Communication and Interpretation of Results of Route Risk Analyses of Hazardous Materials Transportation by Railroad

Athaphon Kawprasert and Christopher P. L. Barkan

Route risk analysis of hazardous materials transportation by railroad is receiving considerable new attention from industry and government. Such analyses are necessary for effective public policy and development of rational risk management strategies. However, route risk analysis is complex and generates results that can be difficult to properly interpret. Risk analyses are intended to provide risk managers with objective information about how to effectively manage risk and the most effective options to reduce it. This paper uses results from a quantitative risk analysis of hazardous materials shipped by rail to develop and illustrate several new techniques to present, interpret, and communicate risk results more effectively. The analysis accounted for the major factors affecting risk: infrastructure quality, traffic volume, and population exposure along shipment routes, as well as tank car design and product characteristics. Approaches for system-level and route-specific analyses are presented. Both absolute and normalized estimates of risk provide useful information. The question of interest and the user affects which type of information is most useful for effective decision making. Various graphical techniques enable risk metrics to be compared and contrasted, either in a geographic context or independent of it, depending on which is most useful. Identifying the locations that account for the highest concentration of risk and understanding the contributing factors will also clarify the mutual roles of carriers, shippers, and municipalities along a route in regard to risk management, reduction, and mitigation options. In addition, the techniques presented in this paper may also be useful for regulators and researchers who might be interested in a broader view of risk analysis at the network level.

The risk associated with rail transport of hazardous materials is an ongoing subject of interest to industry, government, and the public. A variety of approaches have been considered or adopted to manage and reduce this risk, including special operating practices to reduce the likelihood or severity of accidents (*1*), improve training of personnel (*2*), and enhance tank car safety design (*3–9*). Another approach receiving considerable attention is rerouting of hazardous material shipments (*10–14*).

Rerouting hazardous materials shipments with the objective of reducing risk is complex because of the many variables that interact to affect risk. Quantitative risk analysis (QRA) of hazardous material transportation dates to the 1970s. Although advances in methodology continue, QRA has matured to the point that it is an effective tool and has been used to inform decisions in a variety of contexts. However, risk analysis, especially route-specific analyses, often requires sophisticated analytical techniques and large quantities of data and can produce a bewildering number of numerical results. The challenge for risk analysts is to interpret these large quantities of results and convert them into useful information and effectively communicate with risk managers and other interested parties (*15–17*).

In 2008 the U.S. Department of Transportation issued the interim rule HM-232E, requiring U.S. rail carriers to gather information on the products, routes, and risk factors related to shipments of toxic inhalation hazard (TIH) materials and to determine the security risks to high-consequence locations. Consequently, railroads and government are now engaged in the process of conducting large-scale route risk analyses and will soon be in the position of having to interpret the results and consider their effect on policy. The purpose of risk analyses is to provide decision makers and others with objective information about how to effectively manage risk. In some instances, it may also be used to help gain an understanding of how to most efficiently choose among options to reduce risk. If the results are too complex to understand or are presented in a manner that is prone to misinterpretation, these objectives will not be achieved and could lead to inappropriate conclusions and decisions. The objective of this paper is to illustrate some of the approaches to the presentation of route risk analysis results that will aid in their proper interpretation and communication.

The results used in this paper are based on a case study of shipments of one hazardous material on the North American railroad network. A review is presented of the basic risk analysis method used, but more complete descriptions of risk analysis methodologies can be found elsewhere (*18, 19*). The primary purpose here is to use the results to illustrate the techniques that have been developed to organize and present results to enhance communication and interpretation. Different metrics and approaches to normalization of the results are introduced to allow insight into risk management and planning. A number of new graphical methods have been developed to enhance communication of the risk results and to facilitate more effective consideration of risk mitigation options. A graphical approach to evaluate the

A. Kawprasert, B-118 Newmark Civil Engineering Laboratory, and C. P. L. Barkan, 1203 Newmark Civil Engineering Laboratory, Railroad Engineering Program, Department of Civil and Environmental Engineering, MC-250, University of Illinois at Urbana–Champaign, 205 North Mathews Avenue, Urbana, IL 61801. Corresponding author: A. Kawprasert, akawpra2@illinois.edu.

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benefits of track infrastructure improvement is presented for illustrative purposes, but emphasizing any particular alternatives for risk reduction is not the intention in this paper.

This study aims to help risk managers evaluate and identify the most effective risk management options, that is, the use of resources that will provide the most efficient means of improving safety. Identifying the critical locations on each lane that account for the highest concentration of risk and understanding the most important contributing factors will facilitate more effective consideration of how to best manage distribution risk. It will also help clarify the mutual roles of carriers, shippers, and municipalities along a route concerning risk management, reduction, and mitigation options. The techniques presented in this paper can also be used by regulators and researchers who may be interested in higher-level questions involving multiple carriers and commodities.

SCOPE OF STUDY

The hazardous material traffic considered in this study consists of transportation routes from a single origin traveling to eight different destinations (Table 1). The eight lanes involve trackage owned by several railroads, including three different Class 1 railroads and two non–Class 1 railroads. The major factors affecting risk considered in this analysis are segment-specific track infrastructure, traffic volume, and population exposure along the shipment lanes. Tank car design and product characteristics represent constants in the analysis.

REVIEW OF RISK ANALYSIS METHODOLOGY

Quantitative risk assessment (QRA) methodology was used to develop numerical estimates of risk (*18, 19*). The analysis includes three principal stages: lane analysis, determination of risk parameters, and risk calculation.

For the first stage, the preliminary shipment lanes were determined using rail routing software, PC*Miler|Rail 13, based on the specified origin–destination and intermediate location points. Geographic information system (GIS) data layers were then obtained and prepared using GIS software, ArcGIS Desktop 9.2. These data layers include U.S. and Canadian railroad network data (*20*) and population census data (*21*). After the preliminary lanes had been determined, the final shipment lanes were created using ArcGIS. In addition to GIS' analytical power for handling the data needed for route risk analysis, use of GIS enables the creation of maps to convey geographic information and results related to risk (*22*).

The second stage involved estimation of risk parameters. This consisted of two parts: the estimation of the annual frequency of accident-caused releases and the consequences of the release. The former deals with estimation of lane-segment-specific tank car derailment probability and release rates. The latter involves estimation of the consequence in regard to the number of people affected.

The final stage is to determine annual risk associated with hazardous materials shipments for each lane and for all lanes combined. The final risk output comprises the quantitative estimate of various risk metrics. In addition, several types of graphical output were developed to improve the usefulness of quantitative risk estimates for risk managers and to enhance the communication of the risk results.

RISK MODEL AND PARAMETERS

A formal definition of risk is the multiplication of the frequency of an event times the consequence of that event. In this study, risk was defined as

$$S = MRC \tag{1}$$

where

S = annual risk of transporting product (persons affected per year),
M = annual rate of tank car involvement in Federal Railroad Administration (FRA) reportable derailment on main-line track,
R = conditional probability of release given that a tank car derails, and
C = consequence level, defined as the annual expected number of persons affected.

FRA track-class-specific accident rates were used to determine M (*23*), and it was assumed that the likelihood of hazardous materials car derailment is independent of the material being transported (*24*). Track speed reflects FRA track class, which has been shown to be correlated with railroad accident rates (*25*). For the Class 1 railroads involved, their timetable speeds were used to infer the FRA track class and other operating restrictions for all segments of the lanes considered. For the limited mileage of non–Class 1 railroads involved, the industry average derailment rate for this class of railroads was used (*23*).

TABLE 1 Shipment Lanes

Origin–Destination	Annual Shipments (carloads)	Estimated Mileage	Car Miles	Railroad Carriers: Class I	Railroad Carriers: Non–Class I
L-A	702	2,228	1,564,056	RR-1	RR-4
L-B	162	1,064	172,368	RR-1	—
L-C	75	1,403	105,225	RR-1	RR-4
L-D	42	1,966	82,572	RR-1, RR-2	—
L-E	33	2,048	67,584	RR-1, RR-2	RR-5
L-F	16	1,396	22,336	RR-1	RR-4
L-G	13	2,463	32,019	RR-1, RR-2	—
L-H	11	1,978	21,758	RR-1, RR-3	—

Tank car design has a major effect on conditional probability of release given that a car is derailed in an accident, and the probabilities developed by Treichel et al. were used to determine R (*26*). Release probability is also affected by train accident speed (*27*). In the analyses presented here, the average speed implicit in the statistics of Treichel et al. was assumed when calculating tank car performance. That has the effect of underestimating risk on track segments whose average speed is higher than the average implicit in Treichel et al. and overestimating risk on segments with lower than average speeds. Ultimately, route-specific estimates of risk should take speed into account when R is calculated, but robust statistics needed to properly account for this effect are not presently available. This limitation does not interfere with the objectives of this paper. The study involved multiple car types with different design features, thus the aggregated conditional probability, R', was computed using the weighted mean of the different car types' conditional probabilities.

The consequence, C, is the impact of the release and is generally affected by the characteristics of the product (e.g., its toxicity and reactivity), atmospheric conditions, and proximity of people to the spill. In this study the consequence is expressed as the number of persons who might be evacuated or sheltered in place as a result of a release based on the recommendations in the U.S. Department of Transportation *Emergency Response Guidebook* (ERG) (*28–30*). The consequence here equals the affected area, A, which is defined as the minimum area in which the U.S. Department of Transportation recommends that people be evacuated or sheltered in place in a hazardous materials release incident, multiplied by the average population density in the affected area, D. For some materials, consideration of multiple release scenarios may be necessary; however, for the product studied here, only a single release scenario was analyzed.

Lane segments correspond to the rail links in the railroad network data layer in the GIS database (*20*). Each link (segment) has a unique link ID assigned by the FRA in the rail network. For the shipment lane comprising n segments, Equation 1 can be rewritten as

$$S = VR'A\sum_{i=1}^{n} Z_i L_i D_i \qquad (2)$$

where

V = annual shipments (carloads),
R' = aggregated conditional probability of release given that a tank car derails,
A = affected area per U.S. Department of Transportation ERG recommendation,
Z_i = accident rate associated with lane segment i,
L_i = length of lane segment i,
D_i = average population density along lane segment i, and
n = total number of segments in shipment lane.

Different levels of analysis can be considered depending on the degree of precision required. That is, accident rate and population density may be accounted for at the route level or the lane segment level. The model formulation in this paper considers lane-segment-specific parameters in the risk analysis. The diagram in Figure 1 provides an overview of the principal input factors and the relationship between factors affecting hazardous material transportation risk and summarizes the risk analysis framework for this study.

OVERLAY ANALYSIS USING GIS

ArcGIS 9.2 with the Network Analyst feature was used to create the shipment lanes over the national railroad network and population census tract layers. A buffer was created representing the exposure area—the area within the radius from track center equal to the U.S. Department of Transportation ERG maximum evacuation distance. Then, the average population density of the affected area (A) corresponding to each lane segment was determined (Figure 2) using Equation 7:

$$A = \pi E^2 \qquad (3)$$

where $\pi \approx 3.14159$ and E is the U.S. Department of Transportation ERG–recommended evacuation distance for the worst-case release scenario.

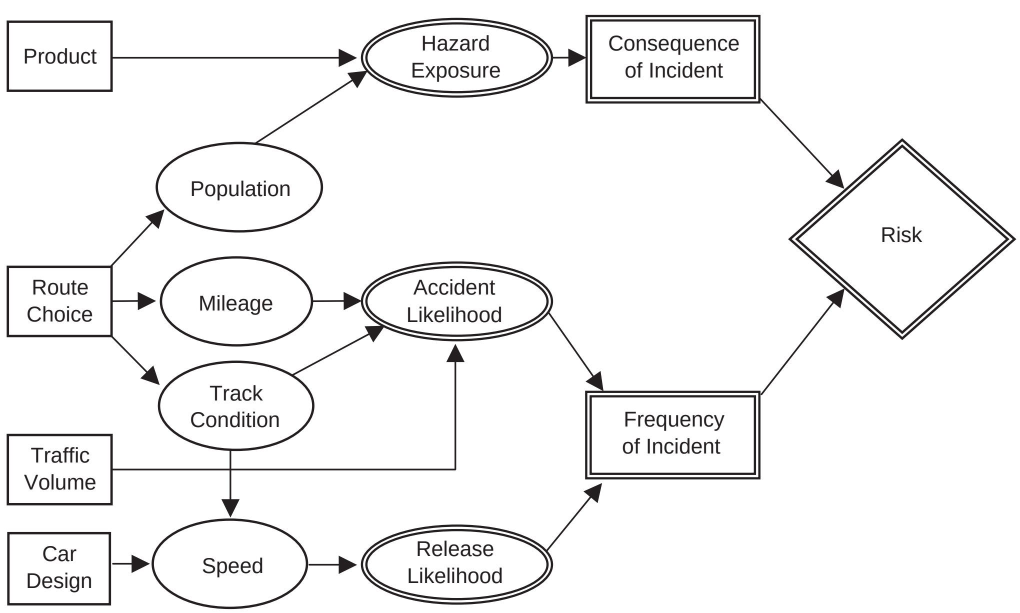


FIGURE 1 Factors and relationships influencing railroad hazardous material transportation risk.

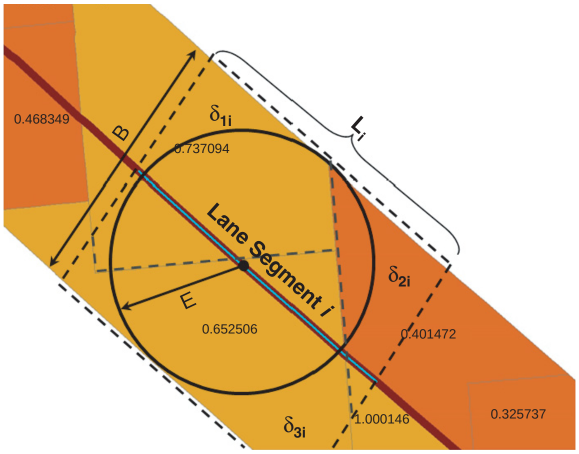


FIGURE 2 Estimation of consequence using overlay analysis in GIS.

$$\text{exposure area, } U_i = BL_i \quad (4)$$

where B equals the buffer width equals $2E$.

$$\text{population exposure, } P_i = \sum_t (\alpha_{ti}\delta_{ti}) \quad (5)$$

where

$$\alpha_{ti} = \text{area of census tract } t \quad (6)$$

coincident with the exposure area for lane segment *i,* and δ_{ti} equals population density of census tract *t,* coincident with the exposure area for lane segment *i.*

$$\text{average population density, } D_i = \sum_t (\beta_{ti}\delta_{ti}) \quad (7)$$

where β_{ti} equals proportion of the area of census tract *t,* coincident with the exposure area for lane segment *i.*

PARAMETER ESTIMATES, NORMALIZATION, AND REPRESENTATION OF RISK

Based on different safety design features of the tank cars considered and the proportion of each tank car type, the aggregated conditional probability of release given that a tank car derails is $R' = 0.1357$. For the single release scenario considered, an affected area that corresponds to the ERG-recommended evacuation distance for the hazardous material studied is $A = 0.785$ mi^2. Time-of-day effects on population were not considered here for purposes of simplicity.

Some risk questions require knowledge of absolute measures of risk, whereas others are more effectively considered if the metrics are normalized using mileage, carload volume, or car miles, depending on the particular question or comparison being made. In addition, several graphical techniques were developed to aid in the visualization of distribution of risk on or along each lane (Table 2).

TABLE 2 Types of Graphical Illustrations of Risk Results

Name	Description
Lane comparison using different normalization metrics (Figures 3*a* and 3*b*)	Annual risk is plotted along with the factors affecting risk (accident rate and population exposure) to visualize the order of magnitude of risk and the factors simultaneously affecting risk for each shipment lane in the network. Furthermore, normalization using different metrication is applied to both of these to understand how the metrics affect the order of magnitude of risk as well as the factors affecting risk for each lane.
Distribution of risk by segment (Figures 4*a* and 4*b*)	This type of chart shows the lane-segment risk ordered by risk magnitude and the cumulative percentage of total risk. Normalization may be applied to show the risk estimates per unit of interest. These charts enable easy identification of the highest risk segments and facilitate understanding of the percentage of risk that is due to any particular number of segments; rank ordered from highest to lowest.
Risk estimates on network map (Figures 5*a* and 5*b*)	Network maps showing segment-specific risk estimates help indicate critical locations with relatively high accident rates or risk on the entire shipment network structure. This information may be useful for collaboration between chemical shippers, railroad carriers, and municipalities to develop appropriate, mutually satisfactory risk reduction strategies.
Risk increment with travel distance and lane segment risk grouped by percentage of total risk (Figure 6*a*)	This chart shows the plot of cumulative annual risk versus the mileage along the shipment lane. The locations where significant changes in risk occur are readily apparent. On the same chart, the lane segment risk, expressed in percentage of total risk on that lane, is plotted together with the cumulative risk along the distance scale. The segments were divided into groups according to the percent contribution to the total risk so that risk managers can better understand the distribution of low- and high-risk segments.
Effects of risk parameters (Figure 6*b*)	Normalized accident rate, population exposure, and annual risk are plotted on the same scale against the distance axis. This chart attempts to show the effects of each parameter on risk and to help suggest the appropriate risk mitigation approach for critical locations along the shipment lane.
Risk profiles aka “F-N curves”	Risk profiles, or “F-N curves,” depict the likelihood of incidents versus various magnitudes of consequence. In the context of rail hazardous material transportation risk analysis, they show the annual rate or frequency of release incident for different levels of the expected number of persons affected. This helps convey the information on the probability distribution of risk outcomes.
Differential risk profiles (*14*)	Differential risk profiles in which the difference between two risk profiles is expressed as an absolute or a percentage graphed versus the magnitude of the consequences. These enable comparison of two options and facilitate understanding the effects of changes or different options on risk at different magnitudes along the consequence scale.

SUMMARY OF RISK ESTIMATES

Quantitative risk estimates were developed for each individual lane and for all lanes combined (Table 3). These include accident rate (expected number of hazardous materials cars derailed per year), release rate (expected number of releases per year), and annual risk (expected number of persons affected per year). These absolute (non-normalized) estimates provide a basic comparison of each lane, while taking into account the lane-specific characteristics, that is, length, population exposure, and traffic volume.

INTERPRETATION OF RISK RESULTS AND RISK COMMUNICATION

Considerable attention has been given to the general subject of risk communication; however generally this has focused on the policy perspectives of industry or government communicating with one another or the public (*31, 32*). Far less attention has been given to technical interpretation and communication of the complex results that risk analyses may produce. This is particularly challenging for hazardous materials route risk analyses. There will often be many types of information for a variety of routes with unique geographic elements, and several different stakeholder groups, each with its own associated interests and perspectives. Information that is suitable in one context for a particular group may be of little value to others. In the following section several methods intended to help this process are introduced and discussed.

Comparison of Lanes

Absolute estimates of risk such as those presented in Table 3 provide high-level understanding, but more detail is needed to address many types of risk management questions. In part this is because shipment lanes are not compared on the same basis, consequently normalized estimates may be more helpful (Figure 3). There are different approaches to normalization when comparing lanes, for example, population exposure versus risk (Figure 3*a*) and accident rate versus risk (Figure 3*b*), based on the risk results from Table 3 and lane information from Table 1. The normalized estimates offer insight into the risk characteristics for each lane with which different parties involved in the supply chain may be concerned. For example, Lane L-A has the highest overall risk because of its high traffic volume; however, when risk per carload is considered, its rank is much lower. Conversely, Lane L-G appears to have low absolute risk, but in fact it has the highest risk per carload and the highest risk per car mile as a result of the combined effects of distance and population distribution.

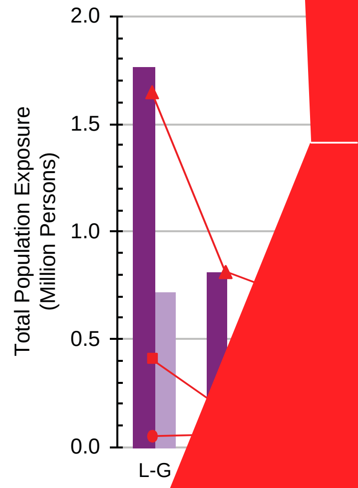
These differences suggest differing strategies for risk management appropriate to the various parties involved with these lanes. Normalized estimates offer shippers insight concerning certain business decisions; shipments to different customers may have widely different levels of risk that could affect pricing. Another question that may arise involves selecting between routes with differing degrees of heterogeneity in risk along a route. This may lead to potentially conflicting objectives among shippers, railroads, and local agencies. Shippers and railroads may prefer to minimize overall risk, whereas local agencies may be more concerned with the consequences in their communities or regions. Each such case will have to be decided individually, but informed decision making will benefit from all parties having a clear understanding of the trade-offs involved. Effective presentation of local versus system-level risk may help put such questions in perspective. Such comparisons may also help communities understand how local risk due to hazardous materials compares with other, more familiar risks.

Combined Shipment Versus Lane-Level Analysis

The following graphical presentations of risk results are divided into two parts: the first considers combined shipment lanes and the second, individual lanes. The principal objective of combined shipment analyses is to identify the highest-risk locations over an entire distribution network. This information is important particularly for risk managers with responsibility for all traffic or an entire network. For shippers, it may facilitate consideration of risk mitigation approaches such as enhanced packaging or alternative routing. Carriers may wish to compare all segments over which they have traffic and identify which ones offer the best opportunity for infrastructure improvement or deployment of technologies that could reduce accident likelihood (*33*). Comparison at this level may also be useful to regulators in making decisions about allocation of inspection resources. Conversely, these comparisons may not be as useful to local authorities along a route, except to help them understand how their communities compare with others.

TABLE 3 Lane Characteristics and Risk Estimates

Lane	Number of Lane Segments	Average Segment Length (miles)	Percentage of Lane Length by Track Class				Annual Accident Rate	Annual Release Rate	Total Population Exposure	Annual Risk
			2	3	4	5				
L-A	1,006	2.20	2	16	46	36	0.174	0.0236	337,268	5.17
L-B	463	2.30	1	12	30	57	0.015	0.0020	72,831	0.19
L-C	613	2.29	1	16	39	44	0.011	0.0015	237,563	0.41
L-D	819	2.40	4	18	45	32	0.011	0.0016	344,740	0.44
L-E	954	2.15	3	21	36	41	0.009	0.0012	818,035	0.68
L-F	598	2.34	1	16	39	44	0.002	0.0003	230,092	0.08
L-G	1,173	2.10	2	15	49	34	0.004	0.0005	1,772,312	0.65
L-H	790	2.50	2	15	39	45	0.002	0.0003	801,821	0.18
Combined	2,635	2.21	3	22	53	22	0.228	0.0309	3,127,268	7.80



ual Segment Comparison

aspects of effectively managing the risk may require more iled understanding at either the system or the lane level. In the e study a small number of lane segments contributed a large por- on of the risk. About 14% of the total number of segments (or 19% of the total length) accounted for 90% of total risk (Figure 4*a*). Closer examination showed that the 20 segments with the highest risk contributed 35% of the total risk, but less than 1% of the total length (Figure 4*b*). Actions that reduce risk on these segments will have a substantially greater impact on reducing risk than would similar improvements on other, lower-risk segments in the carrier's network. Information such as this can help guide certain risk management activities. If cost information is available, these results can be used to develop cost-effectiveness analyses that will further assist in prioritizing actions.

Geographic Comparisons

The preceding approaches help identify the highest relative risk segments; however, they do not provide information in a geographic context. Some types of questions may benefit from that type of consideration. As mentioned above, use of GIS software facilitates production of maps that can help managers visualize the risk associated with different portions of the network being studied. Segment-specific risk accounting for all traffic of a particular material can be portrayed, in this case in regard to absolute and normalized risk

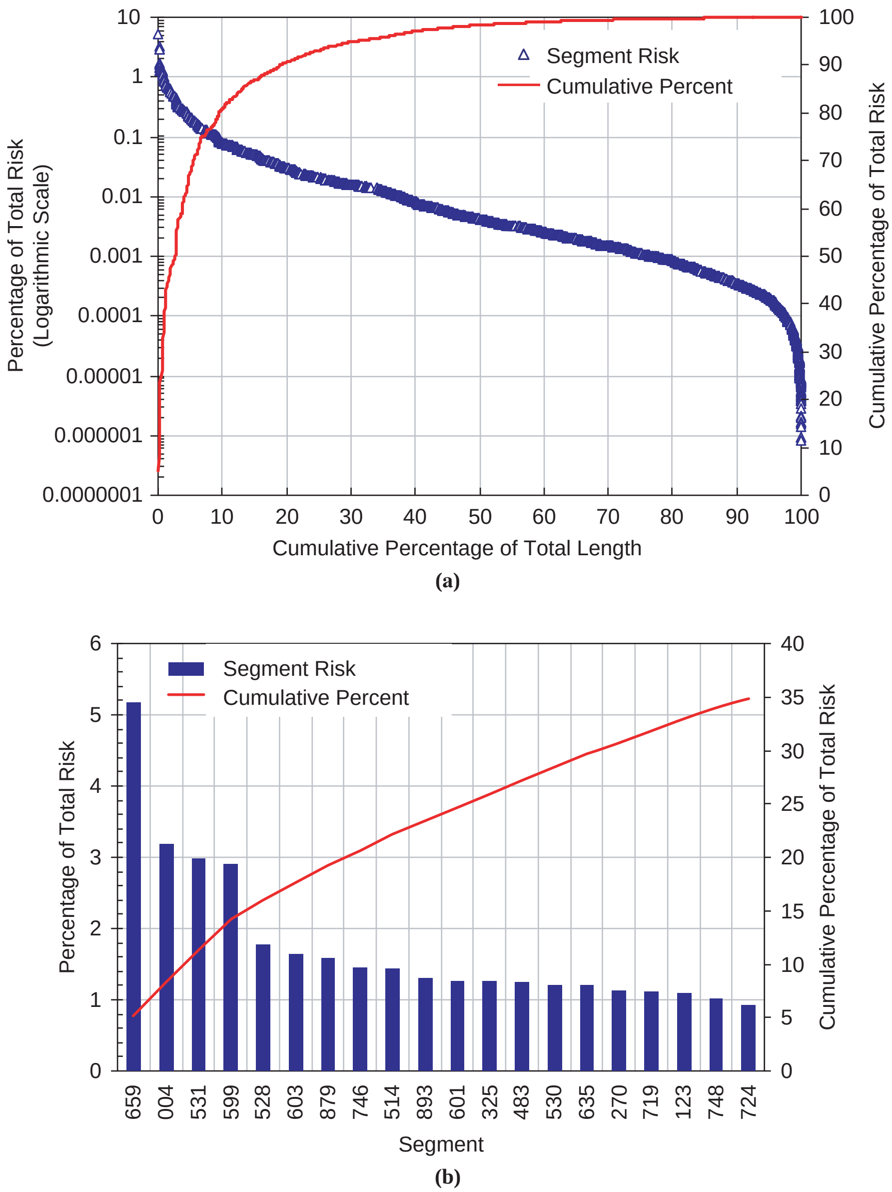


FIGURE 4 Graphical representation of combined lanes risk estimates: (*a*) all segments and (*b*) top 20 segments with the highest risk.

(Figures 5*a* and 5*b*, respectively). Darker segments indicate those with higher risk. For absolute risk, shipment volume and segment length are accounted for in the risk calculation. Normalized risk is the absolute risk divided by the car miles on the segment, and thus the distribution of risk on several critical segments differs from the former one. The merit of this is to provide appropriate and useful information for the parties who may need different information. For example, on the basis of the authors' experience it is likely that the graphic depicting the absolute risk estimate (Figure 5*a*) is more useful for shippers interested in knowing where and how much their own current or anticipated shipments are contributing to risk. However, railroads responsible for infrastructure quality and operation may be interested in track-segment condition and risk distribution throughout their networks regardless of shipment volume, the differential segment lengths, or both. Therefore, they may find the normalized estimates (Figure 5*b*) more appropriate and helpful for infrastructure and operational improvement planning.

Although these maps are useful for some types of information, they impose certain constraints in understanding the relative risk along a route. Other approaches that combine a geographic element with differences in risk magnitude can be useful in helping risk managers visualize quantitative, lane-specific risk information. Figure 6*a* portrays lane-segment risk data divided into two groups with high- and low-risk segments plotted on a log scale, versus mileage from origin to destination. In this example the segment-risk-level threshold for the different symbols is 0.1% of the total risk, that is, individual segments contributing more than 0.1% were plotted using dark-colored triangles, and those with less, using light-colored circles. This technique clearly highlights the areas along the route that are contributing most of the risk. In this case, 77% of lane length

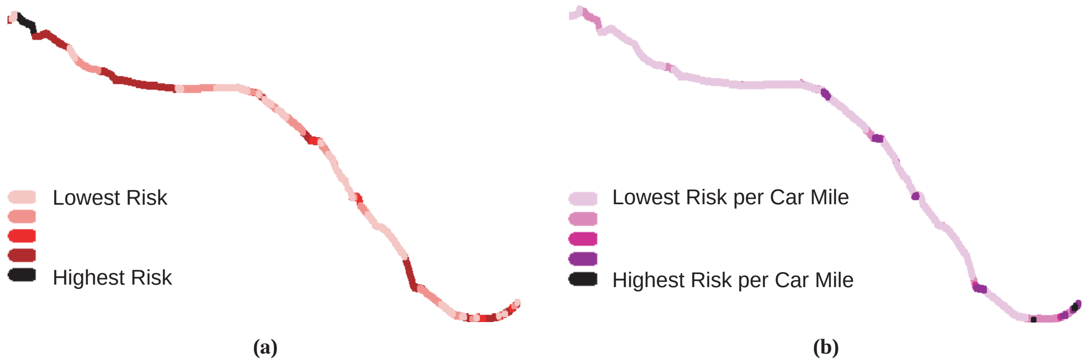


FIGURE 5 Map showing track segment-specific risk based on (*a*) absolute risk estimates and (*b*) risk per car mile.

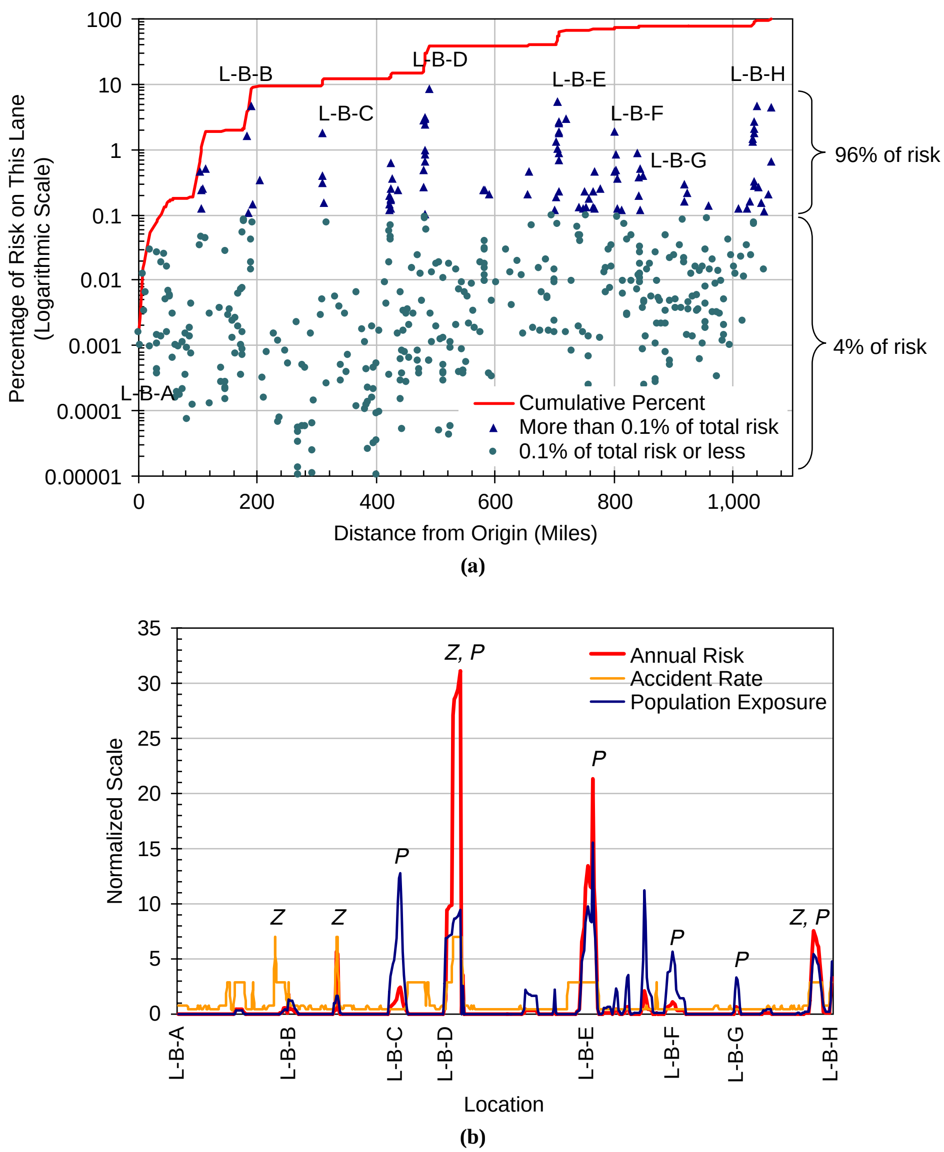


FIGURE 6 Graphical representation of lane-specific risk estimates: (*a*) lane segment risk grouped by percentage of total risk and (*b*) effects of risk parameters.

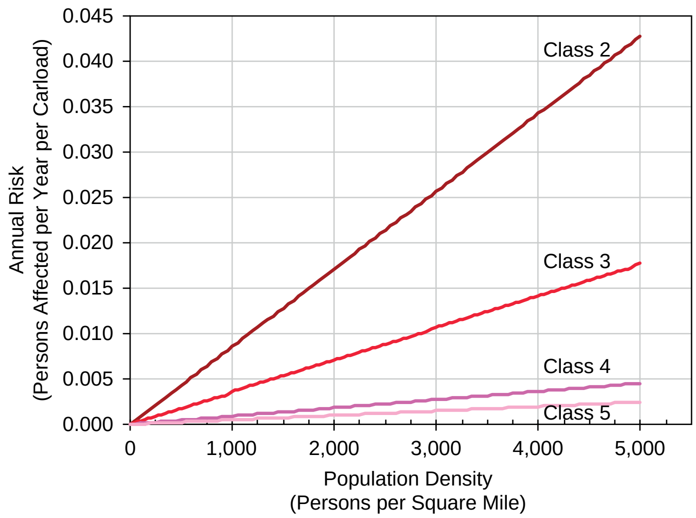
accounted for only 4% of risk, and 23% of the lane accounted for 96% of risk. The solid line indicates the cumulative percentage of total risk proceeding from origin to destination along the route. Locations with substantial changes in risk are indicated with abbreviations signifying specific points along the route.

Risk Factors

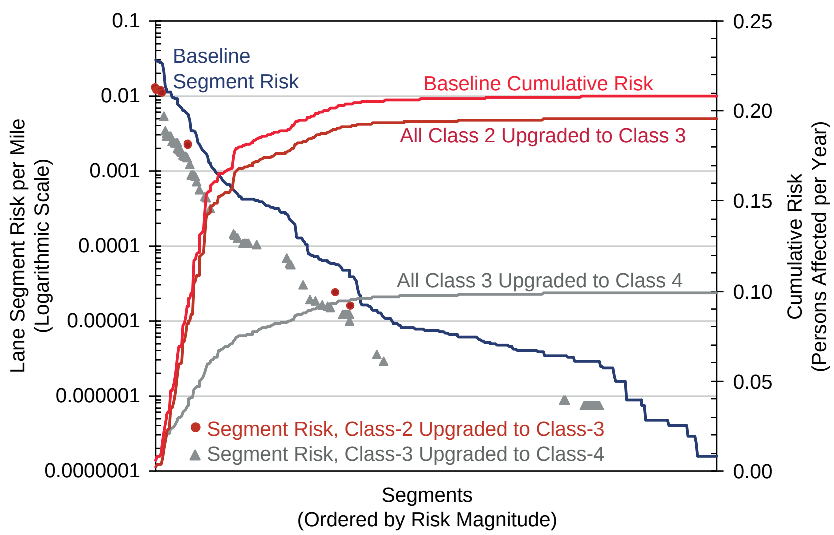
Results such as these lead to questions about what is affecting the elevated risk at various locations along the route. In this example the product and tank car were constant throughout the route so the two factors affecting the heterogeneity in risk are accident probability (which infers infrastructure quality) and population density. Either or both of these may be contributing to the elevated risk at particular locations. Figure 6*b* is intended to help risk managers visualize the degree to which each parameter is influencing localized risk. The letter "*Z*" on the chart indicates that risk is influenced mainly by accident rate, whereas "*P*" indicates locations where population is the major factor. Such information may suggest the most appropriate risk management strategy to consider for different locations, in particular where to consider infrastructure upgrades, operational changes, or emergency response training and planning.

SENSITIVITY ANALYSIS AND EFFECTS OF INFRASTRUCTURE UPGRADE

A sensitivity analysis was conducted of options that could affect accident rate so as to understand the effects on risk reduction and to illustrate how to communicate the results of such changes. Based on a 1-mi track segment for each FRA track class, annual risk is plotted versus the population level for the segment. Upgrading lower FRA track classes has a much greater effect on risk as population density increases compared with upgrading higher class trackage (Figure 7*a*). This graphical technique helps risk



(a)



(b)

FIGURE 7 Effects of track infrastructure on risk: (*a*) effect of track class changes on risk as function of population density and (*b*) effect of infrastructure upgrade on risk reduction.

managers understand the relative benefits of these options in different contexts.

Figure 7*b* illustrates the effects of track class upgrade on risk reduction along a particular lane. It is interesting that although the lowest track classes have relatively high sensitivity, improving these track segments does not have much effect on risk because they represent only a small proportion of total lane length (Table 3). However, the extent of risk reduction is greater if Class 3 tracks are upgraded to Class 4, although the cost would be much greater as a result of the greater length of trackage involved. Such analyses can help managers in understanding that the degree of risk reduction varies for different lanes because of the difference in geographic characteristics such as infrastructure characteristics and population distribution along the lane.

Risk management resources are often constrained, so a critical purpose for risk analysis is to help identify the most efficient means of reducing risk. In the example above, instead of upgrading all lower FRA track class segments, a more effective strategy would be upgrading a limited number that provide the most benefit. To determine the locations where track segments should be upgraded to yield the most reduction in risk, an optimization model could be used to determine the segments to be upgraded with the objective of minimizing the total annual risk. By using the expression of annual risk in Equation 2, the optimization model can be formulated in the form of a mixed integer programming model as follows:

minimize annual risk

$$S = \sum_{i=1}^{n} \sum_{k=1}^{2} C_k L_{ik} Z_{ik} VR' AD_i \quad (8)$$

subject to

$$\sum_{i=1}^{n} L_{ik} \le X \qquad \text{for } k = 1 \quad (9)$$

$$L_{ik} \le C_k L_{ik+1} \qquad \text{for } k = 1 \quad (10)$$

and

$$C_k = \begin{cases} 1 & \text{if a lane segment is to be upgraded} \\ 0 & \text{otherwise} \end{cases} \quad (11)$$

$$L_{ik}, Z_{ik}, A, D_i, X \ge 0 \quad (12)$$

where

L_{ik} = length of lane segment *i* for decision *k,*
Z_{ik} = accident rate of lane segment *i* for decision *k,*
V = annual shipments (carloads),
R' = aggregated conditional probability of release given that a tank car derails,
A = affected area as per the U.S. Department of Transportation recommendation,
D_i = average population density along lane segment *i,*
X = total distance to be upgraded,
n = total number of segments in the shipment lane, and
k = decision (1 if upgrade, 2 otherwise).

The length of the upgraded track is used as a proxy for budget as the resource constraint in the model. Furthermore, the formulation presented here neglects the differential track upgrade costs for different track classes. However, it can be modified to accommodate various constraints if more information is available.

DISCUSSION OF RESULTS

Effective management of hazardous materials transportation risk will generally benefit from mutual cooperation between carriers, shippers, and the municipalities along a route. Each of these parties plays a different role in rail transportation risk management. Understanding their own and each others' roles will facilitate better individual and collective decision making concerning implementation of risk management practices. Quantitative route risk analyses generate a large amount of numerical results that can be difficult for even one of these parties to interpret, never mind all of them. Different portions of these data are important to different parties, and the value of various summaries and comparisons may vary as well. This study provides examples of different types of information that can be generated. In particular, shippers may have shipment lanes they wish to evaluate and compare using various absolute and normalized risk estimates. Carriers may use the segment-specific risk estimates to focus maintenance-planning and equipment-health-monitoring technology for high-risk segments on corridors (Figure 4). Similarly, in coordination with shippers and carriers, municipal authorities and regulators may allocate emergency response and inspection resources at locations based on priorities established using the types of information presented here (Figure 5*a*). Emphasizing and clarifying these roles for each party using the techniques and options described can help them better understand the critical information most relevant and useful to each. In addition to helping the different parties coordinate their activities, these approaches will be helpful in assisting stakeholder groups to understand the rationale for other groups' risk management decisions.

CONCLUSION

This study presents results of a quantitative risk assessment of rail transportation of a hazardous material. New graphical representations of the results are introduced that are intended to more effectively illustrate results to risk managers and communicate them to other interested parties. Various methods are presented to identify shipment lanes and segments that account for the greatest amount of risk in various contexts and groupings. Within lanes, the segments with the highest accident and release rates, population densities, and risk were also identified using various graphical representations developed to enhance communication of risk results.

This study provides examples of graphical techniques developed to help risk managers focus priorities for risk management and mitigation concerning hazardous material shipments and facilitate comparison and communication of risks at the local and network levels. The study provides examples of different ways that route risk analysis results can be presented for the benefit of various stakeholders and enable them to work individually and cooperatively applying safety resources in the most efficient and effective manner possible.

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