Comparing Risks of Transporting Chemicals by Highway and Rail: A Case Study

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The risks of moving chemicals by rail and highway are compared using a distribution risk decision support tool. Described are the problems faced by those who must evaluate how hazardous materials are to be transported, what attributes are needed in a decision support tool that quantifies the risk along competing routes, and how these results are used to select a mode and a route. This is achieved through the presentation of a case study involving the movement of anhydrous ammonia.

Although great care has always been taken to ensure the safe transportation of hazardous materials, the deregulation of the transportation industry coupled with chemical industry initiatives such as Responsible Care® have caused all involved to place more concern on the safe distribution of all hazardous material shipments. The development of better shipment containers and improved handling practices has led to a significant decline in the release of hazardous material during shipment, especially by rail; however, the industry is dedicated to further improvements, which many feel can be achieved through better planning, mode choice, carrier selection, and routing of individual shipments. There now exists a desire to thoroughly analyze the comparative risks associated with a range of mode and routing options of a much larger portion of chemical shipments. This desire is placing a significant demand on both the development of decision support tools that can effectively compute those risks and on the interpretation and judgments, based on those computed risks, made by the users of the decision support tools.

Addressed in this paper are some of the major issues facing the developers and users of hazardous materials transportation risk analysis tools. Desirable attributes of the tools are presented. The main purpose of the paper is to describe how a routing risk assessment decision support tool is currently being used by one chemical company to address the mode choice and routing issues company. This is achieved through the presentation of a case study involving the movement of anhydrous ammonia. This analysis is made on the basis of the decision support tool, PC*HazRoute™.

HAZARDOUS MATERIAL TRANSPORTATION OVERVIEW

According to the Office of Technology Assessment (*1*), annually in the United States there are more than 150 million shipments of hazardous materials that accumulate to require some 784 billion ton-miles of transportation demand. An extremely small number of these shipments, on the order of 10,000, incur some problem that leads to a release of some of the cargo (*2*). Of these releases, one-third are the result of transportation accidents and two-thirds are nonaccident related; for example, failure to properly load or secure a container (*1*). Most of these incidents are noncatastrophic and result in little environmental impact; however, a very few are severe. In the last few years an average of 12 deaths/year can be attributed to transport accidents involving the release of chemicals (*2*). The main characteristics of hazardous materials transportation in the United States are summarized as follows:

- 150 million shipments annually
- 784 billion ton miles annually
- 10,000 releases/year
- 1/3 are accident related
- 12 deaths on average/year

Thus accidents involving hazardous materials are extremely rare but potentially catastrophic events. The focus of analyses of alternate modes and routes is not only to reduce as much as possible the likelihood of an accident, but to also to reduce the damage to people and the environment in the event of an accident. Thus any risk measure involves the combined effect of release probabilities and intensity of consequences should a release occur. The intensity of the consequences is dependent not only on the environment and population in the vicinity of the release but also on the type of hazardous material being released. The term "hazardous material" spans a wide spectrum of products, from those having extremely high hazard, such as hydrogen cyanide and phosgene, to nonregulated, least-hazardous products like titanium dioxide and ethylene glycol. In Figure 1, hazardous materials are ranked using a product pyramid analogy having the most hazardous at the top and the least hazardous at the bottom. The width of the pyramid represents the inverse of the amount of analysis that has traditionally been undertaken to evaluate the shipment of the materials in each stratum. Those at the top have traditionally had a complete fault-tree analysis done in planning for their distribution. The analyses involve not only mode, container, and route, but also issues of alternate sourcing including reducing the on-site risk with less hazardous raw materials. Those at the bottom have had little quantitative analysis. A main benefit to be derived from the development of less expensive and more effective routing risk assessment decision support tools is that they would be applied to a broader spectrum of the materials contained in the

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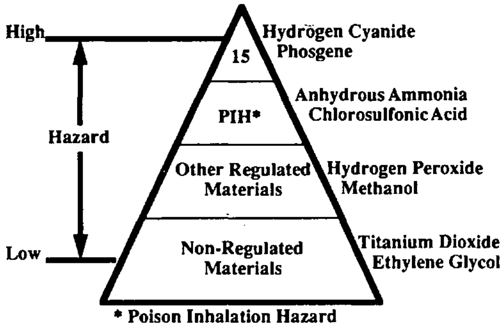

FIGURE 1 Product pyramid ranking hazardous materials.

product pyramid, thus significantly reducing the risk associated with the transport of the entire family of hazardous materials.

ELEMENTS OF THE MODAL DECISION PROCESS

There are several key elements in any modal decision process, of which the distribution risk is but one. Other considerations include volume and frequency of shipments, distance, product handling and inventory considerations at origin and destination, investment requirements in shipping containers, and operating cost considerations. Although each of these other elements is important, their quantification requires economic considerations that are not considered as part of this paper. Instead, the focus is on the identification, quantification, and interpretation of the relative distribution risk associated with alternative routes used by different modes of transport.

Decisions can best be reached when there is a clear understanding of business requirements, including customer and vendor needs. Attention must be given to gathering the best input data and statistics available relevant to the task at hand. The analysis should be objective and performed by persons disciplined in logistics, the risk assessment process, and design features of transportation equipment. Quantitative decision support tools are essential to performing meaningful risk assessment. They move us from the realm of qualitative reviews to quantitative analysis by reducing the analyses to "doable" tasks while providing the ability to perform "what-if" scenarios.

The components of the distribution risk element that must be addressed involve the inherent hazards of the material, the population and environs that are potentially exposed, the accident frequency along the proposed route, and the chances of a release given an accident. The literature contains many models and methods by which distribution risk can be estimated, and the validity of each is strictly dependent on the quality of the data for each of the parameters. Moreover, the precision of the risk estimation is controlled by the least-reliable data element. Thus, a more reliable measure of risk can be obtained from a less precise yet consistent analysis than it can from an analysis that is detailed in parts but fraught with data gaps in other parts. For example, it is more precise to consider plume formation and dispersion, but only if meteorological statistics for all highly populated, environmentally sensitive, or high accident rate locations can be obtained. Only then is it of any value to have detailed geographic distributions of population and environmentally sensitive areas. Although it is desirable for the analysis to use the best models of risk, if the data to support these models are not readily available, the cost of any analysis will become exorbitant and can be justified only when dealing with the most hazardous of materials. Thus there is a distinct link between the availability of data and the risk analysis model used in the decision support tool.

ATTRIBUTES OF A QUANTITATIVE ANALYSIS FOCUSED ON DISTRIBUTION RISK

For each mode to be considered, there must be the capability to obtain quantitative measures for every route to be considered. With these quantitative measures it is then possible to assess the risk of all the alternative routes for all of the modes. This allows the user to determine a candidate "best route" for each mode, which is then incorporated into the broader modal decision process. The ultimate distribution mode selected must attempt to satisfy customer and business requirements while striking a balance among safety, cost, and efficiency. This objective defines many of the components of a quantitative decision support tool.

For each mode to be properly evaluated, a set of realistic routes that may be used must first be identified and the distribution risk along each of the routes assessed. Usually many routes are possible; consequently, the user needs help in identifying a handful of candidate "best" routes among which to choose. Thus a fundamental attribute of a distribution risk decision support tool is that it be able to find realistic "best" routes. This means that if there exist route restrictions for a particular hazardous material; for example, tunnel restrictions, these should be readily excluded from any feasible route. Moreover, when dealing with rail shipments of all but the most hazardous materials when payment for special train services is available, it is important to restrict routes to single carriers, or if multiple carriers are used, to minimize the number of corporate interchanges and restrict the interchange locations at which significant traffic is interchanged among railroad companies. To do otherwise is either operationally unachievable or would submit the shipment to extremely high risks unless very expensive precautions were taken.

In order to have a quality quantitative decision support tool, its data bases must be consistently credible. Because the quality of the data base limits the quality of the analysis, it is imperative that the best available data be used. It is of little value to include more precise data that are not consistently available. For example, precise data available for just one state are of some—but unfortunately little—value unless shipments only within that state are being considered. This does not mean that there should not be an effort to improve the various data bases one state at a time, but it must be realized that the benefits derived from the better data will not be realized until the data for all states have been obtained. This implies that data-enhancement efforts should be focused on those that can be completed for all states. In any case, it is imperative that any decision support tool clearly identify its data limitations and that the user be totally aware of its shortcomings.

Because many different routes need to be compared, it is better if the system automatically finds the "best" route for the user. As each user may wish to weigh different attributes of risk differently, the system should allow the user to easily customize the weighting of different risk measures. In addition, the system should have "what-if" capabilities to allow the user to modify

some of the route restrictions, edit data elements, and easily change assumptions.

Possibly the most important attribute is that the system needs to be novice friendly in terms of its dealing with the operation of the software. It is assumed that the user is an expert on the hazardous materials that are being transported, but it should not require that the user be any more than a novice when it comes to the operation of a computer or this decision support tool. The system should provide proper prompts, reminders, simplified editing, and archiving capabilities. It should assume that the user has other work to do besides the operation of this software.

The distribution risk decision support tool used in this analysis is ALK Associate Inc.'s PC*HazRoute™. The data bases and routing methodology included in ALK's products have been used by the transportation industry and its customers for more than 14 years.

For a true analysis of a rail or highway movement, population, accident rates, release rates, and road quality should all be studied. A well-respected paper on rail routing was published in the journal *Accident Analysis and Prevention* in 1983, which pointed out that minimum population routes may not be the safest routes because diverting traffic to these routes results in longer trips under worse track conditions, and the net effect is often a degradation of safety (*3*).

CASE STUDY: MOVEMENT OF ANHYDROUS AMMONIA VIA RAIL AND HIGHWAY

Any transportation distribution risk study involves three key steps: (*a*) identification of the hazards, (*b*) determining the probabilities of an accident and material release, and (*c*) assessing the impact a release might have on the public and the environment. Ideally, efforts should be made to reduce risks in all risk study efforts.

The options for risk reduction can be numerous and include one or more system changes involving container design, mode of transport, route of transport, varying chemical or physical properties of the material, and material exchanges. This case study will focus on modal decision and route selection. Although this paper is based on an actual risk assessment performed by DuPont, certain elements have been "sterilized" to protect business interests.

Proper mode selection is essential to the safe, cost-effective, and efficient distribution of hazardous materials. The distribution system selected must attempt to satisfy all business requirements while striking a prudent balance between safety, cost, and efficiency. The needs of all stakeholders, which include the public, shareholders, customers, and employees, must be met.

In the same way, route selection within a mode is a function of and must strike a prudent balance among accident probabilities, container release rates, effects on population and the environment, and the inherent hazards of the material. This case study will attempt to show how these route and mode elements come into play in the risk-assessment process.

DuPont purchases anhydrous ammonia (NH_3) from a source in West Lake, Louisiana, for consumption at its Gulfport, Mississippi, facility. The material is delivered in vendor-supplied rail tank cars at a volume of 20,000/year. Rail freight is for DuPont's account. DuPont procurement, on reviewing this contract, believed the freight rate was high and in cooperation with the supplier opened this move up for bid.

The historic route ran from West Lake to New Orleans, Louisiana, then up to Jackson, Mississippi, and back to Gulfport, Mississippi. This route involved three railroads and required 6 to 7 days of loaded transit. The route bidding process offered DuPont a viable alternative route at a reduced freight rate (viable from the viewpoint of service and transit time). It was necessary to determine whether this route, designated Alternate 1, was equal to or safer than the historic route. It runs from West Lake north to Shreveport, Louisiana, then east to Jackson and south to Gulfport. Only two railroads were involved and transit time was comparable.

The risk-assessment process began with a review and clear understanding of the inherent hazards of the material, both chemical and physical properties. Anhydrous ammonia (liquefied or solutions with more than 50 percent ammonia) is classified by the U.S. Department of Transportation (DOT) as a nonflammable gas (*4*). However, each bulk and nonbulk package must be marked "Inhalation Hazard." Internationally, NH_3 is classified as a poison gas (*5*). [Corporate Material Safety Data Sheets (MSDS) usually contain the necessary information to characterize the material under consideration. If not, then the specific product group and published technical literature can be consulted.] From the DuPont NH_3 MSDS, it was determined that anhydrous ammonia is an inhalation hazard and thus posed a threat to human life if released. Environmental concerns were low because NH_3 is very soluble in water. Therefore, population along the route becomes significantly important, even though ammonia's intensely pungent odor will cause persons to flee or seek shelter from a release. Flammability and reactivity with other materials are low and were not a consideration in this mode-route study.

DOT regulations also spell out minimum packaging requirements for hazardous materials. Both rail and highway require pressure containers of substantial design (*6,7*). Although pressure ratings, shell thickness, and additional protective features differ between the rail tank car and highway cargo tanks authorized for the transportation of NH_3, as shown in the following table, their relative product containment capabilities are equivalent. This assessment is made on the basis of calculated threshold puncture velocities tempered with years of experience.

	Transport Containers	
	Rail	*Highway*
DOT spec.	112S340W	MC-331
Capacity	180 K lb	40 K lb
Thickness	5/8 in.	3/8 in.
Head shield	1/2 in. full	None
Bottom outlet	No	Yes

DuPont uses ALK Associates' rail and highway networks and accident-incident data base statistics for its transportation risk studies. DuPont chose to use mainline release frequency for pressure tank cars with head shields from data provided to the Chemical Manufacturers Association (CMA) by Arthur D. Little, Inc., Cambridge, Massachusetts, for use by the CMA in its Distribution Code Risk Management Workshops.

ALK provided rail statistics for the historic and Alternate 1 routes based on the specific routing provided by DuPont. ALK's computer program then generated a minimum population route, minimum accident route, and minimum impedance or best service route and all related statistics. For purposes of this study, the historic and Alternate 1 route statistics were analyzed against the minimum accident and minimum impedance route, which in this

TABLE 1 Rail Route Data Analysis

PC*HazRoute™	Historic	Alt. 1	Minimum Acc./Imp.
Annual Vol.-Tons	20,000 →		
Capacity/Trip	90 Tons →		
Trips/Year	222 →		
Loaded Miles/Trip	558	563	292
Ton-Miles/Year	11.15×10^6	11.26×10^6	5.84×10^6
Acc. Prob./Trip	0.8×10^{-4}	0.9×10^{-4}	0.2×10^{-4}
Rel. Prob./Acc.	0.045 →		
Population Exposed	276,120	155,826	175,998

TABLE 3 Highway Route Data Analysis

PC*HazRoute™	Practical	Minimum Soc. Risk	60/40 Weighted
Annual Vol.-Tons	20,000 →		
Capacity/Trip	20 Tons →		
Trips/Year	1,000 →		
Loaded Miles/Trip	267	445	302
Ton-Miles/Year	5.34×10^6	8.9×10^6	6.04×10^6
Acc. Prob./Trip	1.5×10^{-4}	5.6×10^{-4}	1.9×10^{-4}
Rel. Prob./Trip	1.2×10^{-5}	5.4×10^{-5}	1.6×10^{-5}
Population Exposed	276,806	55,346	161,867

case are one and the same. The minimum population route was not viable from a service standpoint.

The goal of the study was to balance the accident-release frequency and population affected along any given route and to avoid the New Orleans population center if possible. Rail route data and calculated indices for each of the three routes under consideration are shown in Tables 1 and 2. Although the historic route offered a release frequency of 1 in 1,235 years and a population-release index of 0.994, the Alternate 1 route provided a 36 percent reduction in this index. The population-release index that was used is the product of the accident rate times the population at risk times the conditional release rate, and is an extension of the Relative Population Risk factor defined by the DOT in their routing guideline (*8*). This substantial improvement was brought about by the 43 percent reduction in population despite the 124-year decrease in years between releases. Although the minimum accident-impedance route offers attractive indices, it does not avoid the New Orleans population center. Thus the Alternate 1 route was selected from the rail mode to compare with the highway mode.

The highway statistics were generated by and obtained from ALK's PC*HazRoute™ computer software for managing hazardous materials routing. There was speculation that direct movement of cargo tank via Interstate highway might provide a viable alternative from a safety standpoint. PC*HazRoute™ was given only the origin, destination, and population impact radius. Route data and statistics were then generated for the most practical route, minimum population, minimum societal risk route, DOT route, and a weighted route. All route statistics were reviewed, and three were chosen for this study: namely the practical, minimum societal risk, and a weighted route. The weighted route is based on 60 practical and 40 percent societal risk.

Highway data and calculated indices for each of the three routes under consideration are shown in Tables 3 and 4. Years between releases vary from 18.5 to 83.3, and the population-release indices vary by less than 15 percent above and below the minimum societal risk population-release index. The practical route was chosen to compare with rail because it provides the shortest, most direct route on quality Interstate highways and avoids the New Orleans population center.

There are no order of magnitude differences in statistics or calculated indices when comparing alternative routes within modes. However, comparison of relative risks between modes reveals significant differences, as summarized in Table 5.

- Years between releases for rail are 13 times greater than for highway;
- Population-Release index for rail is only 19 percent of highway; and
- Despite the greater than 2 to 1 ratio of ton-miles for rail, releases per ton-mile are less than for highway by a factor of 28.

These indices provide the degree of measure necessary to make a prudent decision. Any one index by itself could be challenged

TABLE 2 Rail Route Analysis Indices

PC*HazRoute™	Historic	Alt. 1	Minimum Acc./Imp.
Accidents/Year	0.018	0.020	0.0044
Years Between Acc.	55.56	50.0	227.27
Releases/Year	8.1×10^{-4}	9.0×10^{-4}	1.98×10^{-4}
Years Between Rel.	1,234.7	1111.1	5,050.4
Acc./Ton-Mile	1.61×10^{-9}	1.78×10^{-9}	0.753×10^{-9}
Rel./Ton-Mile	7.26×10^{-11}	7.99×10^{-11}	3.39×10^{-11}
Pop.-Acc. Index	22.1	14.0	3.5
Pop.-Rel. Index	0.994	0.631	0.158

TABLE 4 Highway Route Analysis Indices

PC*HazRoute™	Practical	Minimum Soc. Risk	60/40 Weighted
Accidents/Year	0.15	0.56	0.19
Years Between Acc.	6.67	1.79	5.26
Releases/Year	0.012	0.054	0.016
Years Between Rel.	83.33	18.52	62.5
Acc./Ton-Mile	2.81×10^{-8}	6.29×10^{-8}	3.15×10^{-8}
Rel./Ton-Mile	2.25×10^{-9}	6.07×10^{-9}	2.65×10^{-9}
Pop.-Acc. Index	41.5	31.0	30.8
Pop.-Rel. Index	3.32	2.99	2.59

TABLE 5 Comparison of Relative Risks Between Rail and Highway Modes

	RAIL	HIGHWAY
•Route	Alt.1	Practical
•Trips/Year	222	1,000
• Ton-Miles	11.3×10^6	5.3×10^6
• Population	156K	277 K
• Years Between:		
Accident	50	6.7
Release	1,111	83
• Pop.-Rel. Index	0.631	3.32
• Rel./Ton-Mile	8×10^{-11}	225×10^{-11}

and subject to question. However, when two or more indices are pointed in the same direction (i.e., toward risk reduction), it can be assumed that in fact the potential risk of harm to the public will be reduced.

The difference in transport container capacity can only truly be addressed when performing full-blown quantitative risk assessments in which material dispersion calculations are made on the basis of the nature of the release, rate of release, amount released, meterological data, and geographical location. However in this case, even if the rail indices are arbitrarily adjusted by a factor of 4.5, to try to account for the differences in container capacity, the relative risk comparison would still favor rail.

Modes, routes, or transport containers should not arbitrarily be switched, even though the indices point favorably in that direction. The consequences of any change must be thoroughly evaluated, taking into account business needs while striking a prudent balance between safety, cost, and efficiency.

In this rather straightforward case study, DuPont chose to retain the rail mode and change routes. The rail route change from Historic to Alternate 1 yielded the following results:

	Historic	*Alt. 1*
Population exposed	276K Base	156K 43% reduction
Releases per year	8.1 × 10-4 Base	9.0 × 10-4 11% increase
Pop.-Rel. Index	0.994 Base	0.631 36% reduction

Thus, with the aid of a decision support tool, DuPont was able to make an informed decision, which reduced overall risk to the public by one third without affecting service and decreased freight costs. This provides an excellent example of a cost-driven question being acted on and yielding significant risk reduction.

CONCLUSIONS

There is no one right answer. Informed decisions involve tradeoffs and balance among risk factors. In the quest for risk reduction, care must be taken to reduce risk and not just "transfer" it to another area of the distribution system. For example, certain mode and container size changes could increase on-site inventory or handling requirements. This increase in on-site risk (and potential risk to the plant community) could possibly offset any gains obtained in transportation. The art and science of risk assessment must take into account the consequences of all actions.

Proper analysis can lead to significant reduction in distribution risk. Quantitative support tools are essential to this analysis. Pending regulations and safety performance improvement initiatives like the Chemical Manufacturers Association's Responsible Care® Program are encouraging industry to become more proactive. Easy-to-use management-decision support tools based on respected methodology and credible data bases will enable the transport of more hazardous material to be carried out more responsibly in the future.

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