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

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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

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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 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

Truck Type	Load	LINK ACCIDENTS — Location: Freeway, High Vol. >15,000 AADT	Freeway, Low Vol. <15,000 AADT	Non-Freeway, High Vol. >15,000 AADT	Non-Freeway, Low Vol. <15,000 AADT	NON-LINK ACCIDENTS (Ramps, Intersections, etc.)
		(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)

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
		(Accident rates per million car-kilometers)							
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*).

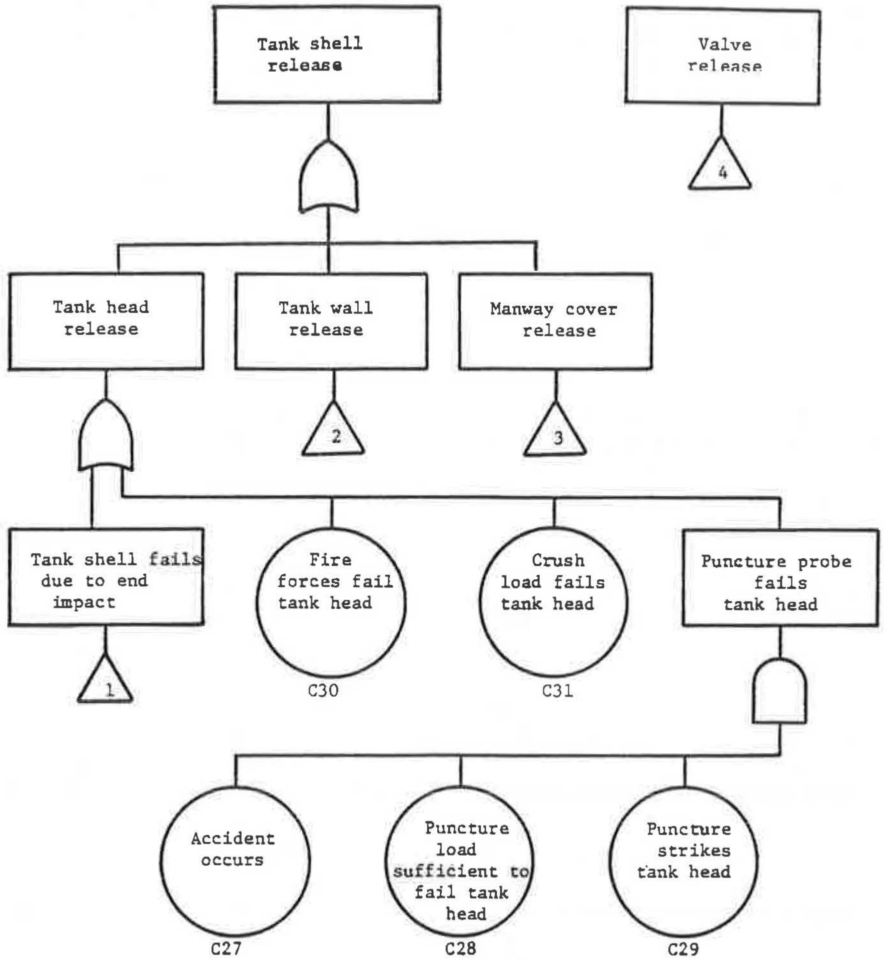

FIGURE 1 Portion of simplified fault tree structure for chlorine release.

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 tonne	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 /mil veh-km	Accident Rate /mil tonne-km	Spill Prob	Pot Damage Areas (km^2)	Pop Density (/km^2)	Shield Factor	Emerg Response Factor	Expected Damages - for Spill: Fatality 1 /mil veh-km	Fatality 1 /mil tonne-km	Injury 1 /mil veh-km	Injury 1 /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 /mil veh-km	Fatalities from spill /mil tonne-km	Fatalities due to accident (b) /mil tonne-km	Total Fatalities (c) /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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REFERENCES

1. Toronto Area Rail Transportation of Dangerous Goods Task Force. Final Report, prepared for Transport Canada, July 1988.
2. T. S. Glickman. Benchmark Estimates of Release Accident Rates in Hazardous Materials Transportation by Rail and Truck. In *Transportation Research Record 1193*, TRB, National Research Council, Washington, D.C., 1988, pp. 22–28.
3. C. Swoveland and J. Cawdery. *LPG Transport Research and Development Risk-Benefit Analysis*. Quantalytics, Inc., Vancouver, British Columbia, Canada, 1984.
4. F. F. Saccomanno, J. H. Shortreed, and M. Van Aerde. *Assessing the Risks of Transporting Dangerous Goods by Truck and Rail.* Reports I and II, Institute for Risk Research, University of Waterloo, Waterloo, Ontario, Canada, 1988.
5. *Ontario Commercial Vehicle Survey—1983*. Ontario Ministry of Transportation and Communications, Policy Planning Branch, Toronto, Ontario, Canada, 1984.
6. *1986 Summary of Railway Accidents/Incidents as Reported to the Canadian Transport Commission*. Railway Transport Committee, Operations Branch, Ottawa, Ontario, Canada, 1986.
7. *Risk Management in the Handling and Transportation of Dangerous Goods, Phase II.* Institute for Risk Research, Final Report, WRI Award No. 0889685, University of Waterloo, Waterloo, Ontario, Canada, February 1987.
8. F. F. Saccomanno and C. Buyco. Generalized Loglinear Models of Truck Accident Rates. In *Transportation Research Record 1172*, TRB National Research Council, Washington, D.C., pp. 23–31.

9. F. Saccomanno, A. Stewart, K. Bera, and M. Van Aerde, Fault Tree Analysis for the Transport of Dangerous Goods. In *Risk Management in the Handling and Transportation of Dangerous Goods*. Final Report, Appendix C, Institute for Risk Research, University of Waterloo, Waterloo, Ontario, Canada, Feb. 16, 1987.
10. W. B. Andrews, M. L. Clark, J. R. Friley , D. J. McNaughton, T. Buckingham, and B. A. Ross. *An Assessment of the Risk of Transporting Liquid Chlorine by Rail*. Report No. PNL-3376. Battelle Pacific Northwest Laboratory, Richland, Wash., March 1980.
11. C. A. Geffen, W. B. Andrews, T. M. Buckingham, A. L. Franklin, J. Friley, D. J. McNaughton, and B. A. Ross. *An Assessment of the Risk of Transporting Propane by Truck and Train*. Report No. PNL-3308. Pacific Northwest Laboratory, Richland, Wash., March 1980.
12. *Effectiveness of Shelf Couplers, Head Shields and Thermal Shields on DOT 112, 114, and 105 Tank Cars*. Report RA-02-5-51. Railway Progress Institute, Chicago, Ill., June 13, 1985.
13. G. M. Grange. *Report of the Mississauga Railway Accident Inquiry*. Ministry of Supply and Services, Ottawa, Ontario, Canada, 1980.
14. A. W. Dennis, J. T. Foley, W. F. Hartman, and D. W. Larson. *Severities of Transportation Accidents Involving Large Packages*. Report SAND77-0001. Sandia Laboratories, Albuquerque, N.M., May 1978.
15. *Second Report of the Advisory Committee on Major Hazards*. Health and Safety Executive, Her Majesty's Stationery Office, London, England, 1979.
16. I. J. Jordaan, J. W. Duncan, S. C. Wirasinghe. *Risk Analysis of Movement of Dangerous Goods by Rail through Calgary*. Department of Civil Engineering, University of Calgary, Calgary, Alberta, Canada, 1984.
17. Philip E. Wade Associates. *Hazardous Good Transportation by Rail in Toronto: A Strategic Overview*. City of Toronto Planning and Development Department, Toronto, Ontario, Canada, November 1986.
18. *Environmental and Technical Information for Problem Spills: Chlorine*. Environment Canada, Technical Services Branch, Environmental Protection Programs Directorate, Environmental Protection Service, Ottawa, Ontario, Canada, 1984.
19. Concord Scientific Corporation. *Risk Assessment for Rail Transportation of Dangerous Good through the Toronto Area*. Toronto Area Dangerous Goods Rail Task Force, Downsview, Ontario, Canada, Dec. 1987.
20. G. Purdy, H. S. Campbell, G. C. Grint, and L. M. Smith. An Analysis of the Risks Arising from the Transport of Liquefied Gases in Great Britain. Presented at the International Symposium on Major Hazards in the Transport and Storage of Pressure Liquefied Gases, University of New Brunswick, Fredericton, New Brunswick, Aug. 1987.
21. G. A. Clay, R. D. Fitzpatrick, N. W. Hurst, D. A. Carter, and P. J. Crossthwaite. Risk Assessment for Installation where Liquefied Petroleum Gas (LPG) is Stored in Bulk Vessels above Ground. Presented at the International Symposium on Major Hazards in the Transport and Storage of Pressure Liquefied Gases, University of New Brunswick, Fredericton, New Brunswick, Canada, Aug. 1987.