	−2
SI 5	0	0	1	2	0
SI 6	–	−1	2	1	−3
Normalized rating					
SI 1	.50	.50	.16	.33	.50
SI 2	.16	0	.33	.83	.16
SI 3	.33	.33	.16	.5	.33
SI 4	.33	.33	.5	.16	.16
SI 5	.5	.5	.66	.83	.5
SI 6	.33	.33	.83	.66	0
Strategy weight (SW_k)					
SI 1	.2	.2	.06	.33	.2
SI 2	.11	0	.22	.56	.11
SI 3	.17	.17	.08	.25	.33
SI 4	.22	.22	.34	.11	.11
SI 5	.17	.17	.22	.28	.17
SI 6	.15	.15	.39	.30	0

Note: SI = subjective impact.

[a] Refer to the text for the 5 possible transportation routes.

guidelines provided by the Department of Energy (14). Many subjective factors would tend to make one route more favorable than another. The subjective impacts of five routes that were used in this study included

1. Cuts and fills,
2. Tunnels and bridges,
3. Curves and bridges,
4. Length of route,
5. Environmental effects, and
6. Archaeological effects.

Although the first four are tangible factors that indicate the level of effort required for route implementation, they influence the route safety in terms of accident potentials, and thus would subjectively affect the relative desirability of alternative routes. To obtain the subjective strategy weights, information was taken from quadrangle maps of the area prepared by Bechtel Group, Inc. (12). For example, a route that required extreme curves and steep grades would get a strategy weight of −3 and a route that was straight and flat would receive a strategy weight of +3. Table 5 lists the ratings, normalized ratings, and strategy weights (SW_K) for the Issue 2 subjective impacts.

Determination of Decision Weights

After all of the alternatives have been compared by using different subjective impacts, the relative weights of objective versus subjective impacts as well as among the subjective impacts (W_o versus W_s. and SIW_k) are then determined. These weights are usually determined by using the views of various interest groups.

To determine the weight values of these impacts, questionnaires were distributed to six members of the technical staff of the Utah Department of Transportation, three concerned citizens, and one city leader (an elected official). These questionnaires included information so that those questioned could respond to Issues 1 and 2. Ten respondents may be considered a small sample of opinion, but they were carefully selected to represent a balanced make-up of interested sectors. The results of the questionnaire with regard to decision weights are shown in Tables 6-9. For more statistically meaningful results, it would be desirable to enlarge the sample size so that the contracting views of all parties involved could be realistically and accurately reflected. The establishment of relative subjective weights for the various considerations is a social and political issue. A strong point of the proposed model is that it leaves these political decisions to the political arena, and that it can be used to implement whatever values are decided on.

Determination of Subjective Impact Measures

Subjective impact measures (SIMs) of each strategy are defined as the product of the strategy weight and the subjective impact weight as given by Equation 3. The results of SIM values of all alternatives considered for Issues 1 and 2 are given in Tables 10 and 11.

Prioritization of Alternatives

The alternative strategies are ranked by using the values of the composite measure of effectiveness (CMOE) that is computed by Equation 1. The resulting CMOE value of alternatives in Issue 1 and Issue 2 are given in Tables 12 and 13.

Issue 1

After having examined the CMOE values, it is clear that the best transportation alternative for Issue 1 is strategy 6. This corresponds to locating the nuclear waste repository at the Gulf Interior region in Mississippi, with rail as the mode of transportation. (It is interesting to note that rail was pre-

TABLE 6 Results of Questionnaire With Regard to Relative Weights of Issue 1 Subjective Impacts

Subjective Impact	Transportation Alternative[a]										
	1	2	3	4	5	6	7	8	9	10	SIW_k
Fatalities	40	60	50	20	96	50	30	10	30	60	.446
Environment	25	18	20	35	2	15	60	25	45	20	.260
Economic	25	20	20	35	0	15	5	60	20	20	.220
Congestion	10	2	10	10	2	20	5	5	5	5	.074
Total	100	100	100	100	100	100	100	100	100	100	1.000

[a] Refer to the text for the 10 possible transportation alternatives.

TABLE 7 Results of Questionnaire With Regard to Relative Weights of Issue 2 Subjective Impacts

Subjective Impact	Transportation Alternative[a] 1	2	3	4	5	6	7	8	9	10	SIW_k
Cuts and fills	20	10	4	15	10	10	20	10	15	5	.119
Tunnels and bridges	20	20	2	15	10	10	20	15	15	5	.132
Curves and grade	20	30	85	15	10	20	25	20	15	35	.275
Length	25	20	3	5	10	10	0	10	15	5	.103
Environmental	10	10	3	30	30	20	25	25	25	25	.203
Archaeological	5	10	3	20	30	30	10	20	15	25	.168
Total	100	100	100	100	100	100	100	100	100	100	1.000

[a] Refer to the text for the 10 possible transportation alternatives.

TABLE 8 Results of Quesionnnaire With Regard to Relative Weights of Objective Versus Subjective Issue/Impacts

Decision Weight	Transportation Alternative[a] 1	2	3	4	5	6	7	8	9	10	Avg
Objective	60	50	80	50	75	60	70	20	60	35	56
Subjective	40	50	20	50	25	40	30	80	40	65	44
Total	100	100	100	100	100	100	100	100	100	100	100

[a] Refer to the text for the 10 possible transportation alternatives.

TABLE 9 Relative Weights of Objective Versus Subjective Issue 2 Impacts

Decision Weight	Transportation Alternative[a] 1	2	3	4	5	6	7	8	9	10	Avg
Objective	50	50	20	10	50	20	25	20	50	5	30
Subjective	50	50	80	90	50	80	75	80	50	95	70
Total	100	100	100	100	100	100	100	100	100	100	100

[a] Refer to the text for the 10 possible transportation alternatives.

TABLE 10 Subjective Impact Measures for Issue 1

Subjective Impact	Weight	Transportation Alternative[a] 1	2	3	4	5	6	7	8	9	10
1	.074	.004	.004	.004	.004	.012	.012	.012	.012	.012	.012
2	.446	.016	.016	0	0	0	.084	.084	.053	.053	.053
3	.260	.018	.018	.018	.018	.018	.034	.034	.034	.034	.034
4	.220	.024	.024	.024	.024	.024	.020	.020	.020	.020	.020
Total		.062	.062	.046	.046	.054	.150	.150	.119	.119	.119

[a] Refer to the text for the 10 possible transportation alternatives.

TABLE 11 Subjective Impact Measures for Issue 2

Subject Impact	Weight	Alternative Route[a] 1	2	3	4	5
1	.119	.024	.024	.007	.004	.024
2	.132	.015	0	.029	.074	.015
3	.275	.047	.047	.022	.068	.091
4	.203	.044	.044	.067	.022	.022
5	.168	.029	.029	.037	.047	.029
6	.103	.016	.016	.040	.031	0
Total		.175	.160	.202	.246	.181

[a] Refer to the text for the 5 possible alternative routes.

TABLE 12 Composite Measure of Effectiveness and Ranking in Issue 1

Transportation Alternative[a]	Objective Impact Measure	Subjective Impact Measure	Composite Measure of Effectiveness	Rank
1	.137	.062	.1033	6
2	.108	.062	.0878	7
3	.091	.046	.0712	8
4	.077	.046	.0633	10
5	.073	.054	.0647	9
6	.132	.150	.1399	1
7	.110	.150	.1276	2
8	.099	.119	.1078	3
9	.088	.119	.1017	4
10	.086	.119	.1106	5

[a] Refer to the text for the 10 possible transportation alternatives.

TABLE 13 Composite Measure of Effectiveness and Ranking in Issue 2

Alternative Route[a]	Objective Impact Measure	Subjective Impact Measure	Composite Measure of Effectiveness	Rank
1	.205	.175	.1840	3
2	.194	.160	.1702	5
3	.112	.202	.1750	4
4	.228	.247	.2406	1
5	.259	.181	.2044	2

[a] Refer to the text for the 5 possible alternative routes.

ferable to highway transport, regardless of which site is selected.) The other sites are ranked according to their CMOE's in Table 12.

Issue 2

The CMOE ranking for Issue 2 reveals that strategy 4 would be the optimal local-transport route. This corresponds to the Colorado River corridor. The ranking of the other alternatives are also shown in Table 13.

CONCLUSIONS

Little attention has been given to the manner in which transportation requirements might dictate the choice of a nuclear repository site. Because there are no known comprehensive methodologies that specifically address this issue, an effective and comprehensive procedure is needed to aid the concerned agency, and public alike, in prioritizing alternative transportation strategies under given situations.

In addition to discussions of the risk actually involved in transportation of nuclear waste as indicated by historical record, the paper presents a cost-effectiveness model for ranking possible transportation alternatives for nuclear waste disposal. The model has been applied to two current transportation issues; one that involves potential repository sites in the United States and the other that involves possible routes for a given Utah site. Based on the available data, the results show that the best repository location is the Gulf Interior site in Mississippi, with a railroad connection to and from the points of waste production. It was also determined that the best railroad route to the Gibson Dome site in Utah is the Colorado Canyon route. It should be noted that these results are based on the standpoint of transportation only. To facilitate actual applications, the model has been implemented on a microcomputer. The approach presented is expected to provide a major contribution in the area of selecting nuclear waste repository sites from a transportation perspective.

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