The Effect of Rerouting and Tank Car Safety Design on the Risk of Rail Transport of Hazardous Materials

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Abstract
Railroads in North America have recently come under pressure to avoid transporting certain high hazard materials through metropolitan areas. There are two principal reasons- fear of terrorist attack and concern about the risk of an accident-caused release. Consequently, a number of municipalities are considering legislation to block hazardous materials transportation through their communities, thereby requiring the shipments to be rerouted. However, rerouting of hazardous materials is not without its own set of risks. The distance traveled, time in transit, number of visits to classification yards and the number of smaller population centers exposed to the risk would all increase. Furthermore, the track quality may be lower on the alternate routes. All of these factors increase risk but to date, no formal analysis comparing the relative risks for shorter urban routes versus longer more rural routings has been presented.

In this paper we describe a comprehensive risk assessment model that enables evaluation of different rail route alternatives for transporting hazardous materials. Major variables considered are the length of the route, number of shipments, track quality, tank car safety design, chemical-specific exposure area and population density. The model uses up-to-date measurements of accident probability as a function of track quality, tank car accident performance and chemical-specific hazard analyses. We use the model to consider an example case in which the effect of both alternative routing and tank car design are considered and risk profiles for each are presented.

What's new?
This paper presents an analytical model in which route-specific parameters can be compared to alternative design tank cars to assess their relative effectiveness in reducing the risk of hazardous materials transported by rail.

1.0 Introduction

Railroads in North America have come under pressure to avoid transporting certain high hazard materials through metropolitan areas. There are two principal reasons- fear of terrorist attack and concern about the risk of an accident-caused release. Consequently, a number of municipalities are considering legislation to block hazardous materials transportation through their communities, thereby requiring it to be rerouted. However, rerouting of hazardous materials is not without its own set of risks. The distance traveled, time in transit, number of visits to classification yards and the number of smaller population centers exposed to the risk could all increase. Furthermore, track quality may be lower on the alternate routes.

There are several studies focusing on different aspects of hazardous transportation risk. Brockhoff et al [4] developed a simple consequence model for chlorine and ammonia releases based on a fatality index approach. Others introduced more detailed models to estimate associated transportation risks of chlorine and other hazardous materials [12, 13, 15]. Dennis [6] used cost data from Class 1 railroads in the U.S. to estimate risk costs per unit of exposure associated with transportation of hazardous materials. Saat & Barkan [14] developed a release risk approach to estimate the expected quantity of release from a tank car involved in an accident. Glickman [9] developed a rerouting risk model for system-wide rail networks. Others have used Geographic Information Systems (GIS) to develop a rerouting model for hazardous material transportation [1].

To date, there is no risk-based study combining all the related uncertainties and consequences specific to hazardous materials transportation by rail to determine the optimal strategy involving the issue of rerouting, improvement in tank car safety design and/or infrastructure improvements. The objective of this study is to introduce the framework of a risk model to systematically assess the risk of different route alternatives, while simultaneously considering the use of an alternative, enhanced-safety design tank car.

The risk model was developed for chlorine transport in a hypothetical rail corridor to represent a typical area where rail rerouting may be considered. It can be adapted to any local or regional rerouting problem and any hazardous material of interest.

2.0 Risk Analysis Model

A formal definition of risk is the multiplication of the probability of an event by the consequence of that event. In the context of railroad hazardous materials transportation, risk is defined as followed:

$$R = P_R \, P_C \, C \qquad (1)$$

where:

- R = annual risk of transporting a hazardous material
- P_R = annual probability that a tank car is involved in a release accident
- P_C = probability of a particular release scenario occurring
- C = consequence level (defined here as the number of people affected)

Each element in the risk calculation will be discussed in the following sections. In Section 2.4, the annual expected risk is calculated by considering all possible scenarios as follows:

$$R = \sum_{ijk} P_R \, P_{Cijk} \, C_{ijk} \qquad (2)$$

where:

- *i* = small or large spill size
- *j* = atmospheric condition (day or night)

k = population density classes

2.1 Tank Car Design Features

Two basic tank car designs were compared (Table 1) and their effect on risk evaluated. The baseline car is a 105A500W with a gross rail load (GRL) of 263,000 lbs (263K), which is the most common type of car currently in use for chlorine transport in North America. The alternate car is a 286,000-lb-GRL 105J600W with additional safety enhancements similar to those found in cars currently used to transport hydrogen cyanide (HCN). The reason why different gross rail loads were used is explained later when the risk model is presented.

Tank car specifications	**Baseline Car 105A500W**	**Alternate Car 105J600W**
Maximum GRL (lbs)	263,000	286,000
Product Density (lbs per gal.)	11.22	11.22
Head Thickness (in.)	0.787	1.250
Shell Thickness (in.)	0.787	1.125
Tank Inside Diameter (in.)	102.000	100.625
Insulation Thickness (in.)	4	4
Outage (%)	5	5
Headshield	None	Full-Height, 0.75 in.
Jacket Thickness (in.)	0.1196	0.25
Top Fittings Protection	Typical design	Typical design
Light Weight (lbs)	80,000	105,601
Shell Capacity (gal.)	17,368	16,881
Nominal/Payload Capacity (gal.)	16,043	16,037
Payload weight (lbs)	180,002	179,938
Calculated maximum GRL (lbs)	260,002	285,540
Difference in capacity from baseline car	na	-0.04%

Table 1: Tank Car Designs Considered

2.2 Rail Route Features

Route-specific variables considered in this analysis include the distribution of different FRA track classes by length, total length and population density distribution. A hypothetical rail corridor considered in this analysis consists of a baseline route with good track conditions with the highest proportion of the track through urban and high population density areas [5], and an alternative route with lower track quality but with the highest proportion of the track through suburban and rural population density areas [5]. In addition, the alternate route was assumed to be 50% longer than the baseline route of a 100-mile total length. Each of these route features will be explained in more detail in the following sections.

2.3 Accident-Caused Release

The estimated annual rate of release for a tank car is a product of the conditional probability of release given the car is derailed in an FRA-reportable accident and the accident rate, defined as follows:

$$P_R = P_{R|A} \times Z \tag{3}$$

where:

P_R = annual rate of accident-caused release from a tank car

$P_{R|A}$ = conditional probability of a tank car release given the car is derailed in an FRA-reportable accident

Z = accident frequency or exposure to accident
= P_A x M
where:
P_A = tank car derailment rate per mile traveled
M = annual number of car miles = S x L
where:
S = annual number of shipments
L = route-specific distance per shipment

The alternative tank car design considered here decreases the likelihood of a release for a tank car in a derailment. However, increasing the tank thickness to make the car more robust in an accident also increases the weight of the tank. The maximum gross rail load (GRL) for cars in unrestricted interchange is fixed, so *ceteris paribus*, the increase in light weight due to the thicker tank reduces the capacity of the tank car [3, 14]. Consequently, more shipments and car-miles would be required to transport the same quantity of lading. To compensate for this, the analysis considers an alternative tank car design with enhanced safety features and a maximum GRL of 286,000 lbs (286-k). As a result, the reduction in capacity as shown in Table 1 is negligible, and the number of annual shipments or car-miles, assuming a constant demand, does not change significantly. To account for the change in tank capacity with the alternative car, the term Z, exposure to accident, is modified as follows:

$$Z = P_A \times M \times Cap/Cap' \qquad (4)$$

where:
Cap = nominal capacity of baseline tank car
Cap' = nominal capacity of alternative design tank car

2.3.1 Conditional Probability of Release, $P_{R|A}$

The conditional probability of release for the baseline and alternate tank cars was calculated using the probability model developed by Treichel et al [19]. The conditional probabilities of release given that a tank car is derailed in an FRA-reportable, mainline accident for the baseline and alternate tank cars considered here are, 0.0509 and 0.0236, respectively.

2.3.2 Annual Number of Car Miles, M

The total number of annual chlorine shipments originated and terminated in the hypothetical rail corridor was assumed to be 1,000. The total annual number of car miles was determined by multiplying the total shipments by the length of the original and alternative routes, (100 x 1,000 = 100,000 car miles for the original route, and 150 x 1,000 = 150,000 car miles for the alternative route). In an actual analysis, chemical-specific car-mile exposure to accidents can be estimated using the Association of American Railroads (AAR) railcar movement database, TRAIN II waybills [17] and the Surface Transportation Board waybill sample [16].

2.3.3 Tank Car Accident Rate, P_A

Anderson & Barkan [2] analyzed FRA accident data for use in hazardous materials transportation risk analysis. Their work updated and extended previous work by Nayak et al [11] and Treichel & Barkan [18] that found that derailment rate was inversely correlated with FRA track class. FRA track class and the associated derailment rates are used in this analysis as a proxy for track quality. The accident rate per car mile traveled, P_A, is determined in this analysis for each specific route as follows:

$$P_A = \sum_f \left(P_{Af}\, x \frac{L_f}{\sum_f L_f}\right) \tag{5}$$

where:

P_{Af} = accident rate for a tank car on FRA track class *f* (per billion car miles)
L_f = total length of FRA track class *f* (miles)

In this study, 70% of the baseline route is assumed to be track classes 5 and 6, while the alternative route has 80% track classes 3 and 4. Table 2 summarizes the P_A calculations.

	FRA Track Class	**Track Class Proportion**	**P_A (per billion car miles)**	**Net P_A (per billion car miles)**
Original Route	X & 1	0%	3,979	53
	2	0%	726	
	3	0%	300	
	4	30%	77	
	5 & 6	70%	42	
Alternative Route	X & 1	0%	3,979	182
	2	0%	726	
	3	50%	300	
	4	30%	77	
	5 & 6	20%	42	

Table 2: Tank Car Accident Rate

2.3.4 Annual Probability of Release, P_R

Conditional probabilities of release $P_{R|A}$ are multiplied by the number of car-miles M, the ratio of the baseline tank car's capacity and the alternate car's capacity (Cap/Cap'), and the tank car accident rate P_A (Table 2) to estimate the annual frequencies or probabilities of release (P_R). These P_R's as summarized in Table 3 were used for the risk estimation.

Route Selection	**Tank Car Design**	**$P_{R\|A}$**	**P_A**	**M**	**Cap/Cap'**	**P_R**
Baseline	Baseline	0.0509	53	100,000	1.0000	0.00027
Baseline	Alternative	0.0236	53	100,000	1.0004	0.00012
Alternative	Baseline	0.0509	182	150,000	1.0000	0.00139
Alternative	Alternative	0.0236	182	150,000	1.0004	0.00064

Table 3: Annual Probability of Release, P_R

2.4 Release Consequences

Possible levels of consequences are determined by multiplying the hazard exposure area for all of the scenarios considered in the following section with population densities as described in Section 2.4.2.

2.4.1 Hazard Exposure Model

The Department of Transportation Emergency Guide Response Guidebook (ERG)'s hazard exposure model was used in this analysis [7]. The affected area is defined as the area in which population must be evacuated and/or sheltered in-place. Thus the risk metric used in this analysis is the number of people likely to be affected if emergency response personnel conform to the recommendations of the U.S. DOT ERG. The area is calculated for four different scenarios as specified by the ERG (Table 4).

	Spill Size ($mile^2$)	
Atmospheric Condition	**Small**	**Large**
Day	0.041	2.286
Night	0.641	21.196

Table 4: U.S. DOT ERG Exposure Areas for Chlorine

It is assumed that chlorine transportation in the area is equally likely to occur during the day or night and thus, a 0.5 probability was assigned to these two atmospheric conditions. The proportion of "large" vs. "small" releases was determined using the quantity lost distribution for pressure tank cars in mainline accidents [19]. We classified releases of 5% or less of a car's capacity as small spills, and releases of more than 5% as large spills. Treichel et al [19] found that the proportions of large and small spills so defined are 0.2213 and 0.7787, respectively.

2.4.2 Population Exposure

As mentioned above, the baseline case was assumed to have the highest proportion of trackage through urban and high population density areas, and for the alternative route, the highest proportion through suburban and rural population density areas (Table 5).

		Proportion Population Class, P(Pop_k)	
Population Class *k*	**Average Population Density, ($PopDen_k$) (people/$mile^2$)**	**Baseline Route**	**Alternate Route**
Remote	10	0%	10%
Rural	60	10%	30%
Suburban	550	10%	50%
Urban	2,000	40%	5%
High	6,500	35%	5%
Extremely High	10,000	5%	0%

Table 5: Assumed Population Density Distributions Along Original and Alternate Routes

In an actual analysis, a spatial analysis using Geographic Information System (GIS) software and data to estimate the population densities along the baseline and alternate rail lines would be used. A map overlay of the rail network from the DOT [10] with the census tract map from ESRI's ArcData Portal [8] can be analyzed to estimate the proportion of different population density levels along rail lines as follows: First, GIS buffers would be created using a 4.6-mile radius away from the track representing the worst-case downwind exposure distance for a chlorine release [7] for both the baseline and alternate routes. Then the proportion of the buffer areas for each different population density group and track class would be calculated for both routes.

2.4.3 Possible Release Consequences

The set of release consequences was determined by multiplying the exposure areas (Table 4) by different average population densities (Table 5) as follows:

$$C_{ijk} = PopDen_k \, MaxArea_{ijk} \qquad (6)$$

where:

$PopDen_k$ = average population density of class k along a route
$MaxArea_{ijk}$ = exposure area per chemical-specific guidelines in DOT ERG

2.5 Risk Analysis & Optimization Model

Equation 2 was used to calculate the annual expected risk, R, defined as the expected number of people that would be evacuated and/or sheltered in-place annually. Table 6 shows the R's for each strategy combination of rerouting or using enhanced-design tank cars.

Strategy	Route Selection	Tank Car Design	R (Annual Expected Number of People Exposed)
1	Baseline	Baseline	8.96
2	Baseline	Alternative	4.15
3	Alternative	Baseline	9.18
4	Alternative	Alternative	4.25

Table 6: Annual Risk for Example Chlorine Transportation Analysis

The risk model here can be characterized using a more general mixed integer programming model where more than one alternative route or tank car design can be evaluated as follows:

$$\text{Minimize } R = \sum_{ijk} \Big[\sum_{n} \mu_n P_{R|An} \sum_{m} \gamma_m P_{Am} S\Big(\frac{Cap}{Cap'}\Big) L_m \, PopDen_{m,k} \, MaxArea_{ijk} \Big] \qquad (7)$$

where:

m = baseline and alternative routes considered
n = baseline and alternative tank car designs considered

subject to:

$$\sum_{n} \mu_n = \sum_{m} \gamma_m = 1$$

$$\mu_m = \begin{cases} 1 \text{ if route } m \text{ is chosen} \\ 0 \text{ otherwise} \end{cases}$$

$$\gamma_n = \begin{cases} 1 \text{ if tank car design } n \text{ is chosen} \\ 0 \text{ otherwise} \end{cases}$$

3.0 Discussion

There is a simple, seemingly obvious appeal to rerouting hazardous materials away from high-density population areas. The reasoning is that by avoiding dense populations the potential for exposing a large number of people to the risk of hazardous materials releases is reduced. Unfortunately, several major factors act in opposition to this apparent benefit, making the problem considerably more complex from both a technical and public policy perspective. One is that shipment distance for the affected hazardous materials will often have to increase due to the more circuitous routing required to avoid population centers. Unless the accident rate is proportionately lower, the likelihood of an accident is thereby increased. Second, and somewhat ironically, the accident rate may actually be higher on the longer, alternative route. As would reasonably be expected, railroad investment in infrastructure is generally correlated with traffic density. Thus the most robust track and sophisticated traffic control systems are generally along those lines connecting large metropolitan areas where the majority of traffic flows occur. These same metropolitan areas are where the heaviest population densities also occur. Thus, by diverting hazardous materials traffic away from metropolitan areas the effect is often to lengthen its route of travel and expose it to lesser quality track where the chance of accident is greater.

The example analyzed in this paper represents just such a set of circumstances and the risk profiles illustrate the resulting dilemma (Figures 1 & 2). The combination of a longer route and lower track quality increases the likelihood of having an accident-caused release along the alternative route. Although the reduced exposure to higher population areas does lower the likelihood of a high consequence event (Figure 2), the probability of a lower consequence event is substantially increased (Figure 1). Beyond the elevated risk of a lower consequence event, the transferal of risk from one population to another presents a difficult public policy decision. Although the residents of the higher population area may be happy enough to see their risk reduced, it is by no means obvious that residents along the alternative route will be eager to accept the elevated risk that necessarily will occur due to transferal of hazardous materials traffic into their "backyards".

The other strategy considered here, use of an alternate design tank car, results in a rather different outcome. There is no transferal of risk from one group to another and the reduced likelihood of an event applies to all population levels. Taking steps to modify railroad infrastructure and/or operations to reduce accident frequency or severity will have a similar effect. However, the large capital cost associated with both strategies may limit their practicality except under some circumstances. The cost of changes in infrastructure and operations compared to modification of the tank car would need to be carefully considered to determine which is the most cost-effective.

The last option, in which both an alternate routing and alternate tank car are used, further reduces the risk of a high consequence event. However, the enhanced safety performance of the alternate tank car is not enough to overcome the increased exposure due to the longer shipment distance and higher accident rate. Therefore the probability of a low consequence event is elevated compared to baseline route and tank car.

It should be emphasized that the outcomes presented here for absolute and relative risk of different combinations of strategies are due to the particular combination of parameters regarding mileage, accident rate, tank car performance, population density and chemical hazard that were selected for this analysis. Although they were chosen because they are reasonably typical of North American circumstances, different combinations would have different effects on risk. This is one of the important points of this paper. Each situation is unique and the effect of each potential approach in the context it is to be applied should be considered relative to one another. Also, some aspects are inherently local or regional, such as routing or infrastructure modifications, whereas others such as tank car design, will generally be applied system-wide.

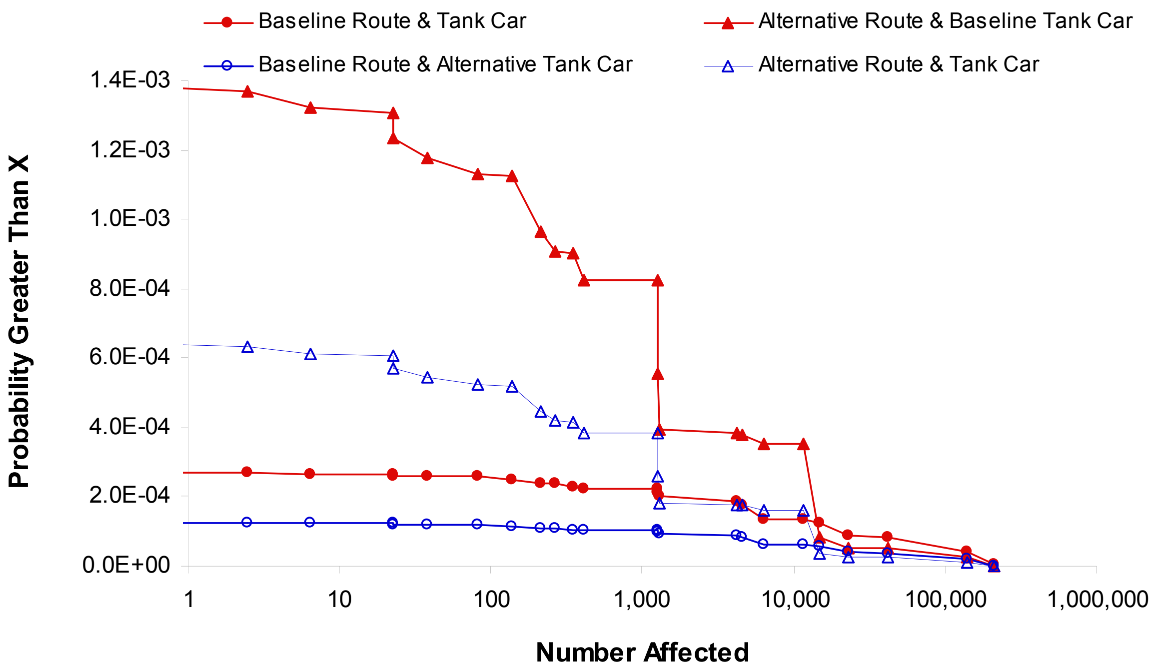

Figure 1: Risk Profiles for Example Chlorine Transportation Analysis

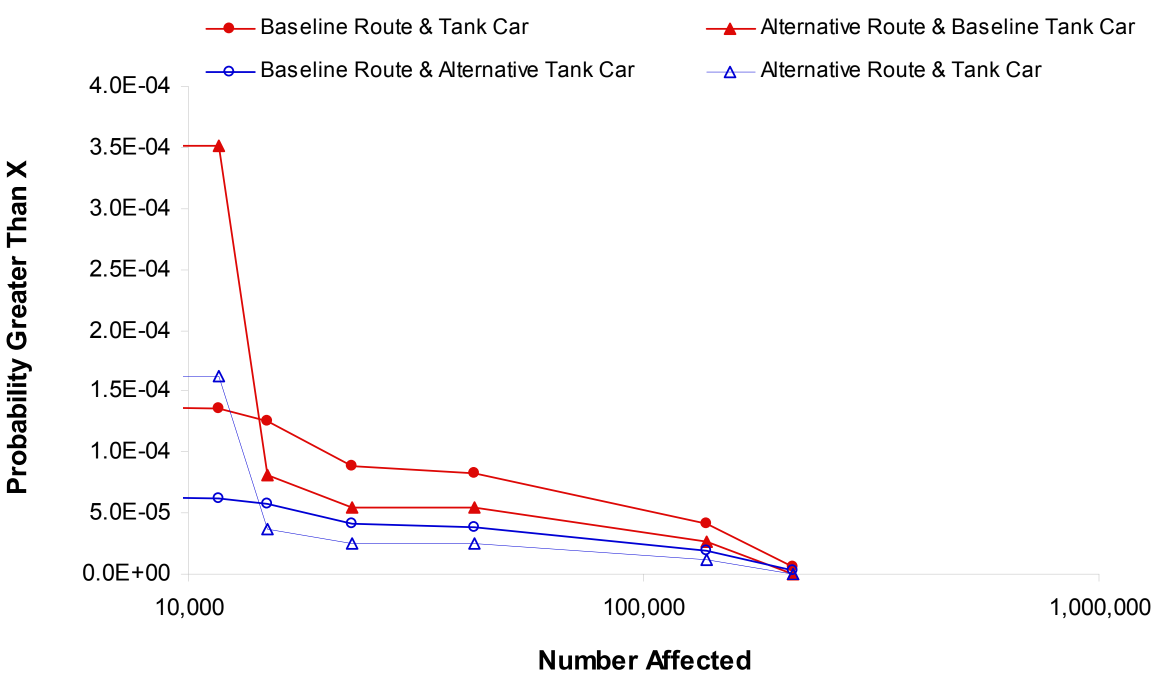

Figure 2: Risk Profiles for Example Chlorine Transportation Analysis
(focusing at the higher level of potential exposure)

4.0 Conclusions

This paper introduces a basic framework to systematically assess and compare the effect of various approaches to manage the risk of rail transport of hazardous materials. Unlike previous work, the approach described here considers various alternative approaches simultaneously. Rerouting, use of alternate design tank cars, modification of railroad infrastructure and railroad operating practices are all options that can be considered. It is in all parties' interest that the most rational choice of options be employed, namely maximizing risk reduction in the most efficient manner possible. Understanding the most cost-effective combination of options is non-trivial and should take into account all of the variables described in this paper. Furthermore, the most cost-effective strategy or combination of strategies may vary depending on the particular circumstances; so informed public policy decisions need to take these factors into account. It should also be noted that there are potential interactions among options in terms of their cost effectiveness and these should also be accounted for when developing the optimal approach to risk reduction. Finally, other aspects that are more difficult to quantify, such as the rationale for transferal of risk from one group to another also need to be considered.

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