

# Release Risk and Optimization of Railroad Tank Car Safety Design

Mohd Rapik Saat and Christopher P. L. Barkan

The performance metric for tank cars and other hazardous materials vehicles involved in accidents has generally been conditional probability of release given involvement in an accident. This metric considers the probability of a release event occurring but does not take into account the quantity of product lost in a release incident. In this paper, a new metric termed “release risk” is introduced; it is defined as the expected value of the quantity lost from a tank car given that it is in an accident. The quantity of product lost varies depending on the part of the car that is damaged in an accident; consequently, use of release risk can affect how different modifications in tank car design are considered. The metric was developed in terms of tank-damage-caused and non-tank-damage-caused releases. It was found that tank-damage-caused releases had a higher release risk than non-tank-damage-caused releases. Important elements considered are the probabilities of release and the expected quantities of release from the tank components and non-tank components of a tank car, and the effect of increasing tank thickness in increasing accident exposure and decreasing expected quantity of release. The release risk metric is also used as the objective function in a tank thickness optimization model. The results suggest that release risk may be a useful means of assessing the relative benefits of different tank car safety design modifications.

For the past several years, the rate of releases of hazardous materials caused by railroad accidents has been fluctuating between 27 and 37 incidents per million carloads (*1*). Though this rate is significantly lower than the rate of about 200 incidents per million carloads in 1982 (*2*), further reduction of accident-caused hazardous material releases remains an important objective. In 2002, there were approximately 1.7 million rail shipments of hazardous materials in the United States and Canada, and approximately 75% of these were transported in tank cars (*1*).

Two of the principal elements in the reduction of railroad hazardous material transportation risk are prevention of accidents and prevention of spills from railcars involved in accidents (*3*). Train accidents declined substantially in the 1980s and more gradually in the 1990s as the result of improvements in track design and maintenance and improvements in equipment and training (*4, 5*). The result is that the annual accident rate has been reduced from approximately 12 accidents per million train miles in 1980 (*6*) to about 4 accidents per million train miles in 2002 (*7*).

Changes in the design of tank cars intended to make them more resistant to damage in accidents have also helped improve the safety

record (*2*). Although analysis of the degree of hazard posed by different products is ongoing, in general, higher-hazard materials are shipped in cars with tanks constructed of thicker and stronger steels. These cars may be equipped with head shields and with more damage-resistant designs for the top fittings.

The objective of this study was to develop a new metric for quantifying hazardous materials releases and to apply this metric by extending the work done by Barkan et al. (*8*) to evaluate tank car thickness and safety. They used optimality techniques to consider tank car design so as to minimize the probability of release and developed a model that considered the trade-off between improved damage resistance of the tank and increased accident exposure due to the reduced capacity of the car. The objective function in their model was probability of release. This paper considers a new metric as the objective function in which the quantity lost is accounted for as well as the probability of release. Previous authors have considered accident-caused release probability and the quantity lost due to different sources of damage to the tank car (*9, 10*), but these factors have not previously been combined into a single metric to evaluate tank car safety design. In this paper, the concept of release risk is developed, as is a new version of the optimal tank thickness model that uses this new metric.

## TANK CAR DAMAGE RESISTANCE

There are two general types of tank-car damage that can lead to releases in an accident: (*a*) tank-caused damage, which includes damage to the head and shell, and (*b*) non-tank-caused damage, which includes damage to other tank car components, principally the top and bottom fittings.

Accident-caused damages to the tank and non-tank components of a car have distinct natures, and different approaches are used to enhance damage resistance. The usual approach to reducing tank-caused damage is to increase the strength of the tank. This can be accomplished by increasing tank thickness, using head protection, applying a tank jacket, or all of the above. In addition, the tank material properties may be improved by using higher tensile strength steel, normalized steel, or both.

Reducing non-tank-caused releases includes measures such as enclosing top fittings in a protective housing (*1*), adding protection for the bottom fittings (*11*), or removing the bottom fittings completely (*8*).

## TANK CAR RELEASE RISK

The conditional probability of release given that a tank car is derailed in an accident is a useful metric for assessing the safety of tank cars. However, it does not take into account the quantity of product lost. This amount varies depending on the part of the car that is damaged

Railroad Engineering Program, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 205 N. Mathews Avenue, Urbana, IL 61801.

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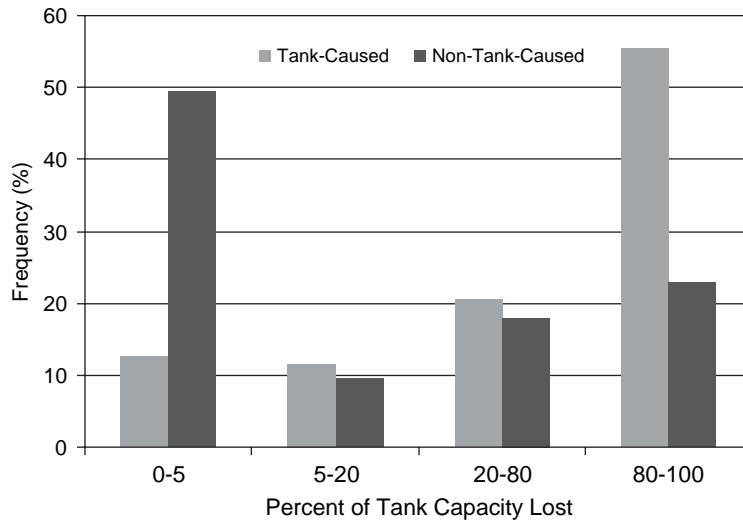


FIGURE 1 Frequency of releases of different sizes by source for noninsulated, nonpressure tank cars in accidents (9).

(Figure 1) (9, 10); for example, for a general purpose DOT-111 tank car with 0.4375-in. tank thickness, non-tank-caused releases are the most frequent source of loss in accidents (Figure 2a), but they result in the lowest average amount of product lost (Figure 2b) (9, 10). Conversely, losses from tank-caused releases are less common but they result in a larger average quantity lost. The reason for this disparity is that in accidents in which fittings develop a leak, the leaks are often small and can be stopped relatively quickly by response personnel. In contrast, holes in the tank head or shell are often caused by impact damage from a rail or another railcar that punctures or tears open the tank. These openings are often fairly large and difficult to plug before a large portion of the tank’s contents are lost. The rate of release and thus the quantity of release depend on the size of the puncture (12), the tank’s internal pressure, and the viscosity of the commodity.

In addition to the hazard level of the commodity, the quantity released affects the severity of the release incident. A larger release will generally create a larger exposure area and consequently have a greater impact on people, property, and the environment and incur higher response, evacuation, and hazard mitigation costs. Therefore, when evaluating the benefit of applying various risk reduction options to tank cars, it may be beneficial to consider the amount lost from different parts of the car.

The following example illustrates the idea of the release risk metric for the general purpose tank car. The conditional probability of a tank-caused release given that a tank car is derailed in an accident is 0.117, and the conditional probability of a non-tank-caused release is 0.207 (9). The corresponding average amount of content lost for each source is 62.0% and 32.1% of tank capacity, respectively. The product of the conditional probability and the average amount of content lost is the expected value of the percentage lost, or release risk, given that a car is derailed or damaged in an accident (Figure 2c). This example considers the average release risk for a particular type of tank car with a specific thickness. This study is intended to develop a more general release risk model for tank cars with different tank thicknesses. In addition, instead of considering the average percentage of tank capacity lost for each source, the distribution of release size (Figure 1) is taken into account in the development of the model described in the following section.

### MODEL DEVELOPMENT

Risk is defined as the frequency of an event multiplied by the consequences of that event. In the context of the model described here, frequency is defined as the probability of release, and consequence is defined as the quantity of product lost expressed as a percentage of the tank’s total volumetric capacity. Important aspects considered in the development of the release model are (a) the functional relationship between tank thickness and release risk caused by damage to the tank (tank-caused releases), (b) the release risk caused by damage to other tank car appurtenances (non-tank-caused releases) that are not directly affected by tank thickness, (c) the relationship between tank thickness, weight, capacity, and number of shipments, and (d) the relationship between tank thickness, weight, capacity, and expected quantity of release. All damage-caused release sources and discrete release sizes are incorporated in the release risk model shown below:

$$R_R = \sum_{j=1}^n \sum_{i=1}^m R_{Ri,j}$$

where

- $R_R$  = release risk for a tank car in percentage of tank capacity lost,
- $n$  = number of release sources considered,
- $m$  = number of release sizes considered, and
- $R_{Ri,j}$  = release risk for release size  $i$  from release source  $j$ .

### Tank-Caused Release Source

The frequency of a tank-caused release of size  $i$  can be defined as

$$F_{TRi} = P_{TRi|A} Z \tag{1}$$

where

- $F_{TRi}$  = frequency of tank-caused release of size  $i$ ;
- $P_{TRi|A}$  = conditional probability of tank-caused release of size  $i$  given the car is derailed in an accident =  $P_{Ri|TR} P_{TR|A}$ ;

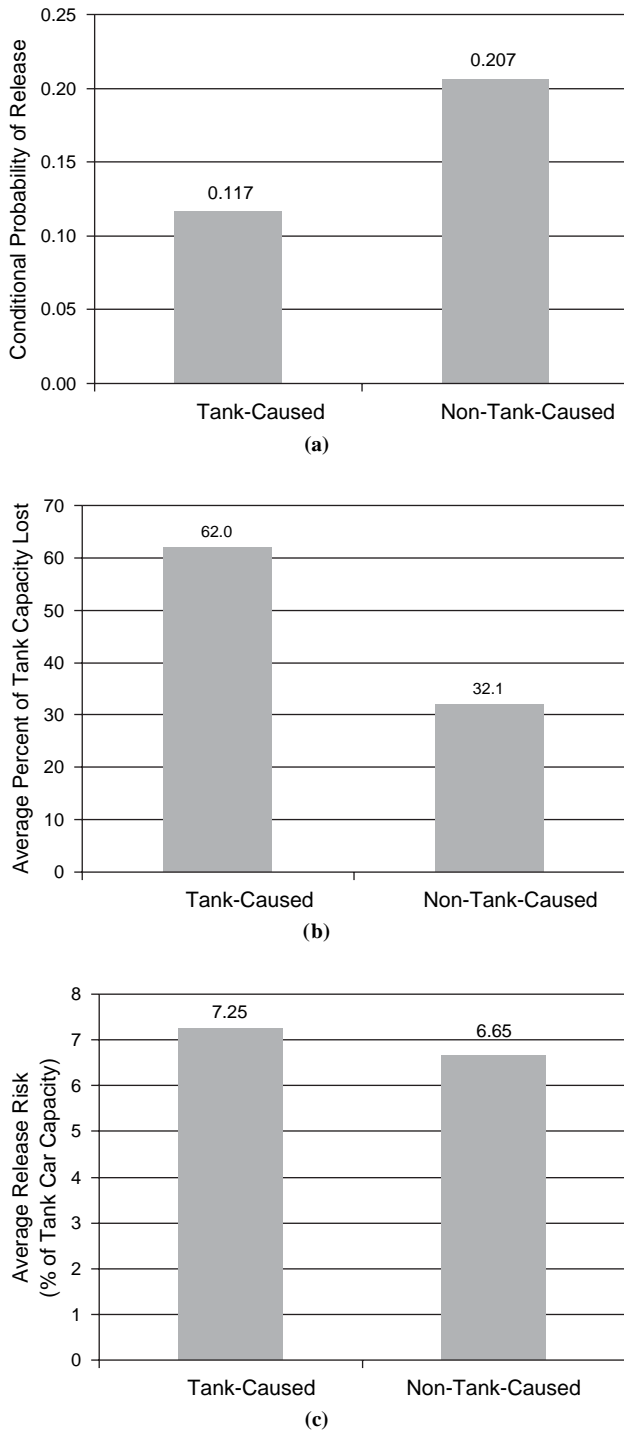


FIGURE 2 (a) Conditional probability of release by source for general purpose noninsulated DOT-111 tank cars (9), (b) average percentage of tank capacity lost by source for general purpose noninsulated DOT-111 tank cars that lost lading in accidents (9), and (c) average release risk by source for general purpose noninsulated DOT-111 tank cars that lost lading in accidents.

$P_{Ri|TR}$  = conditional probability of release size  $i$  given a tank-caused release occurrence;

$P_{TR|A}$  = conditional probability of a tank-caused release occurrence given the car is derailed in an accident;

$Z$  = exposure to accident =  $P_A M$ ;

$P_A$  = probability of a tank car derailed in an accident per mile traveled; and

$M$  = number of car miles.

Thus, Equation 1 can be modified as follows:

$$F_{TRi} = P_{Ri|TR} P_{TR|A} P_A M \tag{2}$$

The associated release consequence for tank-caused release is defined as  $V_{TRi}$ , the average percentage of tank capacity lost for release size  $i$  in a tank-caused release occurrence.

With the four release sizes shown in Figure 1, the risk for tank-caused release of size  $i$  can be defined as the product of the associated frequency and consequence as expressed below:

$$R_{TR} = \sum_{i=1}^4 F_{TRi} V_{TRi} \tag{3}$$

Expanding the tank-caused release risk definition in Equation 3, it can be seen that the accident exposure terms  $P_A$  and  $M$  appear as constants for each release size. If excluded from the release risk definition, a new term called conditional tank-caused release risk is introduced as follows:

$$R'_{TR} = \sum_{i=1}^4 P_{Ri|TR} P_{TR|A} V_{TRi}$$

where  $R'_{TR}$  is the conditional tank-caused release risk given the tank car is damaged or derailed.

Hughes et al. published data on conditional tank-caused release probability with respect to tank thickness (13). With the data and quantity of release data from Phillips et al. (9) (Table 1), the relationship between tank thickness and conditional tank-caused release risk was calculated (Figure 3). For this study, regression analysis was conducted, data were fitted to a negative exponential model to determine the functional relationship between tank thickness and the estimated conditional tank-caused release risk. Over the range of thicknesses in use for tank cars in North America, the conditional release risk conforms well ( $R^2 = 0.8837$ ) to a negative exponential distribution of the following form:

$$R'_{TR} = v + w e^{(-y+z)}$$

where

$t$  = tank thickness;

$v$ ,  $w$ ,  $y$ , and  $z$  = regression coefficients in the negative exponential model, as follows:

$v = 0.40951$ ;

$w = 4.72098$ ;

$y = 6.35515$ ; and

$z = 3.22174$ .

The net tank-caused release risk is calculated by multiplying the conditional tank-caused release risk by the exposure terms, probability that a tank car will derail in an accident per car mile, and

**TABLE 1 Tank-Caused Conditional Release Risk Expressed as Percentage of Tank Capacity Lost (9, 12)**

Tank Thickness (in.)	Percentage Tank Contents														Fitted $R_{TR}^*$	
	0-5				> 5-20				> 20-80				> 80-100			Calculated $R_{TR}^*$
	$P_{TRIA}$	$P_{RI TR}$	$V_{TR1}$	$R_{TR1}^*$	$P_{R2 TR}$	$V_{TR2}$	$R_{TR2}^*$	$P_{R3 TR}$	$V_{TR3}$	$R_{TR3}^*$	$P_{R4 TR}$	$V_{TR4}$	$R_{TR4}^*$			
0.4375	0.1170	0.037	0.037	0.168	0.168	0.168	1.200	1.200	1.200	5.849	7.254	7.750				
0.5000	0.1090	0.034	0.034	0.157	0.157	0.157	1.121	1.121	1.121	5.465	6.777	5.344				
0.5625	0.0430	0.014	0.014	0.062	0.062	0.062	0.443	0.443	0.443	2.158	2.676	3.726				
0.6250	0.0440	0.014	0.014	0.063	0.063	0.063	0.451	0.451	0.451	2.198	2.726	2.639				
0.6875	0.0270	0.009	0.009	0.039	0.039	0.039	0.279	0.279	0.279	1.359	1.685	1.908				
0.7500	0.0280	0.009	0.009	0.040	0.040	0.040	0.288	0.288	0.288	1.404	1.741	1.417				
0.8125	0.0190	0.125	2.5	0.006	0.115	12.5	0.027	0.205	50	0.193	0.555	90				
0.8750	0.0070	0.002	0.002	0.010	0.010	0.010	0.075	0.075	0.075	0.365	0.452	0.865				
0.9375	0.0160	0.005	0.005	0.022	0.022	0.022	0.160	0.160	0.160	0.779	0.966	0.716				
1.0000	0.0000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.615				
1.0625	0.0030	0.001	0.001	0.004	0.004	0.004	0.029	0.029	0.029	0.140	0.173	0.548				
1.1250	0.0260	0.008	0.008	0.037	0.037	0.037	0.261	0.261	0.261	1.274	1.580	0.502				
1.2500	0.0060	0.002	0.002	0.009	0.009	0.009	0.062	0.062	0.062	0.300	0.372	0.452				

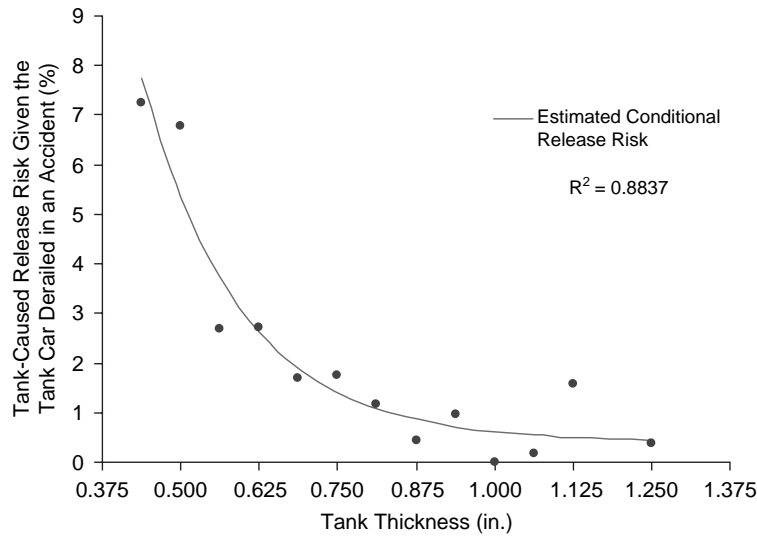


FIGURE 3 Conditional tank-caused release risk given tank car is derailed or damaged in an accident as a function of tank thickness ( $t$ ); points represent data and line indicates regression function fitted to data.

number of car miles. With the fitted regression model above, tank-caused release risk as a function of tank thickness  $t$  can be modified as follows:

$$R_{TR}(t) = [v + we^{(-yt+z)}]P_A M \tag{4}$$

**Non-Tank-Caused Release Source**

As mentioned above, non-tank-caused release risk does not depend on tank thickness. The frequency of a release of size  $i$  can be defined as

$$F_{NRi} = P_{NRi|A} Z \tag{5}$$

where

- $F_{NRi}$  = frequency of non-tank-caused release of size  $i$ ; and
  - $P_{NRi|A}$  = conditional probability of non-tank-caused release of size  $i$  given the car is derailed in an accident.
- $$= P_{Ri|NR} P_{NR|A}$$

where

- $P_{Ri|NR}$  = conditional probability of release size  $i$  given a non-tank-caused release occurrence; and
- $P_{NR|A}$  = conditional probability of a non-tank-caused release occurrence given the car is derailed in an accident.

$Z$  is defined as above.

Thus, Equation 5 can be modified as follows:

$$F_{NRi} = P_{Ri|NR} P_{NR|A} P_A M \tag{6}$$

The associated release consequence for a non-tank-caused release of size  $i$  is defined as  $V_{NRi}$ , the average percentage of tank capacity lost for release size  $i$  in a non-tank-caused release accident

The product of the associated frequency and consequence gives the following non-tank-caused release risk:

$$R_{NR} = \sum_{i=1}^4 F_{NRi} V_{NRi}$$

With the quantity of lost data (Table 2) and with the terms  $P_{NR|A}$ ,  $P_A$ , and  $M$  held constant, the non-tank release risk can be simplified as follows:

$$R_{NR} = 32.125 P_{NR|A} P_A M \tag{7}$$

**Relationship Between Tank Thickness, Tank Car Capacity, and Number of Shipments**

The size of tank cars is generally optimized for the density of the specific product they are intended to transport (14, 15). Products vary considerably in their density, and the size of a tank car is inversely related to the density of its intended product. The maximum weight of a loaded rail car is referred to as the gross rail load (GRL). It consists of the car’s empty weight plus the maximum lading weight. The empty or “light” weight of a car is the weight of the running gear

TABLE 2 Expected Non-Tank-Caused Release Quantity (9)

$i$	Percentage Tank Contents			
	0–5	>5–20	>20–80	>80–100
$P_{Ri NR}$	0.495	0.095	0.180	0.230
$V_{i, NR}$	2.5	12.5	50.0	90.0
$P_{Ri NR} V_{i, NR}$	1.2375	1.1875	9.0000	20.7000
$V_{NR}$	32.125			

and tank fittings, which are relatively constant, and the weight of the tank itself, which varies with its size, its thickness, and whether it has a jacket and insulation.

Increasing the tank thickness to make a tank car more robust in an accident increases the weight of the tank. The maximum GRL for cars in unrestricted interchange is fixed, so the increase in the light weight due to the thicker tank reduces the capacity of the tank car. Consequently, more shipments or car miles are required to haul the same quantity of lading. The number of car miles is directly proportional to tank thickness. Barkan et al. developed the variable  $K$  that is the proportional increase in the number of shipments required with respect to increased tank thickness (8). The term  $K$  is unique and tank-car specific; it depends on the volumetric capacity that corresponds to product density, the GRL, and the tank car's light weight.

To illustrate the idea, a general purpose DOT-111 tank car with a baseline thickness of 0.4375 in. and a capacity of 20,000 gal can be considered. With IlliTank, a tank car size and weight program, the effect of increased tank thickness on the number of car miles was calculated (M. R. Saat, Illini Tank Capacity: Railroad Tank Car Weight and Capacity Program, unpublished work, 2003). The tank inside diameter and non-tank light weight constant were set at 110.25 in. and 33,000 lb, respectively. The program solves the optimal tank size problem and calculates the change in tank capacity for each tank thickness. For instance, for the baseline tank car used, an increase in  $\frac{1}{16}$  in. reduces the tank capacity by approximately 1% and correspondingly increases the number of shipments about 1% (Table 3). In general the number of extra shipments is equal to  $1/(1-p)$  times the baseline number of shipments, where  $p$  is the percentage reduction in tank capacity.

Car miles are proportional to shipments, and thus tank thickness (Figure 4). Linear regression was used to calculate  $K$ , the proportion

increase in shipments needed to compensate for the reduced capacity of a thicker but heavier tank. In the example above,  $K = 0.236$  (Figure 4).

The effect of increasing the number of car miles is that the more robust tank car also has a correspondingly higher exposure to the chance of accident involvement. To account for the increased number of car miles with respect to tank thickness  $t$ , the accident exposure term  $Z$  can be modified as follows:

$$Z(t) = P_A M [1 + K(t - t')] \tag{8}$$

where

- $t$  = tank thickness,
- $t'$  = base tank thickness, and
- $K$  = proportion increase in shipments due to the change in tank thickness.

Incorporating Equation 8 into Equations 4 and 7, the tank-caused release risk and non-tank-caused release risk with respect to tank thickness,  $t$  can be rewritten as follows:

$$R_{TR}(t) = [v + we^{(-yt+z)}] P_A M [1 + K(t - t')] \tag{9}$$

$$R_{NR}(t) = 32.125 P_{NR/IA} P_A M [1 + K(t - t')] \tag{10}$$

The sum of  $R_{TR}(t)$  and  $R_{NR}(t)$  is the net release risk for a tank car in percentage of tank capacity lost with respect to tank thickness  $t$ :

$$R_R(t) = \{P_A M [1 + K(t - t')]\} [(v + we^{(-yt+z)}) + 32.125 P_{NR/IA}] \tag{11}$$

**TABLE 3 Effect of Increasing Tank Thickness on Tank Car Capacity and Number of Car Miles ( $K = 0.236$ )**

Tank Thickness (in.)	Nominal Lading (U.S. gallon)	Capacity Reduced	Number of Shipments	Proportion of Shipment Increased	Change in Tank Thickness
0.4375	20,000	0.00	1.00	0.00	0.00
0.5000	19,715	0.01	1.01	0.01	0.06
0.5625	19,437	0.03	1.03	0.03	0.13
0.6250	19,166	0.04	1.04	0.04	0.19
0.6875	18,902	0.05	1.06	0.06	0.25
0.7500	18,645	0.07	1.07	0.07	0.31
0.8125	18,394	0.08	1.09	0.09	0.38
0.8750	18,149	0.09	1.10	0.10	0.44
0.9375	17,909	0.10	1.12	0.12	0.50
1.0000	17,676	0.12	1.13	0.13	0.56
1.0625	17,447	0.13	1.15	0.15	0.63
1.1250	17,224	0.14	1.16	0.16	0.69
1.1875	17,006	0.15	1.18	0.18	0.75
1.2500	16,793	0.16	1.19	0.19	0.81
1.3125	16,585	0.17	1.21	0.21	0.88
1.3750	16,381	0.18	1.22	0.22	0.94
1.4375	16,182	0.19	1.24	0.24	1.00
1.5000	15,987	0.20	1.25	0.25	1.06

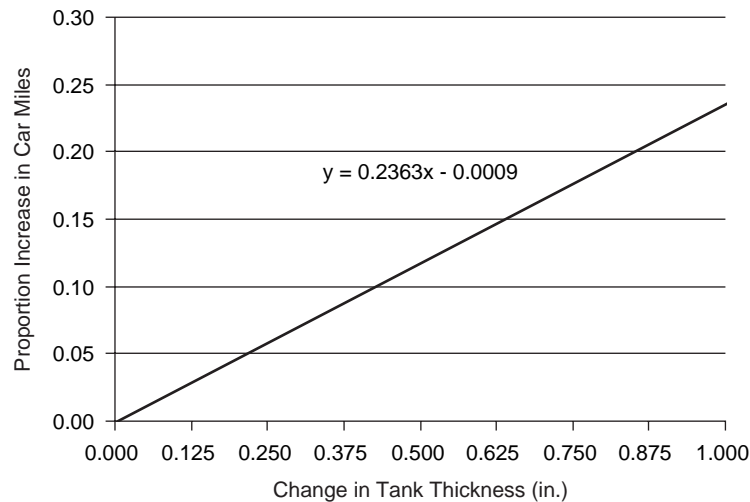


FIGURE 4 Increase in car miles with respect to tank thickness for 20,000-gal, 263,000-lb GRL noninsulated tank car.

### Relationship Between Tank Thickness, Tank Car Capacity, and Expected Quantity of Release

In addition to the trade-off between reduced release probability and increased accident exposure with increased tank thickness, as discussed previously, the reduction in expected quantity lost due to the reduced volumetric capacity is also a factor to be considered. The lower volume of heavier and thus smaller tanks reduces risk from both tank-caused and non-tank-caused releases because tank cars with lower capacity have less quantity to release. In the formulation of the tank car thickness optimality model in Barkan et al., probability of release was considered (8). The following section considers the effect of modifying this model with the use of minimization of quantity released as the objective function and focuses on the effect on optimal tank thickness.

### EVALUATING RISK REDUCTION WITH INCREASING TANK THICKNESS

The release risk model presented so far estimates the percentage of tank capacity lost for a tank car derailed in an accident. When the risk between tank cars that have different tank thicknesses is compared, the absolute release quantity, in terms of volume or mass, should be calculated. As noted above, *ceteris paribus*, thicker tank cars have lower capacities. As such, for tank cars with different safety designs, an identical release risk in terms of percent tank capacity corresponds to different absolute quantities of release. The expected gallon capacity lost can be calculated as follows:

$$Q_R(t) = \sum_{j=1}^n R_j(t) \text{cap}(t) \quad (12)$$

where

$Q_R(t)$  = expected gallon capacity lost for a tank car with tank thickness  $t$ ,

$n$  = number of tank- or non-tank release sources considered,

$R_j(t)$  = release risk from source  $j$  in percentage of tank capacity lost with tank thickness  $t$ , and

$\text{cap}(t)$  = gallon capacity for a tank car with tank thickness  $t$ .

The corresponding mass of material expected to be released for a specific chemical can be calculated using its density.

Barkan et al. developed a model in which minimization of release probability was the objective function (8). The tank-caused probability of release was a negative exponential function, as is the case here, and the non-tank-caused release probability was a monotonically increasing linear function (Figure 5). Therefore, the benefit of having a thicker tank represented by the decreasing probability of a tank-caused release,  $P_{TR}(t)$ , was offset by the increase in non-tank-caused probability of release,  $P_{NR}(t)$ . Barkan et al. found that there was an optimal tank thickness,  $t^*$ , when release probability  $P_R(t)$  was minimized.

This study considered the same 20,000-gal noninsulated tank car with  $K = 0.236$  with the minimization of  $Q_R(t)$  as the objective function. The average rail car derailment rate per car mile ( $P_A$ ) used was  $1.28 \times 10^{-7}$  (7), and a baseline of 1 million car miles ( $M$ ) was used. For the non-tank-caused release risk calculation, the conditional probability of release given a tank car derailed in an accident is constant:  $P_{NR|A} = 0.207$  (9).

The baseline tank thickness,  $t'$ , is 0.4375 in., and release risk and expected gallon capacities lost from the tank and non-tank components were evaluated with respect to increased  $t$  in  $1/16$ -in. increments (Table 4). The model was used to calculate the expected quantity lost from the tank and non-tank components (Figures 6 and 7). The scale of the ordinate is different in Figures 6 and 7 to emphasize the change in sign of the slope for the non-tank quantity lost. The same data, along with the sum of the two sources, are shown in Figure 8.

For tank-caused releases, the safety benefit from increased tank thickness, generated by both increased damage resistance and decreased capacity available to be released, dominates the incremental risk caused by the increase in accident exposure over the entire range of tank thicknesses considered. As described previously, the expected quantity lost from tank-caused releases follows a negative exponential distribution. Increasing the tank thickness provides no direct safety benefit in terms of improving non-tank components' damage resistance, but there is a reduction in their release risk caused by the reduced capacity of the tank. The relationship between  $t$  and  $Q_{NR}(t)$  is a concave function (Figure 7). There is an initial increase in the expected quantity released because of the increased exposure to accidents due to the decreased capacity. However, this increase is



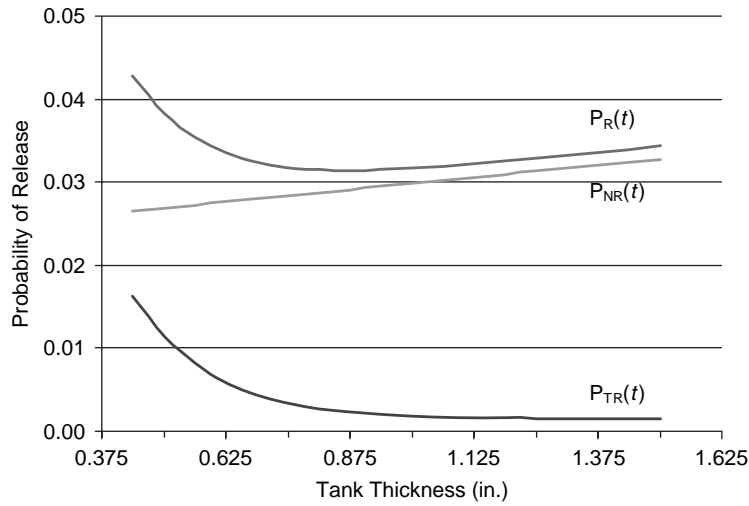


FIGURE 5 Probabilities  $P_R(t)$ ,  $P_{NR}(t)$ , and  $P_{TR}(t)$  as function of tank thickness  $t$ , per million car miles ( $\beta$ ).

TABLE 4 Calculated Values for Tank-Caused, Non-Tank-Caused and Total Release Risks and Expected Gallon Capacities Lost ( $K = 0.236$ )

$t$ , in.	$R_{TR}(t)$ , % Tank Capacity	$R_{NR}(t)$ , % Tank Capacity	$R_R(t)$ , % Tank Capacity	Cap( $t$ ), Gallon	$Q_{TR}(t)$ , Gallon	$Q_{NR}(t)$ , Gallon	$Q_R(t)$ , Gallon
0.4375	0.99	0.85	1.84	20,000	198.39	170.24	368.63
0.5000	0.69	0.86	1.56	19,715	136.84	170.30	307.14
0.5625	0.49	0.88	1.37	19,437	95.45	170.35	265.80
0.6250	0.35	0.89	1.24	19,166	67.62	170.39	238.01
0.6875	0.26	0.90	1.16	18,902	48.90	170.43	219.33
0.7500	0.19	0.91	1.11	18,645	36.32	170.46	206.78
0.8125	0.15	0.93	1.08	18,394	27.86	170.48	198.34
0.8750	0.12	0.94	1.06	18,149	22.17	170.49	192.67
0.9375	0.10	0.95	1.05	17,909	18.35	170.51	188.85
1.0000	0.09	0.96	1.05	17,676	15.77	170.51	186.28
1.0625	0.08	0.98	1.06	17,447	14.05	170.51	184.55
1.1250	0.07	0.99	1.06	17,224	12.88	170.50	183.38
1.1875	0.07	1.00	1.07	17,006	12.10	170.49	182.59
1.2500	0.07	1.02	1.08	16,793	11.57	170.47	182.04
1.3125	0.07	1.03	1.10	16,585	11.22	170.44	181.66
1.3750	0.07	1.04	1.11	16,381	10.98	170.41	181.39
1.4375	0.07	1.05	1.12	16,182	10.82	170.38	181.20
1.5000	0.07	1.07	1.13	15,987	10.71	170.34	181.05
1.5625	0.07	1.08	1.15	15,796	10.63	170.30	180.93
1.6250	0.07	1.09	1.16	15,609	10.58	170.25	180.83
1.6875	0.07	1.10	1.17	15,425	10.55	170.20	180.74
1.7500	0.07	1.12	1.18	15,246	10.52	170.14	180.66
1.8125	0.07	1.13	1.20	15,070	10.50	170.08	180.58
1.8750	0.07	1.14	1.21	14,898	10.49	170.01	180.50
1.9375	0.07	1.15	1.22	14,729	10.48	169.94	180.42
2.0000	0.07	1.17	1.24	14,563	10.47	169.87	180.34



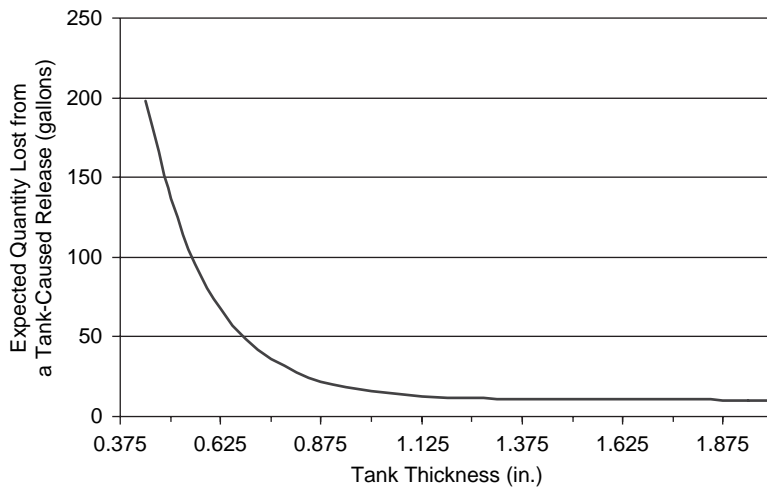


FIGURE 6 Expected quantity lost from tank-caused release  $Q_{TR}(t)$ , as function of tank thickness ( $t$ ), per million car miles.

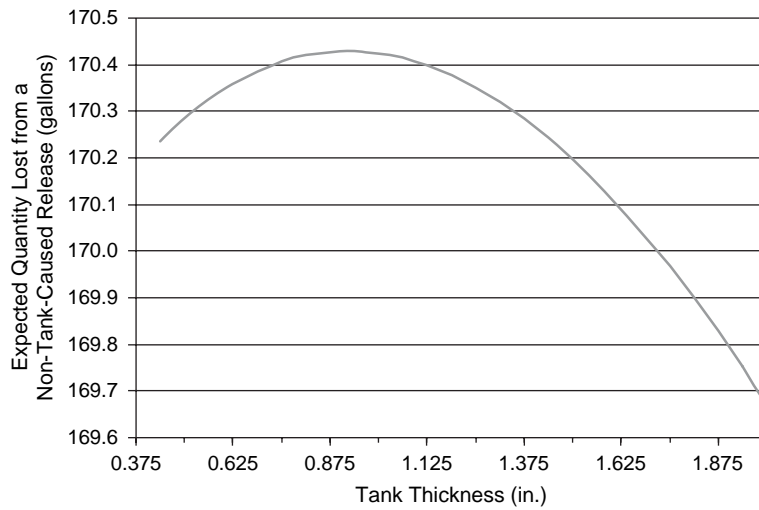


FIGURE 7 Expected quantity lost from non-tank-caused release  $Q_{NR}(t)$ , as function of tank thickness ( $t$ ), per million car miles.

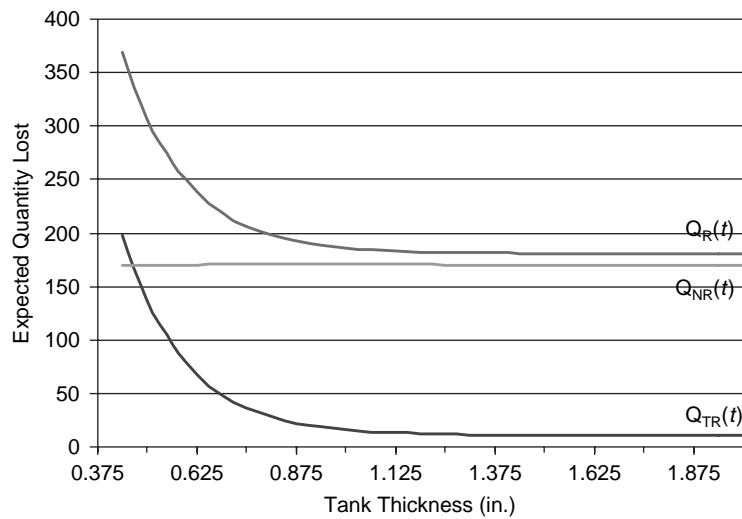


FIGURE 8 Expected gallons lost  $Q_R(t)$ ,  $Q_{TR}(t)$ , and  $Q_{NR}(t)$ , as function of tank thickness ( $t$ ), per million car miles.

counteracted by the decline in the quantity available to be released as  $t$  increases. This contrasts with the monotonically increasing function for  $P_{NR}(t)$  in Barkan et al. (8) and therefore does not have the same offsetting effect.

When minimization of expected quantity released is used as the objective function to optimize tank car thickness, there is no optimum within the range of the tank thicknesses considered. Despite the initial positive slope of  $Q_{NR}(t)$ ,  $Q_{TR}(t)$  always dominates the overall release risk function (Figure 8). As such  $Q_R(t)$  is a continuously declining function of tank thickness over the range of thicknesses evaluated.

The contrast between the results of these two approaches is not intended to suggest that one is better than the other. In fact, either can be used depending on whether the objective is minimization of release probability or minimization of expected quantity released. Either approach may be appropriate depending on the characteristics of the particular hazardous material and the potential consequences of a spill.

## DISCUSSION AND CONCLUSIONS

The release risk metric is potentially useful for assessing the benefit from changes in tank car safety design because unlike previous analyses, it simultaneously considers both release probability and release amount. The distribution of release quantity is related to the source of damage-caused leaks on tank cars in accidents; consequently, changes in design will have different potential benefits in terms of risk reduction. This paper explores the implications of this with respect to one option for enhancing tank car safety: modification of tank thickness.

The analysis performed here indicates that release risk can be reduced by constructing tank cars with tanks that are thicker than those typical of most cars in service. However, tank cars constructed in this manner would be considerably more expensive to build and operate, and the resultant reduction in risk would often not be justified. All regulated materials are not equally hazardous, and, in general, tank car safety specifications, including tank thickness, are commensurate with the degree of risk posed by the product.

The model presented here focuses on releases from tank and non-tank components. A more refined approach is being developed that will differentiate the head and shell elements of tank-caused release risk and the top and bottom fittings in non-tank-caused release risk. The resultant metric can be used to analyze the effectiveness of each safety feature alone or in combination. Such analyses can ultimately be used in conjunction with the different capital and operating costs associated with different tank car modifications, and the hazard characteristics of the products they transport, to enable tank car designs to be finely tuned to efficiently balance risk and cost.

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