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Contents

Foreword

Accidents involving the transportation of hazardous materials have increased public concern about this subject. The papers included in this Record will aid professionals involved in the safe and effective movement of hazardous materials to make intelligent decisions in this critical area.

Saccomanno et al. provide a comparison of the risks of transporting hazardous materials by truck and by rail. Methods of measuring risk and the relationship between risk and the transportation environment are considered in their analysis, as are accident rates, spill probabilities, and expected impacts along specified corridors.

A lack of sufficient data for making risk assessments is a frequent problem for transportation officials. Abkowitz and Cheng address this problem in their evaluation of alternative techniques for estimating risk with limited data.

Harwood et al. and Saccomanno and El-Hage identify specific characteristics of accidents and incidents in hazardous materials transportation. Harwood et al. use traffic accident data to determine the probability of hazardous materials release for various types of highway traffic accidents. With Canadian rail accident data as a source, Saccomanno and El-Hage used the position of rail cars in a train as a factor in assessing the probability that specific cars would be derailed.

The analysis of multiple problems in a single model often provides a unique solution that could not be determined by analyzing each problem separately. Zografos and Samara describe a model that analyzes both the hazardous waste routing problem and the challenge of locating waste disposal/treatment facilities. Their approach appears to minimize both disposal and routing risk.

Chin and Cheng present their efforts to assess both the costs and the population at risk in hazardous materials transportation. Their approach minimizes the distance traveled and the population at risk within a fixed band along the selected path.

Comparison of Risk Measures for the Transport of Dangerous Commodities by Truck and Rail

F. F. SACCOMANNO, J. H. SHORTREED, M. VAN AERDE, AND J. HIGGS

Current empirical evidence concerning the relative risks of transporting dangerous commodities by truck and by rail has been plagued by highly variable and inconsistent results. Much of the problem can be attributed to the nature of the risk assessment and its failure to consider two important aspects: (a) different ways of measuring risks and (b) a strong dependence between risk and the nature of the transport environment in which dangerous commodities are shipped. In this paper, the risks of transporting dangerous commodities by truck and rail are expressed by four constituent elements: accident rates, spill probabilities in an accident situation, hazard areas for different classes of damage, and expected impacts on population and environment along a specified road or rail corridor. Changes in the level of risk for individual shipments are considered for different material properties, spill characteristics, and transportation environments. Under most conditions, trucks exhibited significantly higher accident rates than trains. These results were consistent for two measures of shipment exposure: on a per-vehicle-kilometer and a per-tonne-kilometer basis. On the consequence side, the relative merits of one mode over another were not as clearly defined. Both trucks and trains reflect certain safety advantages over one another depending on the nature of the material being shipped and the assumed transport environment.

The study reported in this paper follows the development of a risk assessment methodology for evaluating the shipment of dangerous commodities by truck and rail. The results of this risk assessment focus on the issue of inconsistencies between predictive risks and risks that are observed in the available data. Several risk measures are considered for each mode and for different material properties and transport environments.

CURRENT EMPIRICAL EVIDENCE

Current empirical evidence on the relative risks of transporting dangerous commodities by truck and rail has produced inconclusive results as to which mode is safer, with respect to accident involvement and consequent damage. A recent survey of six countries on the question of "Is rail safer than road?" produced the following results (*1*):

Responses	*No. of Countries Responding*
Yes	1
Subjectively, rail is safer	2
No evidence either way	1
About the same	1
More truck accidents, but higher rail consequences	1

In a recent study, Glickman (*2*) concluded that, under most conditions, trucks reflect lower risks than rail. On the other hand, Swoveland and Cawdery (*3*) concluded that, for most materials, trucks reflect significantly higher risks than rail for similar shipment volumes. Saccomanno et al. (*4*) suggested that the risks of transporting dangerous commodities by truck and rail are modified by the nature of the material being transported and the environment under which each shipment takes place. They argue that, under certain conditions, rail is safer than truck; while under different conditions, the opposite may be true.

Most empirical evidence consistently attributes higher accident rates to trucks, relative to rail, for comparable shipment volumes (*4*). However, it is unclear whether these same truck accidents are also likely to result in more frequent and larger spills, with more extensive damage to nearby population and environment.

The issue of truck and rail safety in transporting dangerous commodities cannot be resolved through a review of historical data alone—primarily because of low-probability, high-consequence events. Many of the high-consequence events being considered are likely to occur once over a long time frame (1,000 years or more). The existing data bases simply do not reflect this extensive time frame. Therefore, low-probability events involving dangerous commodity shipments are likely to be unrepresented in historical records of truck and rail accidents. As a result, an objective appreciation of relative modal safety can be formed only after a careful risk assessment.

A thorough comparison of the risks of transporting dangerous goods by truck and rail must first establish appropriate measures of risk for each mode, type of shipment, and level of exposure. Second, it must consider the sensitivity of various risk measures to changes in the transportation environment.

Several measures can be used to reflect the risks of transporting dangerous goods by truck and rail, including accident rates, spill probabilities, hazard impact areas for different levels of damage, and expected impacts to population and property for a given spill situation.

Frequently, risks are estimated for a so-called worst-case scenario, where the entire accident environment is assumed to mitigate in the direction of maximum damage. In reality, the level of risk produced by individual shipments of dangerous commodities can be modified significantly by the physical and operating environment under which these shipments occur (for example, freeway versus nonfreeway road type for truck shipments and mainline versus rail yard track type for rail shipments). Conceivably, controlling for changes in the accident environment would reduce the current disparity

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between estimates of theoretical risk obtained through model simulation and observed risk reflected in the empirical data.

A comparison of the risks of transporting dangerous commodities by truck versus rail is further complicated by differences in the volume of dangerous commodities being shipped by each mode (both in total and on a per-vehicle basis). In Canada, for example, the proportion of dangerous commodities shipped by rail comprises 6.6 percent of total rail freight, as compared to 8.7 percent of total freight for trucks. Approximately 40 percent of the dangerous rail shipments are considered to be special dangerous goods (SDGs), as defined by Transport Canada regulations (*1*). The percentage of SDGs transported by truck is thought to be lower than that for rail.

On a per-vehicle basis, however, rail bulk tankers carry at least twice the payload carried by truck bulk tankers for most types of dangerous commodities. In 1988, Saccomanno et al. (*4*) suggested an average payload of 80 tonnes for typical rail tankers carrying gasoline and liquefied petroleum gas (LPG), compared with an average payload weight of 25 to 30 tonnes for similar truck tankers. Differences in both the tanker carrying capacities and the proportion of dangerous commodities being shipped by each mode imply that, in an accident situation, rail tankers are likely to sustain more extensive damage than truck tankers for comparable types of materials, spill rates, and accident environments. A fair analysis of the relative risks of transporting dangerous commodities by truck and rail, therefore, must resolve these differences in vehicle payloads for all materials.

OBJECTIVES OF THIS STUDY

The objectives of this study are twofold:

1. Assess the relative risks of transporting dangerous commodities by truck and rail using a number of comparable risk measures (i.e., accident rates, spill probabilities, hazard areas, and expected impacts to population, and environment).
2. For different measures, assess the sensitivity of risk to changes in the transportation environment for each mode and material shipped.

DEVELOPING APPROPRIATE RISK MEASURES

In this section, a comprehensive risk analysis model is used to develop several risk measures for truck and rail shipments for a given material type, accident, and spill environment. In this analysis, two types of dangerous commodities are used to represent a range of materials being shipped by truck and rail: pressure LPG and pressure liquefied chlorine gas. Risk is assessed in terms of accident rates, spill probabilities, hazard areas, and expected damage to nearby population and environment. For each risk measure, the discussion focuses on three basic aspects: (a) rationale for inclusion, (b) data requirements, and (c) estimation procedures for the risk comparison of the truck and rail modes.

Estimation of Accident Rate Statistics

The risk of transporting dangerous commodities by truck and rail can be assessed in terms of accident involvement. For most dangerous commodity incidents in transit, the consequent damages are either confined to the accident itself or are accident-induced. Frequently, it is difficult to distinguish those fatalities and injuries caused by the presence of dangerous commodities from the fatalities and injuries that would have occurred without the presence of a dangerous commodity. Saccomanno et al. (*4*) suggest that, for accidents involving LPGs, as many as 90 percent and 50 percent of fatalities on truck and rail, respectively, could be attributed to the accident itself.

In most jurisdictions, data on accidents involving truck and rail are readily available. For certain problems, such as the development and evaluation of safe routing options, risks based solely on accident involvement are easier to estimate from the available data. These accident-based risks obviate the need to obtain additional information on the resultant damages. Expected damages from an accidental release of a dangerous material are more difficult to extract from the available data base and require a more extensive appreciation of the damage propagation process for each material under consideration.

For this analysis, truck accident data were obtained for the Province of Ontario. The Ministry of Transportation of Ontario (MTO) annually compiles all motor vehicle accident statistics from provincial and municipal police records. Accidents involving large trucks in Ontario are summarized in Table 1 for the 1982–86 period. In this analysis, large trucks are defined as vehicles requiring either a Class A or D driver's permit. The values summarized in Table 1 assume that, where more than one truck is involved in a single accident, each vehicle is treated as a separate involvement.

As in most jurisdictions, Ontario does not collect detailed information on the distribution of trucks on the provincial road network at various times throughout the year. Useful measures of exposure for truck accidents under different conditions were estimated in this study using several indirect sources of truck flow data for Ontario, including the Commercial Vehicle Survey (*5*), the provincial highway traffic volumes from permanent counting stations, and the provincial highway inventory data.

Rail accident data were obtained from the Canadian Transport Commission (CTC) data base (*6*). Before November 1, 1987, all railway accidents in Canada with damages in excess of $750 were reported to the CTC. This data base contains information on the causes of each accident and on whether a derailment, a collision, or both occurred. The accident data

TABLE 1 TRUCK ACCIDENT INVOLVEMENTS BY LOCATION (*6*)

Location	1982	1983	1984	1986	Total
Links	3,472	3,488	4,383	5,261	16,604
Ramps	171	194	269	219	853
Intersections	256	265	366	320	1,207
Intersection-related	145	169	154	184	652
Private driveway	131	148	157	155	591
Railway crossing	1	5	7	7	20
Underpass	30	20	28	24	102
Overpass	80	88	117	100	385
Total	4,286	4,377	5,481	6,270	20,414

base was classified further into one of four regions that compose the national rail network. For example, Ontario rail accidents are classified under the category of Central Region. The CTC rail accident data considered in this study comprise 2,344 derailment and collision accidents reported between 1980 and 1985 for the entire national network. These rail accident statistics are summarized in Table 2.

Exposure data were extrapolated from published Canadian National and Canadian Pacific Railways annual reports (*7*). In these reports, information on accident frequencies was provided at the subdivision level, along with corresponding measures of exposure, on the basis of train-kilometers and tonne-kilometers travelled annually.

Accident rate data for trucks and rail were fitted with a series of GLIM (Generalized Linear Interactive Models) log-linear expressions (*4*). Contextual factors affecting accident rates were considered in terms of accident location, truck type, loading characteristics, and traffic volumes. Separate log-linear expressions were obtained for truck accidents located at road links and intersections. A detailed description of the GLIM calibration procedure is available in Saccomanno and Buyco (*8*). For accidents occurring on freeway ramps, the

TABLE 2 TRAIN ACCIDENT INVOLVEMENTS BY TYPE (*6*)

Accident Type	1980	1981	1982	1983	1984	1985
Derailments	292	348	327	254	273	278
Collisions	97	108	101	92	102	72
Crossing accidents	826	763	691	567	596	606
Total accidents	1,215	1,219	1,119	913	971	956
Total dangerous commodity accidents	120	201	176	159	176	193

TABLE 3 TRUCK ACCIDENT RATES

		LINK ACCIDENTS Location				NON-LINK ACCIDENTS (Ramps, Intersections, etc.)
		Freeway		Non-Freeway		
		High Vol. >15,000 AADT	Low Vol. <15,000 AADT	High Vol. >15,000 AADT	Low Vol. <15,000 AADT	
Truck Type	Load	(accident rates per million truck-km)				(average annual accidents per million truck-km)
Truck	Empty	2.46	1.06	1.89	1.11	0.39
	Loaded	1.19	0.52	0.86	0.51	0.19
Truck & Trailer	Empty	0.21	0.09	0.47	0.27	0.08 +
	Loaded	0.17	0.08	0.36	0.21	0.08 +
Tractor	Empty	1.53	0.67	2.34	1.44	0.43 +
	Loaded	0.76	0.34	1.09	0.68	0.21 +
Tractor & Trailer	Empty	1.04	0.53	1.57	0.88	0.13
	Loaded	0.62	0.32	0.88	0.50	0.15
Tractor & 2 Trailer	Empty	0.13	0.08	0.39	0.22	0.14
	Loaded	0.72	0.44	2.05	1.22	0.16

+ Estimates based on limited data

resultant log-linear models were found to lack statistical significance. For rail, log-linear models of accident rates were calibrated for mainline derailments. Rail accidents taking place in rail yards did not yield statistically significant expressions. Resultant truck and rail accident rate statistics, obtained in this analysis, are summarized in Tables 3 and 4, respectively.

The vast majority of nonlink truck accidents in the data base (Table 1) was classified as either intersection or ramp accidents. Nonlink accidents on ramps and major intersections accounted for 19.4 percent of all truck accidents in Ontario during the study period, compared with 81.3 percent for accidents on links. Accident rates at nonlink locations were converted to average annual accident rates by truck type and load status, considering overall truck accident experience and exposure in Ontario for the period 1982–1986. The accident rates summarized in Table 3 for intersections and ramps are presented for comparison purposes and, therefore, should be used with caution until more information on ramp and intersection volumes by truck type is available. Truck accident rates on road links were found to vary statistically with road type (freeway/nonfreeway), load status (empty/loaded), truck type (single-unit, tractor with no trailer, tractor semi-trailer, tractor with double trailer, and truck and trailer), and traffic volume on the roadway expressed in terms of the AADT (average annual daily travel) level (fewer than 15,000 vehicles per day, and greater than or equal to 15,000 vehicles per day).

The rail accident rates summarized in Table 4 apply to mainline derailments only and include the total number of railcar involvements in each train accident. Including mainline collision accidents and crossing accidents increases the mainline derailment rates in Table 4 by an average of 0.1 car accident involvements per million car-kilometers, or about 20 percent of these estimates. Rail accident rates in Table 4 were estimated for the 1980–1985 period. Viewed on an annual basis, mainline derailments in Canada have been decreasing between 1980 and 1985. As a result, the average rates in Table 4 tend to overestimate the annual rates for the latter years and underestimate the rates for the earlier years of the 1980–85 period. For example, the derailment rates for 1984 and 1985 were only 79 percent of the average 1980–85 rate given in Table 4. In this analysis, the annual accident data were combined over the six-year period to increase cell membership in the resultant contingency table of factors affecting variation in rates. From Table 4, statistically significant variations in

TABLE 4 RAIL ACCIDENT RATES (MAINLINE DERAILMENTS)

(Accident rates per million car-kilometers)

Volume Class	Track Class	Atlantic High Speed	Atlantic Low Speed	Central High Speed	Central Low Speed	Prairies High Speed	Prairies Low Speed	Mountain High Speed	Mountain Low Speed
1 (Low)	Single	25.32	1.63	1.61	12.99	7.83	6.35	5.31	4.04
	Multiple	-	-	90.61 +	-	-	-	-	-
2	Single	0.62	4.67	1.37	1.46	7.31	1.55	0.68 +	0.84
	Multiple	-	-	-	16.95	-	1.22	1.16 +	-
3	Single	4.05	1.22	0.78	1.04	1.41	0.26	1.67	1.02
	Multiple	1.18	0.48	0.42	0.11 +	1.89	-	-	-
4 (High)	Single	0.56	-	0.26	-	0.06	0.03	0.70	0.35
	Multiple	-	0.18 +	0.47	0.20	0.06	0.29 +	0.43	0.43

Note: - Not included in the calibration (structurally empty cell)
+ Inaccurate due to low number of accidents or low exposure

Volume Class 1: < 100 million ton-miles/year
Volume Class 2: 100 - 1000 million ton-miles/year
Volume Class 3: 1000 - 10000 million ton-miles/year
Volume Class 4: > 10000 million ton-miles/year

Low Speed: < 35 mph
High Speed: > 35 mph

rail accident rates were obtained for four categories of mitigating factors: track volume (four classes of ton-miles per year), track type (single and multiple), average subdivision speed (greater than or equal to 35 mph, and less than 35 mph), and regional affiliation (Atlantic, Central, Prairies, and Mountain regions). Track volume in this analysis serves as a surrogate measure for track quality and level of track maintenance—variables that were unavailable directly from the data. It should be noted that most mainline rail shipments in Canada occur on tracks in the highest volume class.

Analysis of Spill Probabilities

Only a fraction of accidents involving dangerous commodities actually result in a release of material. In Canada, between 1973 and 1981, 3 percent of all dangerous commodities railcar accidents resulted in a loss of lading. (No corresponding data were available for trucks.) For most materials, consequent damage to population and environment depend on the volume and rate of material released in a transport-related incident. As such, the release process is an important component affecting the risk of transporting dangerous commodities on each mode.

The unintentional release of pressure liquefied gases and liquids from bulk tankers in transit can occur either under a normal transportation environment or as a direct result of an accident. Most transport-related spills are not accident-induced. In Canada, approximately 60 percent of the reported railway spills occur under normal transport conditions, mainly due to leaky valves or defective tanker welds (*7*). Releases under normal transportation conditions are generally low-risk events. High-consequence spills tend to be accident induced, and these spills are more interesting from a risk-assessment perspective. Estimating release probabilities for both normal and accident situations requires a complete accounting of the mechanics of the containment system for all mitigating physical and operational factors.

In this study, the accident-induced releases of pressure liquefied gases from rail and truck bulk tankers in transit were analyzed using a fault tree approach (*9*). In a fault tree approach, the containment system and the release process are represented schematically through a cascade structure of input/output relationships and states. This structure is developed deductively for each containment system, beginning with the release from containment (head event) and proceeding through various environmental and operational features that affect this release. The structure is terminated at certain initiating events (basic events) that occur independently of any state otherwise specified in the fault tree. Figure 1 illustrates a portion of a simplified fault tree structure that represents a containment system failure for bulk rail tankers carrying pressure liquefied chlorine gas.

Fault trees permit a mechanistic evaluation of the effectiveness of alternative design and operational standards, as these standards affect release probabilities during transport. The effect of changes in rail and truck bulk tanker design and operations on basic event probabilities must be determined exogenously to the fault tree analysis, using known physical relationships and historical data. The effect of these developments on release probabilities in an accident situation is determined within the fault tree structure. Separate fault tree structures representing the release process for two representative tanker systems (chlorine and LPG) have been considered in this study.

This analysis used the fault trees developed by Pacific Northwest Laboratory (*10,11*), modified for information from the Railway Progress Institute (*12*) to reflect the effects of double-shelf couplers, head shields, and insulation as recommended by the Grange Commission (*13*). The fault probabilities were also modified to reflect historical Canadian incident experience. However, the fault trees did not respond as expected to the Railway Progress Institute changes, and more research is needed before much confidence can be placed in the fault probabilities.

It should be noted that LPG and chlorine are used in this analysis to represent other dangerous commodities with similar properties. Most bulk chlorine shipments in Canada (98 percent) take place on rail. Chlorine shipments by truck are generally confined to smaller one-tonne cylinders. Here, chlorine is used as a surrogate for other highly toxic, heavier-than-air gases. Similarly, LPG serves as a surrogate for other highly flammable, potentially explosive pressure liquefied gases.

Table 5 summarizes the release probabilities for typical truck and rail bulk tanker systems under an assumed accident situation. The fault tree analysis suggests that 1.5 percent of all chlorine accidents involving trucks produces a release of material, as compared with 6.6 percent for railcars. The situation for LPG is reversed, however, with 1.5 percent of truck accidents and 0.1 percent of rail accidents causing a release of material. As more spill data become available for Canada, it is hoped that these estimates of the spill probabilities for individual material properties and containment systems can be improved. The release probabilities for trucks carrying chlorine in bulk have been estimated using the fault tree approach for an assumed set of containment system features and specified inputs.

Analysis of Hazard Areas

In this paper, the area of damage associated with a given material spill is referred to as the hazard area. For a given material, the hazard area represents the distance from an initial spill that is subject to a specified class of damage. Depending on this specified damage, the hazard area could reflect a number of policy decisions—for example, a zone of evacuation for people in the vicinity of an incident or an area that may be subject to special zoning regulations designed to reduce damage to population and property in the event of a spill. Frequently, the hazard area is used to establish the expected number of people and amount of property affected by a spill situation and serves to underscore the potential risks of dangerous commodity incidents at specific locations on the transportation network.

The nature and extent of hazard areas associated with incidents involving certain dangerous goods are affected by four factors: properties of the material being shipped, environment, spill rates and volumes, and extent of damage. Separate damage propagation models were developed for chlorine and LPG. A complete description of the physics associated with each of these models is available in a report prepared by the Institute for Risk Research (*7*).

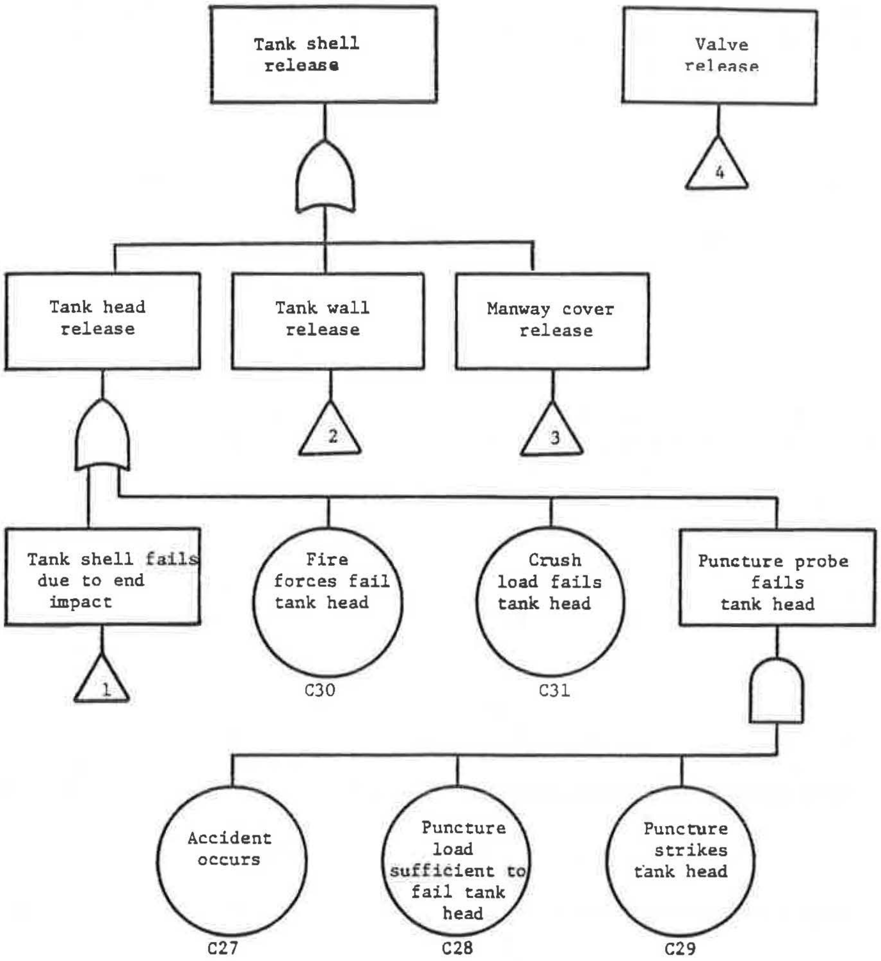

FIGURE 1 Portion of simplified fault tree structure for chlorine release.

The analysis requires information on release sizes and rates. For this study, two types of releases were considered: instantaneous and continuous. Instantaneous releases occur when the bulk of the material is released immediately after an incident, frequently within the first few seconds. Continuous spills, on the other hand, may occur over an extended period, in some cases up to several hours. For some releases, the spill profile can be both instantaneous and continuous. Incidents involving liquefied chlorine gas, for example, produce an initial puff cloud that releases more than 30 percent of the material in the tanker instantaneously. The rest of the tanker contents can be released continuously over the next several hours, depending on the pressure differential between the inside of the tanker and the atmosphere.

The nature of each accident affects the rate and volume of material released and, hence, the resultant hazard area. Sandia Laboratories (*14*) has provided an empirical relationship between energy dissipated in an accident and the probability of a puncture situation. All other factors assumed constant, higher speed accidents are more likely to cause punctures of the tanker wall and a subsequent release of material. Larger perforations produce greater release rates for similar pressure differentials between the inside of the tanker and the atmosphere.

In this study, instantaneous releases are expressed as a volume of the container spilled in 10 minutes. Continuous releases are expressed in kilograms per second over an extended period of time. Critical distances from the source of each spill are developed for representative materials and specified levels of damage. Eight damage categories are considered for each incident: 50 percent mortality, 1 percent mortality, severe injuries, moderate injuries, greater than 90 percent property damage, 50 to 90 percent property damage, 10 to 50 percent damage, and less than 10 percent property damage.

Estimates of hazard areas obtained by applying the model to a number of assumed release situations are summarized in Tables 6 and 7 for chlorine and LPG, respectively. These hazard areas have been estimated for two tanker systems (truck and rail), two release mechanism (instanteneous and continuous), three release levels (high, medium, and low), four classes of damage for chlorine (50 percent lethality, 1 percent lethality, Injury 1, and Injury 2 as defined in Tables 6 and 7), and the eight damage categories previously mentioned for LPG (which include four levels of property damage).

A number of studies have considered potential damages from dangerous goods spills. A comparison of these results with those obtained from the damage propagation models is presented in Table 8. It was somewhat difficult to make a direct comparison between some of the results because damage types and damage categories in these studies were variable. However, from the results in the literature, there seems

TABLE 5 RELEASE PROBABILITIES FOR TRUCK AND RAIL

PROBABILITY OF RELEASE GIVEN AN ACCIDENT FOR CHLORINE

Road Accident:	Off-road		Collision		Fixed-object		Non-accident	
	low	high	low	high	low	high	low	high
							(Prob. per truck-km)	
loaded shell fire	0.0058	0.0096	0.0058	0.0096	0.0012	0.0019	0.0000	0.0000
loaded shell nofire	0.0052	0.0086	0.0052	0.0086	0.0010	0.0017	1.803E-05	1.803E-05
loaded valve fire	0.0011	0.0019	0.0011	0.0019	0.0011	0.0019	0.0000	0.0000
loaded valve nofire	0.0001	0.0002	0.0001	0.0002	0.0001	0.0002	9.058E-05	9.058E-05

Rail Accident:	Derailment		Collision		Other		Non-accident	
	low	high	low	high	low	high	low	high
							(Prob. per car-km)	
loaded shell fire	0.0046	0.0083	0.0046	0.0083	0.0009	0.0020	0.00(	0.0000
loaded shell nofire	0.0150	0.0280	0.0150	0.0280	0.0030	0.0060	1.803E-05	1.803E-05
loaded valve fire	0.0005	0.0010	0.0005	0.0010	0.0004	0.0009	0.0000	0.0000
loaded valve nofire	0.0018	0.0032	0.0018	0.0032	0.0013	0.0030	9.058E-05	9.058E-05

PROBABILITY OF RELEASE GIVEN AN ACCIDENT FOR LPG

Road Accident:	Off-road		Collision		Fixed-object		Non-accident	
	low	high	low	high	low	high	low	high
							(Prob. per truck-km)	
loaded shell fire	0.0040	0.0060	0.0040	0.0060	0.0008	0.0012	0.0000	0.0000
loaded shell nofire	0.0140	0.0220	0.0140	0.0220	0.0028	0.0044	1.803E-05	1.803E-05
loaded valve fire	0.0030	0.0040	0.0030	0.0040	0.0030	0.0040	0.0000	0.0000
loaded valve nofire	0.0080	0.0130	0.0080	0.0130	0.0080	0.0130	9.058E-05	9.058E-05

Rail Accident:	Derailment		Collision		Other		Non-accident	
	low	high	low	high	low	high	low	high
							(Prob. per car-km)	
loaded shell fire	0.0001	0.0002	0.0001	0.0002	0.0009	0.0020	0.0000	0.0000
loaded shell nofire	0.0004	0.0007	0.0004	0.0007	0.0030	0.0060	1.803E-05	1.803E-05
loaded valve fire	0.0001	0.0001	0.0001	0.0001	0.0004	0.0009	0.0000	0.0000
loaded valve nofire	0.0003	0.0005	0.0003	0.0005	0.0013	0.0030	9.058E-05	9.058E-05

TABLE 6 POTENTIAL HAZARD AREAS BY DAMAGE CLASS (CHLORINE)

	Release Type and Level					
	Instantaneous			Continuous (24 hr max)		
	High (100%)	Medium (69%)	Low (39%)	High (14.5 kg/s)	Medium (3.9 kg/s)	Low (0.1 kg/s)
Road Potential Damage Areas (km²), Chlorine (Damages: 27 tonnes)						
Fatality 1 (50%)	8.7	5.5	2.7	8.7	8.6	2.1
Fatality 2 (1%)	9.5	6.0	3.0	9.5	9.5	2.3
Injury 1	29.5	18.8	9.5	29.5	29.4	7.6
Injury 2	109.1	71.7	38.1	108.9	108.7	30.8
Rail Potential Damage Areas (km²), Chlorine (Damages: 90 tonnes)						
Fatality 1	41.1	25.6	12.4	40.9	41.1	2.1
Fatality 2	45.1	28.1	13.6	44.8	45.1	2.3
Injury 1	135.0	84.9	41.7	134.3	135.2	7.6
Injury 2	460.2	295.2	150.7	457.8	460.7	30.8

NOTE: Fatality 1 = Fatal after few breaths (3.0 g/m³); Fatality 2 = Death in 30 min. (2.4 g/m³); Injury 1 = Pulmonary edema in 30 min. (0.18 g/m³); Injury 2 = Tolerance limit for 30 to 60 min. (0.012 g/m³). Pasquill Weather Condition D used in damage propagation model.

TABLE 7 POTENTIAL LPG HAZARD AREAS BY DAMAGE CLASS

	ROAD POTENTIAL DAMAGE AREAS - LPG (18 tonnes)			RAIL POTENTIAL DAMAGE AREAS - LPG (63.5 tonnes)		
Release Type:	Instantaneous			Instantaneous		
Level:	high (100%)	medium (90%)	low (69%)	high (100%)	medium (90%)	low (69%)
	Potential Damage Areas (km^2)			Potential Damage Areas (km^2)		
Fatality 1 (Fireball)	0.070	0.070	0.050	0.230	0.210	0.160
Fatality 2 (Fireball)	0.130	0.120	0.090	0.410	0.370	0.290
Injury 1 (Fireball)	0.100	0.090	0.070	0.260	0.240	0.190
Injury 2 (Fireball)	0.430	0.390	0.300	1.350	1.230	0.960
Fatality 1 (Pool Fire)	0.005	0.005	0.004	0.019	0.017	0.013
Fatality 2 (Pool Fire)	0.010	0.009	0.007	0.034	0.030	0.023
Injury 1 (Pool Fire)	0.006	0.005	0.004	0.020	0.018	0.014
Injury 2 (Pool Fire)	0.032	0.029	0.022	0.112	0.101	0.078
Property 1 (Vapour Cloud)	0.004	0.004	0.003	0.009	0.009	0.007
Property 2 (Vapour Cloud)	0.022	0.020	0.017	0.050	0.046	0.039
Property 3 (Vapour Cloud)	0.036	0.033	0.028	0.082	0.077	0.064
Property 4 (Vapour Cloud)	0.176	0.164	0.138	0.407	0.379	0.318

Note:
Fatality 1 - 50% Mortality
Fatality 2 - 1% Mortality
Injury 1 - Ignition of Cellulose Material
Injury 2 - Blistering of Bare Skin
Property 1 - >90% Damage
Property 2 - >50% Damage
Property 3 - >10% Damage
Property 4 - <10% Damage

to be no consensus on typical or expected damage areas, especially in the case of chlorine. Modeling of chlorine dispersion is more complex than for LPG, because of the difficulty in accurately representing heavier-than-air gas dispersion, which requires information on the terrain in the area of the spill and prevailing weather conditions. Some confusion seems to exist between the representation of expected damage areas from a spill and the lethal zone (the area where deaths will occur). For example, in the output from the damage propagation models, areas of 50 percent lethality are given, but this does not necessarily imply that 50 percent of the total population within this area will die. The 50 percent lethality value refers to the precise distance from the spill where the probability of death is 0.50. Within this distance, the cumulative probability of death is actually greater than 0.50, ranging from a value of 1.0 immediately next to the spill to a value of 0.50 at the 50 percent distance (assuming the person is outdoors).

It should be noted that the wide range of results found in the literature, as summarized in Table 8, points to the need for more research on hazard areas—both from the perspective of modeling spill areas and spill dispersion, and from the perspective of a more complete understanding of the damage process as it affects population and environment in the vicinity of a spill.

Measures of risk associated with accident rates, spill probabilities, and hazard areas can be treated generically because they are applicable to any location on the transportation network for comparable conditions. The final two risk measures are based on expected injury to people and damage to property in the vicinity of each incident for a given spill situation and are, therefore, location-specific.

Expected Injury to People from Selected Dangerous Commodity Incidents

Expected population injuries are defined as the cross product of (a) accident rate, (b) spill probability, (c) hazard area, and (d) number of people located within a given damage range.

Several classes of population densities were considered as representive of typical urban and rural areas. For this analysis, it was assumed that population is distributed uniformly in distance from each spill site. However, where the population distribution in a given area cannot be characterized uniformly, it is possible to generate expected damage levels for selected distance bands from each spill site. Each band would have unique population densities and, hence, similar expected impacts.

Some typical transportation link characteristics used to estimate location-specific damages are defined in Table 9 for road and rail corridors. For these conditions, Table 10 gives the resulting risk estimates for two types of damages: Fatality 1 (50 percent lethality) and Injury 1 (50 percent injury) for spills involving chlorine and LPG.

Total Expected Population Injuries

Thus far, expected population injuries have focused on the actual spill situation. To obtain a complete appreciation of the total risks associated with the transport of dangerous commodities by truck and rail, it is also important to consider potential damage from the accident itself. Injuries that can be attributed directly to the accident have been shown to be significant in the consideration of total risk (*4*). For average Canadian conditions, each class of dangerous commodity inci-

TABLE 8 COMPARISON OF HAZARD AREAS WITH OTHER STUDIES

Other Study Results						IRR Results				
Source	Commodity	Damage Type	Amount Spilled	Damage Category	Damage Radius/Area	Commodity	Damage Type	Amount Spilled	Damage Category	Damage Area
Jordaan et al. (*16*)	chlorine	Vapor cloud	38.2 tonnes	LD-50	88.1 km^2	chlorine	Vapor cloud	55 tonnes	50% fatality	21.9 km^2
			76.4 tonnes	LD-50	113.2 km^2			90 tonnes		41.1 km^2
		Potential lethal zone	1 or 2 rail cars		0.89 km^2			90 tonnes	1% fatality	45.1 km^2
Hade (*17*)	chlorine	Toxic gas release	Full rail tank car	Lethal zone	2000 ft = 0.37 km^2	chlorine	Vapor cloud	55 tonnes	50% fatality	21.9 km^2
Environment Canada (*18*)	chlorine	Vapor cloud	20 tonnes	10 * TLV (0.03 g/m^3)	171.6 km^2 (max. distance)	chlorine	Vapor cloud	16 tonnes	Injury 2 (0.012 g/m^3)	60.6 km^2
Concord (*19*)	chlorine	Vapor cloud	Large release (rail)	50% lethality	1.5 km (range) = 2.25 km^2	chlorine	Vapor cloud	55 tonnes	50% fatality	21.9 km^2
Jordaan et al. (*16*)	LPG	Potential lethal zone	1 or 2 rail cars		0.002 km^2	LPG	Fireball	63.5 tonnes	1% fatality	0.41 km^2
Purdy et al. (*20*)	LPG	BLEVE	20 tonnes	50% lethality	110 m range = 0.012 km^2	LPG	Fireball	18 tonnes	50% fatality	0.07 km^2
				1% lethality	175 m range = 0.031 km^2				1% fatality	0.13 km^2
			40 tonnes	50% lethality	160 m range = 0.026 km^2			63.5 tonnes	50% fatality	0.23 km^2
				1% lethality	245 m range = 0.06 km^2				1% fatality	0.41 km^2
		Flash fire	20 tonnes	50% lethality	70 m range = 0.005 km^2		Pool fire	18 tonnes	50% fatality	0.005 km^2
				1% lethality	90 m range = 0.008 km^2				1% fatality	0.01 km^2
			40 tonnes	50% lethality	80 m range = 0.006 km^2			63.5 tonnes	50% fatality	0.019 km^2
				1% lethality	110 m range = 0.012 km^2				1% fatality	0.034 km^2
Wade (*17*)	LPG	Pool fire	Full rail tank car	Lethal zone	600 feet = 0.03 km^2	LPG	Pool fire	63.5 tonnes	50% fatality	0.019 km^2
		Vapor fire			1180 feet = 0.13 km^2					
		Vapor cloud explosion			3600 feet = 1.2 km^2		Vapor cloud explosion	63.5 tonnes	50% fatality	0.009 km^2
		BLEVE			590 feet = 0.032 km^2					
Clay et al. (*21*)	LPD	Fireball		Radius of fireball	$R = 29m^{0.33} =$ 0.006 km^2 (m = 18 tonnes)	LPG	Fireball	18 tonnes	50% fatality	0.07 km^2
Concord (*19*)	propane	Flash fire	Large release (rail)	50% lethality	~100 m = 0.01 km^2					
	gasoline	Pool fire	Large release (rail)	50% lethality	~100 m = 0.01 km^2	LPG	Pool fire	63.5 tonnes	50% fatality	0.019 km^2

dent was investigated to obtain the potential fatalities resulting from the accident.

For rail, accident fatalities have been modified to include fatalities associated with collision and grade-crossing accidents (not considered in Table 4). By using the risk model, these fatalities were then compared with the expected fatalities attributed to the spill for an assumed set of conditions. The results of this analysis are summarized in Table 11 for road and rail involving chlorine and LPG shipments. Distinctive fatality levels have been estimated for different tanker capacities and population densities.

The average results in Table 11 indicate that, when expected fatalities for spills and for the accident are combined, fatalities per tonne-kilometer associated with the shipment of chlorine may be higher for rail than for truck. This reflects the disproportionately higher dispersal area associated with the higher capacity rail tanker relative to the assumed capacity of a truck tanker carrying chlorine. For shipments of LPG, truck fatalities on a per tonne-kilometer basis may be higher than for rail. In interpreting these results, it should be noted that the error is at least one order of magnitude.

In general, the consequences resulting from the accident itself must be considered when the expected damage from the spill of a dangerous commodity is low. In the case of chlorine, potential damage is higher from the spill itself than from the accident, leaving rail somewhat more hazardous than truck by virtue of higher tanker carrying capacities per vehicle. For LPG, fatalities due to the accident are higher than those expected from the spill, reflecting higher accident rates and fatalities on trucks than on rail.

It should be noted that these results are based on limited data. While caution is recommended in assigning too much meaning to these results, this analysis has demonstrated that, for both materials under consideration, the risk consequences of the accident itself are an important component of the entire risk analysis process.

TABLE 9 ASSUMED ROAD AND RAIL LINK CHARACTERISTICS

		ROAD	RAIL
CHLORINE			
1. HIGH	Load	27 tonnes	90 tonnes
	Type	Tractor-Trailer	
	Route Characteristics	Freeway	Mainline, Central Region Multiple Track, High Speed
	Volume	High Volume	Volume Class 4
	Population Density	1000/km^2	1000/km^2
2. LOW	Load	16 tonnes	55 tonnes
	Type	Tractor-Trailer	
	Route Characteristics	Non-Freeway	Mainline, Central Region, Multiple Track, High Speed
	Volume	Low Volume	Volume Class 3
	Population Density	100/km^2	100/km^2
LPG			
1. HIGH	Load	18 tonnes	63.5 tonnes
	Type	Tractor-Trailer	
	Route Characteristics	Freeway	Mainline, Central Region Multiple Track, High Speed
	Volume	High Volume	Volume Class 4
	Population Density	1000/km^2	1000/km^2
2. LOW	Load	18 tonnes	63.5 tonnes
	Type	Tractor-Trailer	
	Route Characteristics	Non-Freeway	Mainline, Central Region, Multiple Track, High Speed
	Volume	Low Volume	Volume Class 3
	Population Density	100/km^2	100/km^2

TABLE 10 RISK ESTIMATES FOR SOME TYPICAL LINKS

Link #	DG	Amt in tonnes	Accident Rate		Spill Prob	Pot Damage Areas (km^2)	Pop Density (/km^2)	Shield Factor	Emerg Response Factor	Expected Damages - for Spill			
										Fatality 1		Injury 1	
			/mil veh-km	/mil tonne-km						/mil veh-km	/mil tonne-km	/mil veh-km	/mil tonne-km
Road													
1	chlorine	27	0.77	0.0285	0.004	8.7 (a)	1000	0.1	0.3	0.40194	0.01489		
						29.5 (b)						1.36290	0.05048
2	chlorine	16	0.65	0.0406	0.005	2.7 (a)	100	0.1	0.3	0.01316	0.00082		
						9.5 (b)						0.04631	0.00289
3	LPG	18	0.77	0.0428	0.0046	0.07 (a)	1000	0.1	0.6	0.00744	0.00041		
						0.1 (b)						0.01063	0.00059
4	LPG	18	0.65	0.0361	0.0074	0.05 (a)	100	0.1	0.6	0.00072	0.00004		
						0.07 (b)						0.00101	0.00006
Rail													
1	chlorine	90	0.48	0.0053	0.007	41.1 (a)	1000	0.1	0.3	2.07144	0.02302		
						135 (b)						6.80400	0.07560
2	chlorine	55	0.46	0.0084	0.01	12.4 (a)	100	0.1	0.3	0.08556	0.00156		
						41.7 (b)						0.28773	0.00523
3	LPG	63.5	0.48	0.0076	0.0002	0.23 (a)	1000	0.1	0.6	0.00066	0.00001		
						0.26 (b)						0.00075	0.00001
4	LPG	63.5	0.46	0.0072	0.0004	0.16 (a)	100	0.1	0.6	0.00009	0.000001		
						0.19 (b)						0.00010	0.000002

Notes: (a) is potential damage area for Fatality 1 (50% fatality)
(b) is potential damage area for Injury 1 (50% injury)

TABLE 11 SUMMARY OF TOTAL CHLORINE AND LPG DAMAGES BY MODE

	Pop Density (/km^2)	Fatalities (given accident)	Fatalities from spill		Fatalities due to accident (b) /mil tonne-km	Total Fatalities (c) /mil tonne-km
			/mil veh-km	/mil tonne-km		
CHLORINE						
Road (27 tonnes)	1000	1.28	0.99	0.036	0.0012	0.0372
	100	0.112	0.086	0.0032	0.0012	0.0044
Rail (90 tonnes)	1000	14.796	7.1	0.078	0.00015	0.07815
	100	1.48	0.71	0.0078	0.00015	0.00795
LPG						
Road (18 tonnes)	1000	0.02903	0.02235	0.00124	0.0012	0.00244
	100	0.00258	0.00199	0.00011	0.0012	0.00131
Rail (63.5 tonnes)	1000	0.00489	0.00235	0.00004	0.00015	0.00019
	100	0.00049	0.00024	0.000004	0.00015	0.000154

Notes: (a) Average value of analysis but the error is at least one order of magnitude
(b) Fatalities from accident (Saccomanno, Shortreed and Van Aerde, 1988)
(c) Total Fatalities = fatalities from spill + fatalities from accident

PERSPECTIVE ON RISK RESULTS

A comparison of statistical risks (obtained through the application of a risk analysis model) with observed risks (obtained directly from historical data) inevitably produces wide discrepancies. The interpretation of statistical risks can become a moot point that can be more volatile than the products carried. In the interest of interpretation, a brief discussion of these discrepancies is warranted.

The Toronto Area Rail Transportation of Dangerous Goods Task Force (*1*) report estimated a high value of 4.1 fatalities per year in the greater Toronto area attributable to the shipment of all dangerous goods on the existing railway system. Yet no death has ever been recorded in Canada as a result of the release of dangerous goods.

The Railway Progress Institute in the United States maintains records of loss of lading incidents involving chlorine. In the 16 years from 1965 to 1980, 16 rail tankcar incidents involving release of chlorine occurred for all of North America. In six of these incidents, a significant release of chlorine was reported, for a total loss of lading of 320 tonnes. The observed personal injuries from all these incidents were 8 fatalities and 169 injuries. The number of fatalities per tonne of chlorine spilled was estimated at 0.025.

Data on 18 chlorine releases compiled by the Health and Safety Executive in the United Kingdom include both rail tankcar and fixed-plant releases (industrial) between 1935 and 1976. The fatality rate estimated from these data was 0.3 per tonne spilled. The largest observed fatality rate per tonne of chlorine released was 30 fatalities in Ypres, in France, where chlorine was used in World War I (*15*).

In this study, the risk estimates summarized in Table 10 for chlorine suggest a fatality rate in the range of 0.023 and 0.04 deaths per tonne. These estimates appear to be consistent with the value quoted by both the Railway Progress Institute and the Health and Safety Executive. Nevertheless, the risks estimated for chlorine and LPG remain high and unsubstantiated when compared to the available records of road and rail incidents.

Supplementary analysis of statistical risks reported in this study has indicated that for a typical fatality rate of 2.5 deaths per year, a 50 to 60 percent probability exists that during any given 16-year period, zero deaths would occur, and an 80 to 90 percent probability exists that the number of deaths in any 16-year period would be fewer than 10. These results indicate why statistical risks tend to overrepresent values observed in the data. Available data bases are simply inadequate to reflect the time frame required to validate the low-probability, high-consequence risks associated with the transport of dangerous goods by truck and rail.

CONCLUSIONS

Several risk measures have been developed for incidents involving representative dangerous goods. The relative risks of transporting dangerous goods by truck and rail depend essentially on the nature of the risk measures used as a basis of comparison. Some conclusions are possible regarding this comparison:

1. Regardless of the material being shipped or the underlying transportation conditions, trucks reflect higher accident rates than rail. When rates are expressed on a per-vehicle basis (truck or railcar), the accident rate for a single-trailer configuration is typically 0.8 accidents per vehicle-kilometer,

compared with a typical value of 0.5 accidents per railcar-kilometer. These accident rate differences are consistent over all track classes and road types. When the higher carrying capacity of a rail car is considered, the comparative accident rate between truck and rail becomes even more significant. For example, tractor-trailer configurations (which comprise more than 50 percent of the large truck fleet in Ontario) reflect average accident rates of 0.03 accidents per tonne-km for typical road and traffic conditions, compared with an average value of 0.005 per tonne-kilometer for rail.

2. For most tanker systems, the probability of release in an accident situation is higher on rail than on trucks for most track and road environments. Release probabilities in an accident situation have been obtained through the application of the risk model for assumed containment characteristics. Release probabilities during an accident obtained through the risk model application were found to differ significantly from the observed data. This comparison is based on an inadequate number of observations from the data. Among other factors, the release process in an accident situation is affected by the operating speed and size of the vehicle. Because, for the same material being shipped, rail bulk tankers tend to be larger than truck tankers, the likelihood that forces generated in an accident impinge on the tanker, inducing a loss of lading, is higher for rail than for truck. Furthermore, the close proximity of rail tankcars in an accident situation increases the likelihood of railcar buckling. This increases the likelihood that puncture forces will be generated during a train derailment.

3. Hazard areas for chlorine and LPG spills are a function of spill rates, spill volumes, and weather conditions. As such, for the same volume of material involved in each accident, the hazard areas associated with truck and rail incidents do not differ. However, because rail bulk tankers carry more material than truck tankers, hazard area estimates expressed on a per-vehicle basis are understandably higher for rail than for truck. Existing estimates of hazard areas suggested by various studies in the literature are plagued by an unacceptable range of values. More research is required to address these inconsistencies.

4. For each location along a road or rail corridor, the expected damage to population and property is a function of the hazard area associated with a given spill, the probability of release in an accident situation, and the accident rate. To the extent that, under most conditions, trucks experience higher accident rates than rail, the expected impacts associated with the rail transport of dangerous goods are lower than for trucks—despite more extensive hazard areas for rail. Considering the same volume of material in transit over a similar distance, the expected damage from truck incidents involving dangerous goods is similar to that estimated for rail. For the same population density of 1,000 persons per square kilometer, the expected fatalities for LPG incidents involving trucks is (on average) 0.0024 per million tonne-kilometer shipment. This can be compared with a value for rail of 0.00019 per million tonne-kilometer for the same material. These estimates are based on similar levels of exposure on both modes. For chlorine, the expected fatalities per million tonne-kilometers shipped are 0.04 for road and 0.08 for rail. For trucks, 97 percent of the expected chlorine fatalities was spill-induced and 3 percent was found to be attributable to the accident. This can be compared with percentages on rail of 99.8 for the spill and 0.2 for the accident. For LPGs, 49 percent of fatalities on trucks and 79 percent of fatalities on rail were found to be accident-induced. A breakdown of expected fatalities caused by the spill and expected fatalities caused by the accident is important from a policy perspective, because both issues would be addressed by different safety regulations in the transport sector.

The results of this study suggest that treatimg risk by using different measures can lead to widely different conclusions regarding the relative merits of transporting dangerous commodities by truck and rail. The situation is rendered more complex by the need to consider the nature of the transportation environment under which shipments of different materials take place. To suggest that one mode is riskier than another on the basis of a single risk measure and one set of conditions would be inappropriate. The result may be policies directed at improving safety that could, in fact, be ineffective in reducing risks for most conditions under which these shipments occur.

Estimates of fatalities for truck and rail suggested by the model appear to be high when compared with actual observations, involving chlorine and LPG incidents. Discrepancies between statistical and observed risks are typical of risk analysis studies and remain one of the major difficulties faced in trying to communicate meaningfully the policy implications of these types of results.

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Hazardous Materials Transport Risk Estimation under Conditions of Limited Data Availability

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As public concern grows over the safety of hazardous materials transport, more policy emphasis is being placed on assessing the relative and absolute risks of various operations strategies. This is particularly apparent in the face of recent catastrophic events worldwide involving hazardous materials. At present, comprehensive hazardous materials transport risk assessments are difficult because of the paucity and poor quality of empirical data. These data problems are most acute for the rare, catastrophic event that is of primary concern to public safety officials. For these reasons, many approaches to risk estimation can be considered. This paper describes alternative approaches to hazardous materials transport risk estimation under conditions of limited data availability, including consideration of statistical inference, fault/event tree modeling, analytical and simulation techniques, subjective estimation, and Bayesian analysis. The hazardous materials transport problem is examined in terms of the feasibility of applying these techniques. Concern is raised over the likelihood of different approaches resulting in conflicting risk estimates, and a procedure for mediating these conflicts is discussed.

As public concern grows over the safety of transporting hazardous materials, more policy emphasis is placed on assessing the relative and absolute risks of various operational strategies. At the heart of this problem is the subject of risk estimation. Traditional approaches to transportation systems analysis have focused on economic analysis and, consequently, much is known about operating costs and costing methodology; however, transport risk estimation is only now reaching adolescence.

A review of previous research efforts in this area reveals that, in the face of limited data availability, many studies have formulated risk estimation methodologies that lack a systematic structure, use subjective indices, neglect important risk components, and do not fully recognize the importance of both event likelihood and consequence. Moreover, several critical issues, such as the analysis of uncertainty and the accurate portrayal of low-probability/high-consequence events, have been largely ignored. This latter consideration is particularly important, because it is the rare, catastrophic event that is of utmost concern to public officials, industry, and the general population.

The objectives of this paper are to review previous work in this area, describe alternative approaches to transport risk estimation under conditions of limited data availability, and comment on the likelihood of conflicting estimates arising from implementing various approaches and how to mitigate these differences. Previous studies are cited to illustrate several of the issues raised in this discussion.

TRANSPORT RISK ESTIMATION

A crucial step in the risk assessment process involves estimating the frequency and consequences resulting from undesirable events, then evaluating the associated risk in quantitative terms (*1*). Risk is commonly expressed as a single number, known as the societal or expected risk. When adequate information is available, this number can be computed directly from historical data; otherwise, more theoretical approaches to risk estimation are required. The risk measure of interest can vary considerably, but typically, risk in hazardous materials transport is expressed in terms relating to expected property damage, injuries, or fatalities.

Expressing risk strictly in terms of a single number may simplify the tasks of estimation and evaluation, but it does not provide as much information as a risk profile, which is a probability distribution of incident likelihood and consequence (*2*). The shape of the risk profile particularly helps in distinguishing between the contribution to the expected risk of high-probability/low-consequence events and low-probability/high-consequence events.

Risk estimation itself is characterized by a sequential process, beginning with understanding the level of exposure (e.g., number of shipments, tons carried, distance moved), the frequency and type of incident occurrence (e.g., tank truck rollover, loose fitting, dropped in handling), and the consequence for a given incident (e.g., death, injury, property damage). The way these components are defined and measured depends on the data available, the purpose of the risk assessment, and the preferences of the risk analyst.

The most frequently studied mode has been trucking, reflecting the fact that trucks carry the largest share of hazardous materials and are responsible for the greatest number of reported incidents (*3*). Truck transport risk has been expressed in terms of community or population indices (*4*–*6*), total dollar cost (*7*), expected population and employment exposure-miles (*8*), expected fraction of shipment released (*9*), and the frequency of N or more fatalities (*10*, *11*).

Risk estimation efforts focusing exclusively on the rail mode have measured annual expected fatalities (*12*) and risk profiles of fatalities (*13*, *14*). Marine hazardous materials transport risk estimation has been more limited; a recent study on tanker and tanker barge transport illustrated the type of activity that

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has been performed (e.g., risk was expressed in terms of expected release per shipment) (*15*). Multi-modal risk analyses have also been conducted, to support the development of a generic approach to risk estimation or the analysis of specific industries that would allow direct comparison between modes (*16–21*).

A detailed review of existing conceptual approaches to risk estimation reveals that most studies have relied heavily on whatever historical data were available, without concern for the quality of the data, its uncertainties, or its biases. There has also been a general lack of sophistication in the risk assessment process, with many studies resorting to the use of statistical inference for the sake of convenience. Furthermore, many of the applications are remiss in their representation of incident consequence, particularly with regard to the distribution of incident severity. Even the more sophisticated approaches have continued to rely exclusively on empirical data in the development of fault trees and Poisson models—using this information to establish event probabilities.

RISK ESTIMATION METHODOLOGY

To accommodate the process of estimating incident likelihood, consequence, and (ultimately) risk in many engineering and science disciplines, several methodological approaches have been offered:

- Statistical inference,
- Fault and event trees,
- Analytical and simulation modeling,
- Subjective estimation,
- Bayesian analysis, and
- Some combination of these procedures (*22–25*).

These approaches may be applied to various elements of hazardous materials transport risk analysis, including estimation of incident occurrence probability, release likelihood, and associated consequence.

In several cases, the methodologies are fundamentally opposed to one another. For example, the use of statistical inference is based on the condition that sufficient data exist to perform an objective analysis. Whereas subjective estimation assumes this is not the case and, therefore, the opinion of an expert is the most appropriate surrogate. Bayesian analysis, where an expert's probability assessment may be combined with historical information, represents a point within this spectrum.

At another level, several uncertainties exist in each methodological process that are tied to the characterization of the transport problem. This is due, in part, to the stochastic nature of failures of engineered systems and the response of decision makers to an event when it occurs (*26*). There is additional difficulty associated with assessing low-probability/high-consequence incidents because of their rare occurrence and lack of opportunity to create experimental conditions to gain further knowledge (*27*). The common approach to addressing this problem is to aggregate to a broader problem focus where better information exists, at the expense of introducing biases that can pose problems with respect to representation and transferability (*28*). The following discussion examines the identified risk estimation methods in greater detail as they pertain to hazardous materials transport.

Statistical Inference

Statistical inference is perhaps the most commonly used procedure for estimating risk. The premise here is that adequate statistical data exist from which to determine the likelihood and consequence of future events. The methodology assumes that a system's incidents occur independently and with constant probabilities. Therefore, past performance can be extrapolated to infer future expectation.

A number of considerations, however, make this technique somewhat troublesome (*2*). First, where accident records exist, information is often not available to estimate the level of exposure (e.g., miles traveled, tons carried); hence, exposure estimates must be made by using a data sample in which there is uncertainty about accuracy. Secondly, the size of the accident data base may be inadequate, as the historical accident data base may have been maintained for only a few years; furthermore, in many cases, reporting quality has been questioned (*3*).

Often, the response to this concern is to expand the problem definition to enlarge the sample to an adequate size for statistical purposes. This can be accomplished by expanding the vehicle class (e.g., the population of oil tankers is used as a proxy for liquid natural gas tankers), the geographic region (e.g., use of national accident statistics for a route-specific analysis), or any number of other parameters. However, care must be exercised to ensure that problem representation is not excessively compromised.

Finally, a problem exists with the assumption of stationarity in the process giving rise to the incidents. There are many reasons why this may not be the case. For example, a previous accident of a serious nature likely results in modifications to policy (e.g., the use of new container technologies), which threaten the stationarity assumption.

The use of statistical inference and its associated problems is well illustrated in a study conducted to develop incident rates for hazardous materials transport by mode and equipment type (*21*). The process included the use of a national data base of incident records involving vehicles transporting hazardous materials and several national data bases from which estimates of exposure could be derived (Table 1).

In this study, the incident data base represents a single year and is known to suffer from problems of underreporting and

TABLE 1 1982 INCIDENT RATE ESTIMATES (*21*)

	Total	Significant Spills	Casualty-Related
All Types of Rail Cars and Trucks			
Rail	1580	615	50.9
Truck (for-hire)	542	145	6.63
Truck (private)	55.6	36.3	1.71
Tank Cars and Tank Trucks Only			
Rail	1830	48.3	62.2
Truck (for-hire)	2524	1805	55.4
Truck (private)	37.6	24.8	0.243

NOTE: Incidents per billion vehicle-miles of hazardous materials.

misreporting. Furthermore, the exposure data suffer from consistency problems, in that truck and rail movements are tracked differently and cannot be compared directly. Several other methodological flaws also exist, which are quite common in studies conducted using statistical inference.

The major concern here is not the specific study in which these problems are identified, but rather the danger of widespread use of biased rates, as many policy makers are looking for such numbers to plug into their risk assessments without knowledge of the derivation of these estimates. Consequently, when a risk estimation methodology depends solely on statistical inference (or any other method), it is imperative to identify the uncertainties in the risk estimation process so that they can be incorporated into the decision process. It is also advisable to develop a risk estimation interval, rather than a point estimate, to reflect these uncertainties and to conduct subsequent sensitivity analyses that include the extremities of this range.

Fault and Event Trees

Fault and event trees are so named because of the logic tree structures that each produces to describe the basis events that must occur to cause an incident and/or consequence (*23*).

A fault tree is formed of events often described by binary (Boolean) variables (the event occurs or not) and related by logical functions, essentially *or* and *and*. One constructs fault trees by identifying a top event—failure of all or part of the system—and sequentially identifying unions or intersections of preceding events that entirely describe each successive binary variable. Thus, the fault tree allows one to obtain a logical path between the top event and a set of basic events. Through this path, one can compute the probability of the top event as a function of the probabilities of the basic events. The application of fault trees requires significant events to have been tracked back through all possible sequences to their initiating events.

Figure 1 is an example of a fault tree. The event of ultimate concern is a potentially fatal hazardous materials transport failure. The logic structure suggests that this can only happen if an accident occurs *and* there is a resulting spill, fire, *or* explosion. The direct cause of an accident can be a result of one of many factors, as identified by the lowest level in Figure 1. Because of the logic structure of the fault tree, however, several initiating events are allowed to occur that do not necessarily result in a potentially fatal episode.

An event tree is formed of a sequence of event sets that can be associated with random variables and a probability distribution defined over them. Each branch on the tree forms a new variable, with its probability distribution conditional on values of previous random variables in the tree. Because the probability of each event is conditional on the occurrence of events that precede it in the tree, the joint probability of the intersection of events that constitute a sequence (scenario) is found by multiplication.

The event tree appearing in Figure 2 is based on an analysis of the same incident data base used in the statistical inference illustration referred to in Table 1. Note that there is an implied sequence with each major branch in the tree: a package failure occurs, which results in a spill, whose impact was property damage in excess of $10,000. The probability of each successive branch on the tree is conditional on the likelihood of the events that precede it. This illustration also demonstrates the importance of structuring a complete tree and a properly ordered one. Also, to maintain a handle on the size of a tree, events must often be aggregated. In Figure 2, death, injury, and property damage were each grouped into two severity categories, and a hierarchy of consequence was established, whereby an event resulting in death and injury or property damage was recorded as a death consequence, while an event resulting in injury and property damage was considered an injury consequence.

Fault trees and event trees have different structures and serve different purposes—although for some risk analysis problems it may be appropriate to use both techniques. For example, in Figure 3, fault trees are commonly used to represent a complex sequence of events, whereas event trees are often used to determine possible impacts of an event. For either methodology to be plausible, however, the probabilities of occurrence of the initiating and all subsequent events must be estimated with adequate precision, and the magnitude of the consequences accurately predicted. In actuality, this can result in the formulation of complex trees consisting of hundreds or thousands of sequences.

The primary advantages of fault and event trees lie in their more efficient use of available data. Data requirements become

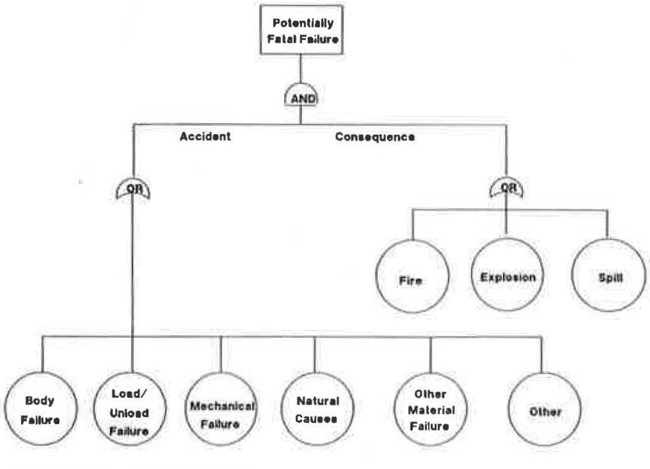

FIGURE 1 Hazardous materials transport fault tree.

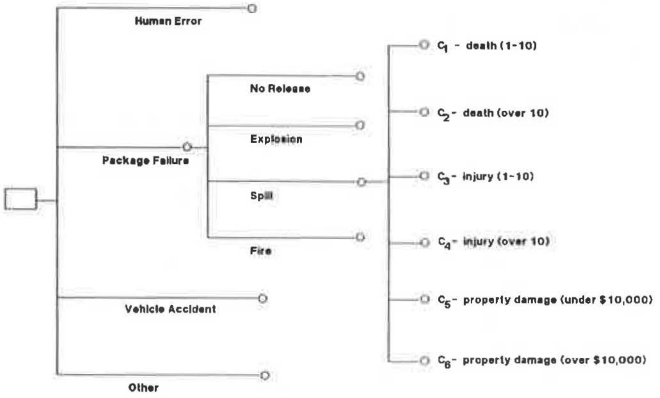

FIGURE 2 Hazardous materials transport event tree.

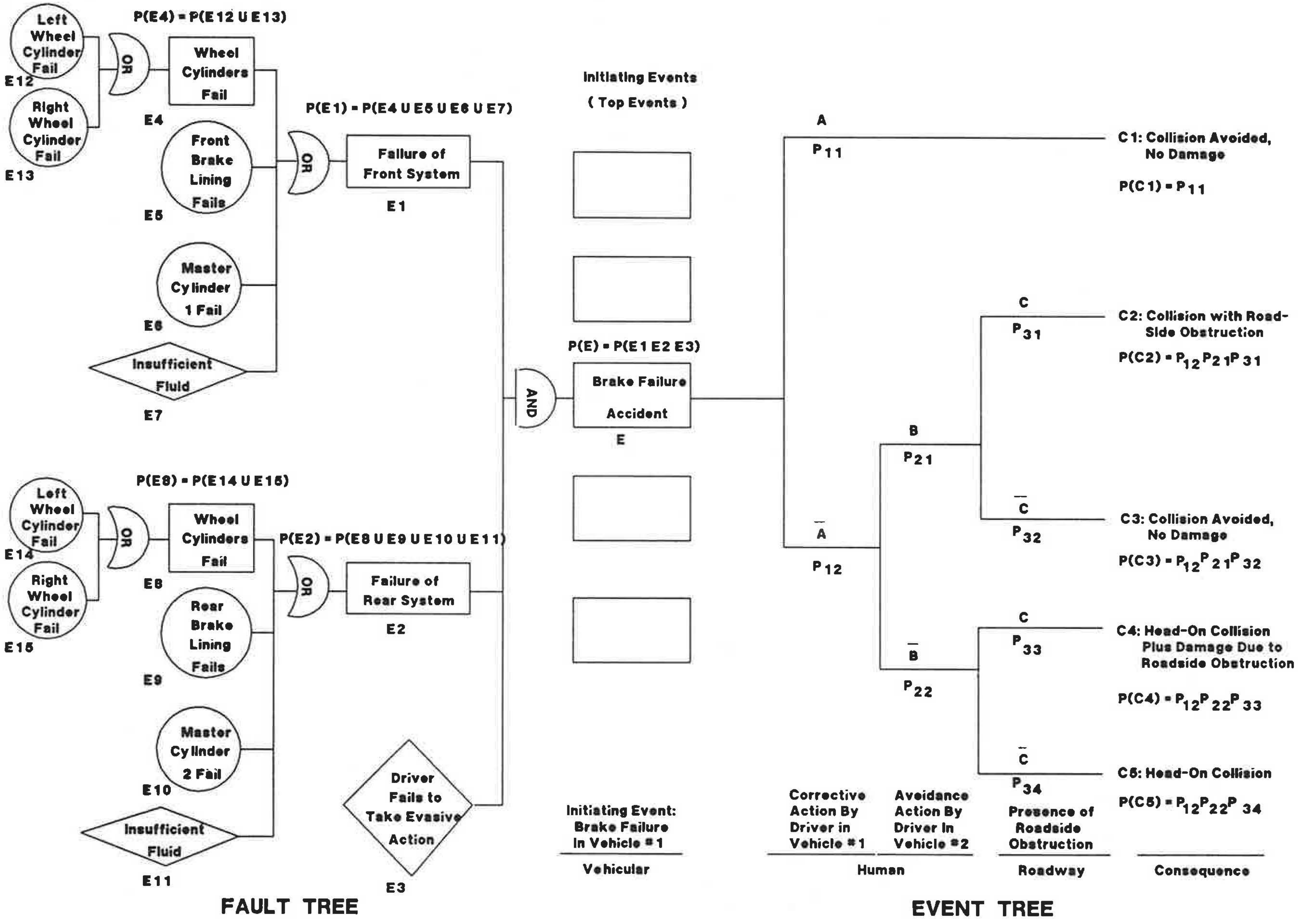

FIGURE 3 Combined tree structure for hazardous materials transport risk estimation.

an issue of obtaining meaningful samples of basic event data, such as the failure of a specific procedure. It is generally agreed that basic event data are easier to cull than data for disaggregate incident circumstances. Fault trees also lend themselves to the evaluation of the effectiveness of mitigating measures because measures under consideration can be represented through changes in the logic flow of the tree.

Analytical and Simulation Modeling

Analytical and simulation approaches to risk estimation express the operations of the system in terms of functional parameters representing system components and external factors. The conditions under which incidents occur and consequences arise are associated with specific combinations of the values of these parameters. In the case of simulation, the parameters are stochastic and values are represented by probability distributions, often derived from empirical data. Simulation runs are made where parameter values are plucked from these distributions to form potential scenarios. Repeated runs must be made to create an adequate sample of simulated scenarios from which responsible evaluation can be conducted.

Analytical models are necessarily simpler because of their use of a deterministic, rather than stochastic, process. For this reason, analytical models have typically been applied to components of the overall risk estimation methodology, such as the development of an incident occurrence model, which is often represented as a Poisson model. Analytical models can also be used as inputs to the simulation process.

A typical analytical approach is to assume that spills are independent events that occur randomly with respect to distance over which material is transported (*29*). The number of spills, n, occurring over a distance, L, is a discrete random variable; if the independence assumption is met, then n is Poisson distributed with parameter, vL:

$$P(n) = [(vL)^n/n!]e^{-vL} \qquad (1)$$

where v is the average number of spills per mile.

This is, in effect, a binomial distribution for a large number of independent events (trips) that result in only a few release occurrences and only two response classes (release or no release); v can be (and often is) derived using empirical data. This approach can be carried one step further by rearranging terms to derive the average number of years between spills, based on the average number of miles traveled per year.

One class of analytical models with special application relates to cases when one is concerned with events having extreme consequences, but only events of lesser consequence have been observed. Thus, it becomes necessary to extrapolate from the less severe to the more severe by assuming the severe events are caused by the same physical mechanisms and processes that caused the less severe events. The only difference is that the catastrophic events are assumed to be more extreme realizations of the same process. The conditions associated with this process are known as extreme value theory (*30*).

A major problem with analytical models is that, in the process of accommodating mathematical simplicity, the model formulation can depart from direct physical significance. Although simulation is more representative, it is typically a cost-prohibitive technique due to the computational time and expense involved in executing a single run, and the need to conduct multiple simulations to accumulate a basis for risk assessment (*2*).

Subjective Estimation

An approach often used in place of sparse data in developing risk estimates is subjective estimation by a so-called expert or panel of experts. These experts are assumed to be sufficiently familiar with the problem at hand that they can meaningfully extrapolate their experience and express it in quantitative and qualitative terms to accommodate the risk assessment process. Subjective estimation is perceived as an inherently low-confidence methodology (*2*). However, this perception may be a result of the general lack of appreciation of more subtle, but often as significant, subjective elements of transport safety.

Akin to subjective estimation is the use of subjective indices to represent risk factors (e.g., community population exposure on a scale of 1 to 10). While it may sometimes be appropriate to a methodology to represent qualitative effects that cannot be quantitatively measured, there is a real danger in developing risk estimation methods that are too dependent on this notion. First, the index scale can be somewhat arbitrary (e.g., How is the rank of "1" defined? In what way is a 1 different from a 2?). Second, various analysts may have different definitions for each classification (e.g., what is low to one may be moderate to another). Finally, it is difficult to translate policy options into this framework so as to evaluate their potential usefulness.

The use of subjective impact ratings by Yu and Judd (*20*) illustrates the application of subjective indices. A linear utility scale running from -3 (adverse impact) to $+3$ (positive impact) was used to classify projected fatalities, environmental impacts, economic impacts, and traffic impacts associated with potential routes serving a proposed nuclear waste repository site. Weights were subsequently assigned to each of these impacts for inclusion into a composite measure of effectiveness from which priorities for alternatives were established. It is interesting to note that the study was used to reach a formal conclusion based on this procedure—despite the appearance of all of the shortcomings raised in this discussion.

Bayesian Analysis

A happy medium between some of the previously discussed approaches may be the use of Bayesian analysis. In essence, this approach permits the acceptance of both prior and posterior information in forming probabilities. Essentially, Bayes theorem states that

$$p(A/B) = p(A)[p(B/A)/p(B)] \qquad (2)$$

where A and B represent information relating to the same event derived from different sources, and $p(A)$ represents the prior probability. $p(A/B)$ expresses the probability that Effect B was caused by Event A.

The Bayesian approach can be designed to accommodate subjective estimation to form prior probabilities, and then use whatever empirical data exist to derive conditional posterior probabilities. This analysis design can, therefore, make full use of available empirical observations (e.g., no catastrophic events in the last five years), without relying exclusively on the implications of this information (e.g., because no catastrophic event occurred in the last five years, there is zero probability of occurrence in the future).

The illustration cited here actually incorporates subjective estimation, analytical (Poisson) models, and empirical data (*31*). Suppose an expert provides an estimate of the frequency of release of spent fuel per transport shipment in the form of a probability distribution, as depicted in Figure 4. If we define $A_1, A_2, \ldots, A_6$ as corresponding to frequency rates of 10^{-3}, $10^{-4}, \ldots, 10^{-8}$, respectively, then $P(A_1)$ would equal 0.01. Now suppose that the historical data base indicated 4,000 shipments of spent fuel without a release. Granted, this does not constitute a significantly large sample size (given the frequencies of release estimated by the expert), but it is valuable information that needs to be assimilated into the analysis framework. This information is used to derive $p(B/A)$ using a binomial (Poisson) distribution:

$$p(B/A_1) = (1 - 10^{-3})^{4000} = 0.0183 \quad (3)$$

$$p(B/A_2) = (1 - 10^{-4})^{4000} = 0.670 \quad (4)$$

Similarly, $p(B/A_3) = 0.961$, $p(B/A_4) = 0.996$, $p(B/A_5) = 0.9996$, and $p(B/A_6) = 0.99996$. Thus

$$p(B) = \sum_i p(A_i)p(B/A_i) = 0.907 \quad (5)$$

This leads to the final computation:

$p(A_1/B) = 0.0002$ $p(A_2/B) = 0.148$ $p(A_3/B) = 0.424$

$p(A_4/B) = 0.329$ $p(A_5/B) = 0.0882$ $p(A_6/B) = 0.01102$

In comparing $p(A_i)$ with $p(A_i/B)$, it can be seen that the presence of empirical information alters slightly the prior probability distribution, as it should. Given that no spills have occurred in the first 4,000 shipments, the likelihood that the true frequency rate is 10^{-3} or 10^{-4} is diminished, while the probabilities of lower frequency rates correspondingly increase.

AGGREGATING VARYING RISK ESTIMATES

Only recently have researchers established the significant impact of risk definition and estimation on hazardous materials trans-

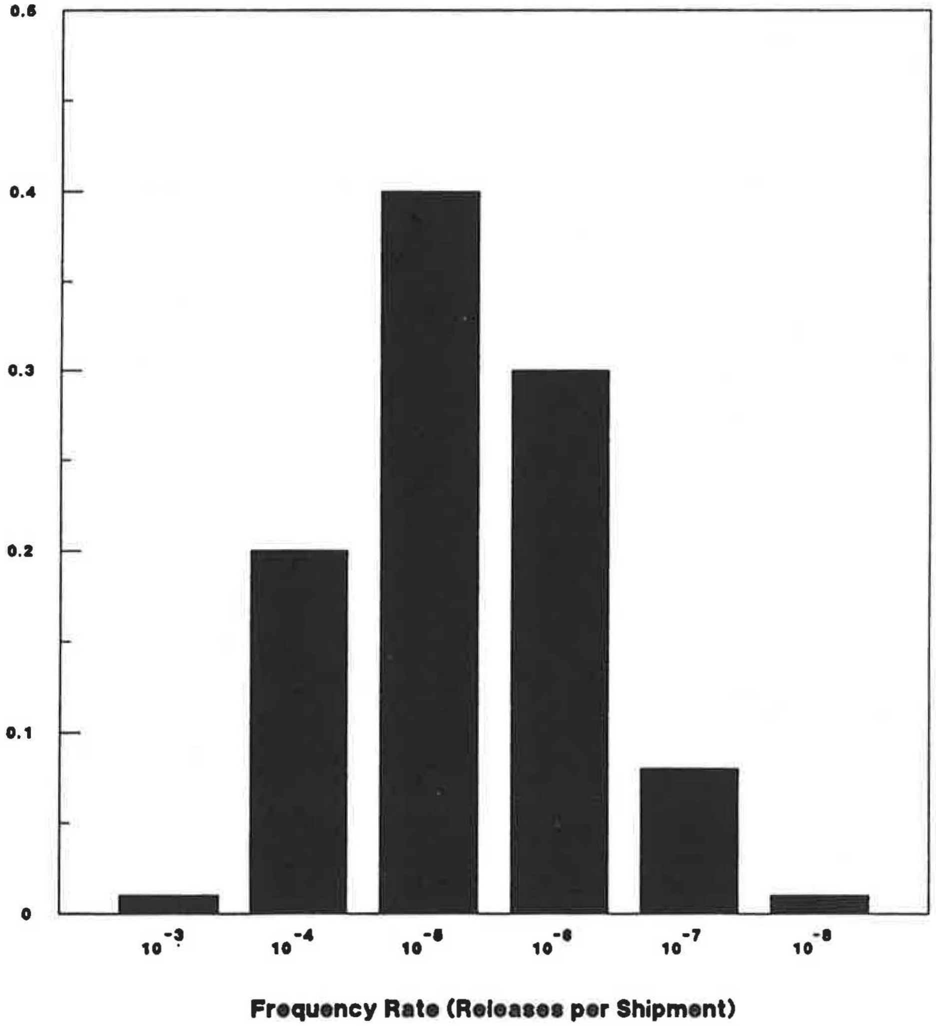

FIGURE 4 **Probability distribution of frequency of releases (*31*).**

port policy. In a study where multiple risk estimation procedures were examined, it was demonstrated that varying risk estimates based on population exposure alone yielded vastly different optimal routing strategies (*32*). Two independent studies of marine transportation of liquefied natural gas have also been conducted using the same information, which yielded risk estimates that differed by several orders of magnitude. From these efforts, the need for reaching consensus risk estimates has been formally recognized.

Prior attempts to find consensus estimates of transport risk have been virtually nonexistent. The exception being a study of subjective estimation in which a group of experts was convened to assess risks, and a consensus was reached using the Delphi technique (*2*). Fortunately, there exist, from other disciplines, fundamental approaches to judgment aggregation that may have partial or full transferability to the problem addressed herein.

For example, an information theoretic approach may be able to achieve this objective by identifying a solution space that satisfies the boundary conditions imposed (*33*). The decision maker initially holds to a fixed viewpoint, expressed by a probability vector P. However, the decision maker is given expert judgment that the true mean of random variable X is u. The decision maker is then compelled to adjust his or her viewpoint to be consistent with the true parametric information that $E(X) = u$. It is reasonable to assume that this adjustment process will result in a new viewpoint as close as possible to the initial viewpoint of the decision maker and yet consistent with the expert (see Figure 5).

Considerable literature exists on this type of adjustment process as viewed in the context of generating prior probability distributions for Bayesian inference. Sampson and Smith proposed to use, as the measure of closeness, the widely employed Kullback-Leibler discriminator $I\ (Q,P)$. This represents the expected difference between viewpoint P versus Q if, in fact, the true probability distribution is Q. In the adjustment process, the expert judgment is given in the form of partial information concerning the parameters of an underlying, but unknown, probability distribution. In particular, it assumes knowledge of the mean of the distribution. This is equivalent in the Bayesian construction to an observed average based on a large sample of observations.

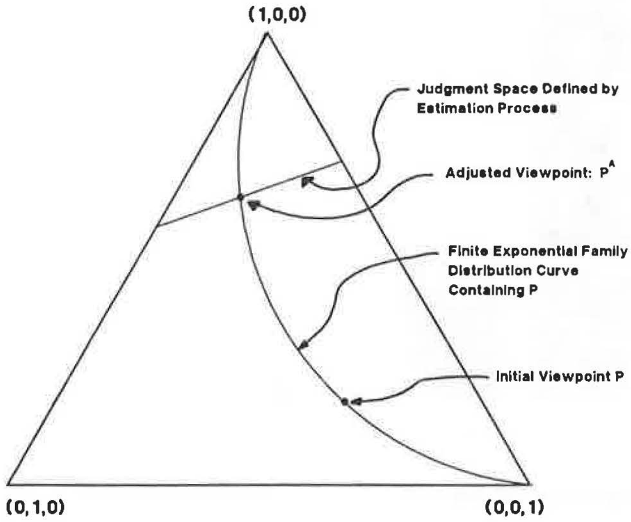

FIGURE 5 Finding-adjusted viewpoints (M = 2) (*33*).

Many situations also exist where the prior information would take the form of interval estimates of P_i. For example, in the case of rare events, it would be difficult to obtain precise estimates of P_i. If S approaches produce probability ranges $a_{is} \le P_i \le b_{is}$, $1 \le i \le n$, then the Sth estimate is consistent if and only if (*34*)

$$\sum_{i=1}^{n} a_{is} \le 1 \le \sum_{i=1}^{n} \mathrm{b}_{is} \qquad (6)$$

Otherwise, no probability vector satisfies the constraints given by the estimation process. The decision maker then pools, or aggregates, this data across the estimation approaches to obtain final interval estimates $a_i \le P_i < b_i$, $1 \le i \le n$. The decision maker might compute a_i and b_i as the averages of the a_{is} and b_{is}, respectively.

Adopting the maximum entropy principle (*35*), the decision maker computes p^*, a solution to

$$\max \left[- \sum_{i=1}^{n} P_i \ln (P_i) \right] \qquad (7)$$

subject to

$$\sum_{i=1}^{n} P_i = 1 \qquad P_i \ge 0 \qquad \forall\, i$$

$$a_i \le P_i \le b_i \qquad \forall\, i$$

Previous research has shown how to solve this problem with the addition of inequality constraints on the P_i (*36*). Factors influencing this process include the number of estimates and the variation in their respective values (*37*).

This approach is illustrated in the following example. Suppose we are interested in the probability of a hazardous materials transport incident occurrence according to five classes of incident severity. Assume that several independent probability estimates were made, which yielded the following intervals:

Class	*Portion of Shipment Volume Released* (%)	*Probability Interval*
1	0	0.45–0.90
2	1–10	0.15–0.55
3	11–30	0.01–0.10
4	31–60	0.00–0.001
5	61–100	0.00–0.001

The index i corresponds to the incident severity class. The a_i and b_i are $a_1 = 0.45$, $b_1 = 0.90$, etc. The following solution is based on an algorithm presented by Freund and Saxena (*35*). First, the function $V_i(x)$ is defined as follows:

$$\begin{aligned} V_i(x) &= a_i & 0 &\le x \le a_i \\ V_i(x) &= x & a_i &\le x \le b_i \\ V_i(x) &= b_i & b_i &\le x \le 1 \end{aligned} \qquad (8)$$

where

$$V(x) = V_1(x) + V_2(x) + \ldots + V_5(x) \qquad (9)$$

Next, an order set, T, is constructed of the a_i, b_i, 0, and 1:

$$T = (0, 0.001, 0.01, 0.1, 0.15, 0.45, 0.55, 0.9, 1.0)$$

The values of $V(x)$ are sequentially evaluated until a pair of consecutive elements of T (t_1 and t_2) is found between which $V(x)$ assumes a value of 1.0. The values of $V(x)$ are computed as follows:

$$V(0.0) = 0.610 \qquad V(0.001) = 0.612 \qquad V(0.01) = 0.612$$

$$V(0.1) = 0.702 \qquad V(0.15) = 0.702 \qquad V(0.45) = 1.102$$

Therefore, $t_1 = 0.15$ and $t_2 = 0.45$. Defining $S_1 = \Sigma_{a_i \geq t_2} a_i = 0.45$, $S_2 = \Sigma_{b_i \leq t_1} b_i = 0.102$, and m_1 and m_2 as the number of $a_i \geq t_2$ and $b_i \leq t_1$, respectively, if $m_1 + m_2 = 5$, then $B = t_1$. Otherwise

$$B = (1 - S_1 - S_2)/(n - m_1 - m_2) \qquad (10)$$

In this instance, $m_1 = 1$, $m_2 = 3$, and $B = 0.448$. The maximum entropy distribution is obtained by setting $P_i^* = V_i(B)$. Therefore, the consensus probability estimates are

$$P_1^* = 0.45 \qquad P_2^* = 0.448 \qquad P_3^* = 0.10 \qquad P_4^* = P_5^* = 0.001$$

It is important to note that in mitigating conflict, the judgment aggregation approach must be applied with care. Situations can arise where the source of the conflict is quite real; that is, sufficient uncertainty exists so that convergence to a point estimate may be a damaging representation of the problem.

CONCLUSIONS

Hazardous materials transport risk assessments are typically faced with the problem of selecting an appropriate risk estimation methodology under less-than-ideal conditions, often a result of the quality of available data. The approaches discussed in this paper show clearly that no methodology is preferred for all circumstances. Rather, good judgment must prevail in determining what is acceptable methodology given the problem at hand, and the strengths and weaknesses of each approach. Contemporary views of risk, particularly Bayesian thought processes, provide a refreshing opportunity to remove some of the dependence of risk estimation on adequate empirical data.

Uncertainties exist in all of the risk methodologies, and where increasing uncertainty exists, an increasing need for responsible risk estimation also exists. For these reasons, it is advisable to develop risk estimation intervals rather than point estimates, and to apply sensitivity analysis, particularly for low-probability/high-consequence events.

As more interest is directed at risk assessment in hazardous materials transport, situations will arise where conflicting risk estimates may emerge. To address this problem, a comprehensive approach to judgment aggregation must be formalized.

In summary, although significant progress has been made by hazardous materials transport researchers in understanding and refining risk estimation methodology, a formidable challenge remains to elevate this activity to a more respected level.

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The views expressed in this paper are solely those of the authors and not of the sponsoring agencies.

Characteristics of Accidents and Incidents in Highway Transportation of Hazardous Materials

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Existing accident and incident data bases provide insight into the nature of the safety risks involved in hazardous materials transportation by highway. This paper presents analyses of data from the U.S. Department of Transportation Research and Special Programs Administration (RSPA) Hazardous Materials Incident Reporting System, the FHWA Motor Carrier Accident Reports, and the Missouri Statewide Accident Reporting System. These analyses document the types of accidents and incidents that occur when transporting hazardous materials by truck on public highways. This paper focuses on the predominant role of traffic accidents as a cause of severe hazardous materials incidents. Existing traffic accident data are used to determine the probability of a hazardous materials release, given an accident involving a hazardous materials-carrying vehicle. The types of accidents in which this probability is higher or lower than average are identified. The purpose of this paper is to present analyses of use to highway agencies in managing hazardous materials transportation on their road networks. Thus, incidents associated with loading and unloading operations that are included in the RSPA data base have been excluded from these analyses.

Hazardous materials (hazmat) transportation is a large and growing segment of the transportation industry. Special concern is addressed to safety in the transportation of hazardous materials because of the potential for fires, explosions, ground water contamination, and toxic effects on human health if hazardous materials are inadvertently released. Effective management of hazardous materials transportation safety requires a thorough understanding of the risks of accidents and incidents and the characteristics of accidents and incidents that may occur.

Most previous evaluations of hazardous materials transportation safety have been broad in scope, covering all modes of transportation. This paper focuses solely on highway (i.e., truck) hazmat transportation. However, highway transportation is a predominant part of the hazmat transportation safety problem, accounting for more than 85 percent of the hazmat releases reported to federal agencies. This paper focuses on those releases that occur during actual transportation on public highways and omits incidents that occur during loading and unloading in terminal or yard areas. While loading and unloading incidents are part of the overall risk of hazmat transportation, such incidents are not part of the safety problem faced by highway agencies in managing the highway system. In addition, loading and unloading incidents are not relevant to the analysis of alternative routes for hazmat shipments.

This paper presents estimates of the probability of a hazmat release, given an accident involving a truck carrying hazardous materials. This probability, which was found in this study to be from 13 percent to 15 percent overall, has only been quantified indirectly in past research. In this study, it is quantified directly from existing data bases. The analyses show that the probability of a hazmat release, given an accident, is strongly dependent on the accident type and other accident-related variables.

The analyses also show the preponderant role of traffic accidents as a cause of severe hazmat incidents. Between 35 and 68 percent of severe hazmat incidents are caused by traffic accidents, depending on the definition chosen for a severe incident.

ACCIDENTS, INCIDENTS, AND EXPOSURE

The analysis of existing data bases related to hazardous materials transportation requires an understanding and careful distinction between accident, incident, and exposure data bases.

Accident data bases contain reports of traffic accidents obtained either from police reports, motorist or motor carrier reports, or independent follow up investigations. Each record in an accident data base documents the characteristics of a particular accident or a particular accident-involved vehicle. The accident data bases of interest in hazmat safety analyses are those that contain data on truck accidents where a determination can be made as to whether the truck (or trucks) involved in an accident was carrying hazardous materials. It is also desirable to be able to determine whether a hazardous materials release occurred in a particular accident.

Incident data bases contain reports of occurrences where a hazardous material was unintentionally released. The incidents of primary interest are releases of hazardous materials during their transportation by highway. Several types of incidents must be considered including releases resulting from (a) traffic accidents, (b) valve or container leaks, and (c) fires or explosions.

Figure 1 presents a classification scheme based on recent work by the Organization for Economic Cooperation and Development that clearly distinguishes between hazmat accidents and incidents (*1*). The figure shows that some accidents are not incidents, some incidents are not accidents, and some

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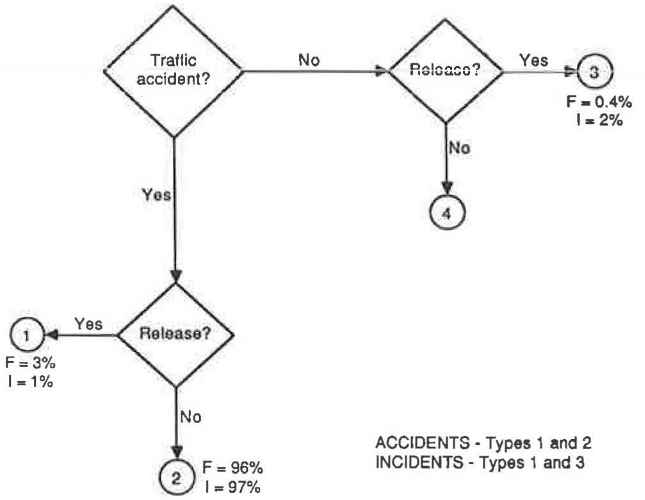

FIGURE 1 Classification scheme for on-highway events and causes of resulting fatalities and injuries for trucks carrying hazardous materials.

occurrences are both incidents and accidents. Figure 1 also presents estimates of the distribution of fatalities and injuries associated with highway transportation of hazardous materials. The development of these estimates is addressed later in this paper.

Accident and incident data are useful because they indicate the frequency with which particular events occur. However, the assessment of accident or incident risk requires *corresponding* exposure data. Exposure is a measure of opportunities for accidents or incidents to occur, such as number of hazardous materials shipments, tons of hazardous materials shipped, or, best of all, vehicle-miles of hazmat shipments.

Risk measures, such as accident or incident rates per million vehicle-miles, can be expressed as the ratio of frequency of accidents or incidents to exposure:

$$R = A/E$$

where

R = a measure of risk (e.g., accident rate),
A = a frequency measure (e.g., number of accidents), and
E = an exposure measure (e.g., vehicle-miles of travel).

To be useful in establishing hazmat transportation policies, risk measures must be quite specific. For example, an accident rate for a specific type of truck traveling on a particular type of road can be obtained only if both the accident and exposure populations are stratified accordingly.

A major weakness of hazmat safety research and truck safety research, in general, is that valid exposure data corresponding to a particular accident data set are seldom available. For this reason, this paper concentrates on what can be learned from existing incident and accident data bases in the absence of exposure data.

HAZMAT INCIDENT ANALYSES

The characteristics of hazmat incidents were determined through analysis of the U.S. Department of Transportation Research and Special Programs Administration (RSPA) Hazardous Materials Incident Reporting System (HMIR) data base. A highway-related hazardous materials incident is an unintentional release of a hazardous material during, or in connection with, its transportation by highway. Hazmat incidents in all modes, including highway transportation, are required by law to be reported to the RSPA HMIR by all carriers engaged in interstate transportation (*2*). RSPA receives nearly 5,000 reports of highway-related hazmat incidents each year. Carriers engaged solely in intrastate transportation are not required to report hazmat incidents to RSPA; therefore, it is not clear how many incidents are not reported to RSPA.

No minimum quantity released or minimum property damage threshold requirement exists for reporting hazmat incidents to RSPA. Any incident, no matter how small, is technically reportable if the hazardous material escapes from its container. It is not necessary for the hazardous material to escape from the vehicle. The only exceptions to this general rule are small-quantity releases of electric battery acid and certain paint products that were excluded from the reporting requirements in 1981.

The RSPA reporting requirements are currently being expanded to include incidents in which a highway is closed for an hour or more or when persons are evacuated from the vicinity of a potential incident site, even if no hazmat release occurs (*3*). There have been instances in which an overturned truck carrying hazardous materials caused a major highway to be closed for many hours and the surrounding population to be evacuated because of the possibility of a release. In the proposed revision, such incidents will now be reportable to RSPA even if no release occurs. The proposed revision to the HMIR report form will also distinguish explicitly between incidents that occur en route and incidents that occur in terminal and loading areas.

The RSPA HMIR data are based entirely on self-reporting by carriers. This self-reporting system undoubtedly leads to underreporting of incidents, but the level of underreporting is uncertain. Further analysis of underreporting problems in the RSPA HMIR is provided by Harwood and Russell (*4*).

Annual Incident Frequencies

The RSPA HMIR data include both on-highway and off-highway incidents, and it is not always possible to distinguish clearly between such locations. For this analysis, the following types of incidents were presumed to occur on the highway:

- Incidents caused by a traffic accident.
- Incidents caused by cargo shifting or damage by other freight.
- Incidents that occurred in a different city or state from either the origin or the destination of the shipment.
- Incidents in which the city or state where the incident occurred is unknown.

The following types of incidents were presumed to occur off the highway:

- Incidents involving loading or unloading.
- Incidents involving material dropped in handling.
- Incidents involving external puncture not caused by a traffic accident.

The location of incidents that do not fit any of the above definitions was treated as unknown.

Given these definitions, 39 percent of the 28,433 hazmat incidents in the RSPA data for 1981–85 (inclusive) occurred at locations off of public highways, such as in terminals or shipping yards. Approximately 48 percent (13,547) of hazmat incidents occurred on the highway, and the locations of the remaining 13 percent of incidents could not be determined.

Hazmat incidents that do not occur on public highways are not of direct concern to highway agencies, because these incidents could not involve a release onto a highway right-of-way. Therefore, the subsequent analyses in this paper address the 13,547 incidents that one can be reasonably sure occurred on public highways.

Causes of Hazmat Incidents

Table 1 presents the distribution of hazmat incidents by the type of failure that occurred. For all reported incidents, the major failure types are body or tank failures (20 percent), valve or fitting failures (24 percent), and cargo shifting (37 percent).

Traffic accidents were found to constitute approximately 11 percent of all hazmat incidents. This is a higher proportion of traffic accidents than reported in previous studies (*4–6*), because off-highway incidents have been excluded from the data.

Severe incidents are of greatest concern in the management of hazardous materials transportation safety. However, no commonly accepted definition exists as to what constitutes a severe incident. Table 1 illustrates the distribution of failure types in on-highway hazmat incidents for progressively less-restrictive definitions of incident severity ranging from "death only" to "all reported incidents." The severe nature of unintentional releases of hazardous materials in traffic accidents can be clearly seen in Table 1. Note that, although traffic accidents constitute just 11 percent of all reported incidents, they account for 35 to 68 percent of the severe incidents, depending on the definition selected for severe incidents. In the 35 incidents in which a fatality occurred as a result of a release, more than 90 percent (32 incidents) were caused by traffic accidents.

Valve or fitting failure is the second leading failure type in these various definitions of severe incidents. Valve or fitting failures, which constituted 24 percent of all incidents, were attributed to 29 percent of the incidents that resulted in deaths or injuries and lesser percentages of the other severity level definitions. No other failure type accounted for more than 14 percent of the severe incidents for any of the severity levels examined. Thus, regardless of the definition selected for a severe incident, traffic accidents account for a more important part of the hazardous materials highway safety problem than is suggested by overall release statistics.

In the analyses that follow, severe incidents have been defined as those that involve either (a) a fatality or injury caused by the hazmat release, (b) property damage of $50,000 or more caused by the hazmat release, or (c) a fire or explosion. Table 1 shows that by this definition, traffic accidents constitute 56 percent of severe incidents. In fact, nearly a quarter of traffic accidents that cause a hazmat release result in a severe incident.

The general causes of hazmat releases are summarized in Table 2. Approximately 50 percent of incidents are attributable to human error and 35 percent are attributable to package failure. Previous analyses of the RSPA data base have indicated that, overall, human error is responsible for more than 60 percent of hazmat releases. The lower proportion of hazmat releases attributable to human error and the higher proportion of incidents attributable to package failure in Table 2 occur because human error predominates in off-highway loading and unloading incidents, which have been excluded from the analysis. It should be noted that the literature suggests driver error is a significant cause of traffic accidents; thus, in this sense, human error is ultimately responsible for a large portion of the traffic accidents shown in Table 2. When the analysis shown in Table 2 is limited to severe incidents, traffic accidents dominate, of course, as they did in Table 1. However, in severe incidents not caused by traffic accidents, package failure is actually a more common cause than human error.

Type of Hazardous Material Involved

The distribution of the type of hazardous material released in hazmat incidents was analyzed in the RSPA data. Where

TABLE 1 DISTRIBUTION OF ON-HIGHWAY HAZMAT INCIDENTS BY FAILURE TYPE AND INCIDENT SEVERITY, 1981–1985

	Death Only		Death or Injury		Death or Injury or Explosion		Death or Injury or Explosion or Fire		Death or Injury or Explosion or Fire or Property Damage Over $100K		Death or Injury or Explosion or Fire or Property Damage Over $50K		Death or Injury or Explosion or Fire or Property Damage over $10K		All Reported Incidents	
Failure Type	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Traffic accident	32	(91.4)	107	(35.5)	112	(34.7)	188	(41.7)	233	(46.4)	355	(56.1)	723	(68.1)	1,427	(10.8)
Body or tank failure	0	(0.0)	37	(12.3)	38	(11.8)	40	(8.9)	42	(8.4)	42	(6.6)	63	(5.9)	2,741	(20.2)
Valve or fitting failure	0	(0.0)	86	(28.6)	88	(27.2)	101	(22.4)	101	(20.1)	104	(16.4)	112	(10.5)	3,289	(24.3)
Cargo shifting	0	(0.0)	39	(13.0)	44	(13.6)	52	(11.5)	52	(10.4)	54	(8.5)	70	(6.6)	4,945	(36.5)
Fumes or venting	0	(0.0)	2	(0.7)	2	(0.6)	2	(0.4)	2	(0.4)	2	(0.3)	2	(0.2)	15	(0.1)
Other	3	(8.6)	30	(10.0)	39	(12.1)	68	(15.1)	72	(14.3)	76	(12.0)	92	(8.7)	1,100	(8.1)
TOTAL	35		301		323		451		502		633		1,062		13,547	

more than one hazardous material was released in a single incident, the incident was classified on the basis of the primary material released (listed first in the RSPA data file).

The predominant hazardous materials released were found to be flammable and combustible liquids (46 percent of all releases) such as gasoline and corrosive materials (40 percent). Poisonous gases and liquids constituted 5 percent of all releases. No other single hazard class constituted more than 3 percent of releases. These RSPA data also indicated that flammable and combustible liquids constituted 71 percent of the releases resulting from traffic accidents, as opposed to 46 percent of all releases. By contrast, corrosive materials accounted for only 13 percent of the releases in traffic accidents, but 43 percent of the releases from other causes. Thus, it appears that corrosive materials, by their nature, are much more likely to produce a valve, fitting, or container failure than other placarded materials.

The distribution of severe hazmat incidents by type of material released was also studied. About 55 percent of severe incidents involved flammable and combustible liquids, as compared with 46 percent of all incidents. Thus, flammable and combustible liquids were overrepresented in severe incidents as compared with total incidents. The opposite appeared to be true for corrosive materials. Corrosive materials were involved in 24 percent of severe incidents, as compared with 40 percent of all incidents.

Consequences of Incidents

The RSPA data base contains the consequences of each reported incident, including the number of deaths and injuries and the dollar amount of property damage. In the case of incidents related to traffic accidents, the RSPA data includes only deaths and injuries that are a direct result of the hazmat release. Other deaths and injuries resulting from the accident are not reported. The same interpretation probably holds for property damage from hazmat incidents, but this point is not clear from the instructions for completing the hazmat incident report (*2*).

The RSPA data show that 0.3 percent of hazmat incidents result in one or more deaths and 2.2 percent of hazmat incidents result in one or more personal injuries. Thus, it is apparent that the deaths and injuries from hazmat releases result from a relatively small proportion of the total number of incidents.

Table 3 summarizes the consequences of hazmat incidents from 1981 to 1985, inclusive. During this period, there were 54 deaths and 473 injuries from on-highway hazmat releases, or an average of approximately 11 deaths and 95 injuries per year in the United States. Approximately 90 percent of the deaths and 25 percent of the injuries were attributed to releases resulting from traffic accidents. On average, 10 deaths and 23 injuries per year were attributed to releases from traffic accidents. Releases resulting from traffic accidents were about 100 times more likely to cause deaths and three times more likely to cause injuries than releases from other causes.

On-highway releases resulted in about $10 million in reported property damage per year at an average reported cost of about $3,600 per incident. Releases resulting from traffic accidents resulted in about 80 percent of the total reported property damage costs. Releases from traffic accidents resulted in about 30 times more reported property damage costs per incident than releases from other causes.

TRAFFIC ACCIDENT ANALYSES

The only nationwide source of truck accident data containing information on hazmat transportation is the Motor Carrier Accident Report data (*7*) maintained by the FHWA Bureau of Motor Carrier Safety (BMCS) (recently renamed the Office of Motor Carriers). This data base is valuable because it iden-

TABLE 2 DISTRIBUTION OF ON-HIGHWAY HAZMAT INCIDENTS BY CAUSE OF RELEASE, 1981–1985

	All Reported Incidents		Severe Incidents Only	
Cause of Release	No.	%	No.	%
Traffic accident	1,457	(10.8)	355	(56.1)
Human error	6,845	(50.5)	101	(16.0)
Package failure	4,691	(34.6)	128	(20.2)
Other	550	(4.1)	49	(7.7)
Total	13,543		633	

TABLE 3 SUMMARY OF CONSEQUENCES OF ON-HIGHWAY HAZMAT INCIDENTS, 1981–1985

	All Reported Incidents	Incidents Caused by Traffic Accidents	Incidents Resulting from Other Causes
Number of incidents	13,547	1,457	12,090
Number of deaths	54	50	4
Deaths per incident	0.0040	0.0340	0.0003
Number of injuries	473	115	358
Injuries per incident	0.035	0.079	0.030
Total property damage ($)	48,297,000	38,412,000	9,885,000
Property damage per incident ($)	3,565	26,364	818

tifies whether each accident-involved truck was transporting hazardous materials and whether those hazardous materials were released. Thus, the BMCS data can be used to compare the frequency and distribution of truck accidents that resulted in a hazmat release, with all accidents involving hazmat-carrying trucks and truck accidents in general.

Two important disadvantages of this data base should be noted. First, while nationwide in scope, the data base does not include all truck accidents, but only those of regulated interstate motor carriers. Second, as do the RSPA hazmat incident data, the BMCS accident data are dependent on self-reporting by carriers. This self-reporting system is known to result in underreporting of accidents to BMCS. One previous study noted that the percentage of property-damage-only accidents is substantially smaller in the BMCS data than in data on police-reported accidents from the National Accident Sampling System (NASS), indicating that minor accidents are probably underreported to BMCS (*8*). The property damage threshold for reporting truck accidents to BMCS was $2,000 for the entire period covered in this paper. On January 1, 1986, however, the reporting threshold was raised to $4,200.

The following section presents tables of the characteristics of truck accidents in general and accidents involving hazmat-carrying trucks. Selected tables also indicate the breakdown of accidents involving hazmat-carrying trucks into accidents where the hazardous materials being carried were and were not released. All tables are based on less than 1 percent missing data unless otherwise noted.

Annual Accident Frequencies

The BMCS data for 1981 through 1985 show that hazmat-carrying trucks were involved in approximately 5 percent of all truck accidents. Approximately 15 percent of accidents involving trucks carrying hazardous materials resulted in a hazmat release, as compared with the 20 percent estimate developed by Abkowitz (*9,10*) in research for the Environmental Protection Agency. The Abkowitz estimate was developed indirectly, while the 15 percent estimate presented here for the probability of a release is based on actual data. Underreporting of accidents to BMCS may produce a bias in the estimate of the probability of a release presented here. However, past research has shown that accident reporting levels increase as accident severity increases (*11–13*). Therefore, accidents resulting in a release are more likely to be reported than other accidents, and 15 percent should be a conservative (upper bound) estimate of the overall proportion of hazmat accidents resulting in a release. The effect of selected factors on the probability of a release, given an accident, is examined in the remaining tables.

The BMCS data base is incomplete for some factors for the years 1982 and 1983. In those years, selected accident factors were not entered into the computer data base as an economy move. Entry of all available data was resumed in 1984. For consistency, the remaining tables that use the BMCS data are based on data for 1984 and 1985 only, so that each table is using the same set of accidents. Approximately 14 percent of accidents involving hazmat-carrying trucks in 1984 and 1985 resulted in a release.

Relationship to Intersecting Facilities

Table 4, which shows the distribution of BMCS-reported truck accidents by their relationship to intersections, freeway ramps, and railroad-highway grade crossings, presents some important findings concerning the likelihood of hazmat releases in different types of accidents. Intersection accidents are less likely to result in a hazmat release than accidents in general; in fact, only 10 (4 percent) of 283 accidents at intersections involving hazmat-carrying trucks resulted in a release. Accidents involving hazmat-carrying trucks on freeway ramps are more likely to result in a release, with 22 percent releases for hazmat accidents on on-ramps and 26 percent releases for hazmat accidents on off-ramps. Railroad grade crossings have the highest likelihood of a release when an accident occurs, with 10 (45 percent) of the 22 reported accidents resulting in a release.

Accident Type

Table 5 presents the distribution of accident types for hazmat accidents and truck accidents in general. Multiple-vehicle collisions are the leading type of accident, both for vehicles carrying (47 percent) and not carrying (52 percent) hazardous materials. However, the leading accident types that result in hazmat releases are single-vehicle overturning accidents, which constitute 41 percent of releases, and single-vehicle run-off-road accidents, which constitute 23 percent of releases. While multiple-vehicle collisions represent 47 percent of the accidents for trucks carrying hazardous materials, these accidents result in only 16 percent of all hazmat releases. Single-vehicle collisions represent 53 percent of the accidents for trucks

TABLE 4 DISTRIBUTION OF BMCS-REPORTED TRUCK ACCIDENTS BY RELATIONSHIP TO INTERSECTING FACILITIES, 1981–1985

Intersecting Facilities	Accidents Involving Trucks Not Carrying Hazmat		Accidents Involving Trucks Carrying Hazmat						Probability of a Hazmat Release Given an Accident (%)
			Combined		No Release		Hazmat Release		
	No.	%	No.	%	No.	%	No.	%	
None	60,828	(85.5)	3,172	(85.7)	2,726	(85.6)	446	(85.8)	14.2
At-grade intersection	5,762	(8.1)	283	(7.6)	273	(8.6)	10	(1.9)	3.5
Off-ramp	2,376	(3.3)	116	(3.1)	86	(2.7)	30	(5.8)	25.9
On-ramp	1,884	(2.6)	110	(3.0)	86	(2.7)	24	(4.6)	21.8
Railroad grade crossing	314	(0.4)	22	(0.6)	12	(0.4)	10	(1.9)	45.5
TOTAL	71,164		3,703		3,183		520		14.0

carrying hazardous materials, but result in 84 percent of all releases.

Accidents involving hazmat-carrying trucks are twice as likely as other truck accidents to result in an overturn. Furthermore, releases occur in 38 percent of hazmat overturns as compared with 14 percent of all accidents involving hazmat-carrying trucks. Hazmat accidents are 1.5 times as likely as other truck accidents to involve a single-vehicle running off the road and such accidents result in a hazmat release 33 percent of the time. These accident types are characteristic of tank trucks and represent the relatively larger use of tankers in hazmat trucking as compared with trucking in general.

By contrast, single-vehicle collisions with parked cars or nonmotorists (i.e., pedestrians, bicycles, and animals) and multiple-vehicle collisions (including both car-truck and truck-truck collisions) are less likely than average to result in a release. This confirms the finding in Table 8 that intersection accidents are less likely to result in a hazmat release, because accidents at intersections typically involve multiple-vehicle collisions.

The principal special concerns in accidents involving trucks carrying hazardous materials are the actual and potential consequences of hazmat releases. From this perspective, the analysis findings indicate that data on accidents involving hazmat-carrying trucks can be misleading without data on whether a hazmat release occurred in these accidents, because the probability of a release, given an accident, varies widely among accident types.

Truck Configuration

Table 6 presents the distribution of BMCS-reported accidents by truck configuration. The table reflects the overwhelming predominance of single-trailer combination trucks in both hazmat transportation and trucking in general. The table indicates that both single-unit and double-trailer combination trucks are slightly less likely than average to release their cargo when involved in an accident, and single-trailer combination trucks are slightly more likely than average to release their cargos, but the differences are not large. Truck trailers (single-unit trucks towing a full trailer) appear to have the highest likelihood of a hazmat release when involved in an accident.

Table 7 presents the distribution of accidents by cargo area configuration (van, flatbed, tanker, and other) for single-trailer combination trucks in the BMCS data. Table 7 shows that the majority of accidents for trucks not carrying hazardous materials involve van semitrailers, while the majority of accidents for hazmat-carrying trucks involve tankers. Table 7 also indicates that the probability of a hazmat release, given an accident, is above average for tankers and below average for vans.

TABLE 5 DISTRIBUTION OF BMCS-REPORTED TRUCK ACCIDENTS BY ACCIDENT TYPE

	Accidents Involving Trucks Not Carrying Hazmat		Accidents Involving Trucks Carrying Hazmat						Probability of a Hazmat Release Given an Accident
			Combined		No Release		Hazmat Release		
Accident Type	No.	%	No.	%	No.	%	No.	%	(%)
SINGLE-VEHICLE ACCIDENTS									
Noncollision Accidents									
Ran-off-road	4,483	(6.3)	357	(9.6)	239	(7.5)	118	(22.7)	33.1
Jackknife	4,864	(6.8)	158	(4.3)	146	(4.6)	12	(2.3)	7.6
Overturn	5,263	(7.4)	574	(15.5)	359	(11.3)	215	(41.3)	37.5
Separation of units	278	(0.4)	36	(1.0)	28	(0.9)	8	(1.5)	22.2
Fire	425	(0.6)	33	(0.9)	32	(1.0)	1	(0.2)	3.0
Cargo spillage	268	(0.4)	21	(0.6)	0	(0.0)	21	(4.0)	100.0
Cargo shifting	206	(0.3)	6	(0.2)	5	(0.2)	1	(0.2)	16.7
Other noncollision	157	(0.2)	7	(0.2)	6	(0.2)	1	(0.2)	14.3
Collision Accidents									
Collision with fixed object	7,774	(10.9)	241	(6.5)	210	(6.6)	31	(6.0)	12.9
Collision with parked vehicle	6,591	(9.3)	254	(6.9)	246	(7.7)	8	(1.5)	3.1
Collision with train	314	(0.4)	22	(0.6)	12	(0.4)	10	(1.9)	45.5
Collision with nonmotorist	1,241	(1.7)	66	(1.8)	65	(2.0)	1	(0.2)	1.5
Other collision	2,508	(3.5)	169	(4.6)	159	(5.0)	10	(1.9)	5.9
MULTIPLE-VEHICLE ACCIDENTS									
Collision with passenger car	28,316	(39.8)	1,360	(36.7)	1,313	(41.3)	47	(9.0)	3.5
Collision with truck	7,758	(10.9)	372	(10.0)	337	(10.6)	35	(6.7)	9.4
Collision with other vehicle type	703	(1.0)	27	(0.7)	26	(0.8)	1	(0.2)	3.7
TOTAL	71,149		3,703		3,183		520		14.0

TABLE 6 DISTRIBUTION OF BMCS-REPORTED TRUCK ACCIDENTS BY TRUCK CONFIGURATION, 1984–1985

	Accidents Involving Trucks Not Carrying Hazmat		Accidents Involving Trucks Carrying Hazmat						Probability of a Hazmat Release Given an Accident
			Combined		No Release		Hazmat Release		
Truck Configuration	No.	%	No.	%	No.	%	No.	%	(%)
Single-unit	6,861	(9.6)	350	(9.5)	311	(9.8)	39	(7.5)	11.1
Single-trailer combination	57,603	(80.9)	2,886	(77.9)	2,460	(77.3)	426	(81.9)	14.8
Double-trailer combination	3,079	(4.3)	278	(7.5)	253	(7.9)	25	(4.8)	9.0
Triple-trailer combination	53	(0.1)	10	(0.3)	10	(0.3)	0	(0.0)	0.0
Truck trailer	423	(0.6)	118	(3.2)	93	(2.9)	25	(4.8)	21.2
Bobtail	2,796	(3.9)	42	(1.1)	40	(1.3)	2	(0.4)	4.8
Other	349	(0.5)	19	(0.5)	16	(0.5)	3	(0.6)	15.8
TOTAL	71,164		3,703		3,183		520		14.0

Type of Cargo Involved

Table 8 presents the frequency distribution of BMCS-reported accidents by type of cargo involved (hazardous or otherwise). The table indicates quite a distinct difference in the distribution of cargo types for hazmat-carrying trucks and trucks in general. Trucks carrying liquids in bulk constitute 50 percent of accidents involving hazmat-carrying trucks, but only 2 percent of all other truck accidents. The predominance of tank trucks carrying bulk liquids represents a major difference in exposure between hazmat trucking and other forms of trucking.

The data in Table 8 show that liquid tankers (19 percent of releases) are slightly more likely than average to release their cargo in a traffic accident; and releases in the 40 accidents involving trucks transporting bulk solids occurred two times more often than average (30 percent of releases). On the other hand, trucks transporting gases in bulk, explosives, and hazardous materials in general freight are less likely than average to release their cargo in a traffic accident.

Consequences of Accidents

Table 9 summarizes the consequences of the BMCS-reported accidents, and refers to all deaths, injuries, and property damage resulting from the accident. Unlike the consequences reported for hazmat incidents, these consequences are not necessarily the result of a hazmat release. It should be noted in Table 9 that accidents involving hazmat-carrying vehicles tend to involve slightly greater consequences than truck accidents in general. Accidents in which a hazmat release occurs clearly involve more deaths, more injuries, and more property damage than accidents in which there is no release. The greater consequences when a release occurs may be due in part to the consequences of the release, but also indicate that the accident involved higher speeds or greater collision forces than other accidents, which in turn may cause both the hazmat release and the higher damages.

Table 10 summarizes the distribution of the BMCS truck accident data by accident severity levels. The table shows that a hazmat release is more likely in fatal and injury accidents than in property-damage-only accidents, undoubtedly because of the greater forces involved. It is important to note that 83 percent of the fatalities and 85 percent of the injuries in accidents involving hazmat-carrying trucks occur in accidents in which there is no hazmat release. A comparison of all cases common to both the BMCS and RSPA files provides insight into the cause of injuries and fatalities in accidents in which a release occurs.

The 130 cases common to both files in 1983 (i.e., accidents with releases) involved 10 fatalities and 109 injuries. How-

TABLE 7 DISTRIBUTION OF BMCS-REPORTED TRUCK ACCIDENTS BY CARGO AREA CONFIGURATION FOR SINGLE-TRAILER COMBINATION TRUCKS, 1984–1985

Configuration	Accidents Involving Trucks Not Carrying Hazmat		Accidents Involving Trucks Carrying Hazmat						Probability of a Hazmat Release Given an Accident (%)
			Combined		No Release		Hazmat Release		
	No.	%	No.	%	No.	%	No.	%	
Van	30,349	(64.3)	621	(24.5)	557	(26.0)	64	(16.6)	10.3
Flatbed	7,890	(16.7)	70	(2.8)	60	(2.8)	10	(2.6)	14.3
Tank	3,389	(7.2)	1,764	(69.7)	1,470	(68.5)	294	(76.4)	16.6
Other	5,597	(11.8)	76	(3.0)	59	(2.7)	17	(4.4)	22.4
TOTAL	47,225		2,531		2,146		385		15.2

Note: Cargo area configuration missing for 17.8% of accidents.

TABLE 8 DISTRIBUTION OF BMCS-REPORTED TRUCK ACCIDENTS BY CARGO TYPE, 1984–1985

Cargo Type	Accidents Involving Trucks Not Carrying Hazmat		Accidents Involving Trucks Carrying Hazmat						Probability of a Hazmat Release Given an Accident (%)
			Combined		No Release		Hazmat Release		
	No.	%	No.	%	No.	%	No.	%	
General freight	23,651	(33.7)	741	(20.1)	680	(21.4)	61	(11.8)	8.2
Gases in bulk	42	(0.1)	259	(7.0)	238	(7.5)	21	(4.1)	8.1
Solids in bulk	1,310	(1.9)	40	(1.1)	28	(0.9)	12	(2.3)	30.0
Liquids in bulk	1,618	(2.3)	1,831	(49.6)	1,486	(46.8)	345	(66.6)	18.8
Explosives	12	(0.1)	70	(1.9)	63	(2.0)	7	(1.4)	10.0
Empty	15,989	(22.8)	220	(6.0)	210	(6.6)	10	(1.9)	4.5
Other	27,478	(39.2)	529	(14.3)	467	(14.7)	62	(12.0)	11.7
TOTAL	70,100		3,690		3,172		518		14.0

TABLE 9 SUMMARY OF CONSEQUENCES OF BMCS-REPORTED TRUCK ACCIDENTS, 1984–1985

	Trucks Not Carrying Hazmat	Trucks Carrying Hazmat		
		Total	No Release	Hazmat Release
No. of accidents	71,164	3,703	3,183	520
No. of deaths	4,994	326	273	53
Deaths per accident	0.070	0.088	0.086	0.102
No. of injuries	54,522	2,955	2,514	441
Injuries per accident	0.77	0.80	0.79	0.85
Total property damage ($)	743,643,000	56,927,000	39,609,000	17,318,000
Property damage per accident ($)	10,450	15,373	12,444	33,304

TABLE 10 DISTRIBUTION OF BMCS-REPORTED TRUCK ACCIDENTS BY ACCIDENT SEVERITY, 1984–1985

	Accidents Involving Trucks Not Carrying Hazmat		Accidents Involving Trucks Carrying Hazmat						Probability of a Hazmat Release Given an Accident
			Combined		No Release		Hazmat Release		
Accident Severity	No.	%	No.	%	No.	%	No.	%	(%)
Fatal	4,034	(5.7)	265	(7.2)	221	(6.9)	44	(8.5)	16.6
Injury	33,569	(47.2)	1,777	(48.0)	1,493	(46.9)	284	(54.6)	16.0
Property-damage-only	33,561	(47.2)	1,661	(44.9)	1,469	(46.2)	192	(36.9)	11.6
TOTAL	71,164		3,703		3,183		520		14.0

ever, only two of these fatalities and four of these injuries had causes that were attributed to the release (by being reported on the RSPA form). Although the size of the accident sample, particularly that of the sample involving fatalities, is small, this result suggests that, in accidents in which a release occurs, about 80 percent of the fatalities and 95 percent of the injuries are not directly attributable to the release. Thus, traditional accident causes, and not the properties of the hazardous material transported, may be responsible for the vast majority of the fatalities and injuries in accidents involving hazmat-carrying trucks.

Combining the above estimate with the previously noted finding that, for release events, approximately 90 percent of deaths and 25 percent of injuries were attributable to traffic accidents, the estimates of the distribution of fatalities and injuries shown in Figure 1 can be derived. The dominant role of traffic accidents is clearly shown through the estimate that roughly 96 percent of all fatalities and 97 percent of all injuries involving trucks transporting hazardous materials resulted from traffic accidents in which no release occurred. It is important to note, however, that one major disaster involving numerous fatalities or injuries as a result of a release could greatly alter these estimates. The concern over such possibilities, along with the potential for major evacuations or route closures is, in fact, the key reason for interest in hazardous materials transportation as a separate highway safety issue.

STATE ACCIDENT DATA

The discussion of the BMCS accident data base indicates that the highway-related variables found there, including highway type (number of lanes, divided or undivided, access control) and area type (urban or rural), are generally inaccurate, incomplete, or unavailable. Therefore, alternative sources for these data elements in state accident data were investigated.

A review of the NHTSA publication *State Accident Report Forms Catalogue 1985* (*14*) indicates that the police accident report forms of 15 states indicate whether hazmat-carrying vehicles were involved in each reported accident. These states are Alabama, California, Florida, Illinois, Kansas, Louisiana, Maine, Minnesota, Missouri, New Hampshire, New York, Ohio, Pennsylvania, South Carolina, and Wyoming. In 13 of these states, the police report forms clearly distinguish which of the accident-involved vehicles was carrying hazardous materials. However, only three of these states (Louisiana, Missouri, and Wyoming) make it possible to determine whether a hazmat release had occurred. Supplementary analyses of hazmat accident characteristics were conducted with accident data from Missouri.

Missouri Accident Data

Since July 1, 1984, police-reported accidents in Missouri have included data identifying whether each vehicle involved in an accident was carrying hazardous materials, what type of hazardous materials was being carried, and whether a hazmat release had occurred. The Missouri data include all accidents investigated by police agencies in the state, not just those voluntarily reported by carriers—an advantage over the BMCS data. The Missouri data also include accidents for all types of trucks and all types of carriers, not just regulated interstate carriers. In addition, each accident was investigated by a police officer. While the experience and training of police officers vary widely, police officers generally are expected to have more training and experience in accident investigation and would use the accident reporting form with greater consistency than the individual motor carriers who report accidents to BMCS. However, it should be noted that accident data based on police reports are subject to the same types of underreporting biases as carrier-reported data, although perhaps not to the same extent.

The property-damage threshold for reporting accidents in Missouri is $500, which is substantially lower than the $2,000 threshold used by BMCS. Thus, the Missouri data may contain a greater proportion of property-damage-only accidents. On the other hand, Missouri, as do most states, classifies accidents involving Type C injuries (no visible injury) as injury accidents. BMCS classifies an accident as an injury accident only if a person receives medical treatment away from the scene. Therefore, the proportion of injury accidents in the Missouri data would also be expected to increase for this reason.

Approximately 200 accidents occurred in Missouri involving hazmat-carrying vehicles in both 1985 and 1986. About 13 percent of these Missouri accidents resulted in a hazmat release, which agrees with the percentage in the BMCS data for the entire United States (15 percent). Many of the analyses performed for the nationwide BMCS data were repeated for the Missouri data. The results of the Missouri analyses generally agree with the results obtained from BMCS analysis, given the smaller sample size of Missouri accidents.

Highway-Related Factors

No variable is available for the Missouri accident data that explicitly identifies the type of highway (number of lanes, divided or undivided, freeway or nonfreeway) on which each accident occurred. The highway class is a useful surrogate for highway type. Table 11 presents the distribution of the Missouri hazmat accident data by highway class.

Table 11 indicates that all of the highway classes described previously experience a substantial proportion of hazmat accidents. The probability of a hazmat release, given an accident, is highest on the U.S. and state routes and county roads (primarily rural) and lowest on city streets.

Table 12 confirms the importance of area type (urban or rural) in predicting the probability of a hazmat release. These are nearly equal numbers of accidents in urban and rural areas in Missouri, but rural accidents are approximately three times as likely to result in a hazmat release. The greater likelihood of a hazmat release in rural accidents undoubtedly results from the higher speeds involved (and, thus, the higher forces generated in accident situations), but could also relate to the types of accidents that occur, the types of cargos transported, and the types of trucks used.

Similar findings are also evident in Table 13, which presents the distribution of hazmat accidents in Missouri by speed limit. The table demonstrates that the probability of a hazmat release given an accident is highest on highways with speed limits of 45 mph or more.

TABLE 11 DISTRIBUTION OF POLICE-REPORTED HAZMAT ACCIDENTS IN MISSOURI BY HIGHWAY CLASS, 1985–1986

	Accidents Involving Trucks Carrying Hazmat						
	Combined		No Release		Hazmat Release		Probability of a Hazmat Release Given an Accident (%)
Highway Class	No.	%	No.	%	No.	%	
Interstate	96	(23.1)	82	(22.6)	14	(26.4)	14.6
U.S. or state route	145	(34.9)	121	(33.3)	24	(45.3)	16.6
Supplementary or county road	55	(13.2)	46	(12.7)	9	(17.0)	16.4
City street	118	(28.4)	113	(31.1)	5	(9.4)	4.2
Other	2	(0.5)	1	(0.3)	1	(1.9)	50.0
Total	416		363		53		12.7

TABLE 12 DISTRIBUTION OF POLICE-REPORTED HAZMAT ACCIDENTS IN MISSOURI BY AREA TYPE, 1985–1986

	Accidents Involving Trucks Carrying Hazmat						
	Combined		No Release		Hazmat Release		Probability of a Hazmat Release Given an Accident (%)
Area Type	No.	%	No.	%	No.	%	
Urban	210	(50.5)	197	(54.3)	13	(24.5)	6.2
Rural	206	(49.5)	166	(45.7)	40	(75.5)	19.4
Total	416		363		53		12.7

TABLE 13 DISTRIBUTION OF POLICE-REPORTED HAZMAT ACCIDENTS IN MISSOURI BY SPEED LIMIT, 1985–1986

	Accidents Involving Trucks Carrying Hazmat						
	Combined		No Release		Hazmat Release		Probability of a Hazmat Release Given an Accident (%)
Speed Limit (mph)	No.	%	No.	%	No.	%	
≤ 25	60	(14.7)	59	(16.5)	1	(1.9)	1.7
30	35	(8.6)	32	(9.0)	3	(5.8)	8.6
35	65	(15.9)	59	(16.5)	6	(11.5)	9.2
40	26	(6.4)	24	(6.7)	2	(3.8)	7.7
45	21	(5.1)	17	(4.8)	4	(7.7)	19.0
50	2	(0.5)	2	(0.6)	0	(0.0)	0.0
55	200	(48.9)	164	(45.9)	36	(69.2)	18.0
Total	409		357		52		12.7

NOTE: All data were collected before increase in Interstate highway speed limit to 65 mph for passenger cars and 60 mph for trucks in May 1987.

CONCLUSIONS

Existing accident and incident data bases provide insight into the nature of on-highway safety risks in hazmat transportation by highway. The following conclusions were drawn from analysis of these data bases:

Fatalities and Injuries

Approximately 99 percent of all fatalities and 96 percent of all injuries involving trucks carrying hazardous materials are not related to hazmat releases. Of the small remaining fraction of fatalities and injuries associated with releases, more fatalities occurred in releases caused by traffic accidents than in releases from other causes. For injuries, the reverse was found—more injuries were due to releases not caused by traffic accidents. It is important to note that one major disaster involving a release could greatly alter these distributions in any given year and, in fact, this concern is the reason that hazardous materials transportation is a separate highway safety issue.

Hazmat Incidents

Approximately 11 percent of hazmat incidents that occur on public highways is caused by traffic accidents. This estimate of the proportion of incidents caused by traffic accidents is higher than found in previous studies, because incidents that occur off the highway in terminals, yards, and loading areas have been eliminated.

About 90 percent of the deaths and 25 percent of the injuries resulting from hazmat releases were caused by traffic accidents. Between 35 and 68 percent of severe hazmat incidents are caused by traffic accidents, depending on the definition adopted for a severe incident. Thus, traffic accidents are far more likely to result in a severe incident than other causes.

Traffic Accidents Involving Hazmat-Carrying Trucks

Approximately 99 percent of the fatalities and injuries in accidents involving trucks carrying hazardous materials result from the physical collision itself, rather than the hazardous materials being transported. Approximately 13 to 15 percent of accidents involving hazmat-carrying trucks result in a hazmat release.

Higher than average probabilities of a hazmat release are found in traffic accidents involving the following:

- Truck-train accidents at railroad-highway grade crossings (45 percent release probability, based on 22 accidents).
- Freeway off-ramps (26 percent release probability).
- Freeway on-ramps (22 percent release probability).
- Overturning in a single-vehicle accident (38 percent release probability).
- Running off the road in a single-vehicle accident (33 percent release probability).
- Highways with speed limits of 45 mph or more (18 percent release probability).
- Trucks transporting solids in bulk (30 percent release probability, based on 40 accidents).

Lower than average probabilities of a hazmat release are found in traffic accidents involving:

- At-grade intersections (4 percent release probability).
- Truck collisions with parked vehicles (3 percent release probability).
- Truck collisions with pedestrians, bicyclists, and animals (2 percent release probability).
- Truck collisions with passenger cars (4 percent release probability).
- Truck collisions with other trucks (9 percent release probability).

Trucks carrying liquids in bulk constitute 50 percent of accident involvements for hazmat-carrying trucks and 2 percent of accidents for other trucks. This large difference is indicative of a major difference in tank truck exposure between hazmat and other trucking.

Data Sources

A number of states have added a data element indicating the presence or absence of hazardous materials to their police traffic accident report forms. At present, most of these state forms do not also note whether the hazardous material was released as a result of the reported accident. In truck accident analyses, it cannot be presumed that any fatalities and injuries that occur are related to the presence of hazardous materials because releases occur in only 15 percent of accidents and the probability of a release varies widely between accident types. Thus, accident report forms should also include a data element indicating whether a hazmat release occurred.

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The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of the FHWA.

Minimizing Derailments of Railcars Carrying Dangerous Commodities Through Effective Marshaling Strategies

F. F. SACCOMANNO AND S. EL-HAGE

Effective marshaling and buffering strategies can reduce the likelihood of special dangerous commodity (SDC) cars being involved in a train derailment. The objective of these strategies should be to minimize the probability that an SDC car is located in a potential derailment block, subject to external rail corridor characteristics that affect derailments. A procedure is developed for predicting derailments for different railcar positions in a train, on the basis of the point of derailment and the number of cars involved. The number of cars involved in each derailment is assumed to be a function of the train operating speed, the cause of derailment, and the number of cars following the point of derailment. Canadian rail accident data for the period 1980–1985 are used to calibrate a probabilistic expression of number of cars involved in derailments. The Canadian accident data base is also used to estimate point-of-derailment probabilities for different railcar positions and derailment causes. Alternative marshaling and buffering strategies for SDC railcars are evaluated using a combinatorial approach. The results of this analysis indicate that SDC car derailments can be reduced appreciably by considering the derailment potential of different positions along a train for various rail corridor conditions.

Prior to 1987, all train accidents in Canada with consequent damages exceeding $750 were reported to the Canadian Transport Commission (*1*). For the period 1980–85, approximately 75 percent of these reported train accidents involved one or more car derailments. More than 7 percent of railcar derailments that occurred between 1980 and 1985 involved some type of special dangerous commodity (SDC). Commodities that are especially hazardous to population and environment (such as toxic substances, corrosives, flammables, radioactive materials, and explosives) have been designated as SDCs by Transport Canada (*2*).

Recognizing that railcars carrying SDCs are more apt to cause greater damage in a derailment situation, the focus of this paper is to apply efficient marshaling and buffering regulations so as to minimize the likelihood that these SDC cars will be involved in a potential derailment block.

A report prepared by A. D. Little (*3*) for the U.S. Department of Transportation suggested that the position of a railcar in the train is a major factor determining its involvement in a derailment situation. Swoveland (*4*) has suggested that the involvement of dangerous commodities in accidents can be reduced through appropriate marshaling and buffering strategies that take into account train derailment profiles on the basis of car position.

OBJECTIVES OF THIS STUDY

Although it is known that the position of cars in a train can influence their involvement in a derailment, the specific nature of this relationship is not well understood. This paper presents a procedure for establishing and evaluating the effectiveness of alternative marshaling and buffering strategies for positioning SDC cars in a given train consist.

The specific objectives of this study are threefold:

1. Establish railcar derailment profiles for different positions in the train on the basis of the point of derailment (POD) and the number of cars involved.
2. Identify critical positions on a train assigned to designated classes of SDC cars for different train consists and marshaling and buffering regulations.
3. For different train derailment causes, evaluate the effectiveness of selected marshaling/buffering regulations in terms of reduced SDC car derailments.

APPROACH AND SOURCES OF DATA

In this section, the major components of a model for predicting derailments by position in the train are described, and the data base used in calibrating derailment expressions is introduced.

Model Framework

As illustrated in Figure 1, this study consists of two major phases:

1. Establishment of derailment profiles for railcars on the basis of position, and
2. Evaluation of alternative marshaling and buffering strategies.

Derailment profiles for railcars on the basis of position in the train are affected by two conditions: the position at which a

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derailment is initiated and the number of cars derailing thereafter. The probability that a railcar in the *i*th position will derail, given that the train is involved in a derailment, can be expressed as

$$P_d(i) = \sum_{k=1}^{i} P_{od}(k) * \sum_{x=i-k+1}^{n-k+1} P(x) \qquad (1)$$

where

$P_{od}(k)$ = probability that the derailment starts at the *k*th position, and

$P(x)$ = probability that exactly x cars will derail.

Equation 1 assumes that a train derailment has already occurred. The term $P_{od}(k)$ for the POD is obtained from an analysis of Canadian rail accident statistics. In this study, the POD was found to be affected by the cause of the derailment and the operating speed of the train. The term $P(x)$, reflecting the number of cars involved in a derailment, is obtained by calibrating a probabilistic model, where the number of cars derailing was found to be a function of operating train speed, cause of derailment, and train length. The results of these model calibrations will be discussed later.

The involvement of SDC cars in a derailment block depends on the probability that certain positions in the train are subject to derailment and the probability that SDC cars have been marshaled into a potential derailment block.

Within the context of this paper, the term marshaling refers to the positioning of designated SDC car blocks along a given train length. Table 1 summarizes the current CTC regulations concerning the marshaling of SDC cars in a conventional train consist. In general, a five-car, non-SDC buffer is provided between any SDC block and inhabited sections of the train (i.e., locomotives at the front of the train and cabooses at the rear). Blocks of SDC cars with incompatible properties are separated by additional five-car buffers. SDC materials having similar damage properties can be marshaled into the same block.

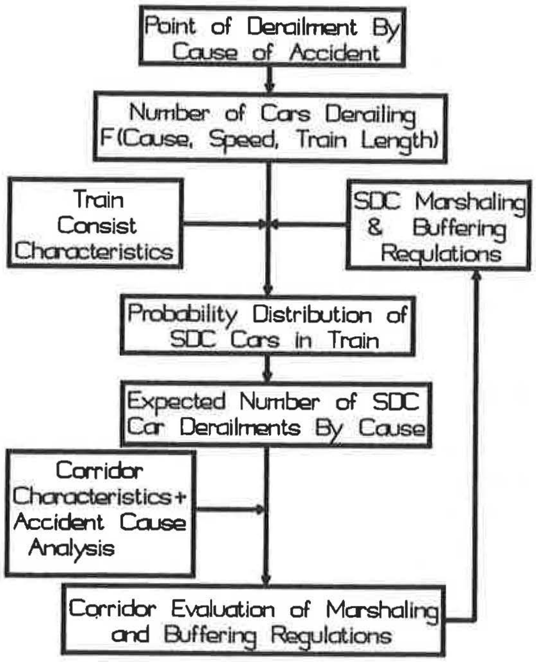

FIGURE 1 Model framework.

The number and mix of SDC cars assigned to a given train will affect the number and length of SDC blocks in a train. For example, all cars carrying liquefied chlorine gas would be marshaled into a single block. This block may contain non-SDC cars or cars carrying materials that are compatible with chlorine (i.e., similar toxic properties).

In this study, noncritical car buffers can be varied depending on the extent of material incompatibility among neighboring blocks. Incompatibility refers to the situation in which a given material can aggravate the damage potential of another material in an accident situation. An example of this is placing an explosive block adjacent to a highly toxic block. Marshaling regulations for critical SDC car blocks are established exogenously to the model.

Data Sources

The calibration of derailment models in this study is based on rail accident data reported to the Canadian Transport Commission. The CTC data base includes 6,739 train accidents for the two national railways (Canadian National and Canadian Pacific rail) for the period 1980–85. The CTC file provides information on mainline and rail yard accident location, subdivision and milepost location, primary cause of each accident, POD, position on the train where derailment occurred, number of cars involved, and total number of cars in the train.

Although the presence of SDC cars in the derailment block is noted in the CTC data base, the actual number of SDC cars involved in a derailment is not specified. All cars that are not carrying SDCs are available to serve as buffers. Where the requirement for buffer cars in a train exceeds the number of non-SDC cars available, empty cars must be added to each train consist.

The CTC accident data base classifies train accidents by primary and secondary causes for derailments and/or collision accidents, on the basis of FRA cause codes. Table 2 summarizes the FRA causes used in this study.

CALIBRATION OF DERAILMENT EXPRESSIONS

In this section, the calibration results for the POD and number of cars involved are presented.

Point of Derailment

The inclusion of a given car in a derailment block affects its position with respect to the POD. More distant positions from the POD are less likely to be involved in a derailment chain reaction.

In this study, the POD was found to be affected by the primary cause of derailment. Logically, causes that are track and roadbed related (for example, rail and joint bar faults, frogs, and switch defects) generally affect the front of the train, because the front cars initially impinge on these faults, producing the derailment. On the other hand, general car

TABLE 1 POSITION IN FREIGHT OR MIXED TRAIN OF CARS CONTAINING DANGEROUS COMMODITIES (CURRENT REGULATIONS)

1	2	3	4	5	6	7	8	9	10	11	12	13
The letter "X" at an intersection of horizontal and vertical columns means that the wording on the top applies for the considered group		When train length permit must not be nearer than 6th from engine, occupied caboose, or occupied car	When train length does not permit must be near middle of train but not nearer than 2nd from engine, occupied caboose, or occupied car	---- MUST NOT BE PLACED NEXT TO ----								
				Car in Placarded Group.				ENGINE	CABOOSE	Open-top car when lading protrudes beyond car or when lading above car end is liable to shift	Any car piggyback on container with automatic heating or refrigeration, lighted heaters, stoves, lanterns, or internal combustion engines	Loaded flat car
Type of Car	Placard group			1	2	3	4					
ANY CAR	Group 1	X	X		X	X	X	X	X	X	X	X
TANK CAR	Group 2	X	X	X		X	X	X(*)	X(*)	X	X (*)	X (+)
ALL OTHER	Group 2			X		X	X					
TANK CAR	Group 3	X	X	X	X		X	X	X	X	X	X (+)
ALL OTHER	Group 3			X	X		X	X	X	X	X	X
ANY CAR	Group 4			X	X	X		X	X			
TANK CAR	Group 5							X(*)	X(*)			

FOOTNOTES : (*) Except when train consists only of placarded tank cars.

(+) Except trailer-on-flat-car, container-on-flat-car, tri-level and bi-level cars and any other car specially equipped with tie down devices for handling vehicles. Permanent end bulk head flat cars considered the same as an open-top car, (Column 13).

PLACARD GROUP:

1. Group 1 consists of Explosives 1.1 and 1.2.
2. Grou 2 consists of Explosives 1.3, 1.4, 1.5; Flammable Gases 2.1;Non Flammable Gases 2.2; Poison Gases 2.3; Flammable Solids 4.1,4.2,4.3; Oxidizers 5.1,5.2; Poisons 6.1,6.2 and corrosives.
3. Group 3 consists of special commodities of the division 2.3.
4. Group 4 consists of Radioactive materials.
5. Group 5 consists of Flammable liquids 3.3 and "Empty Placarded cars"

TABLE 2 FEDERAL RAILROAD ADMINISTRATION CODES OF DERAILMENT CAUSES

CODE	CAUSE OF DERAILMENT	FRA CAUSE CODES
1.1	ROADBED DEFECTS	101,102,110,709,710,715
1.2	TRACK GEOMETRY DEFECTS	110 --> 129
1.3	RAIL & JOINT BAR DEFECTS	130 --> 153
1.4	FROGS, SWITCHES, & TRACK APPLIANCES	160 --> 189 ; 560 --> 569
2.1	GENERAL CAR DEFECTS (MECHANICAL & ELECTRICAL)	400 --> 449 ; 470 --> 499
2.2	AXLES & JOURNAL BEARINGS & DEFECTIVE WHEELS	450 --> 459
3.0	MISCELLANEOUS, OPERATIONS & OTHER CAUSES	500 --> 559 ; 570 --> 708 711 --> 714 ; 716 --> 999

defects (such as wheel, axle, and journal faults) are more randomly distributed throughout the train, as is the resultant POD.

As illustrated in Figure 2, derailments in the CTC data base reflect trains of varying lengths and number of cars. Positions near the front of the train are more represented in the train length distribution than positions nearer to the rear of the train. For example, Positions 1–10 are represented in both a 10- and 20-car train, but positions 11–20 are only represented in the 20-car train. As a result, it becomes necessary to normalize the POD for each train accident with respect to the front of the train. In this study, the normalized point of derailment (NPOD) is expressed as the ratio of the actual position at which derailment takes place (the POD) to the total number of cars in the train.

The NPOD may fail to reflect differences in stability for trains of varying lengths. For example, the 50th percentile position on a 100-car train is subject to different dynamic forces than the 50th percentile position on a 10-car train. The latter position occurs near the front and is more prone to derail, while the former is nearer the middle section, which under certain conditions might be less likely to derail. Because the NPOD treats both cases equally, it is important to test for the effect of train length on the car position where the derailment is initiated.

In this study, the NPOD was estimated for trains of varying lengths (total number of cars) to account for the effect of the absolute car position on dynamic forces in a derailment situation. Figure 2 indicates the presence of two basic groupings of train length in the CTC accident data base: less than or equal to 50 cars, and 50 cars or more. Within each grouping, the POD was normalized and classified according to primary cause of derailment. The results are summarized in Table 3.

A two-way analysis of variance was applied to assess the effects of cause and train length class on the NPOD. From these results, it is apparent that the cause of derailment alone explains most of the variations in the observed NPOD from the data. The two categories of train length (less than or equal to 50 cars, and more than 50 cars) do not have a statistically significant effect on the NPOD. These results suggest that the total number of cars in the train consist can be ignored in estimating the NPOD point.

Figure 3 illustrates the POD probabilities for different normalized positions along the train consist for two derailment causes: (a) roadbed defects and (b) wheel, axle, and journal failures. In the figure, the number above every train section represents the probability of a derailment starting within that section of the train, given that a derailment had occurred on the train.

Number of Cars Derailing

Adopting a nonlinear regression approach, A. D. Little (*3*) suggested that the number of cars involved in a train derailment was a function of train operating speed. Using U.S. accident data for 1975–78, two expressions were calibrated for the mean (N) and standard deviation (SD) of number of cars derailing, such that

$$N = bV^a \quad (2)$$

$$SD = cV^d \quad (3)$$

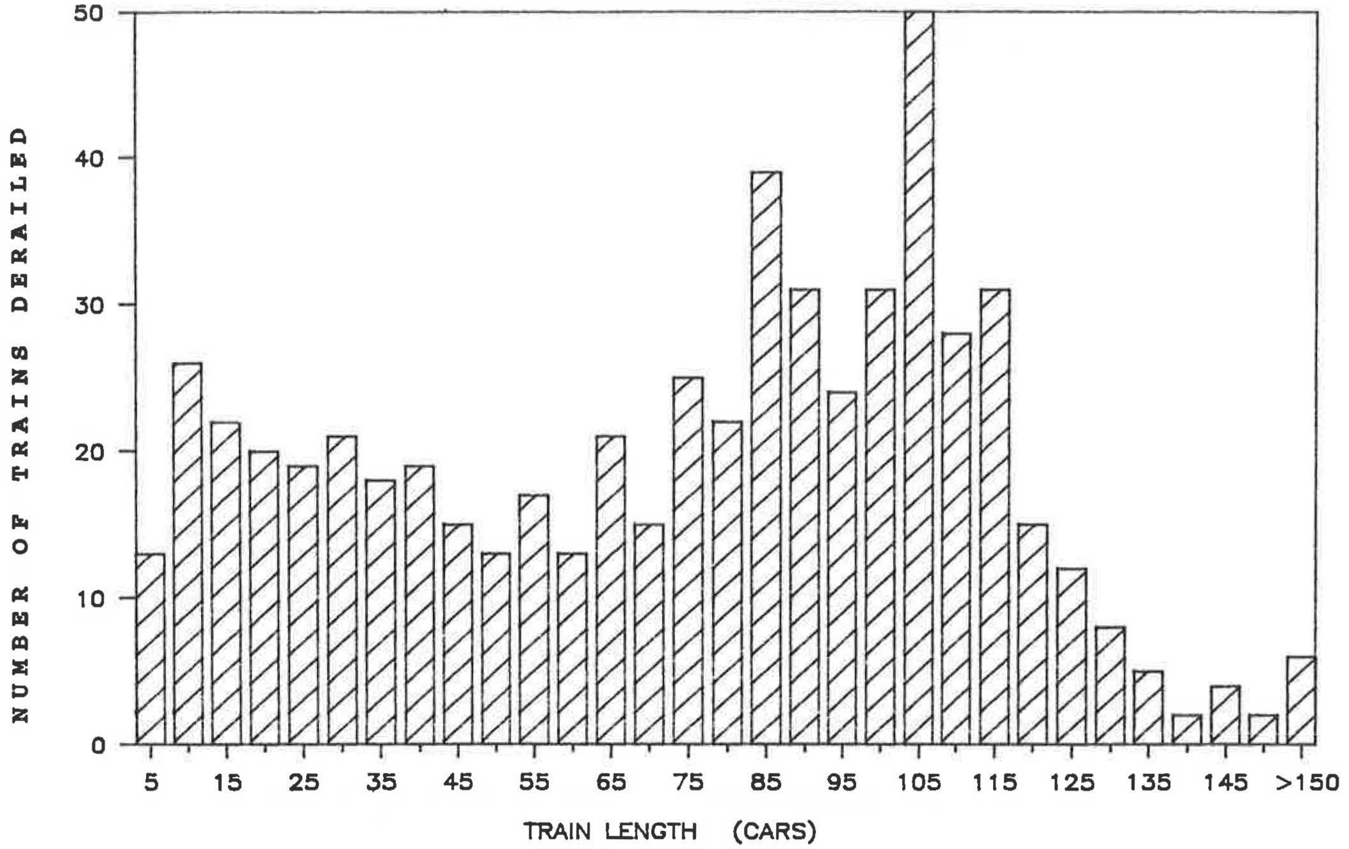

FIGURE 2 Train length distribution (CTC accident data 1980–1985).

where *a, b, c,* and *d* are regression coefficients and *V* is the train operating speed in miles per hour.

Although the number of cars derailing in an accident was assumed to be solely dependent on speed, the Little study found that the results of the model calibration were statistically significant only for trains with more than 25 cars. Even for these trains, the regression did not yield a good fit to the observed data.

The Little expressions (Equations 2 and 3) have been recalibrated using the CTC train derailment data for 1980–85. The expression for the mean cars derailing explained 19.0 percent of the variance in the observed data. An analysis of residuals indicated significant fluctuations in the observed car derailments about the fitted curve. A significant drop in the mean cars derailing was observed for the speed range 56–60 mph in both the Little report and the CTC recalibration exercise. While the Little report argued that this distortion is essentially statistical and can be ignored, it is apparent from these results that other factors beside speed may be affecting the number of cars derailing in a train accident.

In this study, the cause of derailment and the number of cars in the train are assumed to affect the number of cars derailing. Yang (*5*) demonstrated that the forces generated during certain types of derailments are conceivably localized (affecting only a limited section of the train especially at lower speeds), and under these conditions, fewer cars are likely to derail. Furthermore, the number of cars derailing is affected by the POD along the train. Train derailments usually reflect a chain reaction involving cars behind the POD. Accordingly, more cars are likely to be involved following a front section derailment because more cars are available in the trailing section of the derailment block.

Table 4 summarizes the number of cars derailing, on the basis of cause of derailment and speed. Three speed classes were used in this analysis, 0–20 mph, 20–30 mph, and more than 30 mph. A two-way analysis of variance suggests that these factors explain a significant amount of variation in the number of cars derailing. For each cause of derailment, the mean number of cars derailing increases exponentially with train operating speed.

Figure 4 illustrates the frequencies of cars derailing by position for the two derailment causes (roadbed defects and wheel, axle, and journal failures). From Figure 4, it can be seen that the probability distribution of the number of cars derailing is a negative exponential function with a sharp peaking effect for the one- and two-car intervals.

The effect of the total number of cars in the train on the number of cars derailing is demonstrated with reference to Figure 5. The mean number of cars derailing increases exponentially with the residual train length, where the residual train length is expressed as the number of cars from the POD to the end of the train. A function of the form

$$\text{Mean Cars Derailing} = A * (\text{Residual Length})^{B} \qquad (4)$$

was fitted to these observations, with the coefficients A = 1.241 (T-value = 3.240) and B = 0.463 (T-value = 6.013). The results of this calibration were statistically significant,

TABLE 3 STATISTICAL SUMMARY FOR NORMALIZED POINT OF DERAILMENT

CAUSE OF DERAILMENT		TRAIN LENGTH < 50 CARS	TRAIN LENGTH > 50 CARS	ALL TRAINS
ROADBED DEFECTS	COUNT	28	22	50
	MEAN	0.371	0.420	0.392
	ST.DEV.	0.313	0.347	0.326
TRACK GEOMETRY DEFECTS		31	62	93
		0.585	0.607	0.600
		0.246	0.266	0.259
RAIL & JOINT BAR DEFECTS		21	59	80
		0.420	0.497	0.477
		0.262	0.319	0.305
FROGS, SWITCHES, & TRACK APPLIANCES		25	16	41
		0.457	0.323	0.405
		0.284	0.244	0.274
GENERAL CAR DEFECTS (MECHANICAL & ELECTRICAL)		3	44	47
		0.583	0.561	0.562
		0.300	0.263	0.262
AXLES & JOURNAL BEARINGS & DEFECTIVE WHEELS		22	134	156
		0.493	0.491	0.491
		0.280	0.263	0.265
MISCELLANEOUS, OPERATIONS & ALL OTHER CAUSES		21	46	67
		0.544	0.560	0.555
		0.272	0.309	0.296

SOURCE	SUM-SQUARES	DF	MEAN-SQUARE	F-RATIO	P
TRAIN LENGTH	0.000	1	0.000	0.001	0.979
CAUSE OF DERAILMENT	2.104	6	0.351	4.424	0.000
LENGTH*CAUSE	0.299	6	0.050	0.629	0.707
ERROR	41.208	520	0.079		

MULTIPLE R: 0.244

where the residual train length alone explained 10 percent of the variation in the mean cars derailing.

It should be noted that, for train derailments with residual train length of more than 60 cars, the residuals from the above-fitted equation were higher than the other derailments. This is because only a few observed derailments had a residual train length of more than 60 cars.

In this study, the number of cars involved in a derailment is expressed in probabilistic terms on the basis of the geometric distribution. The geometric distribution was assumed to reflect the shape of observed cars derailing as in Figure 4. The probability of x cars derailing in an accident can be expressed as

$$P(x) = p\,(1 - p)^x \tag{5}$$

where $P(x)$ is the probability that x cars will derail, given an accident, and $(1 - p)/p$ is the mean number of cars derailing.

Equation 5 is defined for values of $P(x)$ in the range zero to infinity. In practice, the value of $P(x)$ for a given derailment should be confined to the range of 1 to RL, where RL is the residual number of cars available following the POD. To restrict $P(x)$ to the range of 1 to RL, Equation 5 was modified to yield

$$P(x) = \frac{p\,(1 - p)^{x - 1}}{1 - (1 - p)^{RL}} \tag{6}$$

The mean number of cars derailing can be expressed as

$$U = \frac{1}{p\,[1 - (1 - p)^{RL}]} \tag{7}$$

A logistic function was chosen to evaluate p in terms of train speed (S), cause of derailment (CD), and residual train length (RL), such that

$$p = \frac{e^Z}{(1 + e^Z)} \tag{8}$$

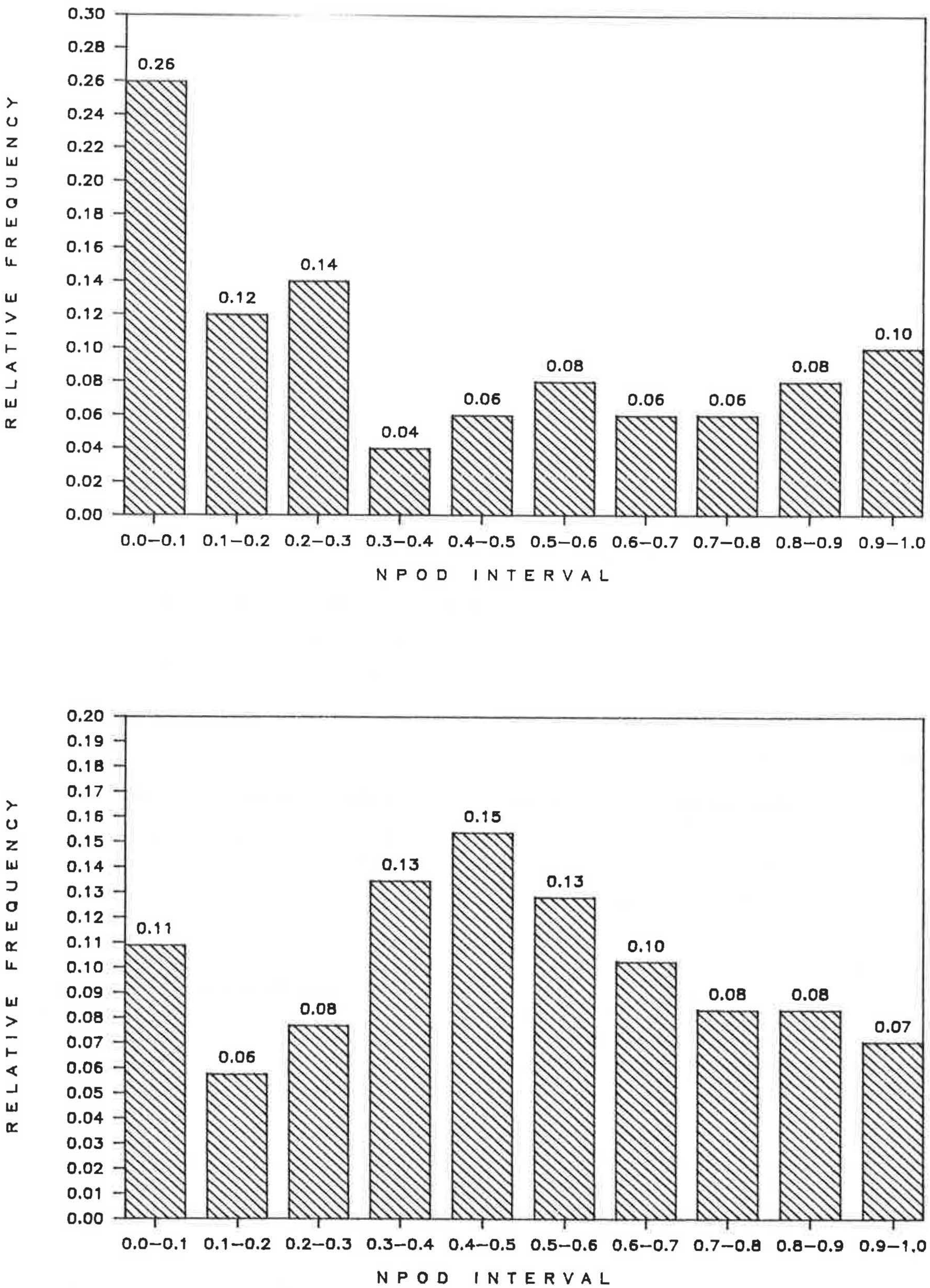

FIGURE 3 **Point of derailment probability distribution; cause of derailment: *top*, roadbed defects; *bottom*, wheel, axle, and journal defects.**

TABLE 4 STATISTICAL SUMMARY FOR NUMBER OF CARS DERAILING BY SPEED AND CAUSE OF DERAILMENT

CAUSE OF DERAILMENT	SPEED 0 TO 20 MPH	SPEED 20 TO 30 MPH	SPEED > 30 MPH	ALL SPEEDS
ROADBED DEFECTS 1.1	30 4.833 3.975	11 8.273 6.482	9 10.222 10.366	50 6.560 6.357
TRACK GEOMETRY 1.2	45 4.267 4.196	28 8.464 6.801	16 13.188 13.172	89 7.191 8.000
RAIL & BAR DEFECTS 1.3	43 7.070 6.442	17 14.000 8.754	23 18.565 12.350	83 11.675 10.133
FROGS & SWITCHES, 1.4	25 3.360 2.481	1 4.000 0.000	2 17.000 5.657	28 4.357 4.407
GENERAL CAR DEFECTS 2.1	13 3.385 3.618	19 3.526 5.243	11 3.545 8.116	43 3.486 5.586
AXLES,WHEELS & JOURNALS 2.2	20 2.450 2.460	26 5.115 9.450	86 4.709 7.614	132 4.447 7.502
ALL OTHER CAUSES 3	28 3.036 2.411	12 5.083 5.712	13 6.077 7.500	53 4.245 4.969
ALL CAUSES	204 4.426 4.458	114 7.289 8.014	160 8.044 10.495	478 6.320 7.946

COUNT
MEAN
ST.DEV.

SOURCE	SUM-SQUARES	DF	MEAN-SQUARE	F-RATIO	PROBABILITY
SPEED	1518.195	2	883.609	17.8832	0.000
CAUSE	4473.604	6	745.601	15.047	0.000
SPEED*CAUSE	1290.904	12	107.508	2.170	0.012
ERROR	28599.832	457	49.551		

and the term, Z, in Equation 8 is a response function of the form:

$$Z = A + B * (S) + C * (CD) + D * (RL). \qquad (9)$$

The parameters (A, B, C, and D) in this response function were calibrated using maximum likelihood techniques. The logistic function (Equation 8) forces the value of p to lie in the range of zero to one.

Table 5 summarizes the results of the calibration exercise. The intercept term "A" of the response function represents the global mean cars derailing in the data base—independent of train speed, cause, or residual train length. In this case, it explains the number of cars derailing in terms of rail and jointbar derailment cause. This was done so as to eliminate redundancy, and thus, no distinctive factor was included for these causes in the response function.

The term "B0" reflects the effect of speed on cars derailing. The negative sign of this parameter indicates that an increase in speed causes a reduction in the response expression Z and a subsequent increase in the number of cars derailing. The term "C0" is also negative, reflecting a positive relationship between the residual train length and the number of cars derailing.

The cause parameters of the response function explain the effect of derailment cause on the number of cars derailing, controlling for speed and residual train length. For example, the term "B5" for journal-related causes reflects the lowest number of cars derailing in an accident situation (highest coefficient).

In general, the values of the cause parameters in the response function agree with the mean number of cars derailing observed in the accident data base (Table 4). For example, rail and jointbar defects exhibit the highest number of cars derailing

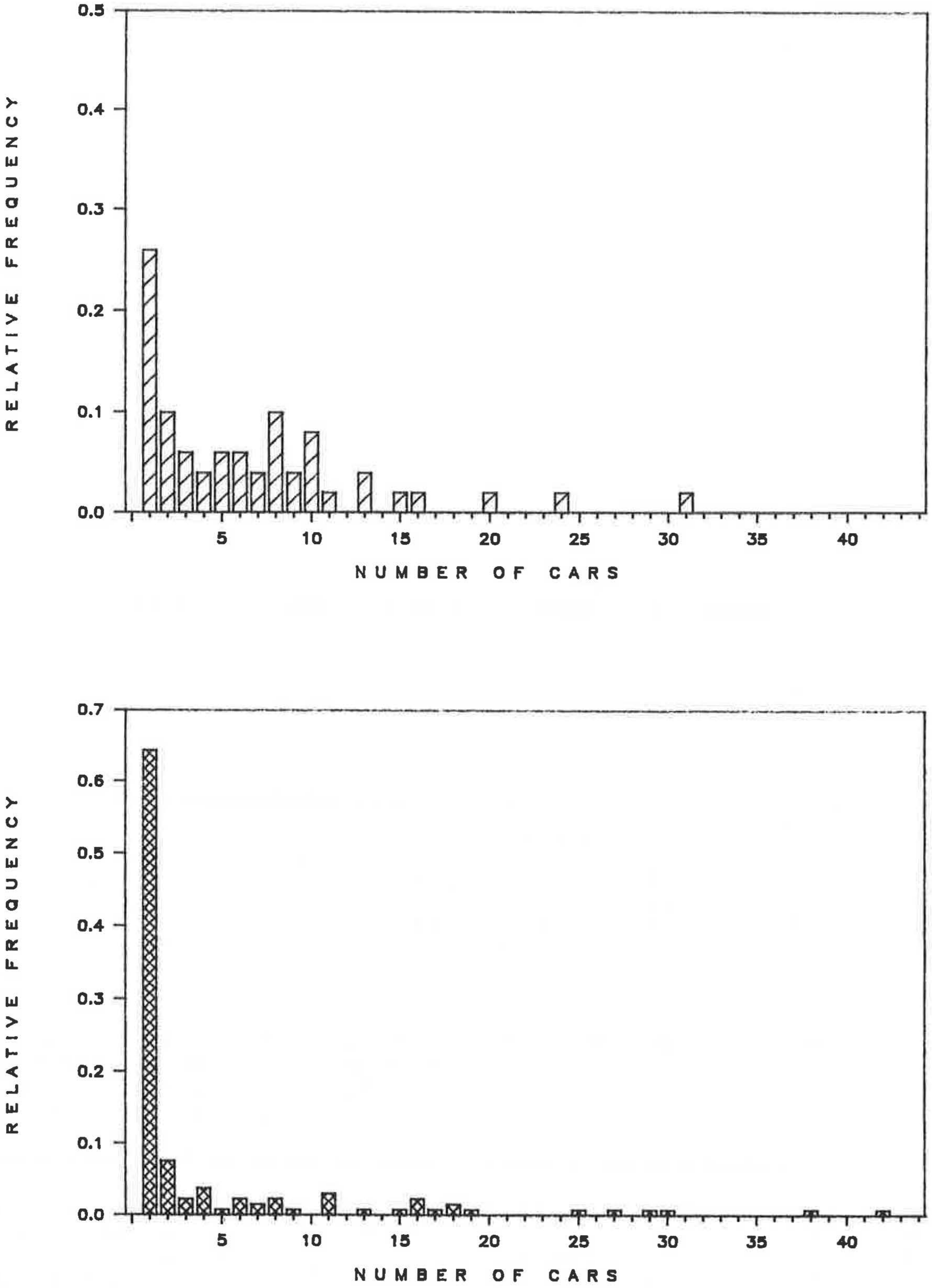

FIGURE 4 Relative frequency histograms for the number of cars derailing, for all speeds and two causes of derailment; *top*, roadbed defects; *bottom*, wheel, axle, and journal defects.

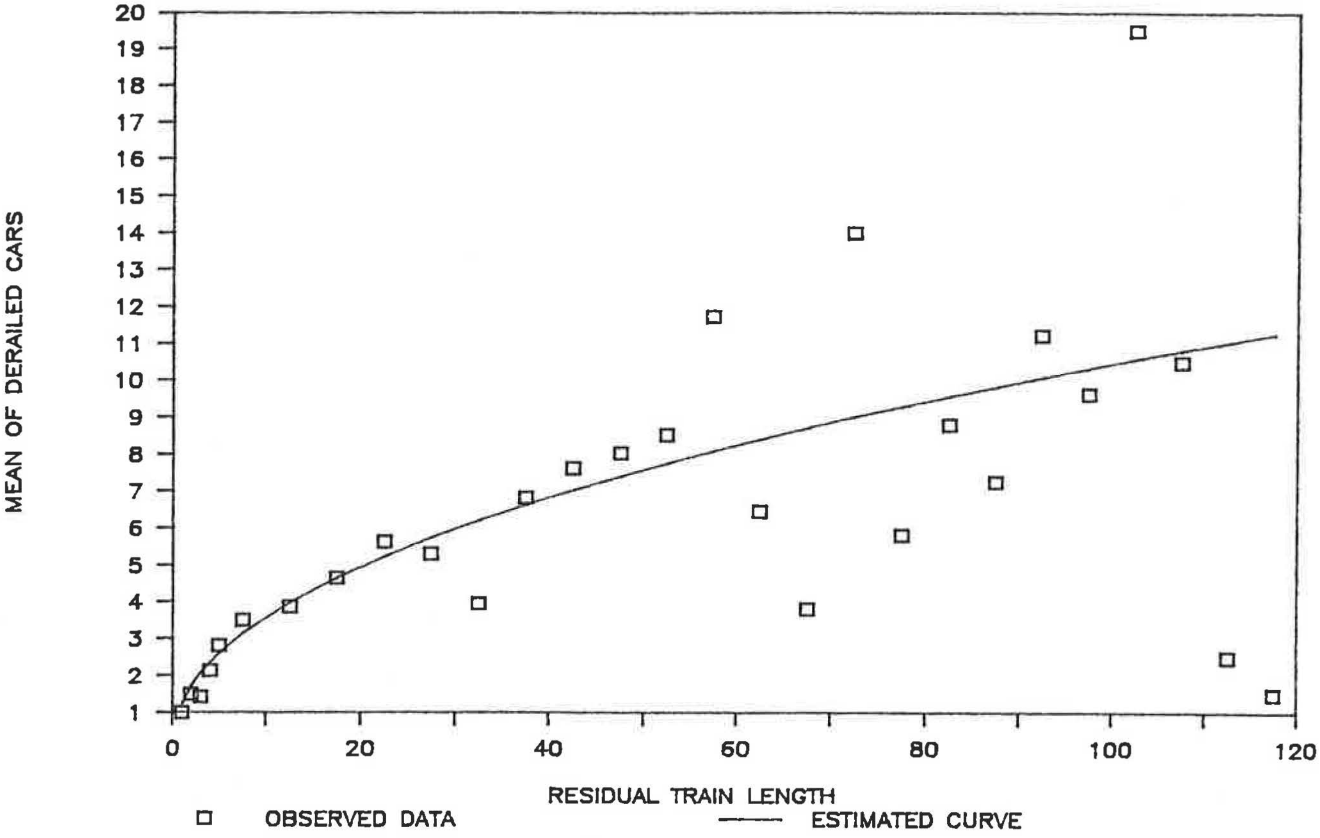

FIGURE 5 Number of cars derailing versus residual train length for all train speeds.

in the CTC data. The coefficients of the response function for all other causes are positive, suggesting fewer cars derailing as a result of rail and jointbar defects.

A comparison was undertaken between the geometric distribution in Equation 6 and the exponential expression calibrated by Little. Deviations from observed values are illustrated in Figure 6. Because the geometric expression in this study is desegregate in nature, it can account for speed, cause, and train length characteristics that are unique to each derailment profile. From Figure 6, it can be seen that the geometric model is better able to predict the number of cars derailing than the Little expression. The scatter of standardized residuals for the geometric expression is uniform and lies within two standard deviations of the zero-zero line, for the entire train speed range.

ANALYSIS OF MARSHALING AND BUFFERING STRATEGIES

The second major phase of the study involves evaluating the effectiveness of alternative railcar marshaling strategies for reducing derailments involving SDC cars.

Predicting the Placement of SDC Cars on a Train

In this study, the likelihood of encountering an SDC car along a given train length is developed using combinatorial procedures. A simple example illustrates the approach. Consider a train n cars long, with m cars carrying SDCs. In this example, it is assumed that individual SDC cars are treated in separate one-car blocks. A buffer of k cars is placed between any two SDC cars. The k-car buffer is also used to separate the inhabited locomotive and caboose segments from the rest of the train. The objective here is to estimate the probability that an SDC car will be in the ith position of the train.

Assuming that $m1$ SDC cars are assigned to the first half of the train, then the number of buffer cars required in the first half becomes $(m1 + 1) * k$ cars, including the front and rear buffer group. Assuming that position i consists of an SDC car, the residual number of non-SDC cars that remain in positions 1 through i is given as, $i - 1 - (m1 + 1) * k$ cars. The number of ways that $m1$ SDC cars can be arranged in the first half of the train becomes

$$\binom{i - 1 - (m1 + 1) * k}{m1} \qquad (10)$$

Similarly, assuming that the remaining $m - m1 - 1$ SDC cars are assigned to the second half of the train (i.e., positions $i + 1$ to n), then the number of ways that this can be arranged becomes

$$\binom{n - i - (m - m1) * k}{m - m1 - 1} \qquad (11)$$

This expression reflects the number of ways $m - m1 - 1$ cars can be arranged among a choice set of $n - i - (m -$

TABLE 5 MAXIMUM LIKELIHOOD SUMMARY STATISTICS FOR THE GEOMETRIC DISTRIBUTION

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F-TEST
REGRESSION	9	29477.4510	3275.2723	81.2851
RESIDUAL	431	17366.5490	40.2936	
UNCORRECTED TOTAL	440	46844.0000		
(CORRECTED TOTAL)	439	28564.6909		

PARAMETER	ESTIMATE	ASYMPTOTIC STD. ERROR	STUDENT T-TEST	ASYMPTOTIC 95 % INTERVAL LOWER	UPPER
INTERCEPT,"A"	1.6741	0.3342	5.0099	1.0173	2.3309
SPEED EFFECT,"B0	-0.5755	0.0818	7.0358	-0.7363	-0.4147
ROADBED,"B1"	0.6479	0.1438	4.5052	0.3652	0.9306
TRACK GEOM.,"B2"	0.3824	0.0942	4.0605	0.1973	0.5676
RAIL.&.JOINT.BAR.DEFECTS	----------------	NO PARAMETER		----------------	
SWITCHES,"B3"	0.4702	1.4246	0.3301	-2.3298	3.2703
GENERAL CAR,"B4"	1.6722	0.3228	5.1809	1.3078	2.3066
AXLES/WHEELS"B5"	1.5105	0.1283	11.7714	1.2583	1.7627
ALL OTHER,"B6"	1.3292	0.2611	5.0913	0.8161	1.8424
RES. LENGTH,"C0"	-0.6381	0.0538	11.8549	-0.7439	-0.5323

```
RESPONSE FUNCTION "Z"=
  A + B0*LOG(SPEED) + C0*LOG(RESIDUAL TRAIN LENGTH) +(B1,FOR ROADBED DEFECT)
    +(B2, IF CAUSE OF DERAILMENT IS TRACK GEOMETRY) +(B3,FOR RAILBAR DEFECT)
    +(B4, IF CAUSE OF DERAILMENT IS SWITCH DEFECTS) +(B5,FOR GENERAL CAR)
    +(B6, IF CAUSE OF DERAILMENT IS OTHER CAUSES)
```

$m1) * k$ available positions. The probability that the ith car in the train includes an SDC car becomes

$$P_i = \sum_{m1=0}^{m} \frac{\dbinom{i-1-(m1+1)*k}{m1} * \dbinom{n-i-(m-m1)*k}{m-m1-1}}{\dbinom{n-(m+1)*k}{m}} \qquad (12)$$

Certain aspects of marshaling regulations can affect the nature of the probability expression as defined above; for example, allowing SDC cars carrying similar materials to be marshaled adjacent to one another in contiguous blocks without any buffer separation. In this study, current marshaling regulations are used to adjust the above expression:

1. SDC cars are separated from other incompatible types of SDC cars by a buffer of k cars (five-car buffers in the current regulations).
2. SDC cars are separated from locomotive and caboose units by the same k-car buffer.
3. SDC cars carrying the same or compatible materials are not separated from one another. These cars are marshaled together in SDC blocks of variable lengths along the train.

The basic features of these marshaling and buffering regulations are illustrated in Figure 7 and reflect current strategies for SDC placement according to CTC regulations.

The probability that ith car in train is lth car of the block carrying SDC type j can be expressed as

$$P_{jl}(i) = \frac{\dbinom{[(i-l)-(MF*K+KE)]-[\sum_{*} NC(*)-MF]}{MF}\dbinom{[NF-i+l-KE-ND+\sum_{*} NC(*)-(MB-MF-1)*(K-1)]}{[MB-MF-1]}}{**\dbinom{[NC+MB-(MB-1)*K-KF-KE]}{MB}} \qquad (13)$$

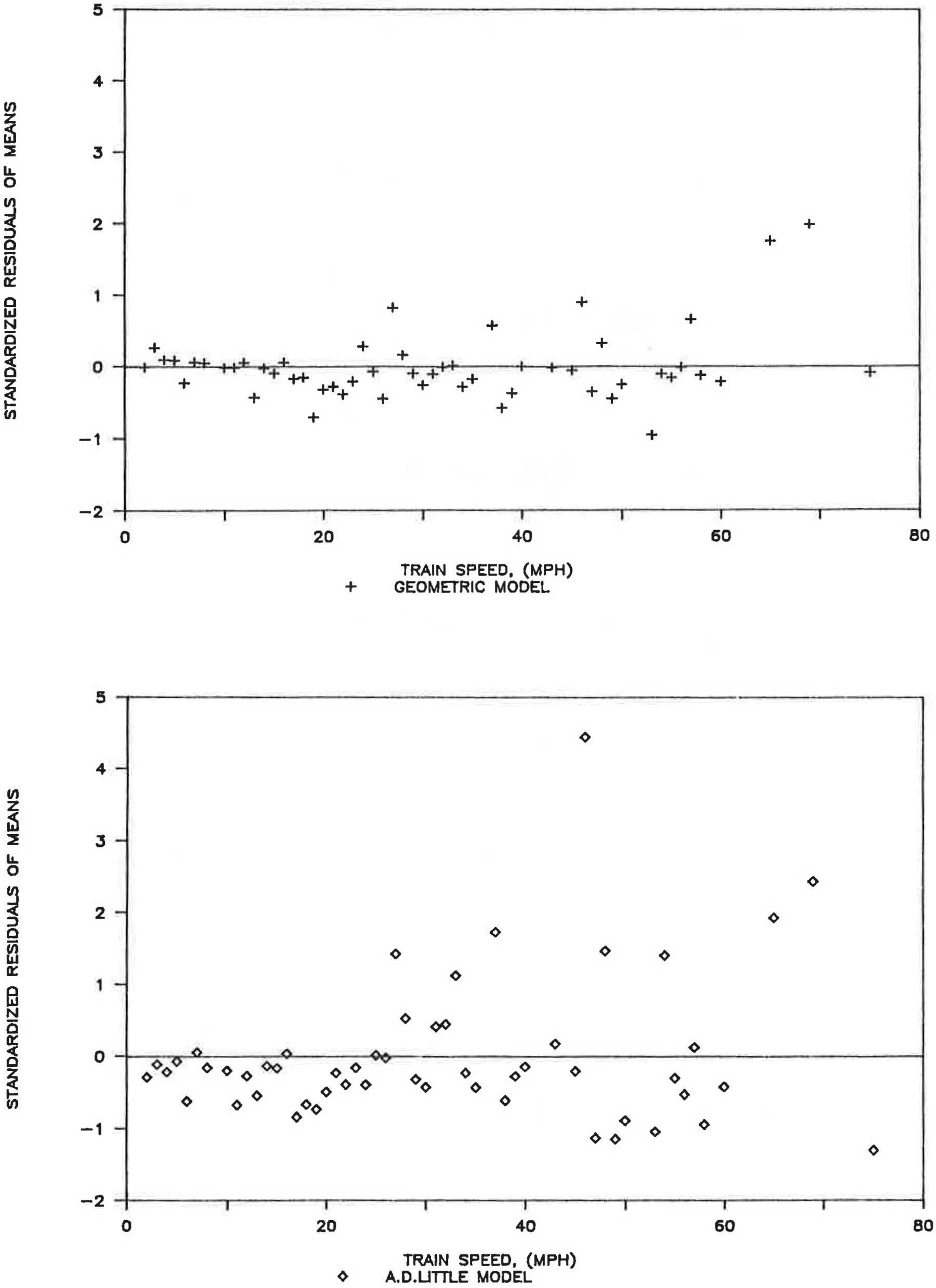

FIGURE 6 Standardized residuals of observed and fitted values for the geometric and Little models.

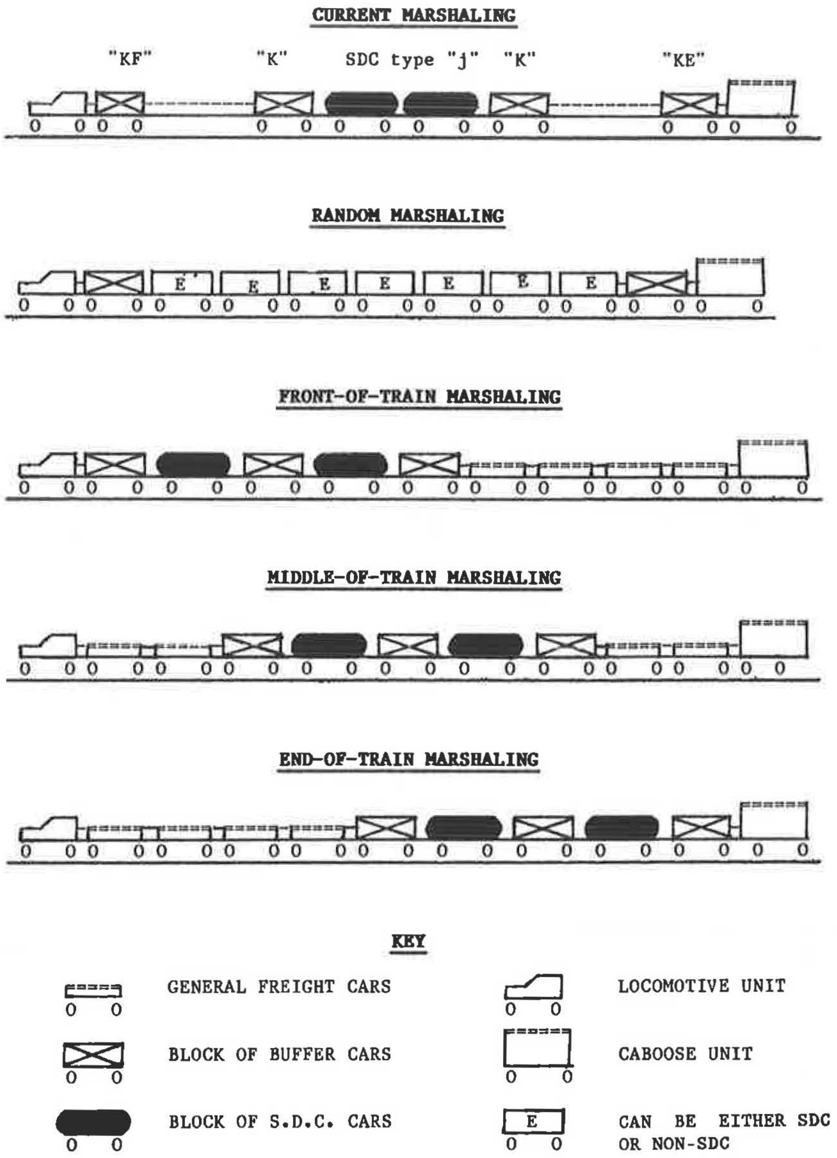

FIGURE 7 Alternative marshaling regulations considered.

where

NF = total number of freight cars;
NL = number of locomotives;
NE = number of caboose units;
NT = total number of cars, equal to $NL + NF + NE$;
MB = total number of SDC types or blocks in the train;
MF = number of SDC types in the section of the train preceding SDC block type j;
$NC(j)$ = number of SDC cars of type j, ($j = 1$ to MB);
ND = total number of dangerous commodity cars [SUM of $NC(j)$];
NC = number of nondangerous commodity cars ($NF - ND$);
KF = number of buffer cars at front of train;
KE = number of buffer cars at end of train; and
K = number of buffer cars between dangerous commodity blocks.

The summation terms Σ_* in Equation 13 give the number of SDC cars for a specific set of the MF SDC blocks that are assembled in the section of the train preceding SDC block type j. Similarly the term $**$ indicates that the above expression is summed over all possible types of the SDC blocks that can be fit in the section of the train preceding SDC block type j. Summing $P_{jl}(i)$ over all values of l in SDC block j, ($l = 1$ to $NC(j)$), gives the probability that the ith car in the train is carrying a type j dangerous commodity. Summing further over all types of SDC blocks ($j = 1$ to MB) gives the probability that the ith position in the train is in an SDC block. Further modifications to Equation 13 allow for the modeling of other marshaling strategies.

Evaluation of Alternative Marshaling and Buffering Strategies

From Equation 1, a derailment probability can be estimated for every position in the train as a function of operating train speed, cause of derailment, and train length. The probability that any position in the train is occupied by an SDC car can be obtained from a combinatorial expression, as in Equation 13, for each marshaling strategy and train consist. The expected number of SDC cars involved in any derailment can be estimated by summing positional joint probabilities of derailment and SDC car involvement in each accident situation. These estimates are a function of the cause of derailment and the train operating speed.

In this paper, five alternative marshaling and buffering strategies are evaluated (Figure 7):

- *Current marshaling.* Marshaling and buffering regulations currently in effect in Canada.
- *Random marshaling.* No restriction on the separation of SDC car blocks, excluding the front and rear buffers.
- *Front-of-train marshaling.* All SDC cars are marshaled to the front of the train with variable buffering.
- *Middle-of-train marshaling.* All SDC cars are marshaled in the middle section of the train with variable buffering.
- *Rear-of-train marshaling.* All SDC cars are marshaled at the end of the train with variable buffering.

For illustrative purposes, several assumed train consist characteristics were considered in this evaluation exercise:

Number of locomotives	5
Number of caboose units	2
Classes of SDCs in each consist	5
Number of SDC cars in the entire train	15
Type 1 SDC cars	5
Type 2 SDC cars	4
Type 3 SDC cars	3
Type 4 SDC cars	2
Type 5 SDC cars	1
Total number of freight cars in the train	70

The evaluation of marshaling strategies was carried out for each of the seven train derailment causes listed in Table 1 and three train speed classes (5, 30, and 60 mph).

Assuming current marshaling regulations (Figure 7), the effect of changing buffer lengths on SDC car positioning can be illustrated with reference to Figures 8a and 8b for a five- and ten-car buffer, respectively. The distribution for the five-car restriction in Figure 8a is relatively uniform throughout the train length. This is expected, given the low proportion of SDC cars in the total train length and the reduced number of cars allocated to buffer positions. When the buffer length is increased to ten cars as in Figure 8b, the distribution of SDC car involvements becomes more peaked, because fewer positions are available for SDC assignment. In the extreme case, where placement of SDC in a train is unique, the distribution becomes discrete and a selected number of positions is assigned SDC cars with probability equal to one.

Derailment probability distributions were obtained for all derailment causes and various classes of train speeds. Figures 9a and 9b illustrate two such distributions for roadbed defects and wheel, axle, and journal failures, respectively. For each derailment cause, three speeds were also considered (5, 30, and 60 mph). Regardless of train operating speed, the cause of derailment has a significant effect on derailment position. Furthermore, it can be shown from Figure 9, that roadbed defects are more likely to affect derailments near the front section of the train than wheel, axle, and journal failures, where the rear positions are more critical. Regardless of cause of derailment, the higher the operating speed of the train the higher the probability of derailments for all positions in the train consist.

Figures 10a and 10b represent the distribution of derailments for two causes (roadbed defects and wheel, axle, and journal failures) for each of the four marshaling strategies (random, front, middle, and rear SDC assignment). Figure 10 clearly demonstrates that the effectiveness of marshaling strategies in reducing SDC derailments is strongly influenced by the potential cause of derailment. The middle marshaling option varies slightly from current regulations. The front marshaling option is more effective for axle and journal failures than for roadbed defects. For roadbed defects, the best policy would be to marshal SDC cars to the rear of the train. In general, train operating speed increases SDC derailments for all positions and marshaling strategies.

CONCLUSIONS

In this paper, the derailment of cars carrying dangerous commodities is described by the POD, the number of cars derailing, and the position of SDC cars in the train. Accordingly, the following conclusions can be observed:

1. The POD was found to be strongly affected by the cause of derailment and train length. Relative frequency tables were generated for predicting the POD position for several causes of derailment and train sections.
2. The number of cars derailing is a function of the cause of derailment, train speed, and the residual train length and depends on the POD and train length. A probabilistic model based on the geometric distribution is used to estimate the number of cars derailing in an accident. The geometric distribution exhibits favorable goodness-of-fit characteristics for the 1980–1985 data.
3. The derailment probability of every car in a train was obtained from probability distribution of the POD and the number of cars derailing. Accordingly, the distribution of railcar derailments by position was found to be prescribed by the cause of derailment and train speed.
4. Derailments involving SDC cars could be reduced significantly by marshaling these cars into positions that are less likely to be involved in a derailment, under certain conditions. This was clearly shown in Figure 10, where different marshaling regulations had different number of SDC cars derailing.

It is apparent from this study that the marshaling regulations considered result in different numbers of SDC cars derailing under each of the different causes of derailment. However, it is important to study these results for the combined causes of derailment. To find the marshaling regulation with the fewest SDC cars derailing, the results of Figure 10 should be combined using the observed distribution of causes of derailment.

However, the distribution of causes of derailments is affected by the rail corridor considered. For example, a new or properly maintained track is expected to have more car- and equipment-related derailments than track-related derailments. Effective marshaling policies for SDC cars in a train consist must reflect rail corridor conditions that influence both the cause of derailment and position of derailed cars along a

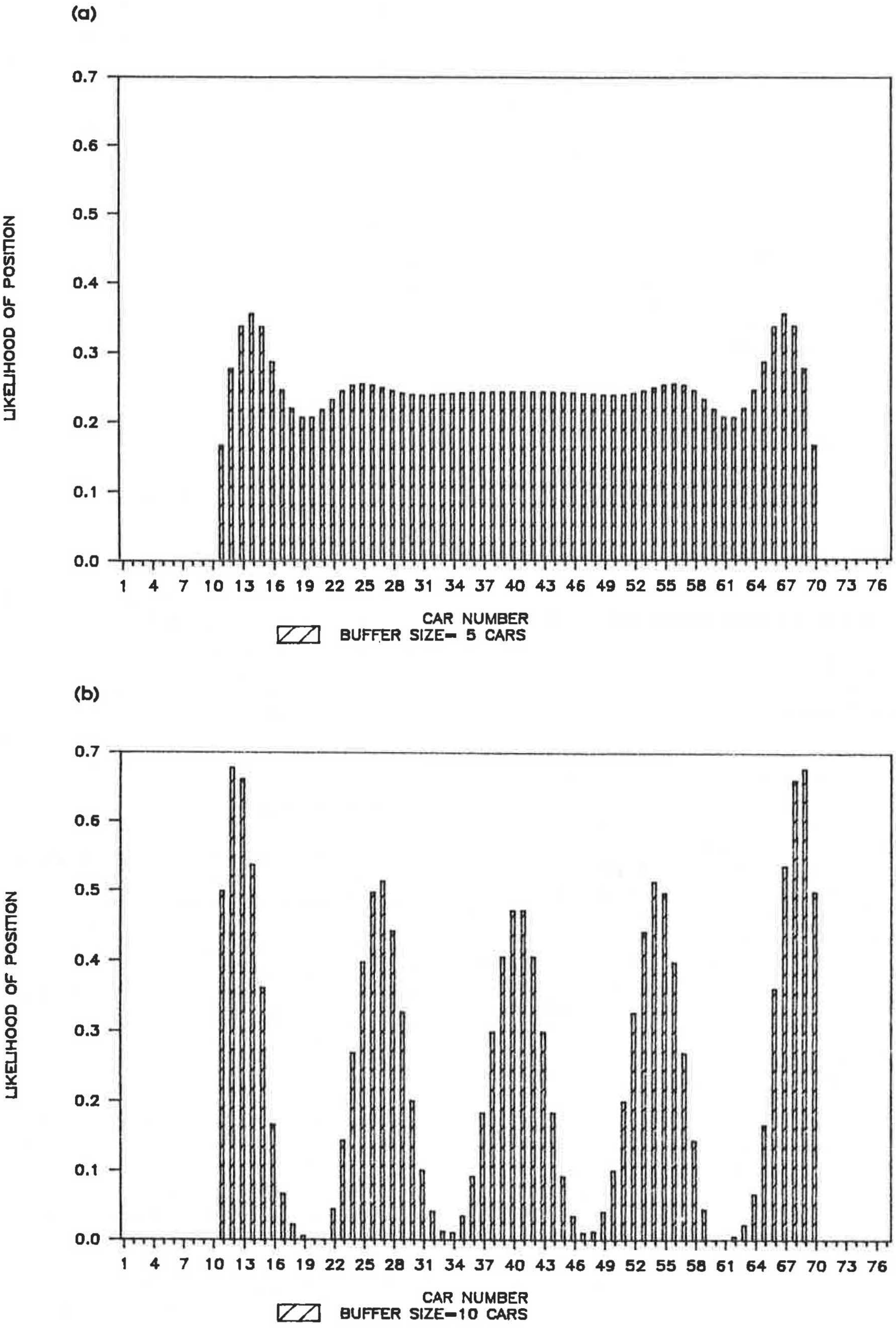

FIGURE 8 SDC car positions for current marshaling regulations: (a) five buffer cars, (b) ten buffer cars.

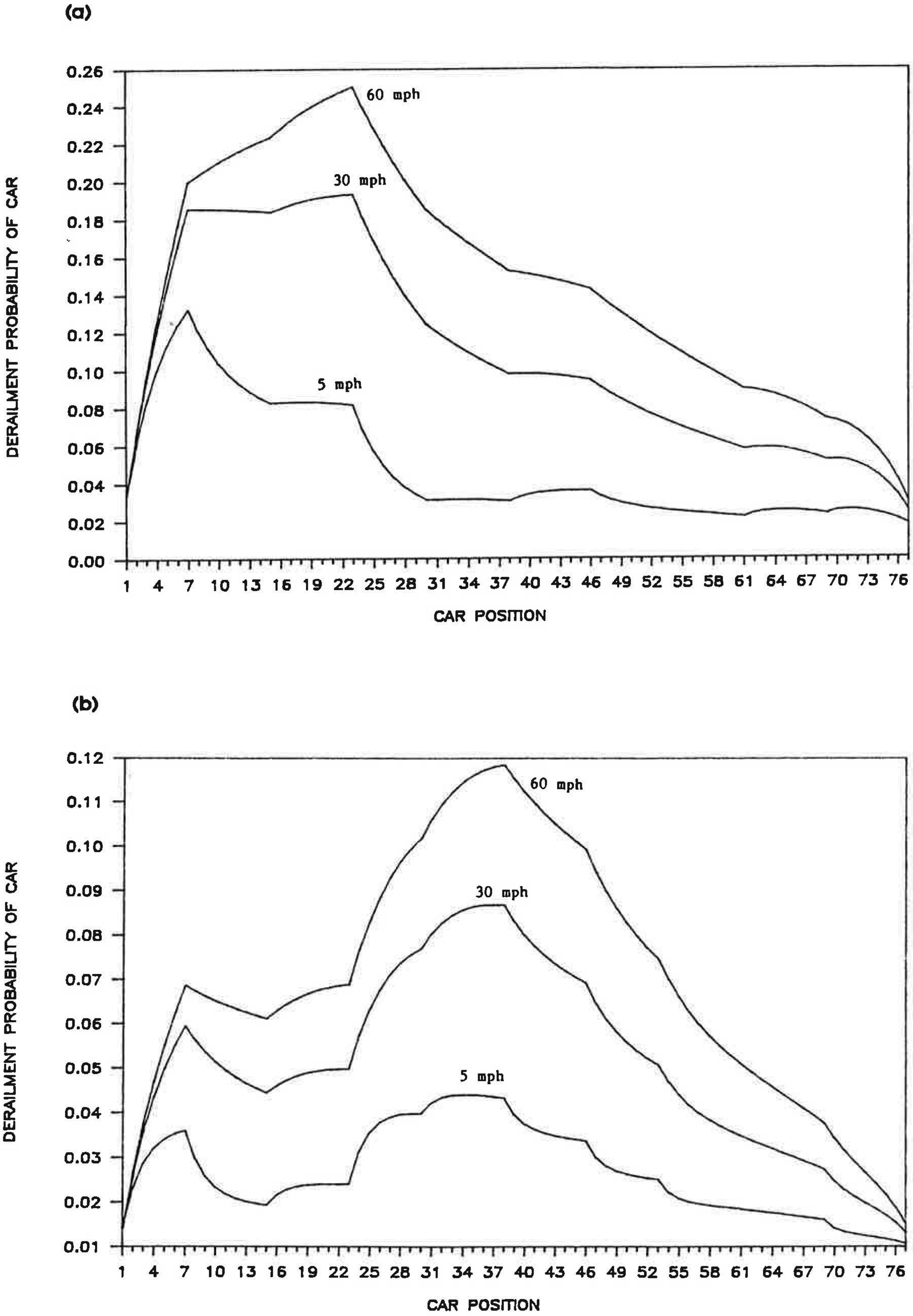

FIGURE 9 Derailment profiles for different car positions by causes of derailment: (a) roadbed defects, (b) wheel, journal, and axle defects.

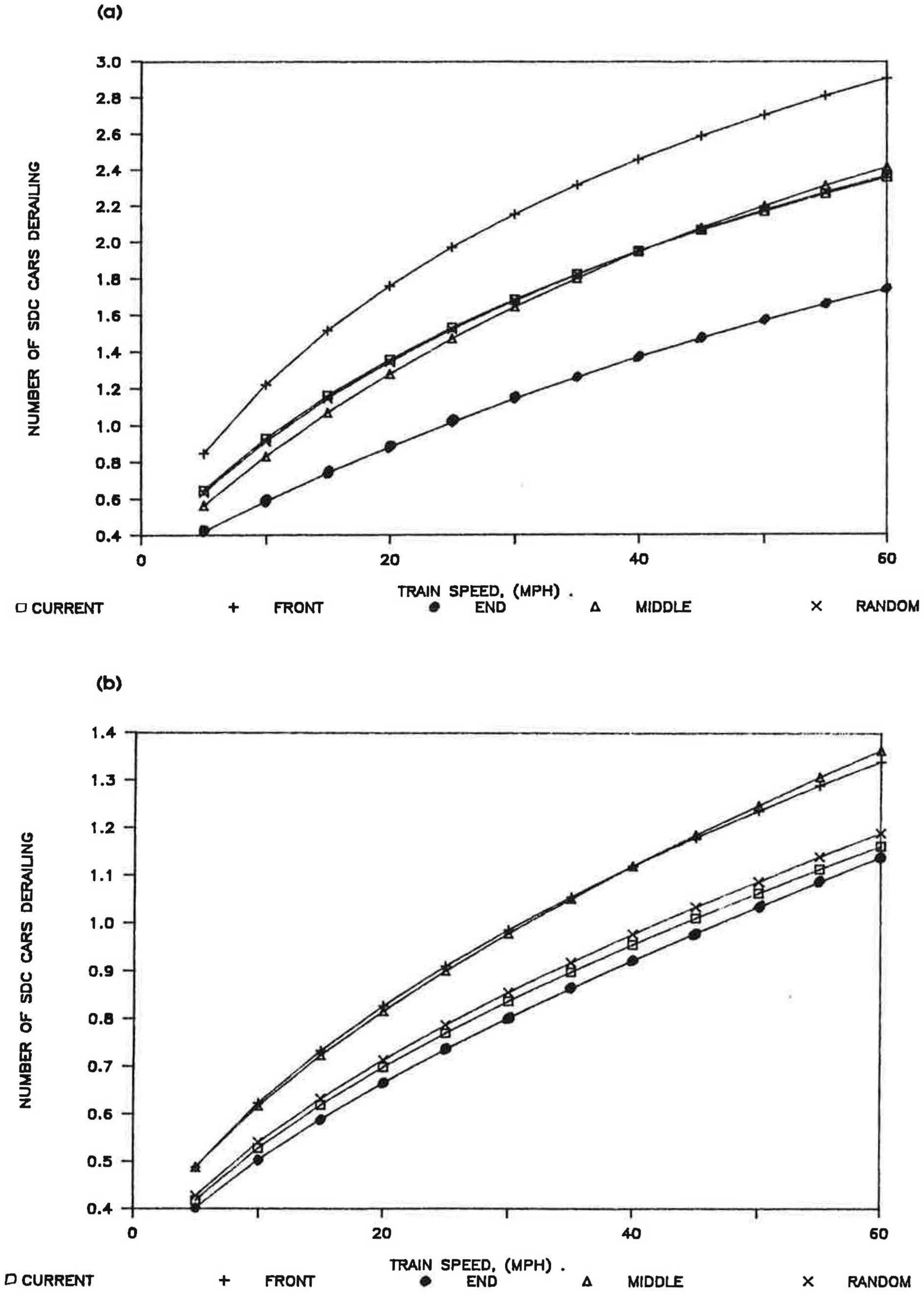

FIGURE 10 Number of SDC cars derailing versus speed for the alternative marshaling strategies: (a) roadbed defects, (b) wheel and axle defects.

train. Therefore, it is recommended that any analysis of marshaling regulations be performed for a specific rail corridor. The approach discussed in this paper can provide useful information for evaluating alternative marshaling strategies for SDC cars.

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Combined Location-Routing Model for Hazardous Waste Transportation and Disposal

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Complementary to the hazardous waste routing problem is the problem of where to locate hazardous waste disposal and treatment facilities. However, the literature lacks combined location and routing models for hazardous waste transportation and disposal. An alternative way to study the hazardous waste transportation and disposal problem is presented herein by considering simultaneously the following location and routing criteria: (a) minimize disposal risk, (b) minimize routing risk, and (c) minimize travel time. A hypothetical example is used to illustrate the applicability of the model. The proposed model can be used by hazardous waste management agencies for planning and policy evaluation.

In recent years, the transportation of hazardous waste from generation sites to disposal or treatment sites has drawn considerable public attention. This heightened public concern stems from the catastrophic damages associated with the accidental release of hazardous waste.

Accidents involving hazardous waste may occur during the transportation, as well as disposal of these materials. Hazardous waste transportation accidents impact negatively on people and properties located along the routes used for transport, while accidents occurring during their disposal or treatment impact negatively on people and properties located in the vicinity of the disposal or treatment facilities.

An effective method of reducing the hazardous waste transportation risk is to select the safest possible routes connecting hazardous waste generation and disposal sites, or select routes that pass through sparsely populated areas. The risk of hazardous waste disposal can be reduced by locating hazardous waste disposal and treatment facilities in areas where the fewest number of people would be potentially exposed to hazardous waste release.

The location of hazardous waste disposal and treatment facilities affects the route selection for transporting the waste and, consequently, affects the hazardous waste transportation and disposal risk. Although there is an interaction between the hazardous waste route selection and the selection of hazardous waste disposal and treatment sites, most of the existing models focus on only one of the two aspects of the problem. Independent consideration of the routing and location aspects of the hazardous waste transportation and disposal problem may lead to inefficient solutions. However, models must be developed that are capable of simultaneously considering both location and routing criteria.

This paper is intended to develop a multicriteria location-routing model for improving the decision making framework of hazardous waste transportation and disposal. The remainder of this paper will present (a) previous related research, (b) the proposed multicriteria location-routing model for hazardous waste transportation and disposal, (c) an application of the proposed model to hypothetical transportation network, and (d) the conclusions of this research.

LITERATURE REVIEW

Routing hazardous materials has been considered by many researchers to be a potential risk-reduction mechanism (*1–7*). As a result, several hazardous materials routing models exist in the literature. These models can be classified into either single-criterion or multiple-criteria (or multicriteria) routing models. Single-criterion models use only one criterion at a time to select routes for transporting hazardous materials.

Examples of routing criteria used in single-criterion hazardous materials transportation studies include population at risk (*3*), community safety index (*5*), truck operating cost (*4*), accident likelihood (*4*), risk exposure (*4*), length of the shipment (*6*), and population exposure (*6*). The major drawback of the single-criterion models is their inability to identify trade-offs between conflicting criteria (*8*, *9*). Thus, a route that minimizes the length of the shipment may not necessarily minimize the population exposed to the hazardous materials shipments, or a route that minimizes the accident likelihood may not coincide with a route that minimizes the truck operating cost.

Multicriteria models, which include more than one routing criterion at a time, have been recommended as a more realistic approach to modeling the route selection of hazardous materials shipments. The main advantage of the multicriteria hazardous materials routing models is their ability to examine trade-offs among conflicting routing criteria.

By definition, the solution of a multicriteria model does not generate a single, optimal route but, rather, generates several efficient routes. A route is efficient if its performance in terms of one criterion cannot be improved without degrading its performance in terms of another criterion.

Several multicriteria routing studies have appeared in the literature; these studies consider various routing criteria and solution techniques. Robbins (*6*) introduced a routing model that considers, simultaneously, the length of the shipment and the population brought into contact as routing criteria.

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Zografos and Davis (*10*) developed a multicriteria model that accounts for population risk, travel time, and property damage. Abkowitz and Cheng (*1*) presented a risk/cost formulation for routing truck movements. Finally, Turnquist (*9*) considered the problem of routing hazardous materials with multiple criteria and curfew restrictions.

Location of Disposal and Treatment Facilities

The main idea behind obnoxious facility location decisions is to minimize the number of people impacted by the operation of these facilities. The *maxi-sum* (*11*), *maxi-min* (*12, 13*), and *anticovering* (*14*) problems have been used to locate obnoxious facilities, including hazardous waste disposal and treatment facilities.

Maxi-sum locates a given number of undesirable facilities so as to maximize the sum of the weighted distances between population centers and their nearest obnoxious facility. Maxi-min locates a given number of undesirable facilities in such a way as to maximize the minimum distance between the obnoxious facilities and the nearest population center. Anticovering defines the maximum number of obnoxious facilities and their location so that no population center is located closer than a minimum safety distance from its nearest obnoxious facility.

These models are targeted to reduce the risk associated with the presence of obnoxious facilities in an area; however, they do not consider the effect of the location of the obnoxious facility on the hazardous waste transportation risk. Therefore, these models are not suitable for use in locating hazardous waste disposal facilities. An alternative approach would be to consider the interaction between the disposal and routing risks. The next section presents a combined location-routing model that considers this interaction.

COMBINED LOCATION-ROUTING MODEL

The proposed combined location-routing (CLR) model examines trade-offs between (a) hazardous waste transportation and disposal risks and (b) routing risk and travel time. Three objectives are used to formulate the proposed model: (a) minimization of transportation risk, (b) minimization of travel time, and (c) minimization of disposal risk.

The transportation risk is defined as follows: The product of the probability of a hazardous waste accident to occur, times the consequence of that accident (*3*). The risk associated with the links of the transportation network is the outcome of a risk estimation process and is an input of the proposed model. The travel time associated with the links of the transportation network is also an input of the proposed model and is given for every link of the transportation network.

The total distance between population centers and disposal sites is used as a surrogate measure of the risk imposed by the disposal of hazardous wastes. The greater the total distance, the lower the risk imposed to the neighboring population.

The maximization of the total distance between population centers and hazardous waste disposal sites (i.e., maxi-sum) was used to locate general obnoxious facilities (*12*). However, the maxi-sum criterion is not the only criterion governing the location of disposal facilities. Several additional criteria (geologic, physiographic, hydrologic, and climatologic) must be used in the initial screening of potential sites for locating disposal facilities (*15*). Thus, the maxi-sum criterion is used in the CLR model to select from a set of suitable hazardous waste disposal sites—the sites that maximize the total distance between them and the neighboring population centers.

The proposed model for hazardous waste transportation and disposal can be stated as follows: Given a set of candidate hazardous waste disposal sites, select a predetermined number of sites so as to (a) maximize the total distance between population centers and disposal facilities, (b) minimize the transportation risk, and (c) minimize the travel time.

The mathematical formulation of the CLR model is presented in the following sections.

Mathematical Expression of the CLR Model

The mathematical formulation of the CLR model is based on the following assumptions:

1. The transportation network, the origin of hazardous waste shipments, and the location of candidate disposal sites are given.
2. The supply of hazardous waste at each generation site must be disposed of entirely.
3. Assignment of supply to disposal sites could be partial (i.e., the hazardous waste of the *i*th generation site can be assigned to one or more open disposal facilities).
4. The risk associated with the links of the transportation network is given.
5. The travel time associated with the links of the transportation network is given.
6. The Euclidean distance between population centers and candidate disposal sites is considered as the separation measure for the part of the model concerning the location of disposal facilities.
7. An upper capacity limit exists for the links of the transportation network.

The CLR model requires the optimization of three, sometimes conflicting, objectives. Therefore, a multi-objective programming technique should be used for the mathematical formulation of the proposed model. Goal programming is a technique frequently used to solve multi-objective decision making problems. In goal programming, each objective is expressed as an inequality or equality constraint. The right-hand side of each constraint represents the desired attainment level of the objective. Each constraint is assigned a deviational variable that measures the underattainment of the objective. The objective of the goal programming method is to find the solution that minimizes the sum of the deviations over all the stated objectives (*16*).

The goal programming formulation of the CLR model can be written as follows:

$$\text{Min } F = P_1 d_1^- + P_2 d_2^+ + P_3 d_3^+ \tag{1}$$

Subject to

$$\left(\sum_{i \in N} \sum_{j \in C^*} S_{ij} Y_{ij} \right) + d_1^- \geq S \tag{2}$$

$$\left[\sum_{(i,j)\varepsilon N}\sum(X_{ij}\,R_{ij}) + \sum_{(i,j)\varepsilon N}\sum(X_{ij}\,W_j)\right] - d_2^+ \leq R \tag{3}$$

$$\left(\sum_{(i,j)\varepsilon N}\sum X_{ij}\,t_{ij}\right) - d_3^+ \leq T \qquad \forall\, i, j \tag{4}$$

$$\left[\sum_{K\varepsilon C^*} S_{ik}\,Y_{ik}\right] + (M - S_{ij})\,Y_{jj} \leq M$$

$$i\ \varepsilon\ N \qquad j\ \varepsilon\ C^* \tag{5}$$

$$\sum_{j\varepsilon C^*} Y_{ij} = 1 \qquad \forall\, i\ \varepsilon\ N \tag{6}$$

$$\sum_{j\varepsilon C^*} Y_{jj} = m \tag{7}$$

$$Y_{jj} \geq Y_{ij} \qquad \forall\, \mathrm{i}\ \varepsilon\ N \qquad \forall\, j\ \varepsilon\ C^* \tag{8}$$

$$\left[\sum_{i\varepsilon Sk} X_{ki} - \sum_{i\varepsilon Nk} X_{ik}\right] = d_k\ k\ K^* \tag{9}$$

$$\left[\sum_{i\varepsilon Sk} X_{ik} - \sum_{i\varepsilon Nk} X_{ki}\right] = O\ K\,\{N - C^* - K^*\} \tag{10}$$

$$\left[\sum_{i\varepsilon Nk} X_{ik} - \sum_{i\varepsilon Sk} X_{ki}\right] \leq C_k\,Y_{kk}\ k\ C^* \tag{11}$$

$$X_{ij} \leq U_{ij} \qquad \forall\, i\ \varepsilon\ N \qquad \forall\, j\ \varepsilon\ C^* \tag{12}$$

Where

C_k = allowable capacity at node k;
C^* = the set of candidate disposal sites;
d_1^- = deviational variable for the first objective;
d_2^+ = deviational variable for the second objective;
d_3^+ = deviational variable for the third objective;
K^* = the set of source nodes;
m = the number of disposal sites to be located;
M = a very large number (larger than the maximum distance between any two nodes on the given network);
N = the set of nodes in the network;
N_k = {i/arc (i, k) defined};
P_1 = priority factor for the first objective;
P_2 = priority factor for the second objective;
P_3 = priority factor for the third objective;
R = attainment level for the second objective (i.e., maximum permissible transportation risk);
R_{ij} = weight of link (i, j) representing the link risk factor;
S_{ij} = Euclidean distance between every note (i) and each candidate disposal site (j);
S_k = {i/arc (k, i) exists};
S = attainment level for the first objective (i.e., minimum allowable total distance between population centers and disposal sites);
T = attainment level for the fourth objective (i.e., maximum permissible travel time);
t_{ij} = travel time along link (i, j);
U_{ij} = maximum allowable flow on link (i, j);
W_j = node weight representing the amount of risk associated with node (j) (a high weight is attached to those nodes ranked first in importance);
X_{ij} = amount of flow along link (i, j); and
Y_{ij} = 1 if node (i) is assigned to node (j), 0 otherwise.

Equation 1 expresses the minimization of the deviation from the established attainment levels S, R, T. Inequalities 2 through 4 are the constraints that correspond to the three objectives of the CLR model. Inequality 5 requires each population center (i) to be assigned to its nearest open disposal facility. Equation 6 ensures that each population center (i) is fully assigned to only one disposal facility (i). Equation 7 requires that exactly m hazardous waste disposal facilities should be located. Inequality 8 restricts the assignment of population centers to open hazardous waste disposal facilities only. Constraints 9 through 11 express the flow conservation along the network, while Inequality 12 expresses the capacity limitation of the network links.

Sample Application of the CLR Model

A hypothetical problem involving the location of hazardous waste disposal facilities and the routing of hazardous waste from given generation sites to those facilities is used to illustrate the applicability of the CLR model. The transportation network of the study area is presented in Figure 1. Nodes 1, 9, and 10 of the network represent hazardous waste generation sites; while Nodes 3, 5, 6, and 15 represent candidate hazardous waste disposal sites.

The number of hazardous waste shipments available at each generation site, the capacity of the candidate disposal facilities, and the risk associated with the network nodes, are inputs of the CLR model and are given in Table 1.

The Euclidean distance (S_{ij}) between each population center (i) and each candidate disposal facility site (j) is given in Table 2. The risk, the travel time, and the capacity limits associated with the links of the hypothetical network are presented in Table 3.

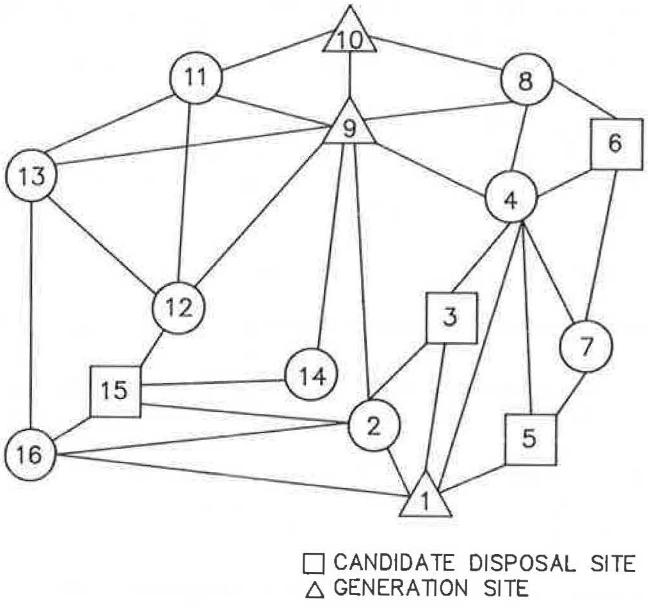

FIGURE 1 The hypothetical network.

TABLE 1 NODE CHARACTERISTICS OF THE HYPOTHETICAL NETWORK

NODE #	RISK ($\times 10^{-7}$)	H.W. SUPPLY	CAPACITY	NODE #	RISK ($\times 10^{-7}$)	H.W. SUPPLY	CAPACITY
1*	10.0	14.0	---	9*	20.0	12.0	---
2	8.0	---	---	10*	5.0	8.0	---
3**	10.0	---	50	11	5.0	---	---
4	19.2	---	---	12	8.0	---	---
5**	6.0	---	50	13	12.0	---	---
6**	5.0	---	50	14	2.0	---	---
7	3.0	---	---	15**	2.0	---	50
8	6.0	---	---	16	5.0	---	---

(*) Hazardous Waste Generation Sites
(**) Candidate Hazardous Waste Disposal Sites

TABLE 2 EUCLIDEAN DISTANCES BETWEEN EVERY NODE AND EACH CANDIDATE DISPOSAL SITE (CDS)

j i	CDS #3	CDS #5	CDS #6	CDS #15	j i	CDS #3	CDS #5	CDS #6	CDS #15
1	12.53	14.87	28.32	9.22	9	9.00	17.00	15.03	19.11
2	7.81*	13.00	24.41	8.06	10	14.00	21.54	16.16	23.02
3	0.00	10.00*	17.00	13.93	11	17.03	26.87	26.48	18.11
4	10.77	10.20	6.40	24.70	12	12.37	21.93	27.46	8.06
5	10.00	0.00	15.65	21.02	13	20.59	30.53	33.06	15.81
6	17.00	15.65	0.00	30.87	14	8.00	17.09	24.35	7.07*
7	18.44	10.20	12.37	31.02	15	13.93	21.02	30.87	0.00
8	17.70	19.42	5.83*	30.81	16	20.59	26.31	37.59	7.07*

The CLR model (Equations 1 through 12) was used for the mathematical formulation of the hypothetical problem under consideration. The Sperry UNIVAC/FMPS mixed-integer programming code was used to solve the problem.

An iterative procedure was used to solve the problem. At the first step of this procedure, the right-hand side values *S*, *R*, *T* of Equations 2 through 4 were calculated. These values indicate the desired goal attainment levels for the maxi-sum, minimum routing risk, and minimum travel time objectives, respectively. The values of *S*, *R*, *T*, were calculated by considering separately the three optimization problems corresponding to the three objectives of the problem.

At the second step of the solution procedure, several alternative scenarios were examined by changing the goal-attainment values and the priority for the attainment of the objectives. Table 4 describes the priority structure and the goal-attainment levels for the examined scenarios. In Scenarios 1 through 3 the goal-attainment values for *S*, *R*, *T* are the optimum values calculated in the first stage of the solution process. The priority structure for the attainment of the goals for Scenarios 1 through 3 is given in Table 4. In Scenarios 4 through 8 the priority structure indicates that the first objective has greater attainment priority than the second and that the second objective has greater attainment priority than the third.

Scenarios 4 through 8 were generated by reducing the attainment level of the first objective by an increment of 10 percent for each scenario. Thus, the value of *S* in Scenario 4

TABLE 3 LINK CHARACTERISTICS OF THE HYPOTHETICAL NETWORK

LINK	TRAVEL TIME (MIN)	LINK RISK $X(10^{-7})$	LINK CAPACITY	LINK	TRAVEL TIME (MIN)	LINK RISK $X(10^{-7})$	LINK CAPACITY
1-2	18.0	11.12	7	6-7	29.0	5.49	15
1-3	54.0	13.50	7	6-8	11.0	4.43	15
1-4	36.0	4.43	15	8-9	25.0	17.93	7
1-5	22.0	16.17	7	8-10	25.0	2.98	15
1-16	29.0	12.10	7	9-10	18.0	16.77	7
2-3	11.0	16.24	7	9-11	50.0	7.56	7
2-9	36.0	37.60	15	9-12	36.0	4.80	15
2-15	36.0	2.67	15	9-13	36.0	5.35	15
2-16	33.0	11.34	15	9-14	29.0	19.20	15
3-4	18.0	3.30	15	10-11	29.0	3.33	7
4-5	18.0	2.95	15	11-12	21.0	1.93	15
4-6	11.0	3.05	7	11-13	31.0	3.80	15
4-7	18.0	5.65	15	12-13	36.0	18.27	15
4-8	18.0	5.49	15	12-15	21.0	4.50	15
4-9	32.0	4.64	15	13-16	36.0	6.20	15
5-7	29.0	3.43	15	14-15	29.0	2.99	15
				15-16	18.0	3.74	15

TABLE 4 PRIORITY STRUCTURE AND GOAL-ATTAINMENT LEVELS FOR ALTERNATIVE SCENARIOS

Objective	SCENARIO NUMBER							
	1	2	3	4	5	6	7	8
Maxi-Sum	P_1^1 (*) S=234.87	P_1^2 S=234.87	P_1^2 S=234.87	P_1^1 S=211.38	P_1^1 S=187.90	P_1^1 S=164.41	P_1^1 S=140.92	P_1^1 S=117.43
Minimum Routing Risk (10^{-7})	P_2^2 R=705.29	P_2^1 R=705.29	P_2^3 R=705.29	P_2^2 R=705.29	P_2^2 R=705.29	P_2^2 R=705.29	P_2^2 R=705.29	P_2^2 R=705.29
Minimum Travel Time (VEH-MIN)	P_3^3 T=1273	P_3^3 T=1273	P_3^1 T=1273	P_3^3 T=1273	P_3^3 T=1273	P_3^3 T=1273	P_3^3 T=1273	P_3^3 T=1273

(*) P_1^1: Superscripts Indicate Goal Attainment Priorities.

is 10 percent less than the value of S in Scenario 3; while the value of S in Scenario 8 is 40 percent less than the value of S in Scenario 3.

The results of the solution of the hypothetical problem are presented in Tables 5 and 6. Table 5 presents the location and routing results for all the examined scenarios. For each scenario, Table 5 shows (a) the location of the disposal sites, (b) the population centers impacted by the selected disposal sites, and (c) the routes over which the waste should be transported. Table 6 gives the values of the deviational variables d_1^-, d_2^+, d_3^+ from the stated attainment levels for each of the eight examined scenarios. These deviations indicate the degree of underattainment for each of the problem objectives.

Table 6 shows the trade-offs existing among the maxi-sum, minimum routing risk, and minimum travel time objectives.

In Scenario 1, the first objective had the highest attainment priority. Thus, the value of the deviational variable d_1^- in this scenario is equal to zero. This means that the maxi-sum objective is fully attained, while the routing risk and the travel time objectives were underattained. In Scenario 2, the highest priority was assigned to the routing risk. Thus, the routing risk objective is achieved at the expense of the location risk and travel time objectives. In Scenario 3, the highest priority was assigned to the travel time objective. Therefore, the minimum travel time objective was achieved at the expense of routing risk. Note here, that the maxi-sum objective was achieved in this scenario, this means that the travel time and the maxi-sum objectives are not in conflict and that they can be achieved simultaneously.

The trade-offs among the three objectives can be studied by using the value path method (*16*) presented in Figure 2. In this figure, the vertical axis measures the percent deviation from the optimum value of each of the three problem objectives. Each scenario is represented by a line (value path) connecting the percent deviation of each objective. Thus, a value path shows the impact of a single routing alternative on each of the three model objectives. The measure of effectiveness of each alternative is the percentage deviation from the optimum goal level. The lower the percentage deviation for an objective, the higher the effectiveness of the routing scenario is with respect to this objective. A decision maker can use the value path method to (a) make quick comparisons among the examined scenarios and (b) reject the solutions that degrade one of the objectives without improving at least one of the other two objectives. The application of the value path method in the hypothetical example indicates that Scenarios 7 and 8 are inferior to Scenario 2 because both Scenarios 7 and 8 provide a higher deviation of the maxi-min objective than does Scenario 2, while they do not yield a lower deviation for the other two objectives (i.e., routing risk and travel time).

CONCLUSIONS

A CLR model for hazardous waste transportation and disposal was developed. The model determines the location of hazardous waste disposal facilities and the routes from given

TABLE 5 SUMMARY OF RESULTS FOR ALL THE EXAMINED SCENARIOS

SCENARIO NUMBER	1		2		3		4		5		6		7		8	
DISPOSAL SITES SELECTED	5	6	6	15	5	6	5	6	5	6	3	15	6	15	6	15
NODES LYING IN THE CATCHMENT AREA OF THE SELECTED DISPOSAL SITES	1 2 3 5 7 12 13 14 15 16	4 6 8 9 10 11	4 5 6 7 8 9 10	1 2 3 11 12 13 14 15 16	1 2 3 5 7 12 13 14 15 16	4 6 8 9 10 11	1 2 3 5 7 12 13 14 15 16	4 6 8 9 10 11	1 2 3 5 7 12 13 14 15 16	4 6 8 9 10 11	2 3 4 5 6 7 8 9 10 11	1 12 13 14 15 16	4 5 6 7 8 9 10	1 2 3 11 12 13 14 15 16	4 5 6 7 8 9 10	1 2 3 11 12 13 14 15 16
ROUTES SELECTED / FLOW UNITS	1-4/7 1-5/7 4-5/12 4-6/7 8-6/8 9-4/12 10-8/8		1-2/7 1-16/7 2-15/7 8-6/8 9-12/12 10-8/8 12-15/12 16-15/7		1-4/7 1-5/7 4-5/5 4-6/7 8-6/15 9-4/5 9-8/7 10-8/8		1-4/7 1-5/7 4-5/12 4-6/7 8-6/8 9-4/12 10-8/8		1-4/7 1-5/7 4-5/12 4-6/7 8-6/8 9-4/12 10-8/8		1-3/7 1-16/7 4-3/1 8-4/1 9-12/8 9-14/4 10-8/1 10-11/7 11-12/7 12-15/15 14-15/4 16-15/7		1-2/7 1-16/7 2-15/7 8-6/8 9-12/12 10-8/8 12-15/12 16-15/7		1-2/7 1-16/7 2-15/7 8-6/8 9-12/12 10-8/8 12-15/12 16-15/7	

TABLE 6 VALUES OF THE DEVIATIONAL VARIABLES FOR ALL EXAMINED SCENARIOS

Deviation	SCENARIO NUMBER							
	1	2	3	4	5	6	7	8
d_1^-	0.00	76.06	0.00	0.00	0.00	0.00	0.00	0.00
$d_2^+ \times 10^{-7}$	212.42	0.00	216.41	212.42	212.42	28.54	0.00	0.00
d_3^+	98.00	406.00	0.00	98.00	98.00	406.00	406.00	406.00

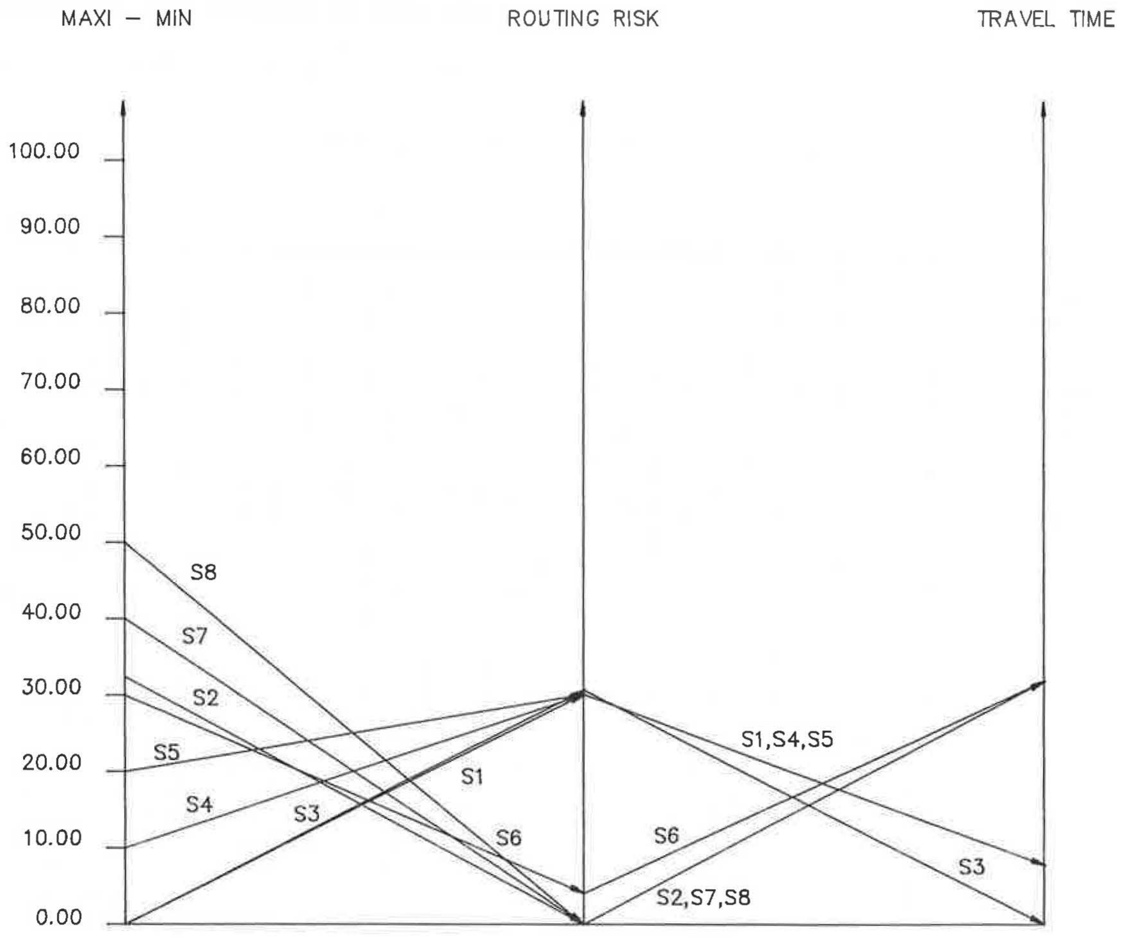

FIGURE 2 Value paths for all the examined scenarios.

hazardous waste generation sites to the selected disposal facilities. Alternative scenarios for locating disposal facilities and routing waste shipments to them can be examined by changing the priority structure and the goal-attainment levels of the problem. Trade-offs among location-risk, routing cost, and travel time also can be examined. The proposed model can be used by hazardous waste management agencies for planning and policy evaluation.

Although the proposed model establishes a good theoretical basis for the study of the CLR problem, more work is needed in addressing some of the practical considerations related to the application of the model to real world large-scale hazardous waste transportation and disposal problems. Suggestions for further research include issues related to (a) collecting the data needed to calculate the routing risk, and (b) examining the uncertainty associated with the parameters of the transportation network used to transport hazardous wastes.

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Bicriterion Routing Scheme for Nuclear Spent Fuel Transportation

SHIH-MIAO CHIN AND PAUL DER-MING CHENG

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

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

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

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

BICRITERION ROUTING PROBLEM

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

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

Therefore, BSPP can be stated as

Minimize

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

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

Subject to

$$\sum_j X_{ij} - \sum_1 X_{1i} = 1 \qquad i = s$$

$$\sum_j X_{ij} - \sum_1 X_{1i} = 0 \qquad i \neq s,t$$

$$\sum_j X_{ij} - \sum_1 X_{1i} = -1 \qquad i = t$$

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

where

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

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

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

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

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

POPULATION DATA

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

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

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

HIGHWAY NETWORK

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

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

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

SENSITIVITY OF POPULATION AT RISK

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

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

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

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

BICRITERION ROUTING CASE STUDY

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

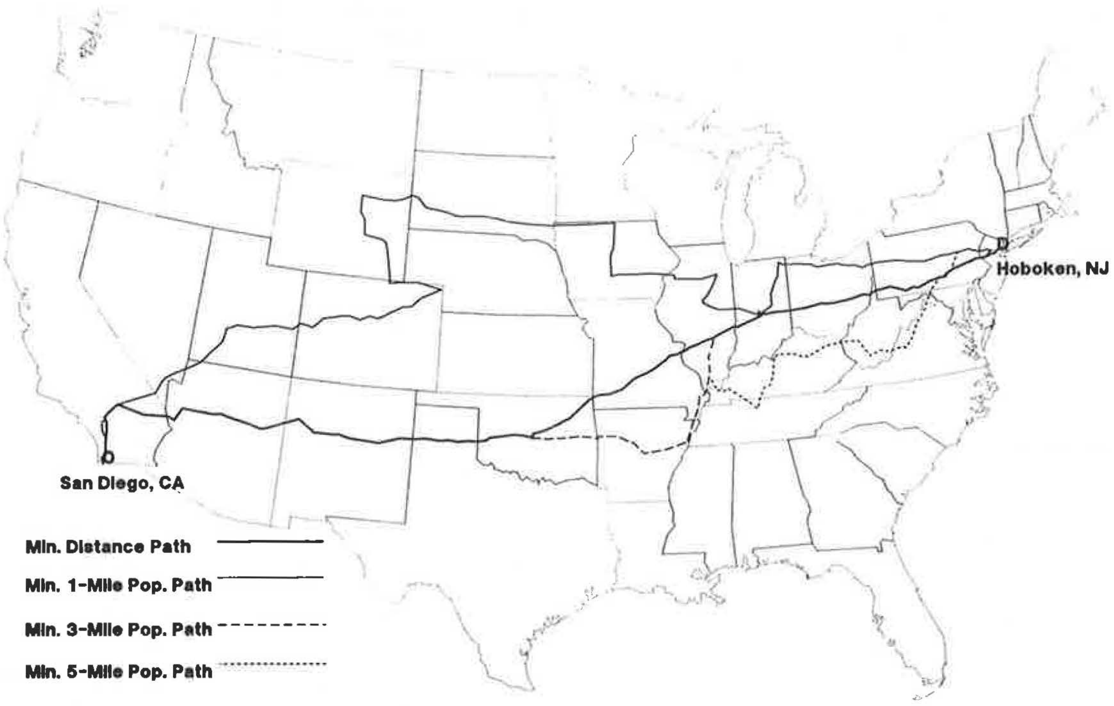

FIGURE 1 Shortest paths on Interstate highway from San Diego, California, to Hoboken, New Jersey.

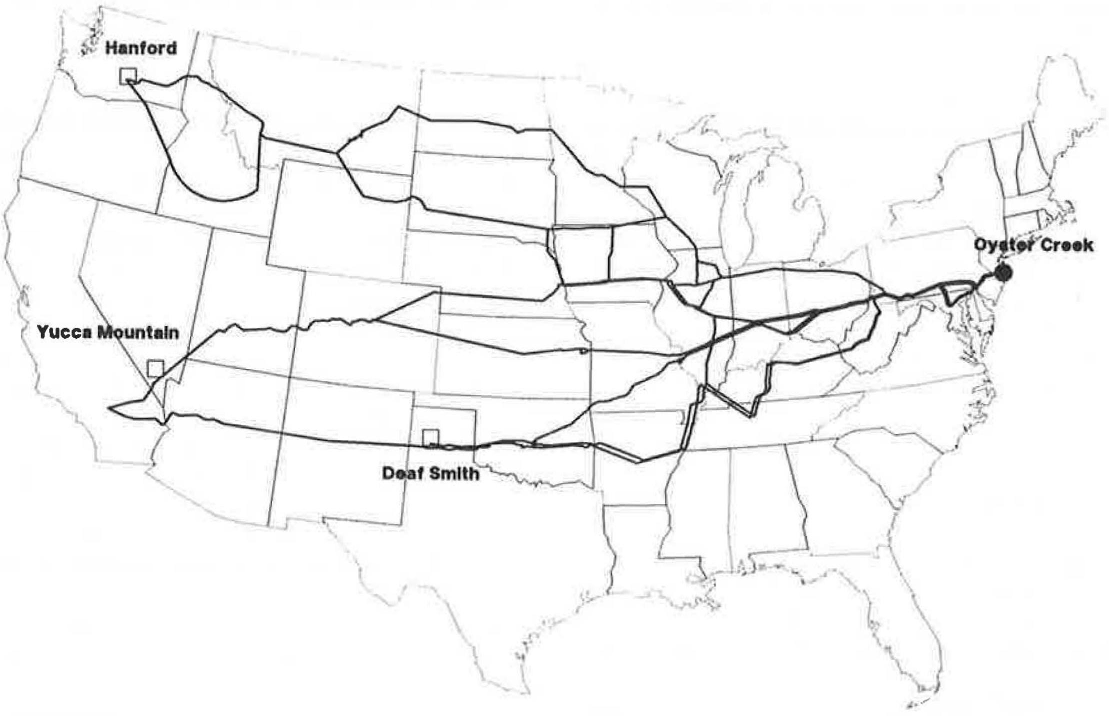

FIGURE 2 Noninferior routes for all cases.

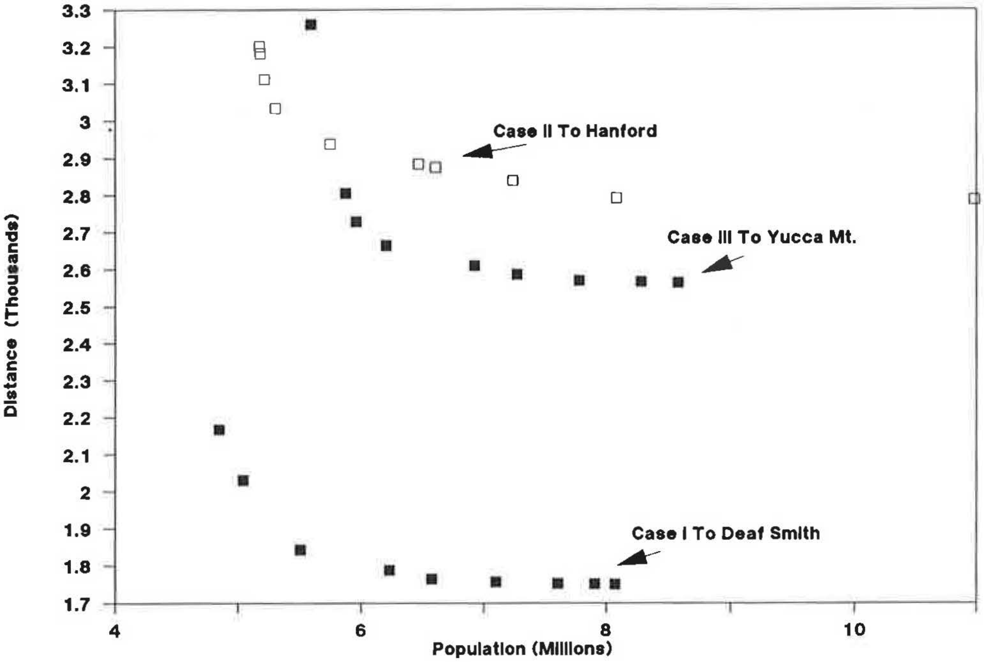

FIGURE 3 Trade-off of noninferior routes for all cases.

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

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

SUMMARY

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

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

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