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Optimizing the design of railway tank cars to minimize accident-caused releases

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Abstract

The design of vehicles transporting hazardous materials has important public safety and economic implications. Conventional wisdom among industry and government has held that a thicker tank on railroad tank cars and trucks reduces risk. However, a thicker tank increases vehicle weight and thus leads to an increase in the number of shipments required to transport the same amount of product and consequently greater exposure to accidents. In this research we develop a model that analyzes the tradeoff between increased damage resistance and greater exposure to accidents in which the objective function is minimization of the probability of release. The model accounts for the reduction in tank car release probability as a function of tank thickness, and the increased exposure to accidents that occurs due to the increased number of shipments needed for the heavier car. Three variables affecting this optimal thickness are considered in this paper: the volumetric capacity of the tank, the probability of release from other, non-tank sources, and the weight capacity of the car. Sensitivity analyses using the model indicate that for any particular configuration of tank car there is an optimal thickness. This optimal thickness is affected by several factors and there is no single optimum for all tank cars.

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1. Introduction

In many aspects of industrial society there are tradeoffs between risk and economics and such is the case with hazardous materials transportation. Society derives benefit from the use of these materials, but also incurs certain risks due to the need to transport them from their place of production to the point of consumption. To minimize the risk, considerable attention has been paid to the proper handling of hazardous materials in transport, including packaging of the materials, loading and unloading practices, transportation operations, routing of shipments, emergency response practices and hazardous materials shipment information [1–21].

One of the most important elements of ensuring hazardous materials transportation safety is the "packaging". Packaging refers to the design of the container and its ability to transport its intended product and withstand both the ordinary and the extraordinary physical aspects of the environment that may be experienced in transit. Both industry and government agencies have developed extensive specifications, regulations and practices for hazardous materials packages [20–23] that are intended to minimize the likelihood of a spill. However, it is also important that these do not place undue economic burden on transportation. Although some overland transport of hazardous materials is via pipeline, a substantial majority of the bulk transportation tonnage is by truck or rail. Consequently, the design of tank trucks and railroad tank cars is of considerable importance when considering the safe transport of hazardous materials.

Type of hazard varies widely among the many different materials classified as hazardous in transportation [21]. For example, the principal hazard for some materials is their flammability, whereas for others it is their acute toxicity to humans or their potential to cause damage to the environment. Within each of these groups there is substantial variability in the degree of hazard they pose.

In the design of containers for transportation of hazardous materials, the first consideration is complete containment of the product throughout the variety of conditions that can reasonably be expected to normally occur in transit. This aspect is driven by safety concerns as well as commercial interest in maintaining product quantity, quality and purity. Above and beyond this, however, is the need to prevent spillage in the event of unusual occurrences such as accidents. Although the probability of such events is low, it is a factor affecting the design of nearly all containers transporting hazardous materials. And for certain hazardous materials it may be the most important factor affecting specific aspects of container design.

Not surprisingly the robustness of containers is generally commensurate with the hazard posed by the products they are intended to transport, the more hazardous the product, the more robust the container. The objective is to design an efficient and economical transportation container that is sufficiently resistant to damage that it will not spill its contents in an accident. A common approach to achieving this is to construct containers with stronger walls, either through use of thicker or stronger material, or both. Extensive engineering and statistical analysis has been conducted to document and quantify the benefits of this [7,24–29]. However, there are limits to the beneficial effect of this approach. Increasing tank thickness results in higher tank car weight and consequent loss in capacity of the car. This means that more shipments must be made to transport the same amount of product, and there is a resulting increase in exposure to an accident. As will be shown in this paper, if this is not properly integrated into the overall design of the container, thickening the tank will not minimize the probability of release of a hazardous material in transit.

Optimization techniques have been previously used to address hazardous materials safety questions particularly regarding routing, modal choice and emergency response [15,30–36]. However, we are unaware of any previous work that considers container design from a formal optimization stand point. We develop a model here that considers the question of optimizing container thickness so as to minimize the probability of an accident-caused release. The model is developed in the context of railroad tank cars, but the concepts and methodology apply to and can be adapted to other transport modes, particularly truck transportation of hazardous materials.

2. Damage resistance of tank cars

There are basically two types of release-causing damage that a tank car can experience in an accident, (1) damage to the tank head and shell, and (2) damage to the various appurtenances such as top and bottom fittings used for loading and unloading the tank (Fig. 1). We will refer to these as tank and non-tank causes, respectively. It is useful to distinguish between them because both the nature and consequences of damage to them differs, and consequently, so does the associated risk. Not surprisingly, design modifications to enhance tank versus non-tank damage resistance also differ, and these modifications have correspondingly different effects on risk reduction. The distinctions between these two general sources of release and the approaches to enhancing their damage-resistance have a direct bearing on the model we develop in this paper.

The typical approach to making the tank more damage-resistant is to improve its ability to withstand the forces it may encounter in an accident. This is generally accomplished by making the tank wall thicker [8,20,21]. A related approach is to add an outer jacket of steel. The function of the jacket is to support and protect a layer of insulation needed to maintain the temperature of the tank contents while in transit, but a secondary benefit of the jacket is that it also increases the car's damage resistance. This factor is acknowledged in the specifications and regulations for certain hazardous materials tank cars [20,21].

The non-tank vulnerability in accidents is due to the various fittings and appurtenances used for loading and unloading, pressure and vacuum relief, gauging, and access to the interior of the tank. Protection of these fittings to make them less susceptible to being opened or damaged in accidents has been accomplished in several ways, including modification of the fittings' design so that they have a lower external profile, moving valves so that they are internal to the tank, and consolidating the fittings in one area of the tank and partly or completely enclosing them within a protective housing [20]. In the case of bottom

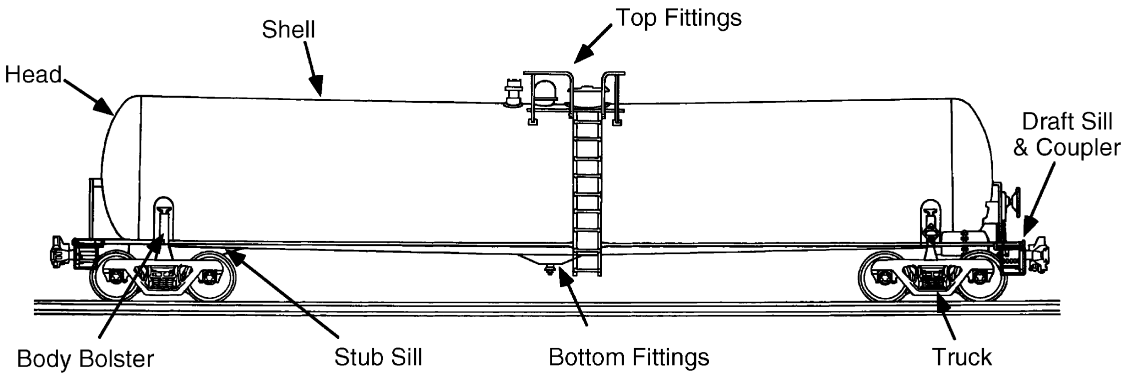

Fig. 1. Diagram of a typical North American general purpose tank car (modified from GATX 1994).

fittings, railroad tank cars are now all constructed with "skid protection" which consists of steel structures mounted adjacent to the fittings [20]. When tank cars are derailed in an accident they may become detached from their trucks and slide along directly on the track. The skid protection shields the bottom fittings from direct impacts in this circumstance [37]. Some cars are also equipped with top-fitting skid protection in the event they are overturned in an accident.

Extensive empirical analysis of tank car performance in accidents has been conducted over the past 30 years [3,7,26]. Over this period a large and robust database on the details of damage experienced by tank cars and the effect of a variety of design features on safety performance has been jointly developed and maintained by the Railway Supply Institute (RSI) and the Association of American Railroads (AAR). As a consequence, extensive statistics have been developed on the probability that both tank and non-tank components of tank cars will lead to a release if a car is involved in an accident [7,38,26,39]. These data enable development of probabilistic models and estimates of risk for tank cars in accidents [8,14,40].

2.1. Tank damage-resistance and weight

As mentioned above, the damage resistance of tanks is increased by strengthening the wall by using thicker and/or stronger material, and on some cars by placement of an extra layer of steel (a "head shield") over the ends (heads) of the tank. The tank thickness of most North American railroad tank cars made of carbon steel ranges from 7/16 in to about 1 in with some having additional protection in the form of the 1/8 in jacket mentioned above. The relationship between tank puncture probability and tank thickness is primarily the result of the mechanical properties of the tank material and the distribution of forces it is exposed to in an accident. The response of any particular combination of material and thickness can be estimated using modeling approaches [41,28,29] and can also be measured empirically [26,42]. However, the distribution of forces a tank is exposed to in an accident is far more difficult to determine.

Fortunately, the database described above enables probabilistic estimates of railroad tank car accident performance, despite the absence of accident force data. Hughes et al. [42] published data on the percentage of tank cars damaged in accidents that released their contents as a function of tank thickness (Fig. 2). Based on previous results by Phillips et al. [26], they assumed that tank and jacket thickness were additive in terms of their effect on release probability and we made the same assumption in our calculations. Analysis of these data shows that the percentage of tank cars damaged in accidents that experience a leak from the tank is inversely proportional to thickness. At the lower thicknesses, there is a steep reduction in release probability for each unit of increase in tank thickness, but as thickness is further increased, the rate of reduction in release probability tapers off.

Using the data presented in Fig. 2 we were able to estimate a negative exponential model of the following form:

$$\mathrm{P}_{\mathrm{TR|A}}(t) = P + Q\mathrm{e}^{(-Rt+S)}, \tag{1}$$

where $\mathrm{P}_{\mathrm{TR|A}}(t)$ is the conditional probability as a function of tank thickness that a tank car will experience a release from the tank given involvement in an accident. t is the tank thickness (in inches), P, Q, R and S are regression coefficients as follows: $P = 0.00982$; $Q = 0.03362$; $R = 6.547$; $S = 4.120$. Thus the conditional probability that a tank car of thickness t involved in an accident will experience a release from the tank is estimated to be:

$$\mathrm{P}_{\mathrm{TR|A}}(t) = 0.00982 + 0.03362\mathrm{e}^{(-6.547t+4.12)} \tag{2}$$

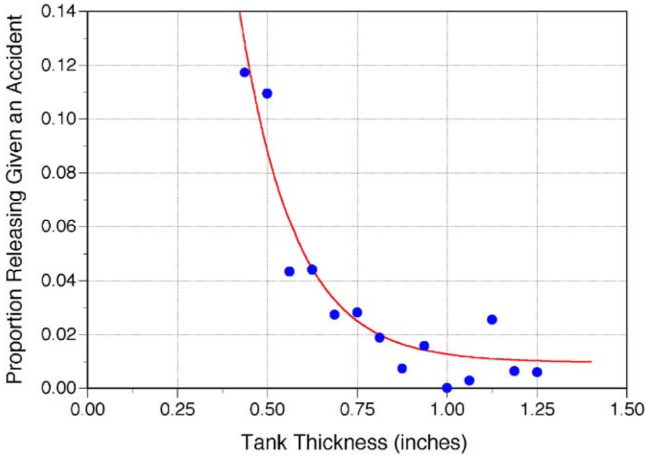

Fig. 2. Relationship between tank thickness (including jacket thickness where applicable) and probability of release (data from Hughes et al. [42]).

The regression parameter P in Eq. (2) represents the change in conditional probability of release due to parameters not related to thickness. The parameter Q represents the change in conditional probability of release due to an increase in the negative exponential of the thickness. Similarly, the parameter R represents the relative change in conditional probability due to unit change in thickness, t. This model provided a good fit to the data ($R^2 = 0.882$) and is depicted by the curve in Fig. 2.

In addition to leaks due to damage to the tank, there is also a probability that they will experience releases from various other fittings and appurtenances. The conditional probability of a release from these sources given involvement in an accident is independent of tank thickness and, *ceteris paribus*, may be considered a constant. On average, approximately 20.7% of the typical, non-pressure specification tank cars that are involved in accidents experience a release from these other sources [42]. We define this probability as $\mathrm{P}_{\mathrm{NR|A}} = 0.207$.

2.2. Tank car size, weight, capacity and efficiency

Although there is clearly a benefit from thicker tanks in terms of reduced probability of release, there is also a penalty in terms of transportation efficiency. The thicker the tank, the greater its mass. Consequently, more material is required to construct the car, and more energy must be expended to transport the empty car, or an equivalent volume of lading because of the greater number of shipments required. The result is higher initial cost and higher operating cost, both of which are disincentives to increased tank thickness and consequent enhanced damage-resistance.

The effect of thickness on weight is exacerbated by the fact that rail cars have an upper limit on their maximum weight. The size of railroad tank cars is often optimized for the density of the specific lading they are designed to transport. The volumetric capacity of the tank is calculated so that when fully loaded its total weight (tank and appurtenances, running gear and lading) is equal to the maximum gross weight or “gross rail load” (GRL) allowed (currently 263,000 lb for four-axle railcars in unrestricted interchange by railroads in North America). Thus, there is an inverse relationship between the volumetric capacity

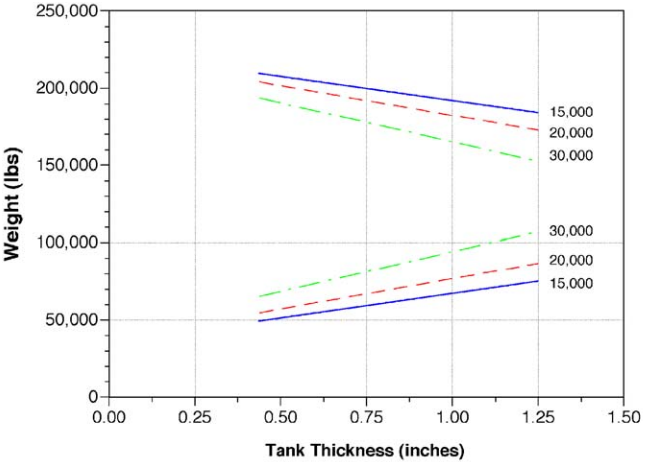

Fig. 3. Effect of tank thickness on light weight and capacity of three sizes of non-insulated, 263,000 lb. GRL tank car (15,000, 20,000, and 30,000 gal).

of a tank and the density of the lading it is intended to transport. The distribution of weight in a railroad tank car can be summarized as follows:

$$\mathrm{GRL} = \mathrm{LW} + \mathrm{C},$$

where $\mathrm{LW} = m_{\mathrm{r}} + m_{\mathrm{t}} + m_{\mathrm{f}}$ = "light weight", m_{r} is the weight of running and draft gear, stub sill, couplers, etc; m_{t} is the weight of tank (head and shell) (plus jacket, insulation and head shields if present); m_{f} is the weight of tank fittings (top and bottom, and other appurtenances); C is the weight of tank contents when fully loaded = capacity.

Because GRL is fixed, for every unit of mass added to the light weight of the car (LW) an equal amount of capacity (C), is subtracted, thereby reducing its transportation efficiency. Larger tank car volume can be achieved by increasing tank length or diameter. However, there are limits to the latter approach imposed by railway line clearances and many tank cars are already near that limit. We assumed that altering the length of the tank was the principal means of altering its volumetric capacity and used a tank size and weight program [43] to calculate the light weight and capacity for several typical tank car sizes as a function of tank thickness (Fig. 3).

Tank car weight as a function of tank volume has fixed and variable components. Some elements of a car's weight are independent of volumetric capacity, such as the running gear (trucks, brake equipment, coupler, and draft gear). Also, the number and weight of top and bottom fittings is generally unaffected by tank volume. The major variable affecting tank car weight is the size of the tank itself. Tank cars commonly in use today have tanks ranging in length from 35 feet with a volume of approximately 13,500 gal, to over 55 feet in length and a volume of over 30,000 gal [44,45]. This variation reflects the range in density of products commonly transported in railroad tank cars.

2.3. Relationship between car weight and shipments required

Given that there is an upper limit on GRL, the consequence of a thicker and heavier tank is that to transport the same amount of product, more shipments are required. For example, a 10% reduction in

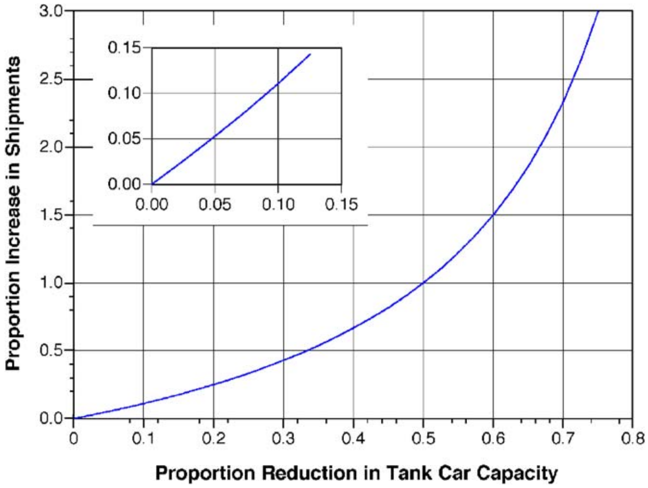

Fig. 4. Reduction in tank capacity versus the increase in shipments required (inset is a larger scale view of the same relationship from 0.0 to 0.15).

the weight capacity of a car will require approximately 11% more shipments. In general C′/C times the number of shipments required for the unmodified car will be the new number of shipments required for the heavier cars, where C′ is the capacity of the baseline car and C is the capacity of the heavier car. We assume that there is a fixed quantity of product to be transported, and that any reduction in tank car capacity will increase the number of shipments required. The general relationship between tank weight and number of shipments is curvilinear because it is an inverse function of the percentage reduction in capacity (Fig. 4). However, the feasible range of tank thicknesses leads to a consequent reduction in capacity that ranges from zero to about 10%. Over this range the relationship is nearly linear (Fig. 4, inset) and for the purposes of this paper we assume that the relationship between proportion of extra shipments required is well-approximated by a linear equation with a coefficient that we term K.

In summary, increased tank thickness increases the damage resistance of tank cars in accidents but simultaneously reduces transportation capacity and thus efficiency. The greater number of shipments required for the heavier car creates an economic disincentive to their use because the extra transportation cost may encourage shifting to competing modes or reduce demand for the product being shipped. Furthermore, the overall exposure to accidents for tank cars in a particular service is increased if heavier cars are used. The interacting relationships raises the question: does the increased damage resistance of the more robust tank offset the greater likelihood of a car being involved in an accident? Or, put another way: is there an “optimal” tank thickness that minimizes the overall probability of a release accident?

3. Model development and analysis

There are three key elements to a model for calculation of optimal tank car tank thickness: the functional relationship between tank thickness and release probability due to damage to the tank, the probability of release due to damage to other parts of the tank that are unaffected by tank thickness, and the relationship between extra tank thickness and exposure to accidents. The first two terms are conditional probabilities that a tank car will release some or all of its lading, given that it has been involved in an accident. The latter term is proportional to the extra number of shipments required due to the reduced capacity of the thicker, and consequently heavier, tank.

An increase in the number of shipments required for any given product(s) will result in an increase in the consequent mileage traveled by cars transporting that product. Nayak et al. [46], and more recently Anderson and Barkan [40], used Federal Railroad Administration accident statistics and data on rail transportation volume to calculate the average railcar derailment rate per car-mile which is defined here as α. Over the period 1992–2001, Anderson and Barkan [40] estimated that the average rate due to derailment-caused accidents was 1.28×10^{-7}, and when all causes (i.e. derailments, collisions, highway-rail collisions and others) were included, it was approximately 10% higher, at 1.41×10^{-7}. The derailment rate per car-mile statistic (α) can be used to estimate the probability that a tank car derails as a function of total car-miles traveled. We assumed that the probability that a rail car in a particular service is involved in an accident is directly proportional to the number of car-miles required for that service. To determine the optimal thickness of the tank car under various scenarios, we formulated the problem as a non-linear convex constrained optimization problem.

3.1. Minimization of tank car release likelihood

In its simplest form the absolute probability of release per car-mile traveled can be expressed as follows (Eq. (3)):

$$\mathrm{P_R} = \alpha \mathrm{P_{R|A}}, \tag{3}$$

where $\mathrm{P_R}$ is the probability of a tank car release due to an accident, per mile traveled; $\mathrm{P_{R|A}}$ is the conditional probability of release given the tank car is derailed in an accident; α is the probability a tank car will be derailed in an accident per mile traveled.

As discussed above, the probability that an accident will occur in which a tank car is involved increases with tank thickness due to the greater exposure to accidents. $K(t - t')$ equals the percentage increase in shipments required to compensate for the reduced capacity of the thicker and consequently heavier tank, where t is the tank thickness; t' is the minimum or base case thickness of tank; K is a tank car-specific constant primarily affected by volumetric capacity of the tank and maximum GRL of the car.

K does not affect the probability that a particular shipment will be involved in an accident since this is assumed to be a constant function of miles traveled. However, because more shipments are required if a heavier car is used, more total car-miles are required to transport the same quantity of product. Consequently, the probability of an accident involving shipments of a particular product using tank cars of thickness t is increased relative to that of tank cars of thickness t' as in Eq. (4):

$$\mathrm{P_A}(t) = [1 + K(t - t')]. \tag{4}$$

3.2. Tank car thickness optimization solution

Taking into account the effect of tank thickness and recognizing that there are two independent causes for releases from tank cars in accidents, the tank and the other fittings, we can reformulate the model as follows:

$\mathrm{P_R}(t) = \mathrm{P_{TR}}(t) + \mathrm{P_{NR}}(t)$ = probability of tank car release as a function of tank thickness, where

$$\mathrm{P_{TR}}(t) = \mathrm{P_A}(t)\mathrm{P_{TR|A}}(t) = \alpha[1 + K(t - t')][P + Q\mathrm{e}^{(-Rt+S)}], \tag{5}$$

which is the probability of a tank-caused release as a function of tank thickness;

$$\mathrm{P_{NR}}(t) = \mathrm{P_A}(t)\mathrm{P_{NR|A}} = \alpha[1 + K(t - t')]\mathrm{P_{NR|A}}, \tag{6}$$

which is the probability of a non-tank-caused release as a function of tank thickness and $\mathrm{P_{NR|A}}$ is the conditional probability of a non-tank-caused release given that a car derails.

α is a constant appearing equally in each term and does not affect the optimal solution, so the objective is to minimize the following expression with respect to t:

$$[1 + K(t - t')][\mathrm{P_{NR|A}} + P + Q\mathrm{e}^{(-Rt+S)}]. \tag{7}$$

To find the optimal thickness we differentiate with respect to t and solve to find the optimal thickness t^* (note that while constraints exist on the optimal thickness, these are simple, feasible bounds that can be applied after finding the unconstrained optimum),

$$\mathrm{d}/\mathrm{d}t[\mathrm{P_R}(t)] = \mathrm{d}/\mathrm{d}t[\mathrm{P_{TR}}(t)] + \mathrm{d}/\mathrm{d}t[\mathrm{P_{NR}}(t)] = 0,$$
$$\mathrm{d}/\mathrm{d}t[\mathrm{P_R}(t)] = [1 + K(t - t')][-RQ\mathrm{e}^{(-Rt+S)}] + K[\mathrm{P_{NR|A}} + P + Q\mathrm{e}^{(-Rt+S)}] = 0.$$

Therefore, $\mathrm{P_R}(t)$ is minimized when,

$$K[P + Q\mathrm{e}^{(-Rt+S)}] + [1 + K(t - t')][-RQ\mathrm{e}^{(-Rt+S)}] + K\mathrm{P_{NR|A}} = 0,$$
$$t^* = t \text{ such that } K[R + Q\mathrm{e}^{(-Rt+S)}] + [1 + K(t - t')][-RQ\mathrm{e}^{(-Rt+S)}] = -K\mathrm{P_{NR|A}}.$$

The above optimality conditions lead to the optimal thickness relationship shown in Eq. (8),

$$t^* = 1/R^* \ln[Q[R(1 + K(t^* - t')) - K]/K(R + \mathrm{P_{NR|A}})] + S/R. \tag{8}$$

The model is characterized by the following non-linear optimization problem (Eqs. (9.1)–(9.3)):

$$\begin{aligned}&\text{Min} \quad [1 + K(t - t')][\mathrm{P_{NR|A}} + P + Q\mathrm{e}^{(-Rt+S)}]\\ &\text{s.t.}\end{aligned} \tag{9.1}$$

$$t' = 7/16, \tag{9.2}$$

$$t \leqslant 24/16. \tag{9.3}$$

The objective function of the model represents the minimization of the probability of a release accident. The constraints denote the lower and upper bounds of tank thickness. The model is open-form and can be solved numerically. If there is an optimal value within these bounds it will be the point at which $\mathrm{d}/\mathrm{d}t\mathrm{P_R}(t) = 0$, giving us the optimality condition of Eq. (8). Otherwise, the optimum will be one of the two boundary constraints.

3.3. Example calculation of optimal tank thickness (t^*)

We initially determined t^* using parameters for a 20,000 gal, 263,000 lb GRL, non-insulated tank car, which is a common, intermediate-size tank car. Using the tank car size and weight program [43] for the

Table 1
Calculated values for the probability that a tank car will be in an accident and various release probabilities as a function of tank thickness (shown in increments of 1/16th in and assuming a base case of 1,000,000 car-miles traveled)

t (in)	$t - t'$	$K(t - t')$	$P_A(t)$	$P_{TR}(t)$	$P_{NR}(t)$	$P_R(t)$
0.4375	0.0000	0.0000	0.1280	0.016354	0.026496	0.042850
0.5000	0.0625	0.0139	0.1298	0.011441	0.026865	0.038307
0.5625	0.1250	0.0279	0.1316	0.008138	0.027234	0.035372
0.6250	0.1875	0.0418	0.1334	0.005918	0.027604	0.033522
0.6875	0.2500	0.0557	0.1351	0.004429	0.027973	0.032402
0.7500	0.3125	0.0697	0.1369	0.003432	0.028342	0.031774
0.8125	0.3750	0.0836	0.1387	0.002767	0.028711	0.031478
0.8750	0.4375	0.0975	0.1405	0.002324	0.029081	0.031405
0.9375	0.5000	0.1115	0.1423	0.002033	0.029450	0.031482
1.0000	0.5625	0.1254	0.1441	0.001842	0.029819	0.031661
1.0625	0.6250	0.1394	0.1458	0.001720	0.030188	0.031908
1.1250	0.6875	0.1533	0.1476	0.001643	0.030557	0.032200
1.1875	0.7500	0.1672	0.1494	0.001597	0.030927	0.032524
1.2500	0.8125	0.1812	0.1512	0.001572	0.031296	0.032868
1.3125	0.8750	0.1951	0.1530	0.001561	0.031665	0.033226
1.3750	0.9375	0.2090	0.1548	0.001559	0.032034	0.033593
1.4375	1.0000	0.2230	0.1565	0.001564	0.032404	0.033967
1.5000	1.0625	0.2369	0.1583	0.001573	0.032773	0.034345

base case $\frac{7}{16}$ in tank car, we found that $K = 0.223$. We set $P_{NR|A} = 0.207$ based on Hughes et al. [42], we set $\alpha = 1.28 \times 10^{-7}$, and $\beta = 1,000,000$ car-miles. $P_{TR}(t)$ and $P_{NR}(t)$ and $P_R(t)$ were each calculated using Eqs. (5)–(7), respectively, as a function of t (Table 1). Numerical analysis of Eq. (8) showed that for this tank car, $P_R(t)$ is minimized when $t = 0.8672$ in $= t^*$.

As stated above α is a simple multiplier on the objective, so it changes the absolute value of the objective function but not the value of t^*. One of the interesting results of this work is this finding that t^* is unaffected by accident rate. If the absolute probability of a release accident for a particular baseline shipment distance is of interest, it can be calculated by multiplication of $PR(t)$ times $\alpha\beta$. Use of any particular value for α or β only affects the scale of the y-axis.

When $P_{TR}(t)$, $P_{NR}(t)$, and $P_R(t)$, are graphed with respect to t, using the parameter values described above, the relationship between the explanation for the optimum is more apparent (Fig. 5). Since $P_R(t)$ is the sum of $P_{TR}(t)$ and $P_{NR}(t)$, it is evident that when the slope of $P_{TR}(t)$ equals the inverse of the slope of $P_{NR}(t)$, $P_R(t)$ is minimized.

4. Implications of model

4.1. Sensitivity analysis of model parameters

Having developed the basic model and illustrated its behavior, it is worthwhile to consider the implications of varying certain key parameters. It must also be stressed that the objective function in the

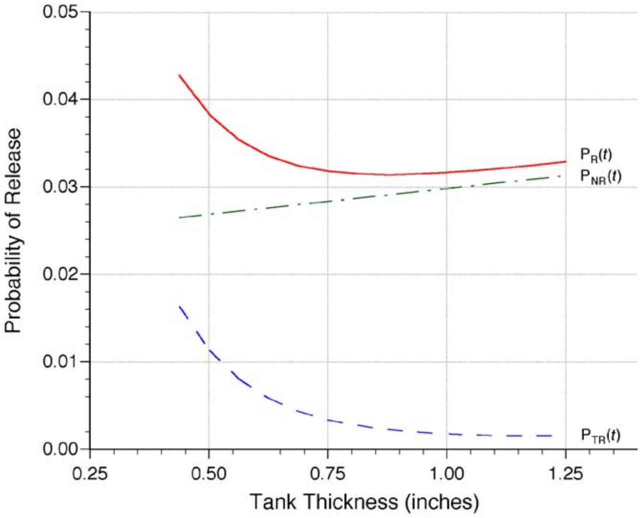

Fig. 5. The probabilities $P_R(t)$, $P_{NR}(t)$, and $P_{TR}(t)$ as a function of tank thickness (t), per million car-miles.

model presented here only addresses minimization of release probability. We do not attempt to factor in cost; however, use of a model such as this for many types of policy decisions would need to do so. There are several non-linearities in the cost functions associated with the various parameters, including the cost of changes in tank car design and in the consequences of releases of different types of hazardous materials that will affect the optimum for any particular set of circumstances. In the context of the model presented here, K and $P_{NR|A}$ are the two principal parameters that vary for different tank cars and affect the optimal solution. Both of these variables are relevant to key design and safety aspects of a tank car's design.

4.2. *Effect of varying K*

As mentioned above, K will vary for different-size tank cars due to the percentage of the weight attributable to the tank versus other components. The weight of the running gear, etc. (m_r) plus the weight of the tank fittings (m_f) comprises the fixed component, and the weight of the tank (m_t) comprises the variable component. The larger the volumetric capacity of the car, the greater the fraction of its light weight is comprised of the tank itself (Fig. 3). We calculated K for three sizes of car representing the range of the most common sizes of North American railroad tank cars. For a 15,000 gal car, $K = 0.1692$; for a 20,000 gal car, $K = 0.2230$; and for a 30,000 gal car, $K = 0.3305$. As these values indicate, proportionally more shipments are required per unit increase in thickness for a larger car than for a smaller car (Fig. 6).

Graphing $P_R(t)$ using the values of K calculated for the three car sizes illustrates that optimal thickness varies with tank car size (Fig. 7). The optimal thickness for the three tank sizes considered declined from 0.9141 in for the 15,000 gal tank, to 0.8125 in for the 30,000 gal tank. In general, K and $P_R(t^*)$ are inversely related to optimal thickness, t^* (Table 2). There is an approximately 6% difference in $P_R(t^*)$ for the optima for the largest compared to the smallest size tank.

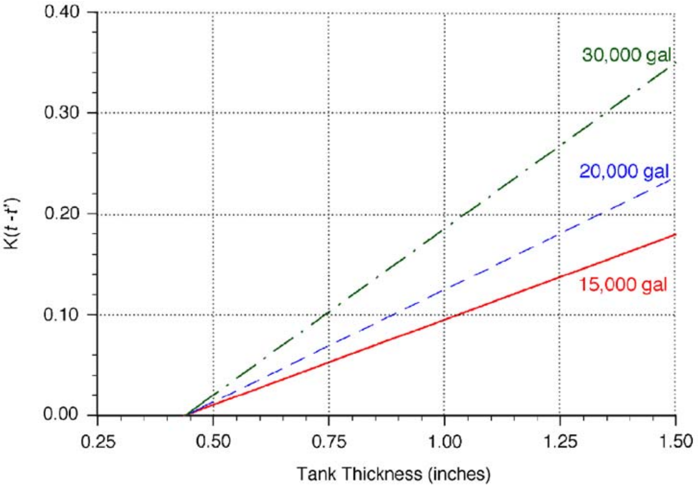

Fig. 6. Relationship between tank thickness, t, $K(t - t')$ given tank volume.

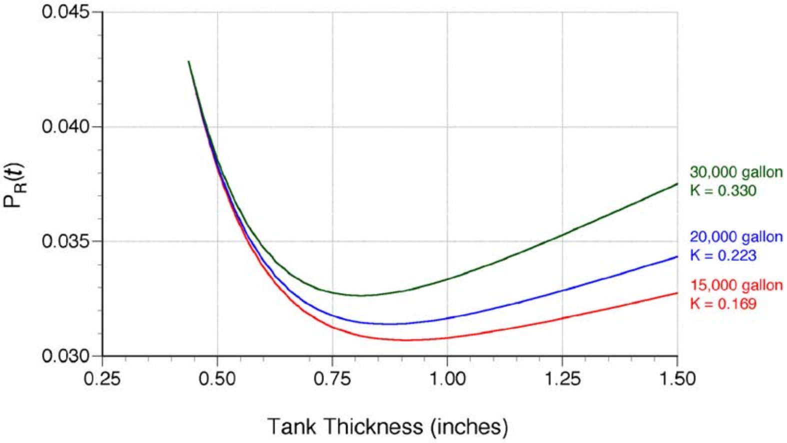

Fig. 7. Relationship between thickness and $P_R(t)$ for three different size tank cars. Arrows indicate t^* for each size car.

Table 2
Optimal tank thickness, t^* and $P_R(t^*)$ for non-insulated, 263,000 GRL tank cars of three different volumes

	15,000 gal	20,000 gal	30,000 gal
t^* (in)	0.9141	0.8672	0.8125
$P_R(t^*)$	0.0307	0.0314	0.0326

4.3. Effect of product density

An implication of the model described here is that it leads to different optimal tank thickness for tank cars designed for different density products. As discussed above the size of normal 4-axle tank cars varies from less than 13,000 gal to approximately 33,000 gal, depending upon the density of the product they are designed to transport. *Ceteris paribus*, the empty weight of these cars varies from under 30,000 lb to over 60,000 lb primarily as a function of tank length. Thus, smaller tank cars designed for transportation of denser products will have an optimal tank thickness greater than larger tank cars intended for lower density products. This is because relative to smaller cars, larger cars experience a greater weight penalty and, a consequently larger number of extra shipments and exposure to accidents.

4.4. Tank material density and damage resistance

Most tank car tanks are manufactured of carbon steel. The steels used in tank car manufacturing have improved over the past several decades due to advances in steel-making and the increasingly more stringent specifications for tank car steels developed by the Association of American Railroads Tank Car Committee [20]. In various respects these changes have had an incremental effect on tank car accident performance. These have the effect of altering the functional relationship between thickness and $\mathrm{P}_{\mathrm{TR|A}}(t)$. Improvement in materials resulting in comparable damage resistance with a lower density material will reduce K and have a corresponding effect on optimal tank thickness as described above.

A small percentage of tank cars in service are constructed of aluminum or alloy steels for reasons of compatibility with their intended lading. Aluminum has a density nearly three times lower than steel (168 vs 490 lb/feet^3), consequently; the weight penalty of a thicker tank is lower than for a steel tank. This has the effect of reducing K relative to a comparable increase in a steel car. Because of its lower density, fewer extra shipments would be required for a thicker aluminum tank than for a comparable increase in thickness of a steel tank. This means that the optimal thickness for lower-density tank material will be greater than for the higher-density material. However, both aluminum and alloy steel have different material properties than carbon steel in terms of puncture resistance [38,47,48]. Aluminum is more susceptible to damage, and alloy steel less so, consequently, the functional relationship between t and $\mathrm{P}_{\mathrm{TR|A}}(t)$ will also differ. These factors would need to be accounted for in estimating t^* for cars constructed of different materials.

4.5. Change in gross rail load (GRL)

Another implication of the model is the effect of GRL limitations. The current AAR limit for maximum GRL for unrestricted interchange of 4-axle freight cars is 263,000 lb. Related to this, since 1971 the United States Department of Transportation (US DOT) has limited the GRL of new tank cars for hazardous material service to 263,000 lb. For the past several years industry and government have been considering increasing the maximum allowable rail load to 286,000 lb for all cars, including hazardous materials tank cars [49]. On behalf of the US DOT and Transport Canada, Rader and Gagnon [49] advised that hazardous materials tank cars exceeding 263,000 GRL should incorporate enhanced running gear components and structural elements to make them more robust in an accident in light of the 9% increase in the mass of the loaded car. A specification for these was developed by a joint industry/government committee [20].

The principal rationale for the higher capacity car is increased transportation efficiency. However, in addition to the requisite safety features referenced above, there will also be a safety benefit due to the reduction in the number of shipments required. Under the assumption that there is a fixed amount of hazardous material transportation demand, increasing tank car capacity will, *ceteris paribus*, result in fewer shipments. This will reduce the consequent exposure of tank cars to accidents by an amount proportional to the increased percentage in lading capacity that these cars can transport. In the context of the model presented here, increasing GRL from 263,000 to 286,000 lb has the effect of reducing K by 9.16%.

The lower values for K for 286,000 GRL cars reduces the slope of $K(t - t')$ as a function of tank thickness and results in a slightly higher tank thickness at which $P_R(t)$ is minimized (Fig. 8) (Table 3). Comparison of Tables 2 and 3 also shows that for all values of t, $P_R(t^*)$ is lower for the 286,000 GRL cars than for a comparably sized 263,000 GRL car. This is due to the reduction in exposure for the higher-capacity cars.

4.6. *Effect of non-tank-caused release probability* ($P_{NR|A}$)

We used $P_{NR|A} = 0.207$ which represents the average for tank cars with no extra protection of the top fittings, and the level of bottom fittings protection currently prescribed by AAR and DOT for most non-pressure tank cars. However, this value for $P_{NR|A}$ may vary and in particular can be reduced via several means. For example, top fittings can be placed within a protective housing that shields them from damage in an accident. Specifications for tank cars that transport higher hazard materials already require this [20]. Bottom fittings protection is required for tank cars with bottom outlets that transport hazardous materials [37,20] and bottom fittings are prohibited altogether on tank cars transporting

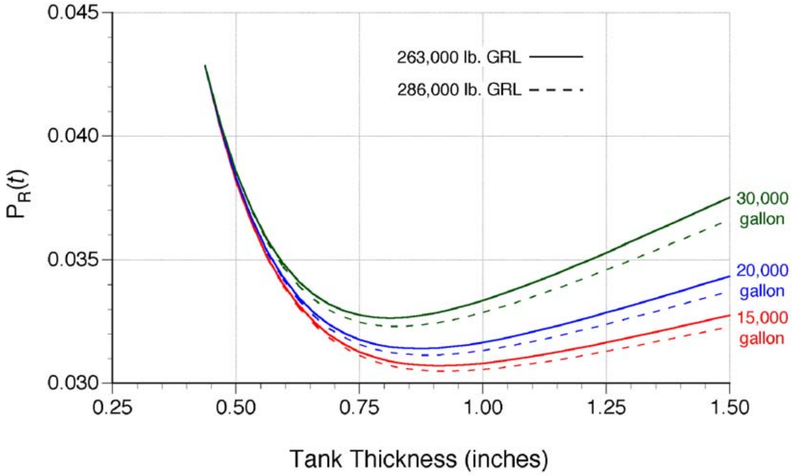

Fig. 8. Effect of maximum GRL on $P_R(t)$ for tank cars of different size and thickness.

Table 3
Optimal tank thickness and $P_R(t^*)$ for different volume, non-insulated, 286,000 GRL tank cars

	15,000 gal	20,000 gal	30,000 gal
t^* (in)	0.9219	0.8828	0.8281
$P_R(t^*)$	0.0305	0.0311	0.0323

certain products [21]. The effect of any of these modifications is to reduce the value of $P_{NR}|A$. Industry statistics enable estimation of how changes in these other aspects of tank car design will affect the value of $P_{NR|A}$.

As noted above, varying $P_{NR|A}$ affects t^*. This is because $P_{NR|A}$ affects the risk from extra shipments resulting from changes in the capacity of the tank car. We considered the effect of various values for $P_{NR}|A$ that are typical of configurations currently used on tank cars. In practice changes in $P_{NR|A}$ are effected through modification of the vulnerability of top and bottom fittings to damage. Enhancing top fittings protection adds a modest amount of weight to the car; however, the elimination of bottom fittings reduces weight. For the purpose of this analysis we assumed no change in weight associated with these changes. The results indicate that the lower the value of $P_{NR|A}$, the higher the value for t^* (Fig. 9, Table 4). This result may seem non-intuitive but the reason is that reducing $P_{NR}|A$ has the

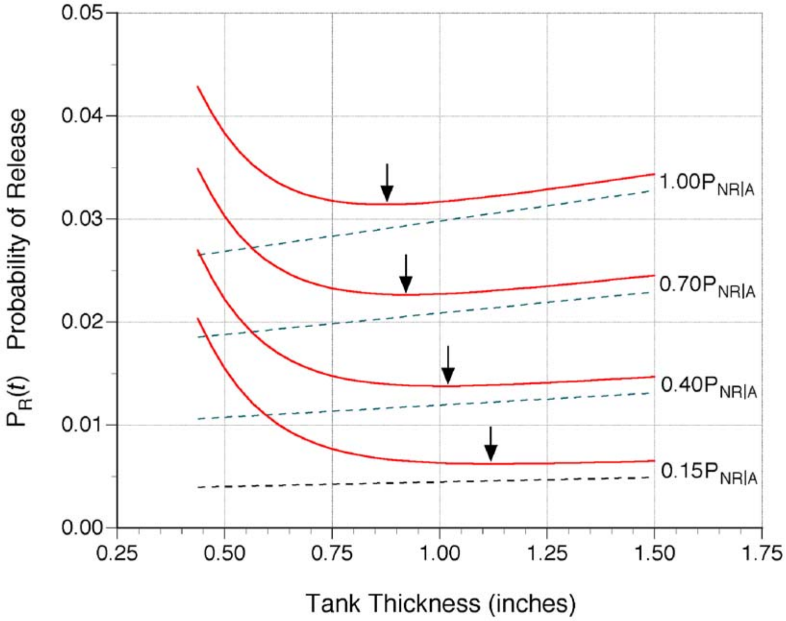

Fig. 9. Sensitivity analysis of $P_{NR|A}$ showing its effect on $P_R(t)$ (solid lines) and $P_{NR}(t)$ (dashed lines) as a function of tank thickness (arrows indicate t^* for each value of $P_{NR|A}$).

Table 4
Effect of varying $P_{NR|A}$ on optimal tank thickness and $P_R(t^*)$ for a 20,000 gal, non-insulated, 263,000 GRL tank car

	t^* (in)	$P_R(t^*)$
1.00 $P_{NR\|A}$	0.8672	0.0314
0.70 $P_{NR\|A}$	0.9219	0.0226
0.40 $P_{NR\|A}$	1.0079	0.0138
0.15 $P_{NR\|A}$	1.1328	0.0062

effect of reducing the increased risk associated with the extra shipments due to the thicker and heavier tank.

5. Discussion

Conventional wisdom among industry and government has held that thicker tanks on railroad tank cars and tank trucks leads to greater safety. Although there is generally a beneficial effect at the lower-range of feasible tank thicknesses, the model and analyses presented here show that there is a limit to this relationship. Increased tank thickness and consequent higher-weight per vehicle reduce its capacity, thereby increasing the number of shipments required to transport the same amount of product. Those elements of tank car design that contribute to release probabilities and are unaffected by tank thickness will have greater exposure to accidents, and thus higher risk. Although risk will be reduced for an individual shipment, it may be increased when the overall shipment volume is accounted for.

In the lower-range of tank thicknesses, where the reduction in tank release probability provided by increasing thickness more than offsets the effect of the increased risk due to releases from other, non-tank sources, there will be a net benefit in terms of overall release probability. However, as the slope of the relationship between tank thickness and tank release probability declines, the effect of non-tank caused releases will overtake tank releases, and further increase in thickness will increase the overall release probability. There is thus an optimal tank thickness in terms of minimization of release probability. This optimal thickness is affected by several factors and there is no single optimum for all tank cars. Three variables affecting this optimal thickness are volumetric capacity of the tank, probability of release from other, non-tank sources, and the weight capacity of the car.

5.1. Implications for current packaging practices

Current North American tank car specifications and regulations are not the result of a comprehensive, formal assessment of the risk posed by the different hazardous materials transported by rail. Instead, current packaging practices have evolved based on over 100 years of experience [50], and engineering analyses of hazardous materials and tank car structural and operating performance [22]. In many respects, however, the results of this century-long process have led to risk-based outcomes. This is reflected in the varying damage resistance of different tank cars used for different hazardous materials, with the highest hazard materials in the most robust cars. Both industry and government are increasingly applying risk analysis methodology to questions regarding hazardous materials packaging to further refine and update packaging requirements [8,14,18,51,52]. The model developed here provides new insights into how this might be done and highlights certain variables and aspects of the process of optimizing tank car design that heretofore were not explicitly addressed.

It is worthwhile to compare the results of the model presented here with current specifications and practices for tank cars. The most common tank thickness for North American tank cars is 7/16 in, which is the regulatory minimum for tank cars constructed of carbon steel. This is the thickness of most DOT 111 tanks cars, which are the most common class of car transporting hazardous materials. The model developed here indicates that the optimal thickness from a release minimization standpoint is higher than this for all sizes of tank (Fig. 7, Table 2). However, many DOT 111 tank cars are insulated and thus have an additional 1/8 in steel jacket that provides additional puncture resistance for the tank that is approximately equivalent to an extra 1/8 in of tank thickness [26].

5.2. Minimizing risk versus release probability

As mentioned earlier, the model developed here uses probability of release, not risk, as the objective function. Although risk is clearly a function of release probability, they are not synonymous. Because of the wide range in type and degree of hazard posed by different hazardous materials, minimization of release probability will not be the most appropriate objective function for all products. Increasing tank thickness raises the initial and the operating cost of tank cars. 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 value of the benefit in terms of the reduced risk from spills will vary widely, depending on the product transported. For many low-hazard materials, this benefit is unlikely to offset the extra cost of the heavier car. The convex nature of the functional relationship between extra thickness and reduction in release probability (Fig. 2) is also a factor. There are diminishing returns in terms of reducing $\mathrm{P_R}(t)$ as t approaches t^* (Figs. 5, 7, 8). Under these circumstances incurring substantial extra expense to reduce the likelihood of spills of these products may be an unwise use of resources.

Conversely, for higher hazard products, particularly those that are acutely toxic to human health, strict cost/benefit considerations are of lesser importance relative to safety. The specifications for these cars require that in addition to the thicker tank (and often a head shield), they have fewer external fittings, and are equipped with a steel housing that protects the fittings from damage in an accident [20]. These features have the effect of reducing $\mathrm{P_{NR|A}}$ in a manner consistent with relationships shown in Fig. 9. It is interesting to note that the tank car specification for chlorine, one of the most common, high-hazard products shipped by rail, is very close to the optimum. The chlorine car specification has been particularly robust since early in the 20th century [53], as have been the specifications for other chemicals long known to be highly hazardous [54,22]. Over the past 25 years there have been a number of major changes in North American specifications and regulations for tank cars that brought packaging requirements for other hazardous materials more in line with the risks they pose [7,8,55,20,21].

5.3. Other risk factors unaffected by tank thickness

The model presented here indicates that changes in the tank thickness requirements above the current minimum of $\frac{7}{16}$ in would reduce the probability of release. However, it also indicates that if this is done there should be consideration of the effect of these changes on other aspects of risk, in terms of both overall release probability, as well as other sources of risk that accrue even if a release does not occur. Release probability due to an accident is not the only aspect of risk that is of interest. Increasing the frequency of hazardous materials shipments needed will have other consequences.

An assumption in this paper is that increasing the thickness of railroad tank cars will result in more shipments and consequent higher frequency of hazardous materials tank car involvement in accidents. Accidents that merely involve a hazardous material car, even without a release, can be disruptive to people and communities as well as railroads. The precautionary evacuations that may result are difficult for all parties. Furthermore, railroads will often incur extra delay and expense in reopening a line following an accident if hazardous materials are involved, even without a release.

Another source of risk that will be affected is non-accident-caused releases (NAR) that occur in transit primarily due to improperly secured fittings on the car [17,19]. Although generally small releases, these NARs outnumber accident-caused releases by more than 20 to 1 [56]. The greater the number of shipments, the higher the likelihood of an NAR occurring, so changes in tank car design that increase the number of shipments will affect this as well.

5.4. Implications for higher GRL tank cars for hazardous materials

Another outcome of the model that is of interest is the result for higher GRL tank cars. The optimal tank thickness is larger for these cars. As discussed above, increasing the capacity of tank cars transporting hazardous materials has the beneficial effect of reducing exposure to accidents because fewer shipments are required. It might be argued that there is an offsetting effect of the larger potential quantity spilled from the bigger cars; however, Phillips et al. [26] found that the majority of spills did not result in the entire contents of a car being lost, so in most release accidents the capacity of the tank will not be a factor. In their consideration of the required specifications for the higher GRL tank car, industry and government recognized the potentially elevated risk due to the larger capacity cars. They used the increase as an opportunity to specify a number of safety enhancements for tank cars. These included an increase in the minimum thickness of the tank, use of a more damage-resistant grade of steel, the application of head shields to protect the ends of the tank, and a protective housing enclosing the top fittings on these cars [20]. A further reduction in accident exposure is possible in some cases by accommodating increase in capacity through use of a larger diameter tank of approximately the same length. This reduces the surface to volume ratio making it a more efficient car and also allows tank car customers' facilities to accommodate the larger capacity cars without modification.

An earlier version of the model discussed here provided the basic information used to decide how these weight increases should be allocated among several options. Related to this, the US DOT, Transport Canada and the AAR have recently developed and adopted standards and recommended practices that are intended to encourage construction and use of hazardous materials tank cars with enhanced safety features by permitting the GRL of these cars to exceed the current limit of 263,000 lb [49,20,57]. The idea is to reduce or eliminate the weight penalty incurred by shippers if they choose to use safer tank cars. This appears to be wise policy because, in the context of the model presented here, it can reduce or eliminate the extra accident exposure due to the loss in capacity of the heavier car. No extra shipments may be required and thus, $K = 0$ for cars that qualify.

5.5. Ongoing packaging changes and future research

There is continuing interest in adjusting packaging standards for several reasons including changes in the operating environment, pressure to continue to improve safety performance, and increasingly sophisticated understanding of the risk from different chemicals. When considering changes in packaging requirements the results presented here should be taken into account. Simply improving the damage resistance of the tank will be beneficial up to a point, but for reasons of transportation efficiency, increasing the weight of the car should only be done when necessary and be allocated in the most efficient means possible among the different options for enhancing damage resistance [57]. The next steps in our research will be to develop the capability to simultaneously evaluate the functional relationship between weight and damage resistance for all the elements of the tank car.

The present model considers the optimal tank thickness under a specific set of conditions. In particular, the objective function used here, conditional probability of release, is the one that has been commonly used in previous studies of tank car safety. Saat and Barkan [58] develop a new metric for assessing tank car accident performance that simultaneously considers conditional probability of release and quantity released from different parts of the tank. Using this metric they extend the model presented here and find that because the amount of lading lost is greater from tank-damage causes compared to non-tank damage causes, the benefit of reducing tank risk is increased relative to non-tank risk. Consequently, t^* is slightly higher when comparable cars are compared using the two different objective functions.

It is in the interest of all parties that modifications in tank car safety design be rationally based and properly account for the associated changes in risk and cost. The longer-term objective is to develop a general model that quantifies this information for different tank car features and various hazardous materials. With the development of these functional relationships, we envision using risk and cost as the basis for the objective function and potentially being able to determine the most efficient combination of tank car safety design features for any type of hazardous material.

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