Risk Uncertainty in the Transport of Hazardous Materials

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During the last several years, a number of risk estimation models have been developed in North America and Europe for the transport of dangerous goods. Despite similarities in the nature of the transport problems, these models have failed to produce agreement on the nature and validity of the reported risk estimates. Notwithstanding major advances in this field of research, inconsistency continues to plague the estimation process. The nature of the inconsistency in risk estimation is not well understood and has not been adequately addressed in the current research effort. Several risk analysis models have been applied to a common transport problem. By applying these models to a common transport problem, much of the variability in risk caused by assumptions and differences in data has been taken into account. The results of a statistical analysis of risk uncertainty among different models is presented. Significant variations are reported for different risk components by model source. Much of the uncertainty in the risk component estimates was found to cancel out for this transport problem, resulting in good agreement among the model sources in the final societal risk estimate, despite lack of agreement on the value of the various constituents of societal risk.

A number of significant advances have taken place in recent years in the estimation of risks for the transport of hazardous materials. These advances have been made possible by a better understanding of the process and access to improved data bases.

With a better understanding of the process, a corresponding increase in the consistency of estimates as provided by different risk analysts would be expected. However, recent research has only underscored a general lack of agreement among the research community on the nature and validity of the reported estimates. Depending on the source, risk estimates continue to reflect significant variability for similar transport situations and contradictory conclusions regarding the most appropriate actions to take. Much of this variability remains unexplained.

The treatment of risk uncertainty requires a thorough understanding of the nature of the risk analysis process as it applies to the transport of hazardous materials. This process consists of five components: (*a*) accident likelihood, (*b*) containment system failure given an accident or fault, (*c*) volume and rate of material released, (*d*) hazard area associated with each potential threat for different releases and materials, and (*e*) population affected for different levels of damage.

Each of the five components of risk requires specification of separate submodels with a unique set of inputs and outputs. Variability in these estimates results from three basic sources (*1*):

1. Underlying assumptions governing the estimates,
2. Jurisdictional differences concerning the validation and application of the models, and
3. Structural differences in the models themselves.

Since many models were developed for specific transportation corridors and shipment conditions, the nature of the adjustments required to yield consistent results is not always evident from the background material provided on each estimate. To understand the nature of risk uncertainty, it is important to account for assumptions and jurisdictional factors that are unique to each model. Any variability in the estimates that cannot be accounted for in this manner is considered "uncertainty" and must be treated statistically.

The purpose of this paper is to present some of the major results and conclusions of a hypothetical corridor exercise on risk uncertainty carried out as part of the International Consensus Conference on the Risks of Transporting Dangerous Goods held in Toronto, April 6–9, 1992. In this exercise, various quantitative risk analysis models were applied to a common transport problem involving the bulk shipment of chlorine, LPG, and gasoline by road and rail along predefined routes.

CORRIDOR APPLICATION

The corridor analysis for the risks of transporting hazardous materials is based on a set of specifications for different modes, weather conditions, and material properties. This problem is designed to limit the extent of variability in the estimates that could be caused by differences in underlying assumptions and jurisdictional data.

Basic Corridor Features

As shown in Figure 1, the test corridor is served by two modes: road and rail. Each route is 100 km in length and is divided into three separate development sections: rural (70 km), suburban (20 km), and urban (10 km). Development densities for population and employment along each of these sections are consistent with densities experienced along typical North American regional transport corridors.

The focus of the corridor risk analysis is on immediate health risks. These risks include fatalities and personal injuries

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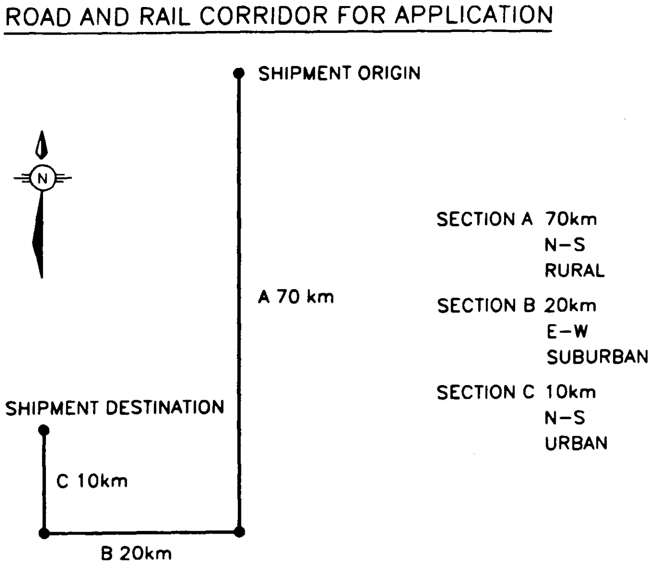

FIGURE 1 Hypothetical corridor features.

experienced near the time of each incident. Long-term health risks and environmental impacts are not considered. For comparison, it is assumed that immediate emergency response capabilities are not available. A number of population and employment distributions and sheltering/evacuation ratios have been assumed for different weather conditions and traffic compositions.

A total of 100,000 tonnes of hazardous materials is shipped annually by each mode along the full length of the corridor from the rural source to the urban destination. Three representative classes of hazardous materials are considered: chlorine (high toxicity, heavy gas), LPG (high flammability and explosiveness), and gasoline (flammable liquid, predominant share of hazardous material road traffic). Representative volumes of materials are shipped in bulk by typical road and rail tankers. The specifications of these tankers are reflective of design standards in use in North America. The use of North American standards of tanker design and corridor development densities should not prejudice the reliability of those models developed for different conditions, since presumably these models are transferable across national boundaries given appropriate specification of the problem and the corresponding model parameters.

The corridor data used in this exercise are "hypothetical," which should not be interpreted to mean unrealistic or impractical. Hypothetical data were used for three major reasons:

1. The estimation process would not be subject to limitations in the data required by more complex risk formulations. Where possible, inputs were provided to reflect the requirements of the most complex models. Simple formulations could choose to ignore these inputs at their discretion.
2. Extreme sensitivities in the results could be assessed while controlling for any combination of factor inputs. The relative consistencies and inconsistencies in the various models could be identified directly in terms of specific corridor features.
3. From a practical perspective, the application would be free from any political controversy generated by a "real" corridor risk assessment. The focus could be better directed at the estimates themselves and not on the political ramifications of the results.

Risk Estimation Sources

Seven risk estimation groups have contributed to the corridor results: Concord Environmental, Health and Safety Executive, Institut de Protection et de Surete Nucleare, Institute for Risk Research, Commission of the European Communities, Netherlands Institute of Environmental and Energy Technology, and Vanderbilt Engineering Center. Background information on each of these model sources is provided elsewhere (*2–7*).

Estimates of risk are reported in terms of each component (i.e., accident, fault, release, hazard area, and population impact) and the final individual and societal risk measures. The analytical basis for each estimate varies considerably from model to model. For example, accident rates were obtained in two ways: direct reference to accident data or as a product of statistical models controlling for any mix of mitigating factors. In some cases, accident rates were estimated by distinguishing vehicles carrying hazardous materials from the accident record of general commodity traffic. In most cases, however, accidents rates were uniformly applied to all kinds of commodity traffic for both truck and rail modes. Release probabilities generally require the occurrence of an accident involving hazardous materials. Estimates of accident-induced release probabilities were obtained in two ways: direct reference to the accident spill data or as a product of a fault tree analysis of containment system failure in an accident situation. In estimating these probabilities, several models distinguished between the occurrence of the containment system fault (breach of containment) and the resultant spill profile; other models treated the two events together. The consequence analysis differed significantly among the various models, depending on the nature of the material involved. In the case of heavy gas dispersion, for example, several models used a Gaussian approximation to obtain the resultant hazard areas; other models used a more detailed heavy gas dispersion formulation that accounts for the puff cloud effect immediately after release. The basic assumptions used by the various sources to obtain the corridor estimates have been summarized by Stewart (*8*) in a background report presented to the International Consensus Conference on the Risks of Transporting Dangerous Goods held in Toronto, April 8, 1992. The implication of these assumptions for explaining variations in the risk estimates has been discussed in some detail by Saccomanno et al. (*9*).

ASSESSMENT OF VARIABILITY IN THE RISK ESTIMATES

The results of this comparative analysis will be presented in two stages:

1. The various risk component estimates are presented graphically for each of the available model sources. Selected

corridor features are invoked where these features are expected to modify the estimates.

2. The models are clustered on the basis of similarities in selected risk component estimates (referred to as seed points). These estimates are used as seed points in the cluster analysis. The resultant model groupings reflect a level of "within group" consistency in these. The significance of the difference in risk component estimates is established statistically using a two-way analysis of variance for the two modes and three shipment materials, with replication for different sources of estimates.

The central issue in this comparative analysis is whether, notwithstanding similarities in the underlying assumptions, the various models yield estimates that differ significantly from one another.

Graphical Analysis of Risk Variability

Figure 2 shows the pattern of accident rates for road and rail along the three sections of the hypothetical corridor. These rates apply to all materials for a given mix of physical design features, traffic composition, and environmental conditions. With the exception of Model D values, most rail accident rates were relatively insensitive to section-specific conditions. On the other hand, most models suggested a gradual reduction in road accident rates from the urban to the rural section, possibly in response to lower volumes and reduced traffic conflicts. A significant amount of variability is present in the road and rail accident rate results among the various models. On the average, rail accident rates per tanker-kilometer are lower than road accident rates by a significant factor of 7.6 for all three development sections. Depending on the source of the estimates, differences in accident rates between the two modes vary significantly. For example, the rail accident rate from Model A on the suburban section is 13.3 times lower than for road per tanker-kilometer traveled. Models B and C consistently yield rates that are lower than the average regardless of mode, whereas Model D yields rail accident rates that are higher than the average and road accident rates that are lower than the average. Despite the use of similar data for the estimates, Model G yields a different result (i.e., lower rail accident rates and higher road accident rates relative to the average). For a given set of corridor conditions, rail accident rates vary by a factor of 10 between the lowest estimate (Model G) and the highest estimate (Model D). For road, the factor of difference is approximately 9 between the lowest estimate (Model B) and the highest estimate (Model A). Notwithstanding these differences, all the models were consistent in predicting lower accident rates for rail relative to road for the same tanker-kilometers traveled.

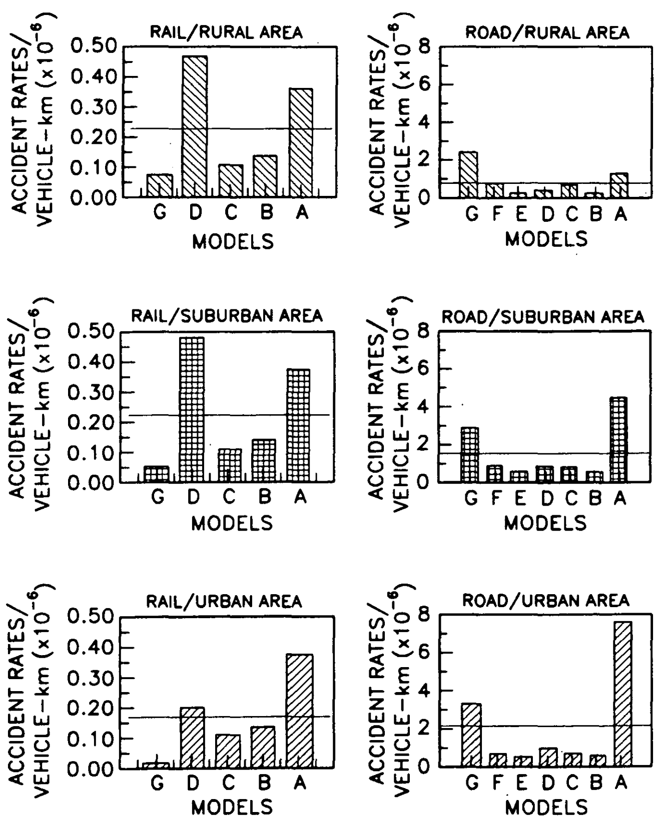

FIGURE 2 Accident rate variations among different models for six conditions.

Are variations in accident rates statistically significant? The answer to this question will be given statistically later in this paper. However, given the fact that all models have been applied to a common set of assumed conditions, the variations cast doubts on the reliability of the final risk estimates. Even if it can be shown that risk values are reasonably close among the various models (i.e., that errors of estimation in the components somehow compensate one another), the case for consistency remains weak, and the resultant risk estimates must be viewed critically. This aspect is important in view of the analysis of variance results that will be discussed later in this paper.

Figure 3 shows the release probabilities for rail and road as estimated by the various sources for each of the three materials being transported (chlorine, LPG, and gasoline). The probabilities assume a prior occurrence of an accident involving a road or rail tanker carrying the designated hazardous material. All models yield release probabilities that are insensitive to section-specific conditions. The models do not appear to yield consistent results as to which mode is more likely to produce a release in an accident situation. Model A suggests significantly higher release probabilities for rail, by a factor of 2.1 for LPG and 4.8 for chlorine. For gasoline, Model A suggests lower release probabilities for road by a factor of 0.8. Whereas most models suggest slightly higher release probabilities for rail than for road, even these results are not consistent for all sources and materials.

Uncertainty in the estimates of release probability renders difficult any conclusions on the relative likelihood of accident-induced releases between the two modes. For chlorine, LPG, and gasoline, an average of 6.5, 8.0, and 18 percent of rail tanker accidents, respectively, result in some type of release. This can be compared with release percentages on road of 2.5, 5, and 18 percent, respectively, for chlorine, LPG, and gasoline. It would appear from these results that material-specific tanker design features are instrumental in explaining variation in accident-induced release probabilities for both road and rail. These results also suggest that the approach

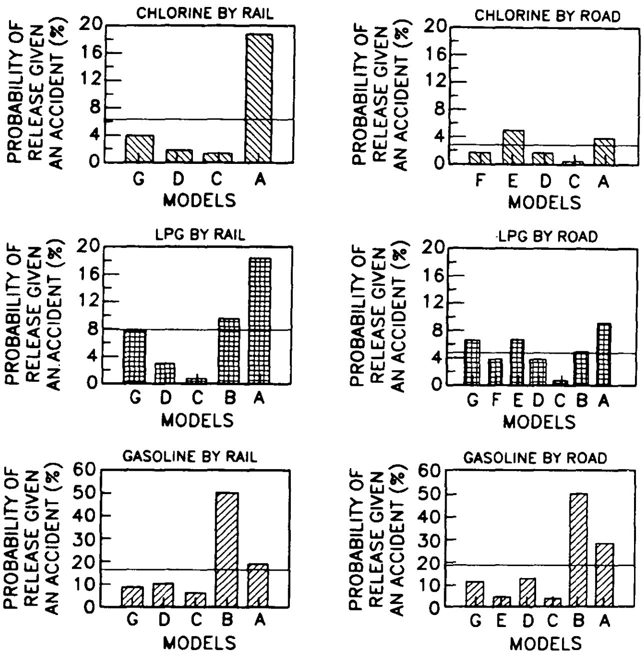

FIGURE 3 Probabilities of hazardous material release per rail and road accident.

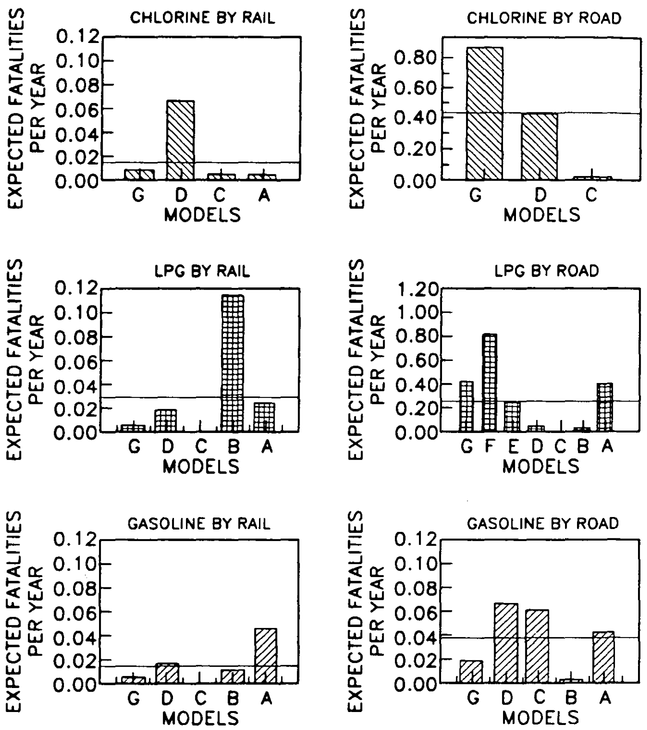

FIGURE 4 Societal risk by mode for chlorine, LPG, and gasoline.

adopted in many studies to lump information on release probabilities for all material types could contribute to significant variability in the estimates depending on the nature of the release data.

Variability in hazard areas was significant among the various sources. Given the complexity of the dispersal relationships and the as yet unaccounted for assumptions, this result was not entirely unexpected. A wide range of hazard area profiles was reported for different materials and shipment conditions. Many applicants based their estimates on assumptions that did not lend themselves to a common basis of comparison. As a result, these estimates have not been presented in this paper.

Societal risk in this analysis is defined in terms of the expectation of fatalities on each mode over the entire length of the corridor for 1 year of shipment activity for each of the three materials. As shown in Figure 4, some variability is present in these values. Much of this variability, however, may be accounted for by differences in one or two model results. For the rail shipment of chlorine, LPG, and gasoline, Models A, B, and D yield values significantly higher than the average. Models C and G were consistently lower than the average for all materials. The ratio of variability between the lowest and highest reported values for chlorine, LPG, and gasoline are 8.5, 14.8, and 5.0, respectively. These values exclude the negligible values reported by Model C for this exercise. Similar results were obtained for societal risks by road. The ratio of variability between the lowest and highest estimate is 2.0 for chlorine, 21.8 for LPG, and 3.8 for gasoline.

All models are consistent in estimating lower material-dependent risks for rail than road. On the average, the annual expected fatality risk for chlorine shipment by rail is 0.02, compared with 0.6 for road. For LPG, the average risk by rail is 0.04 compared with 0.30 by road. For gasoline, the average rail risk is 0.02 compared with 0.04 by road. These risks account for lower per tanker payloads and a higher number of shipments on road relative to rail. This analysis was carried out for comparable population/employment distributions and a mix of environmental conditions along each route.

Despite consistency in predicting lower societal risks by rail, significant variability among the models raises some concerns regarding the true nature of the threat posed and how it can best be reduced. It is questionable whether cost-effective safety policies can be established and justified without first accounting for this uncertainty.

Individual risk is defined in terms of the distance from an incident required to sustain a certain chance of death for 1 year of shipment activity. These results are shown in Figure 5 for those models that were able to provide the information. Most models yield reasonably close results, which is surprising given the variability present in the elements of the individual risk estimate. In general, the rail mode reflects more extensive individual risk isolines than road. This is expected given the larger volume of material being transported by each rail tanker. The important point to observe is that all individual risk estimates are essentially de minimus given a standard level of acceptability of one chance per million per year (the chance of being struck by lightning).

The 95 percent confidence intervals were established on each risk component estimate for each mode. The results are summarized in Table 1 for the transport of LPG by rail and road.

The results in Table 1 suggest that for both rail and road many of the source estimates are outside the 95 percent confidence intervals for each of the selected risk components, including societal risk. The source models, themselves, exhibit

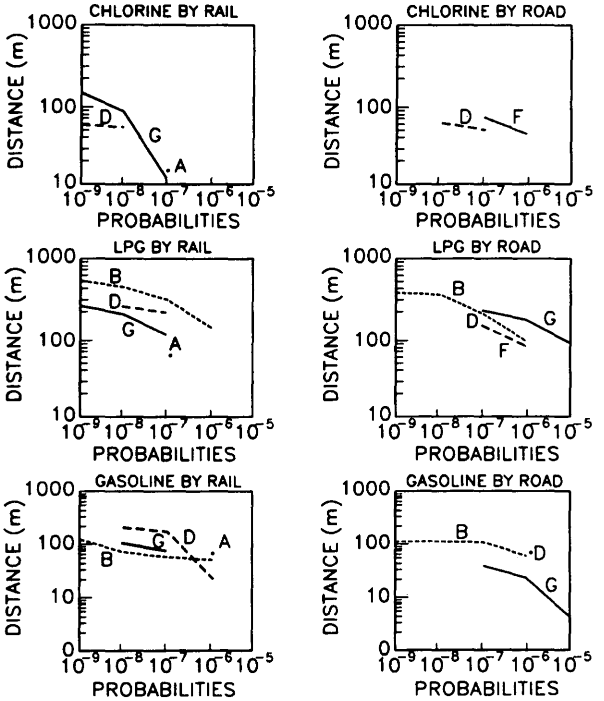

FIGURE 5 Individual risks for rail and road for chlorine, LPG, and gasoline.

some inconsistency as to whether specific risk estimates are within or outside the 95 percent limits. Variability in societal risks is particularly problematic for road transport, where four of the reported five values are outside the confidence limits. For rail transport only one reported societal risk value is outside the established upper limit.

These results suggest a canceling out of errors in estimating societal risks for the various participating groups. Whereas several estimates of societal risks were found to lie within the 95 percent confidence interval, the same groups may have obtained values of accident rates and release probabilities (constituents of societal risk) that were outside the 95 percent intervals. Conversely, several groups failed to satisfy the 95 percent criterion for societal risk despite obtaining acceptable values for the risk constituents, accident rate and release probability.

Analysis of the Significance of Model Variability

A number of risk component estimates were obtained by applying various models to the transport of LPG by road and rail along the sample corridor. The results of these calculations are used as seed points in a hierarchical cluster analysis of the models into groupings of consistent estimates. The distance metric for this clustering exercise is euclidean and makes use of Ward's minimum variance method.

TABLE 1 Confidence Intervals on Selected Risk Estimates for the Transport of LPG by Rail and Road

Rail Transport

Accident Rate	Release Probability	Large Release Probability	Societal Risk
0.37	0.19 *	0.30	2.50
0.14	0.10	0.03 *	11.70 *
0.11	0.01 *	0.50	0.07
0.46 *	0.03	0.86*	1.90
0.06 *	0.08	0.10	0.56
Mean 0.23	0.08	0.36	3:35
SD 0.17	0.06	0.30	4.27
<u>95% Confidence Intervals</u>			
0.09 - 0.37	0.03 - 0.14	0.10 - 0.62	- 0.40 - 7.09

Road Transport

Accident Rate	Release Probability	Societal Risk
2.60 *	0.09 *	0.41
0.31	0.05	0.04 *
0.70	0.01 *	0.002 *
0.58	0.04	0.04 *
0.35 *	0.07	0.26
0.84	0.04	0.82 *
2.60 *	0.07	0.43
Mean 1.14	0.05	0.29
SD 0.94	0.03	0.27
<u>95% Confidence Intervals</u>		
0.44 - 1.84	0.03 - 0.07	0.08 - 0.49

* Estimates outside the 95% limits.

The primary purpose of the cluster analysis is to assign individual models to larger groups on the basis of consistency of results for an array of risk component estimates. The previous graphical analysis was able to assess consistency visually for individual estimates taken one at a time. The cluster analysis is able to account for variations in a more extensive set of risk estimates. Models that failed to provide complete estimates for at least one seed point were not considered in this exercise. For road transport, seven models provided comparable estimates for all the risk components used in this cluster analysis. For rail transport, five models were used. Input values for this exercise are summarized in Table 2 for both the rail and the road modes.

Figure 6 shows the dendrograms for rail and road LPG transport. The dendrograms represent the sequence of linkages between the various models, based on their risk component estimates. A certain degree of intuitive judgment is applied in setting the most appropriate cutoff for distinct groupings. For road transport, the models that reflect the closest initial linkage are Models F and D, Models B and E, Models A and G, and Model C in its own group. At the next higher level, Models B, D, and E can be assigned to a single group. Models A and G continue to be linked together, and Model C continues to comprise its own cluster. Model C joins Models B, D, and E at the two-cluster cutoff. For the road transport of LPG, it appears that, with the exception of Model D, the seven models reporting results can be clustered into a decided North American–European pattern.

For rail transport only five models were grouped. Again the cutoff value is intuitive rather than statistical and is subject to some divergence of interpretation. Nevertheless, the results appear to differ significantly from the pattern associated with road. Models B and G link first, followed by Models A and C, and finally Model D standing alone. Model D continues to occupy its own cluster, well after all the other models have been clustered together.

From this analysis, it remains unclear whether more complex models yield results that differ significantly from simpler formulations. All clusters appear to include models of both types. Models that used fault trees to analyze release probabilities do not yield results that differ from models that obtain their estimates directly from data. Finally, the use of data from similar jurisdictions (as is the case for Models D and G) gives no assurance that the results will also be similar. In general, the patterns suggested by this exercise are difficult to explain in terms of what is known a priori about these models.

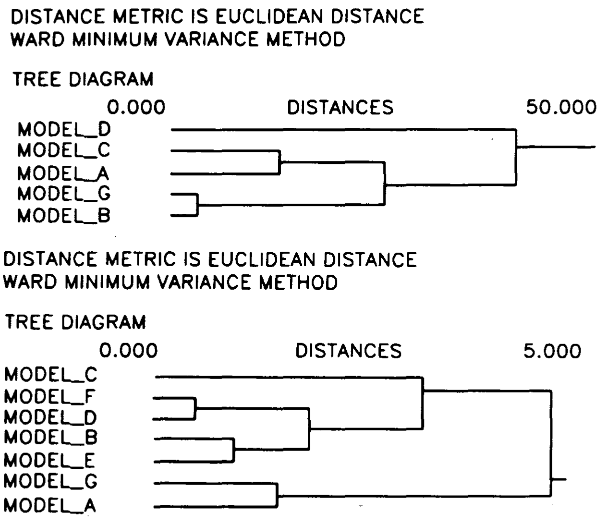

FIGURE 6 Dendrograms for LPG transport: *top*, rail; *bottom*, road.

The results of a three-way analysis of variance of the model estimates are summarized in Tables 3, 4, and 5 for accident rates, release probabilities, and societal risks for road and rail, respectively. At the 5 percent level of significance, the results in Table 3 indicate that accident rates vary by mode and model source. Rail accident rates are significantly lower than road accident rates for all route sections. Individual route sections did not yield statistically different rates for each of the two modes. These results suggest statistically significant

TABLE 2 Risk Input Values to the Cluster Analysis for Road and Rail LPG Transport

Rail Transport

Risk Model	Accident Rate (X 10^{-6})	Release Probability (% of Accident)	Large Release Probability (% of Releases)	Societal Risk E (F/Yr)
MODEL A	0.37	19.0	30.0	0.025
MODEL B	0.14	10.0	3.0	0.117
MODEL C	0.11	1.0	50.0	0.001
MODEL D	0.46	3.2	86.0	0.019
MODEL G	0.06	8.1	10.0	0.006

Road Transport

Risk Model	Accident Rate (X 10^{-6})	Release Probability (% of Accident)	Societal Risk E (F/Yr)
MODEL A	2.60	9.2	0.410
MODEL B	0.31	5.0	0.039
MODEL C	0.70	0.6	0.002
MODEL D	0.58	3.7	0.038
MODEL E	0.35	6.6	0.261
MODEL F	0.84	3.7	0.820
MODEL G	2.60	6.6	0.429

TABLE 3 Results of Three-Way Analysis of Variance for Accident Rates for Rail and Road

Rail Transport

	Route Section		
Model Source	Rural	Suburban	Urban
MODEL A	0.37	0.37	0.37
MODEL B	0.14	0.14	0.14
MODEL C	0.11	0.11	0.11
MODEL D	0.48	0.48	0.20
MODEL G	0.07	0.05	0.02

Road Transport

	Route Section		
Model Source	Rural	Suburban	Urban
MODEL A	1.30	4.50	7.70
MODEL B	0.20	0.50	0.70
MODEL C	0.67	0.70	0.83
MODEL D	0.47	0.76	1.00
MODEL G	2.50	2.90	3.20

ANOVA Summary Statistics

	F - Ratio	Tail Probability
Route Section	0.970	0.395
Model Source	3.006	0.040
Mode of Transport	12.537	0.002

Accident Rates (x 1.0 E -06) per Vehicle Kilometer for LPG Transport

TABLE 4 Results of Three-Way Analysis of Variance for Release Probabilities for Rail and Road

Rail Transport (Units % of Accidents)

	Material in Transit		
Model Source	Chlorine	LPG	Gasoline
MODEL A	19.0	19.0	17.6
MODEL B	1.0	1.0	5.1
MODEL C	1.6	3.2	9.5

Road Transport (Units % of Accidents)

	Material in Transit		
Model Source	Chlorine	LPG	Gasoline
MODEL A	4.0	9.2	27.7
MODEL B	0.4	0.6	3.2
MODEL C	1.6	3.7	12.0

ANOVA Summary Statistics

	F - Ratio	Tail Probability
Material	5.334	0.022
Model Source	16.622	0.000
Transport Mode	0.596	0.455

Probability of Release Given an Accident

TABLE 5 Results of Three-Way Analysis of Variance for Societal Risks for Rail and Road

Rail Transport (Units: Expected Fatalities per Year).

Model Source	Material in Transit Chlorine	LPG	Gasoline
MODEL D	67.00	19.00	15.80
MODEL C	4.20	0.68	0.17

Road Transport (Units: Expected Fatalities per Year).

Model Source	Material in Transit Chlorine	LPG	Gasoline
MODEL D	431.00	37.70	61.00
MODEL C	9.70	2.30	2.90

ANOVA Summary Statistics

	F - Ratio	Tail Probability
Material	1.410	0.306
Model Source	2.693	0.145
Transport Mode	1.380	0.279

Expected Fatalities (x 1.0 E -3) per Year

differences in accident rates, depending on model source for rail and road transport.

The results in Table 4 suggest that at the 5 percent level of significance, variations in accident-induced release probabilities depend on the material transported and on model source. These probabilities do not appear to be affected by the mode. Differences in release probabilities by mode of transport from the previous graphical analysis appear to be random, after the material type and model source have been taken into account.

The analysis of variance results for societal risks in Table 5 are most interesting. At the 5 percent level, variations in societal risks are not dependent on material type, mode of transport, or model source. When all model estimates and materials are taken into account, the lower societal risks for rail suggested by the previous graphical analysis do not appear to be significant. Given the significant variations in accident rates and release probabilities as explained by material type, mode, and model source, it is interesting that societal risk estimates are unaffected by these same factors. Both accident rates and release probabilities are inputs into societal risk.

Is uncertainty a problem for risk estimation? Are the various model sources consistent in the estimation of societal risk, as suggested by the above ANOVA? The results of the ANOVA must be viewed simply as a case of compensation in random errors for a unique transportation corridor exercise. Despite these results, inconsistencies in model sources remain a problem in risk estimation. The whole must be viewed as the sum of its parts. A statistically significant variation in any one of the risk input factors must be viewed as a significant variation in the final risk product.

CONCLUSIONS

The analysis of risk estimation variability among different models suggests the following conclusions:

1. Much of the variability in risk estimation can be accounted for by differences in underlying assumptions, data, and model structure. However, even when many of these factors are taken into account in a common transport problem, significant variability in the estimates was found to be present.
2. Grouping the models into similarities in risk component estimates failed to reveal any pattern among the models themselves. It cannot be concluded that more complex models yield results that differ significantly from simpler formulations or that consistency is more readily obtained when models are calibrated for similar data bases and jurisdictions.
3. Whereas differences in risk component estimates were significant, the various estimates of societal risk for the chosen transport problem were similar. Much of the unexplained variability in risk component estimates appears to have canceled itself out in the final risk estimate (i.e., societal risk). This finding may be unique to the chosen transport problem. Furthermore, it underscores the fact that a simple sensitivity analysis on the final risk estimate, as is often done in this type of study, would show consistency in the estimates by model source where no such consistency is present.

Risk estimation is plagued by problems of inconsistency in the various model sources. Many of the inconsistencies cannot be fully accounted for by controls on assumptions and input data. In the interest of more informed decision making and public credibility, uncertainty in risk estimation must form an integral part of the overall risk analysis process.

The results of this corridor analysis should be viewed as a useful first step in understanding the extent of variability in the risk estimates from different model sources. In this way, effective action can be taken to account for this variability in the reporting of risk analysis results.

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The purpose of this paper is not to comment on the validity of one set of estimates over another, but only to point out the pattern of differences where they occur. The reasons for these differences are best provided by those who carried out the analysis.

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