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

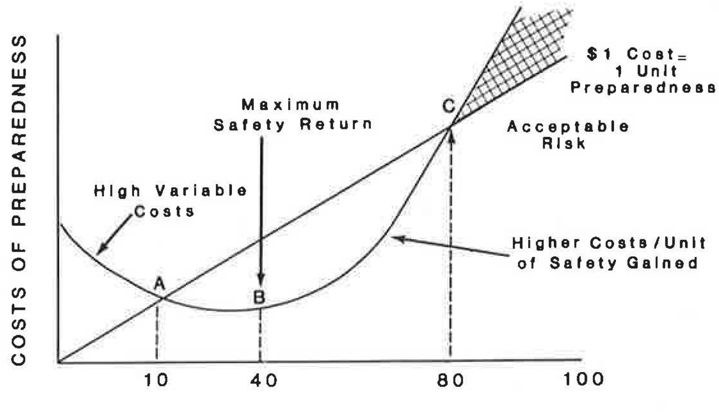

FIGURE 1 Theoretical cost curve of reducing vulnerability.

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	Class B	Class C	Flammable (lb) Liquid	Solid	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:

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

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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Publication of this paper sponsored by Committee on Transportation of Hazardous Materials.

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