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Generalized railway tank car safety design optimization for hazardous materials transport: Addressing the trade-off between transportation efficiency and safety

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ABSTRACT

North America railways offer safe and generally the most economical means of long distance transport of hazardous materials. Nevertheless, in the event of a train accident releases of these materials can pose substantial risk to human health, property or the environment. The majority of railway shipments of hazardous materials are in tank cars. Improving the safety design of these cars to make them more robust in accidents generally increases their weight thereby reducing their capacity and consequent transportation efficiency. This paper presents a generalized tank car safety design optimization model that addresses this tradeoff. The optimization model enables evaluation of each element of tank car safety design, independently and in combination with one another. We present the optimization model by identifying a set of Pareto-optimal solutions for a baseline tank car design in a bicriteria decision problem. This model provides a quantitative framework for a rational decision-making process involving tank car safety design enhancements to reduce the risk of transporting hazardous materials.

1. Introduction

Changes in railroad tank car design to increase resistance to damage in accidents have contributed to improvement in railroad hazardous material transportation safety [1]. The design of railroad tank cars is subject to structural and performance requirements and constrained by weight. They can be made safer by increasing tank thickness and adding various protective features, but in general these modifications increase the weight and cost of the car and reduce its capacity and consequent transportation efficiency. In order to optimize railroad tank car safety design this tradeoff between safety and transportation efficiency must be formally considered.

Optimality techniques were first applied to tank car safety design by Barkan et al. [2] who used minimization of conditional probability of release as the objective function to calculate the optimal thickness of a tank. Saat and Barkan [3] extended this work by considering the effect of damage to different parts of a tank car and developed the concept of "release risk" that combines accident-caused release probability with average amount spilled to estimate the expected value of quantity lost. Barkan [4] described an example of a goal programming approach to assist North American railroads in their development of specifications for higher capacity tank cars for transportation of hazardous materials.

In this paper we develop a generalized bicriteria optimization model to evaluate the tradeoff between tank car weight, a proxy for transportation efficiency, and safety. We develop a new, modular approach that combines a tank car weight and capacity model and a tank car safety performance model. We also extend and generalize the optimization techniques used by Barkan [4] to evaluate all of the current elements of tank car safety design, independently and in combination for any baseline design tank car. We use a detailed tank car sizing program to estimate the changes in tank car weight and capacity, consider a finely incremental range of tank head and shell thicknesses, and incorporate the latest statistical model of tank car release probability [5]. We illustrate the generalized tank car safety design optimization model by identifying a set of Pareto-optimal solutions for a baseline tank car design in a bicriteria decision problem.

2. Tank car weight and capacity model

The volumetric capacity of tank cars is often optimized for the density of the specific product they are intended to transport. The

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Abbreviations: AAR, Association of American Railroads; BFR, removing bottom fittings; DOT, U.S. Dsepartment of Transportation; E-TFP, using enhanced top fittings protection; FHP, adding full-height head shields to the tank head; FRA, Federal Railroad Administration; GRL, gross rail load; H, increasing tank head thickness; HHP, adding half-height head shields to the tank head; JKT, adding an 11-gage (0.1196″ or 0.3038 cm) steel jacket and insulation; RRO, risk reduction option; RSI, Railway Supply Institute; S, increasing tank shell thickness; TFP, adding top fittings protection; TIH, toxic inhalation hazard.

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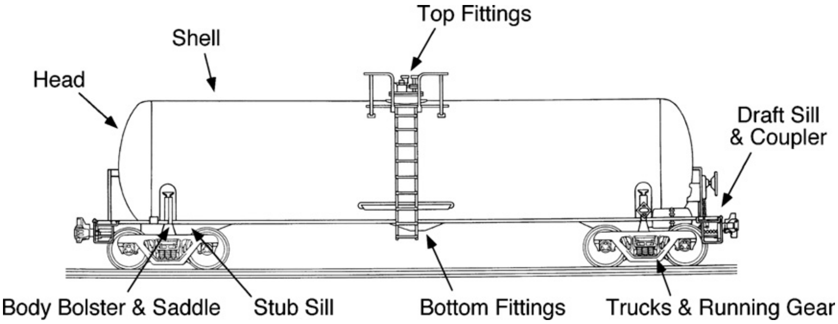

Fig. 1. Diagrams of a typical non-jacketed North American railroad non-pressure tank car.

light or empty weight of a car consists of the weight of its running gear and fittings, which are relatively constant, and the weight of the tank that varies with its size. The maximum allowable weight of a fully loaded railcar in North America is referred to as the maximum gross rail load (GRL). For tank cars transporting hazardous materials the GRL is restricted to 263,000 lb (119,295 kg) [4,6].

The GRL is the sum of the light or empty weight of a tank car plus its lading capacity. The maximum GRL for cars in unrestricted interchange is fixed, so any increase in a car's light weight reduces its capacity. We use a computer program called *IlliTank* [7] to evaluate the change in tank car weight and capacity with the change in its design. *IlliTank* optimizes the size of a tank car by identifying the optimal length of the tank shell to maximize capacity while staying within the GRL limit and other clearance or tank diameter constraints.

3. Tank car safety performance model

The comprehensive statistical analysis of railroad tank car safety performance in accidents conducted by Treichel et al. [5] was used to estimate the effect of each possible change in tank car safety design. Tank car source-specific conditional probabilities of release are calculated using Treichel et al.'s logistic regression model which has the form:

$$P_{R_i|A} = \left[\frac{e^{L(i)}}{1+e^{L(i)}}\right]\varphi \tag{1}$$

$L(i)$ is a linear combination of n statistically significant factors, x, affecting release probability from source i, tank head (H), tank shell (S), top fittings (T) and bottom fittings (B), each with its own regression coefficient, b:

$$L(i) = b_0 + b_1x_1 + b_2x_2 + \ldots + b_nx_n \tag{2}$$

φ is the mainline or yard multiplier used to normalize the conditional probability for tank cars damaged to only include Federal Railroad Administration (FRA)-reportable accidents. This multiplier is equal to 0.533 for mainline and 0.245 for yard accidents [5]. The total conditional probability of release given a tank car is derailed in an FRA-reportable accident is calculated as follows [5]:

$$P_{R|A} = 1 - [(1-P_{R_H|A})(1-P_{R_S|A})(1-P_{R_T|A})(1-P_{R_B|A})] \tag{3}$$

where $P_{R|A}$ is the total conditional probability of a tank car release given the car is derailed in a FRA-reportable accident; $P_{R_H|A}$ is the conditional probability of release from tank head; $P_{R_S|A}$ is the conditional probability of release from tank shell; $P_{R_T|A}$ is the conditional probability of release from top fittings; $P_{R_B|A}$ is the conditional probability of release from bottom fittings.

4. Bicriteria tank car safety design optimization

In this section, we formulate a bicriteria decision problem in which we consider risk reduction options (RROs) that can reduce the likelihood of accident-caused releases from the principal release sources of tank cars involved in an accident. The weight and capacity model presented in Section 2 is incorporated to estimate the relationship between changes in a tank car's light weight due to changes in its design. The conditional probability of release, $P_{R|A}$, in Section 3 is used to estimate tank car safety performance in an accident.

4.1. Tank car risk reduction options

The primary sources of release for a tank car involved in an accident are the tank head, tank shell, top fittings and bottom fittings (Fig. 1). The nature of damage to these components is distinct, and different approaches are used to enhance different components.

The set of tank car safety design features or RROs that can enhance tank car safety design includes:

- Increasing tank head thickness (H)
- Increasing tank shell thickness (S)
- Adding an 11-gage (0.1196″ or 0.3038 cm) steel jacket and insulation (JKT)
- Adding either half- or full-height head shields to the tank head (HHP or FHP)
- Adding top fittings protection (TFP)
- Using enhanced top fittings protection (E-TFP)
- Removing bottom fittings (BFR)
- Combinations of any of the above.

Fig. 2 shows a decision tree framework illustrating possible combinations of RROs (for simplicity, only one branch is expanded at each decision node). Collectively, this figure represents a total of 11,664 ($2 \times 2 \times 3 \times 3 \times 18 \times 18$) unique tank car safety designs. The proposed model can still be used to consider few of these options or with more additional options as long as the safety performance and weight can be characterized.

4.2. Identification of Pareto-optimal tank car safety designs

To illustrate the bicriteria tank car safety design optimization model, a typical general-purpose, non-insulated, non-pressure baseline tank car is evaluated for enhancement. The car has a 20,000-gallon (75,708-L) capacity, has 0.4375″ (1.11 cm) head and shell thicknesses, is equipped with several top and bottom fittings and has a maximum gross rail load of 263,000 lb (119,295 kg).

In general, implementing any RRO increases light weight, with the exception of bottom fittings removal, which slightly reduces the

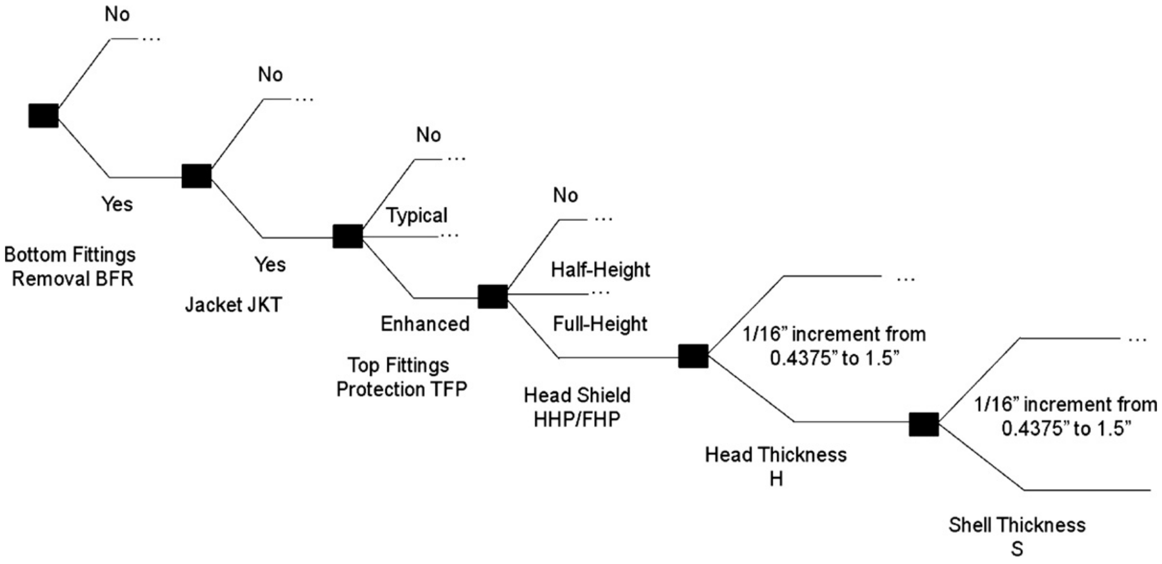

Fig. 2. Decision tree framework of possible RRO combinations.

weight. Each RRO has its own characteristic relationship between changing light weight and conditional probability of release given a tank car is involved in an accident, $P_{R|A}$. The specific functional relationship is also affected by the particular baseline car. Employing each of the individual RROs gives different reductions in the conditional probability of release per unit weight (Fig. 3). The generalized tank car safety design optimization model characterizes the weight and $P_{R|A}$ for all possible RRO combinations, and identifies a set of solutions that will provide the most efficient reduction in the $P_{R|A}$ with the increase in the light weight.

4.2.1. Light weight and $P_{R|A}$ enumerations

Let **RRO** be the set of all possible RRO combinations. Each subset of **RRO** represents any combination of each of the RROs. $\boldsymbol{h_0}$ is the baseline head thickness, $\boldsymbol{h_1}$ is the first increment of head thickness, $\boldsymbol{h_2}$ the second, and so on. Similarly, $\boldsymbol{s_0}$ is the baseline shell thickness, $\boldsymbol{s_1}$ is the first increment of shell thickness, etc. For each pair-wise combination of head and shell thickness, the car light weight, $\boldsymbol{W}$, and conditional probability of release, $\boldsymbol{P_{R|A}}$ are enumerated (Tables 1 and 2). $\boldsymbol{W_0}$ and $\boldsymbol{P_{R|A0}}$ are the baseline light weight and conditional probability of release, respectively. Percentage change in light weight, $\Delta\boldsymbol{W}$, for all solutions i are calculated as follows:

$$\Delta\boldsymbol{W}_i = 100 \times \frac{\boldsymbol{W}_i - \boldsymbol{W}_0}{\boldsymbol{W}_0}$$

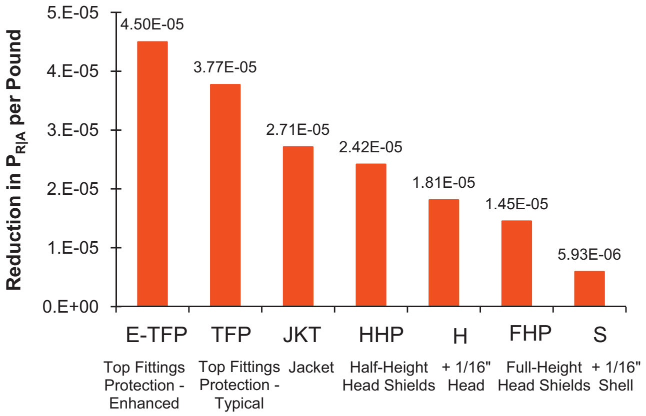

Fig. 3. Reduction in $P_{R|A}$ per unit weight for each RRO except bottom fittings removal (BFR) for a specific size of baseline general-purpose tank car.

Table 1
Tank car light weight (W) enumeration for each RRO combination.

	s_0	s_1	s_2	...
h_0	$W(h_0, s_0)$	$W(h_0, s_1)$	$W(h_0, s_2)$	...
h_1	$W(h_1, s_0)$	$W(h_1, s_1)$	$W(h_1, s_2)$	...
h_2	$W(h_2, s_0)$	$W(h_2, s_1)$	$W(h_2, s_2)$	...
⋮	⋮	⋮	⋮	...

4.2.2. Analytical solutions

A set of Pareto-optimal or non-dominated solutions is determined from the enumerated $P_{R|A}$ and light weight. The optimality in this study is ensured by enumerating and evaluating all possible combinations of design options. By definition, a feasible solution, $x^* \in X$, is Pareto-optimal if there does not exist another point, $x \in X$, such that $F(x) \leq F(x^*)$, and $F_i\ (x) < F_i\ (x^*)$ for at least one objective function [8]. In other words, a feasible set of solutions is called Pareto optimal if there is no other feasible solution that would improve some objective function without causing a simultaneous decline in at least one other objective function.

The calculated $\boldsymbol{P_{R|A}}$ and $\Delta\boldsymbol{W}$ are used in a stepwise decision process to determine the Pareto-optimal (non-dominated) solutions. The decision criteria can be implemented using an updated algorithm modified from Barkan [4]:

(1) Compute **W**, $\boldsymbol{P_{R|A}}$ and $\Delta\boldsymbol{W}$ for all $\mathbf{RRO}_{\boldsymbol{i}}$; set $i = 0$ (base case); initialize the set of Pareto-optimal solutions, $\boldsymbol{S} = \{\varnothing\}$
(2) From $\mathbf{RRO}_{\boldsymbol{i}}$, find **RRO** with the closest $\Delta\boldsymbol{W}$ and lower $\boldsymbol{P_{R|A}}$ than current $\boldsymbol{P_{R|Ai}}$
(3) Insert solution $\mathbf{RRO}_{\boldsymbol{i+1}}$ that has the minimum $\boldsymbol{P_{R|A}}$ among **RRO** identified in step 2 to the set of Pareto-optimal solutions, $\boldsymbol{S}$
(4) Repeat steps 2 and 3 until $i = 11{,}663$ (total number of RRO combinations minus 1).

Table 2
Tank car conditional probability of release ($P_{R|A}$) enumeration for each RRO combination.

	s_0	s_1	s_2	...
h_0	$P_{R|A}(h_0, s_0)$	$P_{R|A}(h_0, s_1)$	$P_{R|A}(h_0, s_2)$	...
h_1	$P_{R|A}(h_1, s_0)$	$P_{R|A}(h_1, s_1)$	$P_{R|A}(h_1, s_2)$	...
⋮	⋮	⋮	⋮	...

4.2.3. Graphical solutions

Fig. 4 shows the decision space for a complete enumeration of percent change in light weight and the $P_{R|A}$ for all RRO combinations and the identified Pareto-optimal solutions for the baseline general-purpose tank car under consideration. From 11,664 enumerated solutions, 161 solutions are identified as Pareto-optimal. All non-dominated solutions correspond to designs with no bottom fittings (BFR). This strategy reduces the overall probability of release while offering a slight increase in capacity with reduced light weight.

Fig. 5a and b provide a detailed view of two parts of the x axis near its origin enabling us to see the optimal sequence of solutions to consider as the weight of the car is increased. The BFR strategy is followed by the strategy with the smallest increase in the car's light weight – increasing tank head thickness. Each of the first five solutions in Fig. 5a represents a combination of BFR and an incremental increase in head thickness. When the net weight of increasing the head thickness exceeds that of adding half-height head shields, the latter enters the Pareto-optimal set. The next-most efficient strategy is to use a typical top fittings protection followed by the use of enhanced top fittings protection (Fig. 5a). Strategies involving an increase in shell thickness and adding a jacket enter the Pareto-optimal set as shown in Fig. 5b.

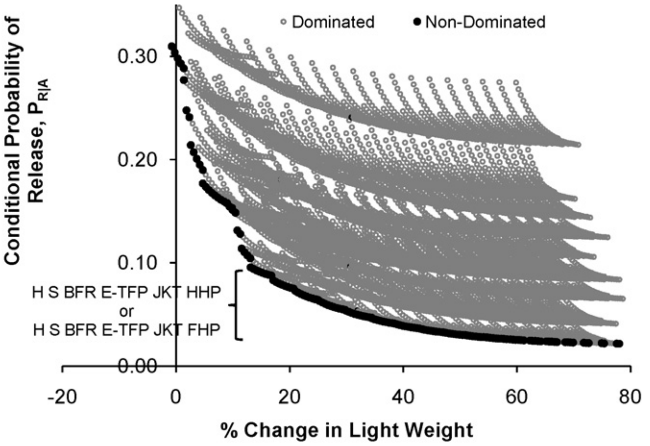

Fig. 4. Decision space for the $P_{R|A}$ vs. the light weight for all RRO combinations.

4.2.4. Conditional probability of release versus expected quantity of release

The Pareto-optimal set identification has been presented in the context of the conditional probability of release given that a tank

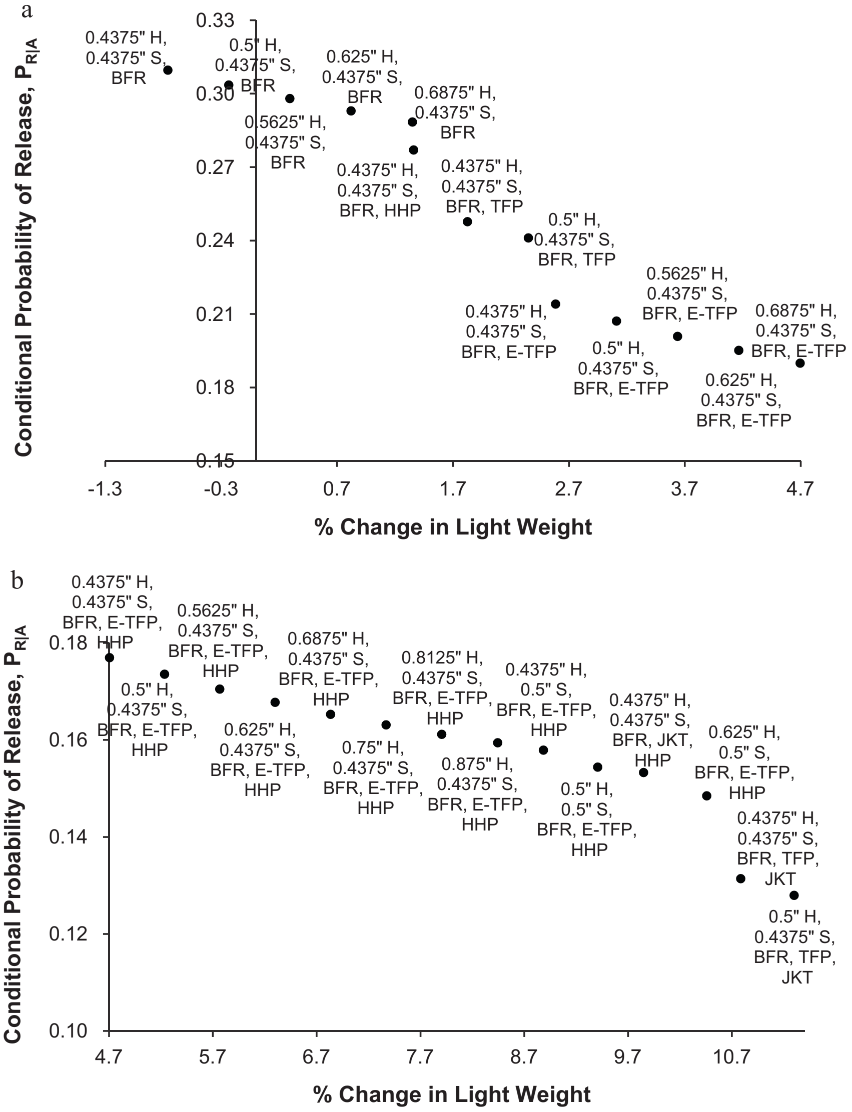

Fig. 5. Initial subset of non-dominated solutions for the baseline general-purpose tank car from (a) −1.3 to 4.7, and (b) 4.7–11% change in light weight.

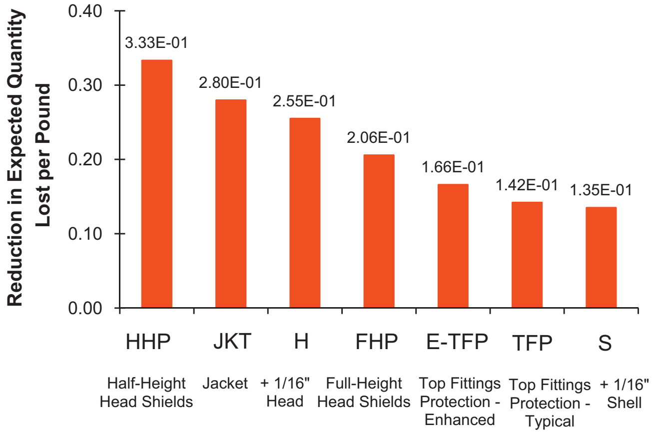

Fig. 6. Reduction in the expected quantity lost per unit weight for each RRO except bottom fittings removal (BFR) for the baseline general-purpose tank car.

car is derailed in an accident. Also of interest is the fact that damage to different parts of tank cars results in different average quantities lost. A larger release will generally result in a larger exposure area and greater impact on people, property and the environment, and incur higher costs. Therefore, when evaluating the benefit of applying various risk reduction options to tank cars, it may also be beneficial to consider the amount lost from different parts of the car.

Saat and Barkan [3] developed the concept of release risk, which is essentially the expected quantity of release from a tank car involved in an accident. In this section, we consider the tradeoff between the expected quantity of release, given a tank car is derailed in an accident, and weight. We identify the Pareto-optimal set for the 20,000-gallon (75,708-L) baseline tank car in the same manner as for the conditional release probability versus weight.

Employing each of the individual RROs gives different reductions in the expected quantity lost per unit weight (Fig. 6). When all the individual RROs are considered simultaneously, the results are generally similar to when the probability of release is considered. Fig. 7 shows the decision space with complete enumeration of the expected quantity lost and weight for the baseline 20,000-gallon (75,708-L) tank car. The sequence of each individual RRO entering the Pareto-optimal set is consistent with the case when the probability of release versus weight is considered (Fig. 8). However, the specific non-dominated solution at a certain level of weight increase is different. This is due to the different efficiencies in RRO-specific reduction of conditional probability of release compared to expected quantity of release (Figs. 4 and 7).

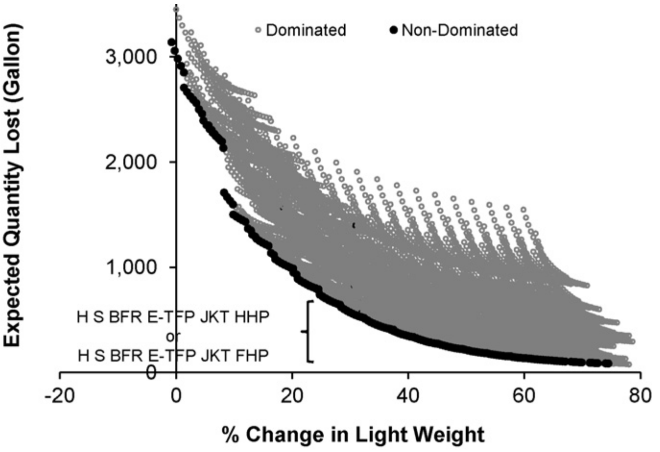

Fig. 7. Decision space for the expected quantity lost vs. the light weight for all RRO combinations for the baseline 20,000-gallon (75,708-L) capacity general-purpose tank car.

5. Discussion

5.1. Implications for current packaging practices

The model presented here provides general insight on the relative impact of various changes in tank car safety design. Furthermore it allows considerably better precision in understanding the tradeoffs involved in improving tank car design and provides a basis for quantitative evaluation of optimal, commodity-specific tank car designs. In the following sub-sections we will discuss several potential applications of the model.

5.1.1. Bottom fittings

Bottom fittings removal is an unusual example of an option that reduces both weight and release probability. This causes it to be included in the optimal set of solutions. However, it requires significant investment to retrofit terminals and tank cars for unloading from top fittings [1]. These costs are external to the tank car itself so additional benefit-cost analysis is necessary to determine circumstances when bottom-fittings removal is cost-effective. The model developed here can be used to identify the Pareto-optimal set of tank car designs, both with and without bottom-fitting removal as an option, thereby facilitating such an analysis.

5.1.2. Higher GRL tank cars

This model can be used to consider tank car designs with a GRL higher than the normal DOT maximum of 263,000 lbs. Construction of such cars offers the opportunity to increase tank car capacity and efficiency while at the same time using some of the extra allowable weight to enhance the safety design of these cars. This provides an incentive to use safer tank cars without incurring a weight penalty. Barkan [4] conducted a specific analysis of certain options for a particular type of car. The model presented here provides a general approach with finer grained capabilities to comprehensively address tank car safety design enhancement with higher GRL limit.

5.1.3. Tank cars for toxic inhalation hazard materials

In the wake of several fatal tank car accidents involving the release of toxic inhalation hazard (TIH) materials, the AAR initiated development of new requirements for tank cars transporting these products [9]. We used a variation of the model described here to identify the most effective designs for such cars. More recently the U.S. Department of Transportation issued an interim final rule [10] with requirements for TIH tank cars based on the AAR's earlier proposal. Both the AAR and the DOT rules give tank car builders flexibility in complying with the requirements. The model presented here can be used for this purpose to help tank car designers achieve the specified safety performance objectives in the most efficient manner possible. In particular, the model can be used to evaluate the best combination of parameters for tank head and shell thicknesses, full-height head shields and enhanced top fittings protection for tank cars transporting TIH materials.

5.2. Implications for new tank car design concepts

The same incidents that motivated the development of new standards for TIH tank cars also inspired research and development investigating fundamentally new tank car safety design concepts. This work is intended to identify designs with considerably better safety performance to weight ratios than are possible using conventional steel tank car designs. In addition to consideration of new and stronger steels, this research is also developing and evaluating new composite materials and corrugated metal structures that are

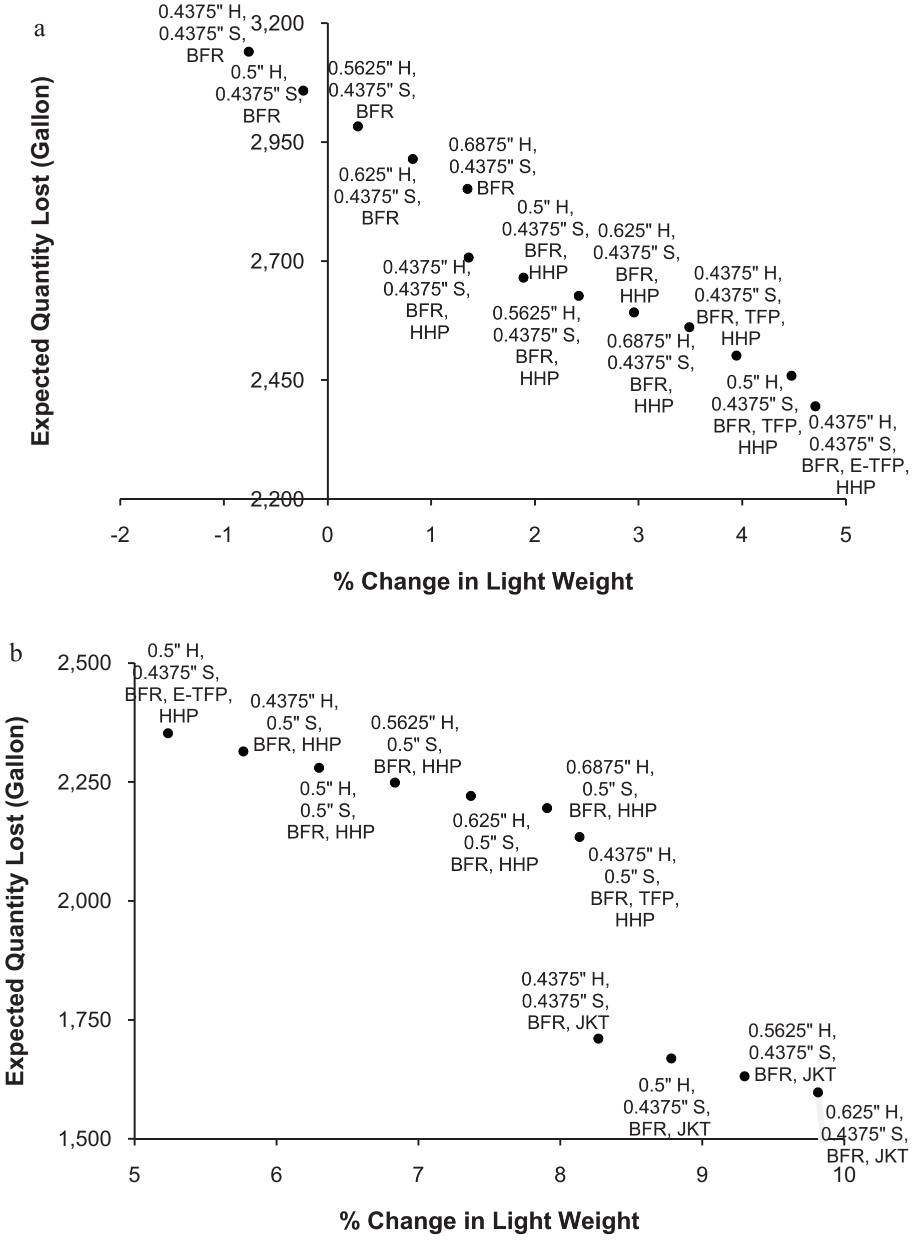

Fig. 8. Initial subset of non-dominated solutions for the baseline general-purpose tank car (expected quantity lost) from (a) −2 to 5, and (b) 5–10% change in light weight.

intended to absorb the energy of an object impacting a tank car before it penetrates the tank itself [11–14]. New valve designs are also being evaluated that will substantially reduce the likelihood of release in an accident [15]. One of the challenges associated with this work is that in the absence of statistical estimates of the performance of these designs in a variety of accident scenarios, it is difficult to quantify their performance as accurately as can be done for more conventional designs for which there is an abundance of statistical data. Nevertheless, if accident performance and weight data can be developed for these new design concepts, the generalized tank car optimization model described in this paper can be used to consider them and help identify the optimal combination of design features.

5.3. Incorporating expected quantity of release

Releases from the head and shell have much higher average percentage losses compared to those from top and bottom fittings. One reason for this disparity is that in accidents in which fittings develop a leak, it may often be small and stopped relatively quickly by response personnel. Conversely, a hole in the tank head or shell is often the result of impact damage from a rail or another railcar that punctures or tears open the tank. These may be more likely to be large and difficult to plug before a large portion of the tank's contents have been lost. Use of the expected quantity of release metric offers a means to explicitly consider benefit in terms of the reduced quantity released, as well as conditional probability of release, when evaluating each safety component of a tank car.

5.4. Incorporating chemical-specific hazard in optimization of tank car safety design

Hazardous material risk is also affected by the physicochemical properties of the product involved in a release incident and its interaction with various characteristics of the environment in which it is released. Tank car safety design is intended to be commensurate with risk, but no formal optimization method has previously been applied to the process of matching safety design features with product hazard. Controlling tank thickness using the nominal burst pressure rating in the DOT tank specification is consistent with the general objective of matching hazard to tank car damage resistance; however, it is inexact because other factors affecting tank thickness are not considered. A more direct means would be to determine the level of damage resistance desired for a particular hazardous material, and engineer the car to achieve this level of performance.

The model in this paper enables comprehensive evaluation of all elements of tank car design that affect safety performance. It facilitates rational consideration and selection of the design combination that maximizes safety for any level of weight or cost increase. Furthermore, if additional information is available that allows quantification of the cost of tank car fleet replacement with enhanced-design cars, and the value of the associated benefit, designs can be optimized on a product specific level.

5.5. Implications for other strategies to reduce risk

In the larger context of hazardous materials transportation safety and risk, tank car design is just one of several important factors. Others that can be evaluated and potentially modified to affect risk are accident likelihood and severity, operational practices and routing. There are a variety of changes in practices that may offer opportunities to reduce risk [16,17]. A major challenge is to understand the inter-relationships among different factors, that is, how changes in one affect another [18]. Additionally, the cost-effectiveness of addressing these different factors will vary, relative to the others at both system and scenario-specific levels.

Ultimately all of these strategies and inter-related factors must be considered to determine the optimal approach to risk reduction; however, development of such a comprehensive approach is a major undertaking. The model presented here is the first step in such an analysis. By isolating the number of possible tank car designs to those that represent the most efficient combination of safety performance and weight, the problem of selecting among them is simplified. The generalized tank car optimization model presented here offers the first phase in a three-level hierarchical process to most efficiently reduce the risk of rail transport of hazardous materials. The second phase involves incorporating chemical-specific hazard level to determine the optimal level of protection for different materials. The third phase will involve risk-based tank car safety design combined with simultaneous consideration of other strategies to reduce risk. This model enables local identification of the optimal solution regarding tank car safety design that can ultimately be incorporated into a global optimization model to reduce overall hazardous materials transportation risk in the most cost-effective manner possible.

6. Conclusions

In this paper, we develop a generalized tank car safety design optimization model to enable quantitative evaluation of nearly all of the tank car safety design enhancement options currently in use by North American tank car manufacturers. Each option is systematically considered alone, and in combination with every other feasible option to calculate the effect on tank car weight and on the probability of release in an accident. The model thus permits estimation of the effect on transport efficiency and safety, and represents the first step in a large, optimization process to most cost-effectively reduce railroad hazardous materials transportation risk.

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