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Improving the design of higher-capacity railway tank cars for hazardous materials transport: Optimizing the trade-off between weight and safety

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ABSTRACT

As with many aspects of modern industrial society, decision-makers face trade-offs in considering hazardous materials transportation equipment and practices. Tank cars used for transport of hazardous materials can be made more resistant to damage in accidents through use of a thicker steel tank and other protective features. However, the additional weight of these features reduces the car's capacity and thus its efficiency as a transportation vehicle. In this paper the problem of tank car safety versus weight is developed as a multi-attribute decision problem.

North American railroads recently developed specifications for higher capacity tank cars for transportation of hazardous materials including enhanced safety design features. A group of tank car safety design features or "risk reduction options" (RROs) were analyzed with regard to their effect on the conditional probability of release in an accident, and their incremental effect on tank car weight. All possible combinations of these RROs were then analyzed in terms of the reduced release probability per unit of weight increase and the Pareto optimal set of options identified. This set included the combinations of RROs that provided the greatest improvement in safety with the least amount of additional weight for any desired level of tank car weight increase. The analysis was conducted for both non-insulated and insulated tank cars and used two objective functions, minimization of conditional probability of release, and minimization of expected quantity lost, given that a car was derailed in an accident. Sensitivity analyses of the effect of tank car size and use of different objective functions were conducted and the optimality results were found to be robust. The results of this analysis were used by the Association of American Railroads Tank Car Committee to develop new specifications for higher capacity non-insulated and insulated, non-pressure tank cars resulting in an estimated 32% and 24% respective improvement in safety.

1. Introduction

An important aspect of modern industrial society and commerce is the production and transport of chemical and petroleum products. Many of these are liquids and in North America much of the transportation of these products, especially over longer distances, is in railroad tank cars. There are approximately 300,000 tank cars operating in North America, with most of them ranging in capacity from 13,000 to 33,000 gal (49,000–125,000 l) with a maximum loaded railcar weight of 263,000 lb (119,295 kg). Approximately half of the tank cars are used to transport hazardous materials; and in 2006 there were over 1.33 million tank car shipments of these materials in the U.S. and Canada [1]. According to U.S. Surface Transportation Board data for the early 2000s, the average U.S. shipment distance for the chemical and petroleum products that make up most of this traffic was approximately 800 miles (1287 km) per carload. In view of the volume of traffic and the consequent risk to persons, property and the environment in the event of a spill, the study of tank car safety is ongoing. Both industry and government are engaged in a continuous process to enhance the safety and efficient transportation of these products [2–5].

As with many aspects of modern industrial society, decision-makers face trade-offs in considering hazardous materials transportation equipment and practices. The example considered in this paper is the trade-off between tank car safety and transportation efficiency. Tank cars can be made more resistant to damage in accidents through use of a thicker steel tank and other protective features. However, the additional weight of these features reduces the cars' capacity and thus efficiency as transportation vehicles. In this paper I provide a general overview of the rationale for tank

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car risk reduction measures implemented over the past century, and then consider a specific recent example in which the problem of tank car safety versus weight is developed as a multi-attribute decision problem. The results of this analysis provided the basis for certain key aspects of recently developed safety design standards for new, larger capacity North America railroad tank cars.

2. Background on tank car safety design and risk management

The North American railroad accident rate has declined considerably over the past two decades [6,7], as has the incidence of hazardous materials releases in these accidents [8]. The reduction in accidents is largely due to substantial investment in railroad infrastructure that has occurred since economic deregulation [9,10]. This investment has substantially improved the quality of the infrastructure, simultaneously allowing higher speeds, improved reliability and fewer derailments caused by failures in the track structure. The reduction in hazardous materials releases has also benefited from improvements in tank car safety design [4]. The tank car and railroad industries, along with the U.S. and Canadian governments, have conducted extensive research on tank car safety over the past three decades. This research has led to a number of improvements in the design of tank cars to make them more resistant to damage if they are involved in an accident. A critical element in this process has been development of a comprehensive database on North American tank car performance in accidents.

The process of improving tank car safety is ongoing and has economic consequences both positive and potentially negative. The investment in the North American tank car fleet is considerable. The average cost of a new tank car in 2006 was approximately $81,000 and the replacement value for the current fleet of 300,000 cars is thus over $24 billion. Enhancements to tank car safety will often make the car more expensive to build and sometimes to operate as well. Given the size of the tank car fleet, even small changes in the unit cost of tank cars can have multi-million dollar effects.

Spills of hazardous materials also have substantial potential impact. Safety itself has intrinsic value to all the parties potentially involved with a hazardous materials spill. Furthermore, evacuations, property damage, environmental cleanup, service disruptions, litigation, etc. that can ensue following an accident involving hazardous materials all cost money. It is not uncommon for a single accident to cost millions, and sometimes tens of millions of dollars [11,12]. Tank car design features that reduce the likelihood of a spill thus have both safety and economic value. A significant challenge for industry and government is to know how to balance improvements in safety with increased cost. This challenge is made more complex when one considers that imposing excessive safety requirements on rail transport could alter the transportation economics in such a way that hazardous materials traffic might shift to highways, which in some circumstances could increase risk.

2.1. Origin of risk management of tank car safety

The process of improving tank car efficiency and safety has been underway for over a century [13,14]. Tank cars were initially developed to transport crude oil from western Pennsylvania to refiners and markets, primarily on the U.S. east coast [15]. In 1902, a serious accident occurred on the Pennsylvania Railroad (PRR) in Sharon, Pennsylvania in which a number of tank cars were involved in a collision that led to a major conflagration [16,17]. Although railroads had been developing and maintaining standards for various railroad car components through its Master Car Builders' Association (MCBA) since 1867 [15], there were no construction standards for tank cars. The accident led the MCBA to form a special Committee on Tank Cars [16] with representatives from the PRR and Union Tank Line Company. Following a series of tests the MCBA published the first set of Recommended Practices for tank car safety design in 1903. After several revisions, these were made Standards in 1910, and in 1912 two additional standards were developed for special, more robust tank cars, one for transport of casinghead gasoline, and the other for transport of chlorine [18]. In that same year, the Interstate Commerce Commission incorporated by reference the MCBA tank car standards, giving them the force of federal regulation [19].

The significance of these early developments is 2-fold. First, the development of specifications for tank car design in 1903 marked the beginning of risk management at the industry level for rail transport of hazardous materials. Second, the establishment of the special standard for chlorine transport in 1912 was the first example of a risk-based standard for tank car design in North America. These initial steps mark the beginning of an increasingly sophisticated set of processes and organization that led to the current North American tank car design standards, maintained by the Association of American Railroads (AAR), the successor organization to the MCBA. The 1918 edition of the MCBA tank car standards [20] comprised 41 pages and 13 figures, whereas the most recent edition of the AAR Manual of Standards and Recommended Practices for tank cars [21] maintained by the AAR Tank Car Committee comprises 666 pages, many dozens of figures and exhibits, and reference to a number of standards maintained by other organizations on specialized topics pertinent to tank car design.

2.2. Development of tank car standards

The evolution and development of modern tank car standards over the past century has occurred for three general reasons: (1) adopting improvements in materials, railcar fabrication and other technologies that enabled safer, more economical and/or more efficient designs to be feasible, (2) changes in the physical environment such as larger and heavier railcars, longer and heavier trains, and higher operating speeds that necessitated changes in design to adapt to the new conditions, and (3) new expectations of safety performance from industry, government or the public. Although these are described here as distinct processes, in practice they have often overlapped, with elements of more than one acting simultaneously in response to the particular set of circumstances that prevailed at the time.

2.2.1. Technology improvements

As advances in technology have occurred, there have been a variety of applications with the potential to improve tank car safety, efficiency, or both. Of particular importance have been materials and tank-fabrication-related advances. A notable example was the development and acceptance of fusion-welding technology for tank car construction in the 1930s. Prior to this, nearly all tanks were riveted together from plates. These cars required frequent testing and maintenance to prevent leakage from the riveted joints. Tanks for products such as liquefied, pressurized gases were forge welded but this was inefficient and expensive. Fusion welding offered an economical means of mass-producing a better tank car and was quickly adopted, first as a replacement for forge welding, and then as a replacement for riveted tank construction. More recent advances in steel making have led to improved grades and treatment of steel plate. These new steels offer better performance in a variety of attributes pertinent to tank car safety design and construction such as fracture toughness, puncture resistance, formability and weldability. Over the past three decades the AAR and the United States Department of Transportation (DOT) have adopted these as standards as their performance advantages became understood.

An important risk-management factor that must be considered with advances in technology is that tank cars are long-lived assets. The typical life span of a tank car is 30 years, and it is not uncommon for cars to operate even longer than this. Given the large investment in these assets and the expectation of investors to receive a return over the full life of a car, there could be a disincentive to private sector research on improved technology if it resulted in premature obsolescence. Consequently, the AAR and the DOT have generally adopted a practice of "grandfathering" which in this context is defined as the "permissive, continued use of tank cars conforming to former regulatory standards" [22]. The presumption is that continued use of these assets for the remainder of their economic life does not reduce safety, even if a newer technology or practice is discovered or developed that will improve it, unless for some reason the continued use of earlier technology poses an unacceptable risk.

The practice of grandfathering has become more controversial in recent years following several fatal accidents in which toxic inhalation hazard (TIH) materials were released. This led to elevated concern about the continued use of pressure-specification tank cars constructed of non-normalized steel [23] that the AAR had prohibited for new pressure car construction in 1989 [21]. The AAR has also called for accelerated retirement of the current design tank cars for TIHs in favor of more damage-resistant designs [24]. These particular questions do not affect the non-pressure tank cars discussed in this paper, but may signal a change in perspective on this question in the future.

2.2.2. Changes in the environment

These changes fall under several subheadings: changes in the physical environment in which tank cars operate; changes in the economic environment; and changes in the safety environment.

As North American train operations have evolved over time (e.g. larger railcars, longer trains, higher speeds), various physical attributes of railcar suspension, coupling, braking, and buff and draft (longitudinal in-train forces) systems have had to be made more robust to accommodate the demands of the environment, and/or to provide satisfactory performance. These changes apply to all railcars, not just tank cars. The process of evaluating the requirements and developing new specifications for railcar components is the purview of the AAR Equipment Engineering Committee. In this respect, tank car manufacturers and owners must respond to another group in addition to the AAR Tank Car Committee and federal regulators.

A characteristic of tank cars that has implications for the risk-management economics is their relatively low utilization. Unlike many railcars, tank cars have an important storage function in addition to serving as a transportation vehicle. It is not unusual for a tank car to spend several weeks following loading awaiting a customer request, or at the consignee end of the journey, to supply feedstock to a manufacturing process for some period of time. This is reflected in tank cars' relatively low average of nine trips per year and the consequent average tank car trip cycle of nearly 6 weeks. This has the effect of reducing the cost-effectiveness of any feature whose benefit is a function of utilization, such as mileage or frequency of shipments.

2.2.3. Changes in the market environment

Changes in customer requirements have also led to changes in tank car design specifications. The growth of the U.S. chemical industry following World War II has been credited in part to the development and acceptance of welded tank cars that altered the transportation economics of chemical transport [13]. Welded cars made it feasible to construct the specialized tank car designs needed to transport a wide variety of chemicals inexpensively. Furthermore, the development of materials technology made it possible to provide reasonable-cost tank car linings or coatings that eliminated problems of incompatibility between the chemical and the tank steel for certain materials. Related to this were a variety of tank car tanks constructed of materials other than carbon steel such as aluminum, stainless steel and nickel. Furthermore, various valves and fittings were developed to permit the safe and efficient loading and unloading of a wide variety of materials.

2.2.4. Economic pressures on railroads to improve efficiency

An over-arching pressure on the railroad industry throughout its existence has been to reduce operating costs by improving operating efficiency. One of the most effective means of accomplishing this has been to increase railcar size. There are economies of scale in railcar size because increasing the size of a car does not result in a proportional increase in the cost to operate the car. Consequently, the weight-carrying capacity of railcars has more than tripled over the past century (Fig. 1). This process is ongoing; the capacity of the standard North American railcar is in the process of increasing from a nominal capacity of 100 to 110 tons. A key element of this process has been the development of more robust mechanical standards for railcars to enable them to withstand the greater loads [25].

A factor that has sometimes limited the increase in railcar size has been infrastructure. *Ceteris paribus*, heavier railcars increase the rate of deterioration of the track structure, thus increasing maintenance and capital replacement costs [26]. The reduction in operating costs will generally more than offset the increase in infrastructure expense, but the necessary upgrades must be made and costs accounted for. Enhancing vehicle design characteristics can also mitigate the effect on infrastructure [27]. Consequently, as part of the AAR's development of new specifications for heavier-axle-load railcars, there have also been enhancements in railcar suspension systems for 110-ton cars [25]. The objective of these has been not only to compensate for the effect of increased loadings on infrastructure and railcar components due to the heavier axle loads, but to actually reduce wear and fatigue by requiring use of components and systems that better prevent, absorb or cushion critical components from damaging loads and impacts. Paralleling the implementation of these more robust designs has been deployment of increasingly sophisticated fault detection systems to locate railcar defects before they become critical [28]. The data from these new systems is being leveraged through centralized processing to better identify trends and forecast railcar safety performance [29–31]. These initiatives appear to be having an effect, in the interval from 2001 to 2006 (the latest year for which data are available),

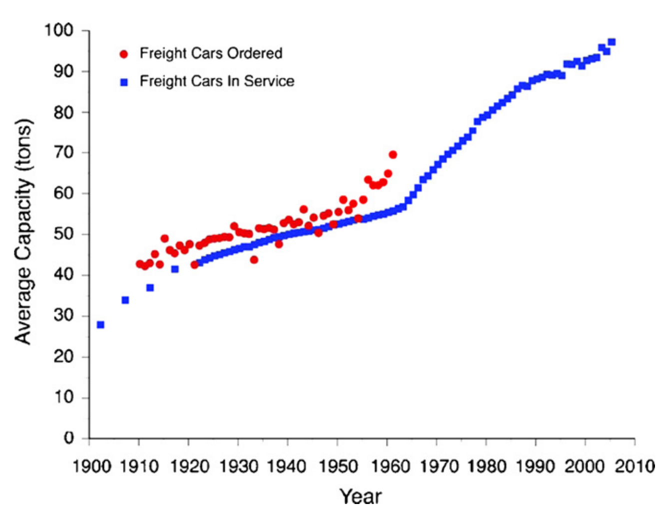

Fig. 1. Growth in U.S. railroad freight car capacity 1900–present ([52,53]).

both the frequency and the rate of the major railroads' mainline train accidents, hazardous materials car derailments, and releases have all declined substantially, while hazardous materials tank car shipments have increased 20% in the same interval [1].

2.2.5. Changes in the safety environment

Last but not least, there is continuous pressure from both the private and public sector to further improve the safety of transportation of hazardous materials. This pressure can be become acute in response to events. Such was the case in the early 1970s following a series of catastrophic hazardous materials accidents that resulted in multiple loss of life. These accidents were due to a combination of factors. Derailments had become more frequent on some railroads due to reduced investment in infrastructure in the era before economic deregulation, and a relatively new class of tank car, the DOT class 112A, was particularly susceptible to failure in accidents involving large fires.

In response, the railroad and tank car industries formed the Railway Progress Institute-Association of American Railroads (RPI-AAR) Railroad Tank Car Safety Research and Test Project in 1970, a cooperative research program on the causes of tank car failures. The subsequent analysis of the failure modes of the 112A tank car revealed the need for several design changes. These were incorporated into the AAR and DOT specifications for tank cars and substantially reduced their incidence of failure in accidents [32].

Another result of these events was recognition of the potential value of detailed statistical understanding of tank car failure modes in accidents. Consequently, the RPI-AAR Project instituted a long-term data collection effort on tank cars involved in accidents. Since the project's formation, data on over 40,000 damaged tank cars and 26,000 accidents they were involved in have been collected. This database provides extensive information about the details of individual tank car component performance, as well as many of the conditions of the accident.

The database enables four quantitative capabilities regarding monitoring and improving tank car safety: (1) ability to monitor trends in tank car safety performance, (2) identification of vulnerable aspects of tank car design, (3) ability to assess the effect of previously adopted changes in tank car safety design, and (4) ability to estimate the effectiveness of proposed changes in design. The database has been used frequently as a source of quantitative and qualitative information on a variety of questions regarding tank car design and safety and appears to be unique in the world.

In some respects, the formation of the project, and particularly the database, marked a turning point in the risk management process for tank car design safety. Following the formation of the Tank Car Safety Project, data on an ever-increasing number of tank cars began to accumulate, providing an increasingly robust database. This enabled the industry to take a proactive approach to tank car safety design [5] and to do so based on robust quantitative data.

2.3. Specifications for higher capacity tank cars

A recent example of the use of the Tank Car Safety Project database was the joint effort by industry and government to develop specifications for tank cars whose capacity exceeds 263,000 lb gross weight on rails ("gross rail load" or "GRL"). Since 1971, DOT regulations have set the maximum gross rail load for new DOT specification tank cars at 263,000 lb [33]. A limited number of higher capacity DOT cars constructed in the 1960s and early 1970s with more than four axles were allowed to continue operating transporting certain regulated materials. DOT regulations require that all but a small number of relatively benign hazardous materials be shipped in a DOT specification tank car. For nearly two decades, this limit was consistent with railroad industry practice and thus did not pose undue constraint on rail transportation efficiency and productivity. However, beginning in the 1980s, and increasingly in the 1990s, the railroads began to expand their use of higher capacity freight cars, typically 286,000 lb GRL [26]. This increase was motivated by both railroad and shipper interest in achieving the greater economies offered by the larger cars. However, the regulatory limit on maximum GRL for DOT specification tank cars prevented shippers of hazardous materials in tank cars from taking advantage of the larger more efficient cars.

DOT's rationale for limiting the GRL of tank cars transporting hazardous materials was based on the belief that if there were an accident resulting in a spill, the 100-ton nominal capacity limited, to some extent, the maximum volume that could be released. However, this limit had been established by DOT in an era when the railroad accident rate was considerably higher [34]. As a result of economic deregulation in 1980 and changes in their accounting systems in 1983, railroads had invested heavily in their physical plant in the ensuing years [9,10,35]. By the early 1990s, this had resulted in a nearly a 4-fold reduction in railroad accident rate [8], and nearly a 10-fold reduction in accident-caused hazardous materials release rate [6]. Consequently, the risk of a hazardous materials accident was considerably lower than it had been when the DOT limit was established.

In light of this, the DOT was open to discussion about increasing the GRL for hazardous materials tank cars but understandably reluctant about any changes that might compromise safety. DOT's initial step in 1994 was the issuance of a regulatory exemption for tank cars whose GRL exceeded the 263,000 maximum but whose extra weight was in the form of enhanced safety features, such as head shields, extra tank thickness and/or use of more damage-resistant specification cars than required by regulation [36,37]. DOT's rationale was to allow options that enhanced tank car safety without penalizing shippers in terms of the reduced capacity of the car due to the extra weight.

Beginning in the late 1990s, the discussion among industry and government representatives gained momentum. A task force composed of industry and government representatives was formed to develop a specification for higher GRL tank cars to be used for transport of hazardous materials. The Federal Railroad Administration (FRA) and Transport Canada circulated a paper that outlined their guidelines for the features of tank cars with a GRL exceeding 263,000 lb. [33]. The overarching philosophy was that these higher GRL cars had to have an equivalent or greater level of safety compared to their 263,000-lb GRL counterparts.

The railroads generally supported the move toward higher GRL tank cars but had two concerns. (1) As owners of the infrastructure that would be subject to the greater static and dynamic loads from the heavier cars, they wanted enhancements in running gear to mitigate the potential for higher expense for maintenance and renewal. Requirements for reducing the heavier cars' impact on railroad infrastructure were not unique to tank cars and applied to all cars being constructed to comply with the new specifications for 286,000 GRL [25,38]. (2) Railroads bear the principal risk associated with spills of hazardous materials in transportation. From the earliest discussions, they viewed the increase of tank car GRL as an opportunity to enhance the safety of the package without imposing additional economic burden on their customers.

3. Enhancements in tank car safety design

An important factor in consideration of tank car safety design is that most safety enhancements increase the weight of the car, thereby reducing its capacity and consequent productivity as a transportation vehicle. The loss in capacity is a concern because of its impact on the transportation economics for shippers of chemical products. For some products, the hazard is sufficiently high that the benefit from the reduction in risk is enough to offset the extra expense of the safer but lower capacity car [11]. However, many products do not pose a high level of risk so the resultant benefit from risk reduction is correspondingly less. Consequently, it is more difficult to cost-justify the loss in productivity that would occur if various safety enhancements were implemented for cars transporting these products.

The move to increase the capacity of tank cars was viewed by industry and government as an opportunity to enhance both productivity and safety simultaneously; however, the trade-off between safety and transportation efficiency was an important consideration. Enhanced safety features generally increase the weight and cost of the car, so the objectives of maximizing safety and minimizing weight are in conflict. The question of which design modifications to adopt and how much weight and cost should be allocated to safety versus productivity was the crux of much of the discussion and analysis. As such it is a classic multi-attribute decision problem as described by Keeney and Raiffa [39, p. 66].

Evaluation of the decision problem required a quantitative understanding of the safety benefit and the weight and cost penalties associated with each option or combination of options so that the trade-off between safety and efficiency could be quantified [39]. Although cost was a critical underlying factor in the decision process, the Tank Car Committee decided that weight could be used as a satisfactory proxy variable for cost. Tank car weight directly affects railroad-operating cost and it also varies directly with material quantity, which is the principal variable affecting car construction cost. Use of weight avoided the need for industry representatives to discuss or share potentially business-sensitive cost information. It also had the analytical advantage of allowing the problem to be treated as a bi-criterion decision problem. The functional relationship between safety and weight would allow the efficiency of the different options to be compared and the determination of the Pareto optimal set [40]. The convexity or concavity of the efficient frontier would also provide insight regarding which solution would be “best”.

The Tank Car Safety Project database enabled development of quantitative estimates of the benefits of various tank car safety enhancements. Engineering calculation of the increased weight of each feature meant that precise understanding of the trade-off for each possible combination of tank car features was possible.

3.1. Damage resistance of tank cars

The most common approach to enhancing tank car safety design is to increase its resistance to external forces that may be encountered in an accident. There are four primary areas of the tank car that are susceptible to release-causing damage in an accident: bottom fittings, top fittings, tank head, and tank shell (Fig. 2). It is useful to distinguish between them because both the nature and consequences of damage to each differs, and consequently so does the associated risk [41–43]. Furthermore, design changes to enhance the damage resistance of each also differ, and these modifications have correspondingly different effects on risk reduction. Consequently the tank car safety database is organized to enable analyses of the failure mode for each component of the tank car.

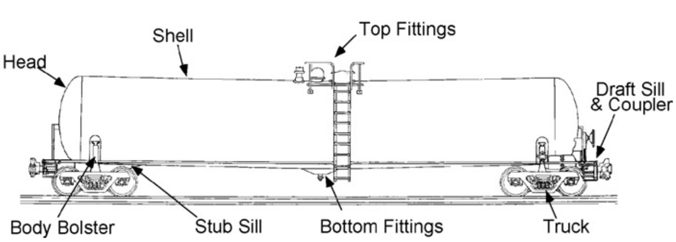

Fig. 2. Diagram of a typical North American railroad tank car (modified from [46]).

Accident performance of tank cars is typically measured in terms of their conditional probability of release, $P_{R|A}$, given that they are derailed in an FRA-reportable accident[1]. Phillips et al. [41] conducted an extensive analysis that considered approximately 10,000 tank cars damaged in mainline railroad accidents. They calculated $P_{R|A}$ for most types of tank car currently in use. They also developed a comprehensive set of mutually exclusive and collectively exhaustive conditional probabilities, $P_{R_i|A}$, for each of the four parts (i) of the tank car ($P_{R_B|A}$, $P_{R_T|A}$, $P_{R_H|A}$, $P_{R_S|A}$) and the probability that a car experiences releases from more than one source and ($P_{R_M|A}$) where

- $P_{R_B|A}$ = conditional probability of release from the bottom fittings given that a car is derailed in an accident.
- $P_{R_T|A}$ = conditional probability of release from the top fittings given that a car is derailed in an accident.
- $P_{R_H|A}$ = conditional probability of release from the head given that a car is derailed in an accident.
- $P_{R_S|A}$ = conditional probability of release from the shell given that a car is derailed in an accident.
- $P_{R_M|A}$ = conditional probability of release from more than one source given that a car is derailed in an accident.

These tables enabled calculation of an estimate of $P_{R|A}$ for a tank car with any combination of the safety design features of interest.

Tank car specifications vary widely depending on the material they are intended to transport, with the most hazardous products transported in the most robust cars [44]. The most common class of tank car in North America is the DOT class 111. The majority of hazardous materials are liquids that pose a low to moderate hazard and the class 111 is the minimum specification tank car allowed for transport of most of these. Certain designs of this class of tank car have the highest $P_{R|A}$ relative to other classes of steel tank car [41] and these were the ones considered for enhanced specifications for higher GRL cars. There are two basic varieties of 111, those with insulation and a steel exterior jacket, and those without these features. Their respective values for $P_{R_i|A}$ differ in some respects (Fig. 3).

3.2. Tank car enhancements considered for higher GRL tank cars

Of principal interest in the consideration of safety requirements for higher GRL tank cars are attributes that affect conditional probability of release from the four sources described above: bottom fittings, top fittings, tank head, and tank shell.

3.2.1. Bottom fittings

Bottom fitting vulnerability has been a source of concern in the past; however, since 1978, all cars equipped with bottom fittings are required to be constructed with protective designs [21] that include recessed valves, breakaway designs on piping and other appurtenances below the valve, and steel structures mounted adjacent to the fittings that are sometimes called “skid protection”. The objective is to prevent or mitigate damage if cars are derailed in an accident. The protective system shields the bottom fittings from

[1] FRA requires railroads to submit detailed reports of all accidents that exceed a specified monetary threshold for damage to roadbed, track, track structures, signals and equipment. The threshold is periodically adjusted for inflation. In 2002 the threshold was $6700 and was increased to $7700 in 2006.

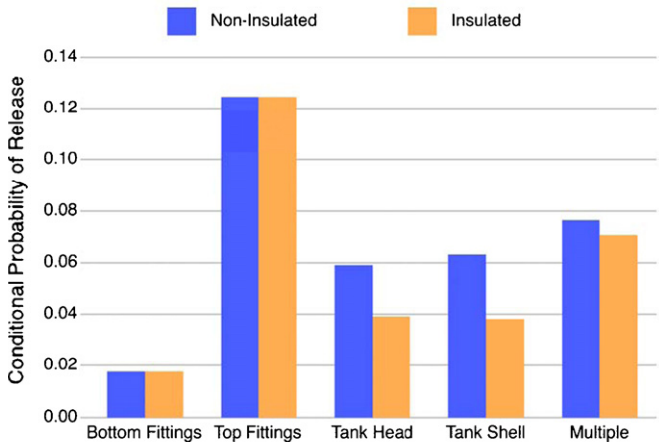

Fig. 3. Conditional probability of release by source ($P_{Ri|A}$) for non-insulated and insulated non-pressure tank cars in mainline, FRA-reportable accidents.

direct impacts in this circumstance. Griger and Phillips [45] found that, compared to unequipped cars, cars with bottom fittings protection were 55% less likely to suffer a release from the bottom fittings in an accident, and if a release did occur, the average quantity lost was 42% lower. As a result of these changes it has become the least likely source of release on non-pressure tank cars (Fig. 3). Based on these results, the Tank Car Committee concluded that further enhancement of bottom fittings protection was not necessary for the higher GRL cars.

3.2.2. *Top fittings protection*

There are a variety of fittings and appurtenances located on the top of a tank car that are used for loading and unloading the car; pressure and vacuum relief; gauging the level of the contents; and access to the interior of the tank for cleaning and maintenance [46,47]. When tank cars are derailed in an accident they may overturn and slide or tumble along the right of way, or impact other railcars or wayside structures. Under these circumstances top fittings may be damaged or sheared off, causing them to leak. Specifications for pressure tank cars that transport higher hazard products such as chlorine, liquefied petroleum gas, ammonia, etc., have long required a form of top fittings protection (TFP) in which all the top fittings are confined within a single, 3/4 in. steel housing or "bonnet" [21]. A similar enclosure can be used on DOT class 111 cars as an optional safety enhancement and therefore was considered as an option for inclusion in the specifications for tank cars over 263,000 lb GRL.

3.2.3. *Tank head and shell protection*

Most class 111 tank cars have a minimum allowable thickness for the tank head and shell of 7/16-in. This was the baseline used for calculation of the incremental benefit of modifications to the head and shell. Additionally it was agreed early on that higher tensile strength steel (TC-128B) should be used on the higher GRL cars. TC-128B has a tensile strength 15.7% higher than A-516, the steel most commonly used for class 111 tank cars. However, this does not imply a comparable reduction in release probability because the forces a tank car is subjected to in accidents are unknown and there are other sources of variance that affect the performance of tank steel in accidents. The statistical evidence of the additional benefit the stronger steel provides in terms of damage-resistance in accidents is inconclusive, thus it was not possible to quantify the benefit due to its use. Instead a more conservative approach was used based on regression analyses by Phillips et al. [41] of the relationship between steel thickness and tank car puncture probability.

Related to consideration of tank thickness is the beneficial effect of the addition of 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 tank's damage resistance. This effect on safety performance is acknowledged in the specifications and regulations for certain hazardous materials tank cars [21,44]. In their analysis Phillips et al. [41] concluded that the extra puncture resistance provided by the 1/8-in. jacket was approximately the same as an equal increase in the thickness of the tank.

Further protection of the tank head can be accomplished through use of head protection systems. These come in several forms, a head shield which is an extra layer of 1/2-in. thick steel mounted over the tank head, or use of a jacket head that is 1/2-in. thick. The former approach is typically used for non-jacketed cars, and the latter for jacketed cars. Head protection may be either half height or full height. Full-height head protection (FHP) covers the entire head and, as the name implies, half-height head protection (HHP) covers the lower half. Half-height head protection is disproportionately more effective than this suggests. Phillips and Role [32] found that approximately 82% of punctures of tank heads without head shields are at or below the midline. This factor is incorporated into the quantitative assessment of tank-head-protection effectiveness.

4. Formulation of multi-attribute decision problem

4.1. *Quantification of the incremental safety benefit of tank car risk reduction options*

The three aspects of tank car safety design discussed above were considered in the analysis: two possible states for top fittings protection, three for head protection, and four tank thicknesses (Table 1). Thus there was a 2 × 3 × 4 matrix of possible combinations of tank car safety design options to consider (Table 2).

4.2. *Conditional probability of release for tank cars with various combinations of risk-reduction options*

The analyses by Phillips et al. [41] enabled the quantification of $P_{R|A}$, for each combination of risk-reduction options (Table 3). $P_{R|A} = 0.3407$ for the baseline case, a non-jacketed, non-pressure, class 111 tank car with a bottom outlet and no top fittings protection. Each of the other cells represents the $P_{R|A}$ for a tank car with the particular combination of modifications indicated. For example, relative to the baseline car, addition of half-height head shields reduces $P_{R|A}$ from 0.3407 to 0.2956, and adding full-height head shields further reduces it to 0.2870. Increasing tank thickness from

Table 1
Summary of basic options for enhanced tank safety features considered for higher GRL tank cars (acronyms for certain options in parentheses)

Feature	Baseline condition	Risk reduction options		
Top fittings protection	None	Yes (TFP)		
Head protection	None	Half height (HHP)	Full height (FHP)	
Tank thickness (in.)	7/16	1/2	9/16	5/8

Table 2
Matrix of all possible combinations of risk reduction options considered (and abbreviations used to denote them)

Tank Thickness (in.)	No top fittings protection			Top fittings protection		
	No head protection	Half-height head protection	Full-height head protection	No head protection	Half-height head protection	Full-height head protection
0.4375	Baseline	HHP	FHP	TFP	TFP, HHP	TFP, FHP
0.5000	1/2 in.	HHP, 1/2 in.	FHP, 1/2 in.	TFP, 1/2 in.	TFP, HHP, 1/2 in.	TFP, FHP, 1/2 in.
0.5625	9/16 in.	HHP, 9/16 in.	FHP, 9/16 in.	TFP, 9/16 in.	TFP, HHP, 9/16 in.	TFP, FHP, 9/16 in.
0.6250	5/8 in.	HHP, 5/8 in.	FHP, 5/8 in.	TFP, 5/8 in.	TFP, HHP, 5/8 in.	TFP, FHP, 5/8 in.

Table 3
Estimated conditional probability of release, $P_{R|A}$ for non-insulated, non-pressure tank cars with different combinations of risk reduction options

Tank thickness (in.)	No top fittings protection			Top fittings protection		
	No head protection	Half-height head protection	Full-height head protection	No head protection	Half-height head protection	Full-height head protection
0.4375	0.3407	0.2956	0.2870	0.2895	0.2502	0.2416
0.5000	0.3098	0.2778	0.2708	0.2644	0.2324	0.2254
0.5625	0.2899	0.2638	0.2581	0.2445	0.2184	0.2127
0.6250	0.2740	0.2528	0.2481	0.2286	0.2074	0.2027

7/16 to 1/2 in. reduces $P_{R|A}$ to 0.3098, and addition of top-fittings protection of the type described above reduces $P_{R|A}$ to 0.2895. All of the values for $P_{R|A}$ presented in Table 3, and elsewhere in this paper use the statistics and methodology developed by Phillips et al. [41] and thus properly account for the effect of design changes on single as well as multiple-cause releases.

4.3. Quantification of the incremental weight of tank car risk reduction options

A similar matrix was developed for the incremental weight increase associated with each combination of risk-reduction options (Table 4). The weight data were either obtained from the tank car companies or calculated based on the geometry and density of the steel components. In the case of the tank shell the effect of an incremental increase in thickness is calculated using a modified version of the geometric formula for a cylinder $L\pi\ [(\delta+\tau)^2-\delta^2]$, where L = length of the tank shell, δ = inner radius of the tank and τ = tank thickness. Combined with the density of steel, the difference in mass due to incremental changes in the thickness of the cylinder can be calculated. The mass of the tank head can be calculated in an analogous fashion. Tank car heads typically conform to a 2:1 ellipse and the geometric formula for the volume of half of an ellipsoid can be used to calculate the change in mass given changes in tank head thickness using the formula $4/3\pi\ (\delta+\tau)^2\ (\delta/E+\tau)/2-4/3\pi(\delta^3/E)/2$, where δ and τ are defined as above and E is the ellipsoid ratio. This formula can also be used to estimate the incremental weight of the addition of half- or full-height head protection.

For example for the car presented in Table 4, addition of half-height head shields adds 1662 lb to the car's weight, and full-height head shields adds 3323 lb and increasing tank thickness from 7/16 to 1/2 in. increases the car's weight by 3543 lb. The addition of top-fittings protection was also calculated based on the geometry of the design and estimated to be approximately 900 lb. and confirmed with a major tank car manufacturer along with the rest of the incremental weight estimates [48]. The incremental increase in weight for any combination of risk reduction options could thus be calculated for any particular size of car (Table 4).

Some assumptions regarding tank size and weight were made in order to develop a general set of estimates for the incremental weights. The diameter of class 111 tank cars commonly in use ranges from 99 to 119 in. (determined by factors such as the volumetric size requirement of the car, vertical and horizontal clearance requirements, the size of the tank head press at tank car manufacturing facilities and possible constraints on car length). The volumetric capacity of class 111 tank cars typically ranges from about 13,000 gal to approximately 30,000 gal, depending on the density of the product the car is intended to transport. The figures used in the analysis were for a 21,000-gal tank which represents the approximate mean volumetric capacity for class 111 tank cars in North America based on an analysis of the AAR Universal Machine Language Equipment Register (UMLER) data. A tank diameter of 110.25 in. was used because it is a common intermediate diameter for these cars. The assumptions regarding tank volume and diameter both affect the incremental weight increase resulting from changes in tank shell thickness. The assumption regarding tank diameter also affects the incremental weight due to changes in head thickness and head protection.

4.4. Incremental safety per unit of weight increase

The objective in developing specifications for enhanced safety features was to minimize the likelihood of a hazardous materials

Table 4
Estimated[a] weight increase in lb for non-pressure tank cars with different combinations of risk reduction options

Tank thickness (in.)	No top fittings protection			Top fittings protection		
	No head protection	Half-height head protection	Full-height head protection	No head protection	Half-height head protection	Full-height head protection
0.4375	0	1,662	3,323	900	2,562	4,223
0.5000	3,543	5,205	6,866	4,443	6,105	7,766
0.5625	7,087	8,748	10,410	7,987	9,648	11,310
0.6250	10,630	12,291	13,953	11,530	13,191	14,853

[a] Assuming a 110.25-in. inside diameter tank which is commonly used for North American tank car construction.

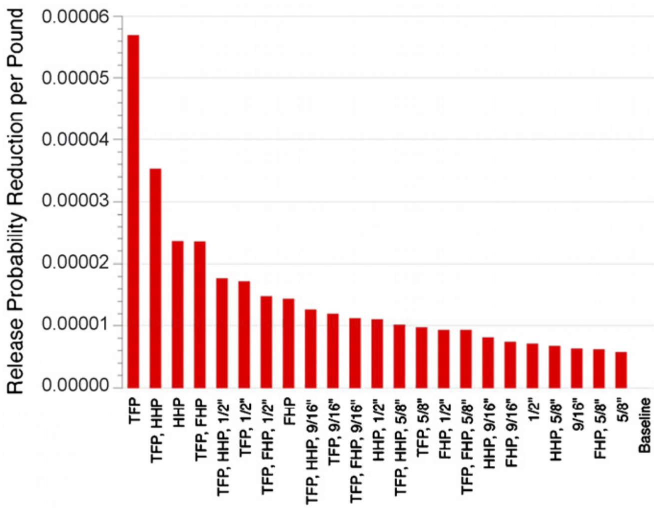

Fig. 4. Reduction in conditional probability of release per added pound of weight.

spill while maximizing the transportation productivity of the new 286,000 lb. GRL tank car. The first step in identifying the most efficient approach to enhancing safety was to calculate the reduction in release probability per pound of additional weight using the data in Tables 3 and 4 and then rank order them (Fig. 4).

Fig. 4 provides insight into the efficiency of different risk reduction options, but does not necessarily yield information on the optimal combination given the objective of minimizing release probability for any particular incremental increase in weight. Because this is a multi-attribute decision problem both objectives must be considered separately but simultaneously [39]. In order to select a combination of options that minimizes conditional probability of release and weight increase, it is necessary but not sufficient to know the value of $\Delta p/\Delta w$ for each combination of options. Identification of the optimal solution required a different approach.

4.5. Identification of the Pareto optimal set of tank car risk reduction option combinations

As mentioned above, achieving a satisfactory solution to the trade-off between maximizing safety and minimizing weight was a principal objective. The Tank Car Committee agreed that up to one third of the difference between the current and the proposed maximum GRL [(286,000–263,000)/3 = 7667 lb] should go toward enhanced safety features (e.g. Tables 1, 2 and 4). Although in principle tank shell and head thickness might be thought of as continuous variables, in practice tank cars are generally constructed in one of a discrete set of thicknesses, consequently a more limited set of thicknesses was evaluated.

The problem was to first identify the Pareto-optimal set of risk reduction options (RRO) for which the reduction in conditional release probability was maximized for any particular increase in weight. The number of options being considered was small enough that the problem could be solved by enumerating all of the possible solutions and then considering each of them relative to the others using the techniques discussed by Marler and Arora [40]. Furthermore, since the maximum weight bound was defined, a goal programming approach to the formal decision process could be used to identify the single optimal combination from among the possible choices represented by the Pareto-optimal set. This approach was useful for consideration of the diminishing marginal return for various combinations of tank car safety enhancements.

Let R be the set of all possible combinations of risk reduction options (as described in Table 2) and r_i be the ith combination of options where i ranges from 0,1, . . ., 23. Note that r_0 is the baseline case with no enhanced safety features, and r_{23} is the combination with the maximum value for each of the possible options. P is the matrix of Δp_{ij}, where

$$\Delta p_{ij} = \max(0,\ p_i - p_j)$$

is the non-negative difference in conditional release probability between the ith and jth combinations of risk-reduction options. Note that $\Delta p_{ij} < 1$ for all i, j, and $\Delta p_{ij} = 0$ if $i = j$. A 24 × 24 matrix of the form shown in Table 5 was developed for calculation of Δp_{ij} for all i, j. A similar matrix of the non-negative difference in weight associated with each pairwise combination was also developed, in which the entries are

$$\Delta w_{ij} = \max(0,\ w_j - w_i), \quad \text{for all } i, j$$

These two matrices were used to calculate a third matrix PW in which the (i,j)th entry is

$$\lambda_{ij} = \frac{\Delta p_{ij}}{\Delta w_{ij}}, \quad \text{if } \Delta w_{ij} > 0;\ \text{or } +\infty \text{ otherwise}$$

As there are only two objectives (weight vs. release probability), a stepwise decision process is used to determine the Pareto-optimal (non-dominated) solutions. The decision criteria can be implemented using the following algorithm.

(1) Initialize: compute Δw_{ij} and λ_{ij} for all i,j; determine the desired upper bound for weight increase, b; $i = 0$ (base case); initialize the set of Pareto-optimum solutions, $S = \{0\}$.
(2) For the current i, find the minimum weight increase, dw_i, that has a positive probability improvement:

$$dw_i = \begin{cases} \min\limits_{j}\{\Delta w_{ij} : \lambda_{ij} > 0\}, & \text{if } \exists \lambda_{ij} > 0 \\ -1, & \text{otherwise} \end{cases};$$

and the set of solutions, C_i, that has that minimum weight increase:

$$C_i = \{j : \Delta w_{ij} = dw_i\};$$

(3) If $dw_i > b$ or $C_i = \Phi$ (empty set), go to 5); otherwise, select the solution with the maximum probability improvement under

Table 5
Matrix illustrating pairwise calculation of the difference in conditional release probability (Δp) for risk reduction option combinations

	r_0	r_1	r_2	···	r_{23}
r_0	$\max(0, p_0 - p_0)$	$\max(0, p_0 - p_1)$	$\max(0, p_0 - p_2)$	···	$\max(0, p_0 - p_{23})$
r_1	$\max(0, p_1 - p_0)$	$\max(0, p_1 - p_1)$	$\max(0, p_1 - p_2)$	···	$\max(0, p_1 - p_{23})$
r_2	$\max(0, p_2 - p_0)$	$\max(0, p_2 - p_1)$	$\max(0, p_2 - p_2)$	···	$\max(0, p_2 - p_{23})$
⋮	⋮	⋮	⋮	⋮	⋮
r_{23}	$\max(0, p_{23} - p_0)$	$\max(0, p_{23} - p_1)$	$\max(0, p_{23} - p_2)$	···	$\max(0, p_{23} - p_{23})$

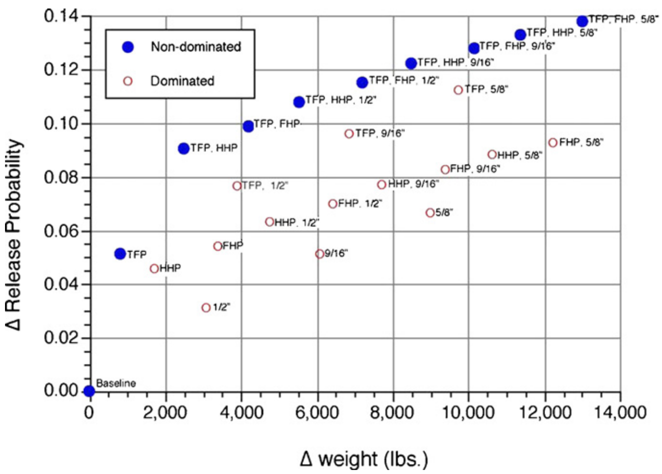

Fig. 5. Reduction in $P_{R|A}$ versus increase in weight relative to the baseline condition for all possible risk-reduction-option combinations considered for non-insulated tank cars (solid points are non-dominated solutions and the open are dominated).

that minimum weight increase:

$$k = \arg\max_{j}\{\lambda_{ij} : \Delta w_{ij} = dw_i\};$$

Update the remaining available weight bound, $b = b - dw_i$; and update the set of Pareto-optimal solutions $S = S \cup \{r_k\}$

(4) Let $i = k$; repeat steps 2 and 3.
(5) Output the set of Pareto-optimum solutions, S.

Use of this algorithm enables a step-wise process that can identify the candidate solutions and also the final optimal combination of risk reduction options that maximizes safety within the specified upper-bound increase in weight.

4.6. Graphical solution

Each solution can also be enumerated and portrayed graphically (Fig. 5). A two-dimensional plot of Δp versus Δw was developed that enabled identification of the Pareto-optimal (non-dominated) set of risk reduction option combinations. It should be pointed out that bi-criterion problems such as this one are typically depicted graphically with the value of one criterion compared directly to the value of the other. However, it was more instructive for the Tank Car Committee to consider the incremental benefit (i.e. reduction in $P_{R|A}$ relative to the baseline car) versus the incremental weight increase associated with different risk reduction option combinations. In other words, the objective was to maximize Δ release probability and minimize Δ weight relative to the current-design car. In terms of the outcome of the decision process these are equivalent so they are presented in the same manner that the Tank Car Committee considered the data.

4.7. Non-insulated tank car solution

There were clearly substantial differences in the efficiency among the possible combinations of tank car safety options for the non-insulated tank car (Fig. 5). Relative to the baseline car, the single best option was the addition of top fittings protection. This is not surprising considering that losses from top fittings are the most common source of release from non-pressure tank cars. Top fittings protection reduces $P_{R|A}$ by 0.0512 and accomplishes this with the lowest incremental increase in weight of any single RRO at 900 lb. Although the addition of full-height head shields reduces $P_{R|A}$ by a greater amount, it does so with a weight penalty more than 3.5 times higher than top-fittings protection. The various RRO combinations identified as non-dominated represent the Pareto Optimal set of possible solutions. The optimal solution was the one that maximized the reduction in release probability without exceeding the upper weight bound, b_u. Using the algorithm described above, the optimal combination was found to be: top-fittings protection, half-height head shields and a 1/2-in. tank thickness (TFP, HHP, 1/2 in.) with a $P_{R|A} = 0.2324$. This represented a nearly 32% improvement in safety performance and was selected for the new specifications for non-insulated, 286,000-lb GRL tank cars [21].

4.8. Insulated tank car solution

The results above apply to the non-jacketed tank car. The majority of non-pressure tank cars have insulation and a steel jacket, and a solution was needed for these cars as well. Because of the extra protection in accidents provided by the steel jacket and insulation, these cars have a baseline conditional probability of release that is lower than the non-jacketed car (0.2899 vs. 0.3407) (Tables 3 and 6). However these features also add a considerable amount to the cars' baseline weight. The same methods were used to analyze the possible solutions for the insulated car (Fig. 6).

Comparison of the differences in the non-dominated set of solutions in Figs. 5 and 6 reveals some differences in the contours of the non-dominated set, and in the absolute position of the dominated solutions (compare the difference in the scale of the Δ release probability axes in Figs. 5 and 6). The principal reason for these differences is that tank puncture resistance is a convex function of tank thickness [41,49] that conforms well to a negative exponential distribution over the range of tank car thicknesses used in North America [50]. Thus, when the effect of the jacket is factored in, the insulated car has a functionally thicker initial tank thickness than the non-insulated car [41]. Because of the negative exponential function, the incremental benefit of each additional unit of tank thickness increase compared to the baseline condition is lower for the insulated than the non-insulated car. Consequently, the relative benefit of top fittings protection is higher compared to the addition of head protection or increased tank thickness.

Despite these differences the composition of the Pareto-optimal set for the insulated car was the same as the non-insulated car. When the weight increase criterion was taken into account, along with the different baseline condition for the insulated versus non-

Table 6
Estimated conditional probability of release for insulated, non-pressure tank cars with different combinations of risk reduction options

Tank thickness (in.)	No top fittings protection			Top fittings protection		
	No head protection	Half-height head protection	Full-height head protection	No head protection	Half-height head protection	Full-height head protection
0.4375	0.2899	0.2666	0.2619	0.2445	0.2212	0.2165
0.5000	0.2740	0.2550	0.2512	0.2286	0.2096	0.2058
0.5625	0.2613	0.2460	0.2429	0.2159	0.2006	0.1975
0.6250	0.2513	0.2388	0.2363	0.2059	0.1934	0.1909

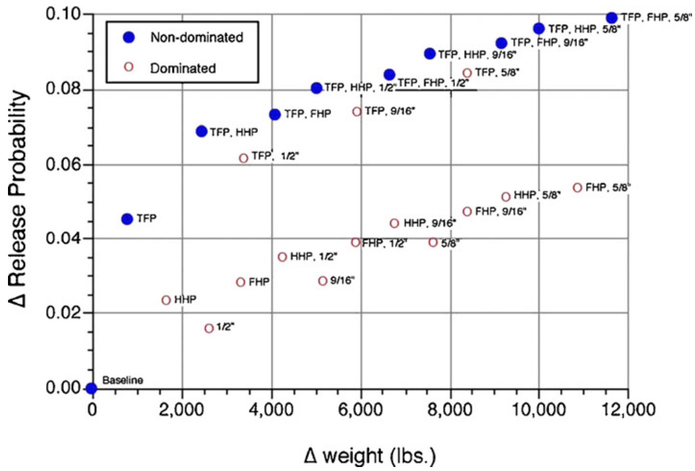

Fig. 6. Reduction in $P_{R|A}$ versus increase in weight relative to the baseline condition for insulated tank cars.

insulated car, the optimal solution was top-fittings protection and full-height head shields (TFP, FHP) with a $P_{R|A} = 0.2165$. This represented a 25% improvement in safety and was selected by the Tank Car Committee for the new specifications for insulated, 286,000-lb GRL tank cars [21].

4.9. Sensitivity analysis of the effect of tank size

As discussed above, certain assumptions were made in the initial analyses regarding the volumetric capacity of the tank and the consequent weight increase associated with increasing tank thickness. Tank size varies considerably depending on the density of the product it is intended to transport. The incremental weight increase for top fittings protection and head protection is not affected by tank length but the effect of tank thickness is. The sensitivity of the optimal solution to this parameter needed to be evaluated.

Sensitivity analyses were conducted in which the volumetric capacity was varied from 13,000 to 30,000 gal and the results plotted for both the non-insulated and insulated cars (Fig. 7A and B). The horizontal bars indicate the range of effects for the solutions among the non-dominated set (the dominated solutions for a given tank thickness would be affected in a similar way but these are not shown for purposes of clarity). It is evident that there is considerable effect along the Δ weight axis and that the exact contour of the efficient frontier would be altered; however, in no case was this variation sufficient to alter the solutions included in the non-dominated set, or even the ordering of the solutions' efficiency. The results were thus robust to this source of variability.

Uncertainty in the estimates of tank car safety performance is another potential factor affecting the outcome of the optimality analysis. A formal uncertainty analysis was not conducted as part of the AAR Tank Car Committee process. Phillips et al. [41] developed a method to calculate uncertainty in the estimates of tank car $P_{R|A}$ at both the component and whole-car level. As a result of the large sample sizes involved with the types of cars considered in this analysis, the confidence intervals for the performance estimates are fairly narrow and do not affect the composition of the non-dominated set and thus the optimal solution.

4.10. Release probability versus release risk

The analyses presented consider the optimal solution in the context of the conditional probability of release. However, damage to different parts of the tank car results in different average quan-

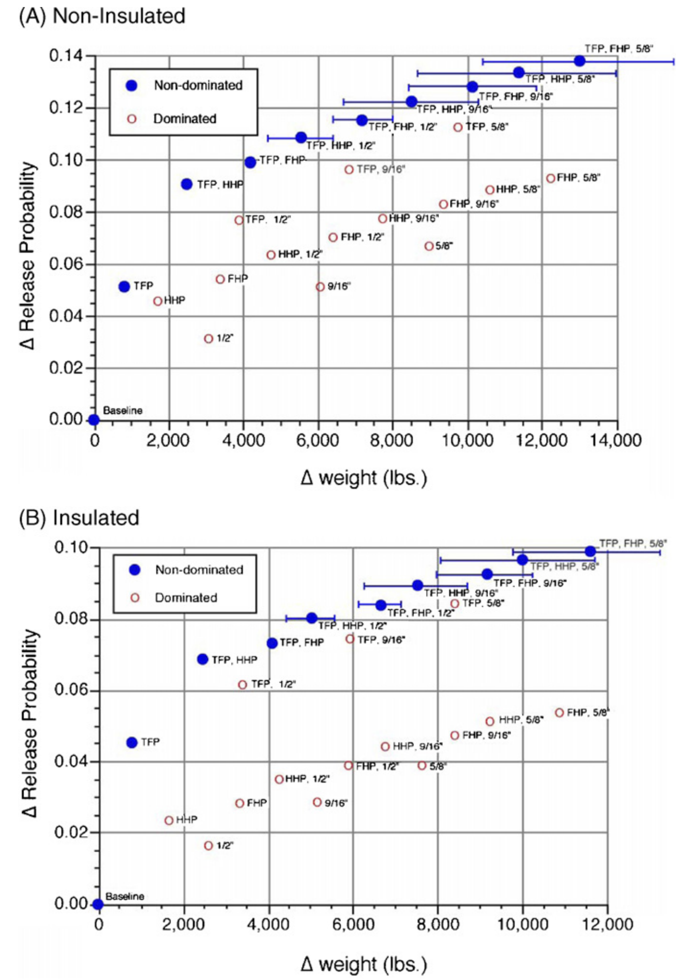

Fig. 7. Sensitivity analysis of the effect of tank car size on the non-dominated solutions for non-insulated (A) and insulated (B) tank cars. Each point represents a 21,000-gallon car, and the left and right ends of the horizontal bars indicate a 13,000 and a 30,000-gallon car, respectively.

tities lost [41,42]. For example, although damage to top fittings is the most frequent cause of accident-caused hazardous materials releases (Fig. 3), on average these leaks result in the smallest quantity lost. Conversely, head punctures are less frequent, but on average result in a considerably larger amount of lading lost. Saat and Barkan [43] develop the concept of release risk, which is the probability of loss from a particular source on the car multiplied by the average quantity lost from that source. The product is the expected value of the percentage of a tank's contents lost, given that it is derailed in an accident. Since the amount lost is a factor affecting hazardous materials risk, it may be appropriate to consider this value, rather than simple conditional release probability when evaluating the relative benefits of different RROs.

With this in mind the data were analyzed taking into account the average quantity lost from each source of damage [42,43]. A new variable, "release risk" which is the expected percentage of a tank car's contents that are lost given that it is in an accident, is calculated for each of the same 24 configurations of RROs previously considered for non-insulated and insulated tank cars (Table 7). The difference in release risk compared to the baseline condition was computed in the same manner as for release probability and compared to the difference in weight (Fig. 8A and B).

Comparison of Figs. 5 and 6 with Fig. 8A and B, respectively, reveals that the Pareto optimal set differs if release risk is used

Table 7
Estimated release risk for, non-insulated and insulated non-pressure tank cars with different combinations of risk reduction options

Tank thickness (in.)	No top fittings protection			Top fittings protection		
	No head protection	Half-height head protection	Full-height head protection	No head protection	Half-height head protection	Full-height head protection
Non-insulated car						
0.4375	0.1573	0.1293	0.1239	0.1414	0.1170	0.1117
0.5000	0.1381	0.1182	0.1139	0.1259	0.1060	0.1017
0.5625	0.1257	0.1095	0.1060	0.1135	0.0973	0.0938
0.6250	0.1158	0.1027	0.0998	0.1036	0.0905	0.0876
Insulated car						
0.4375	0.1257	0.1113	0.1084	0.1135	0.0991	0.0962
0.5000	0.1158	0.1041	0.1018	0.1036	0.0919	0.0895
0.5625	0.1080	0.0985	0.0966	0.0958	0.0863	0.0844
0.6250	0.1018	0.0940	0.0925	0.0896	0.0818	0.0803

rather than release probability, however the difference is small. Other than some change to the contour of the optimal set, the principal change is the addition of HHP to the set of non-dominated solutions. The reason for this is that on average, head punctures result in a much larger loss than top fittings-caused losses. Consequently, the benefit of HHP in reducing release risk is increased relative to TFP in all of the RRO combinations. For the same reason, all of the increased shell thickness RROs are increased relative to the addition of TFP.

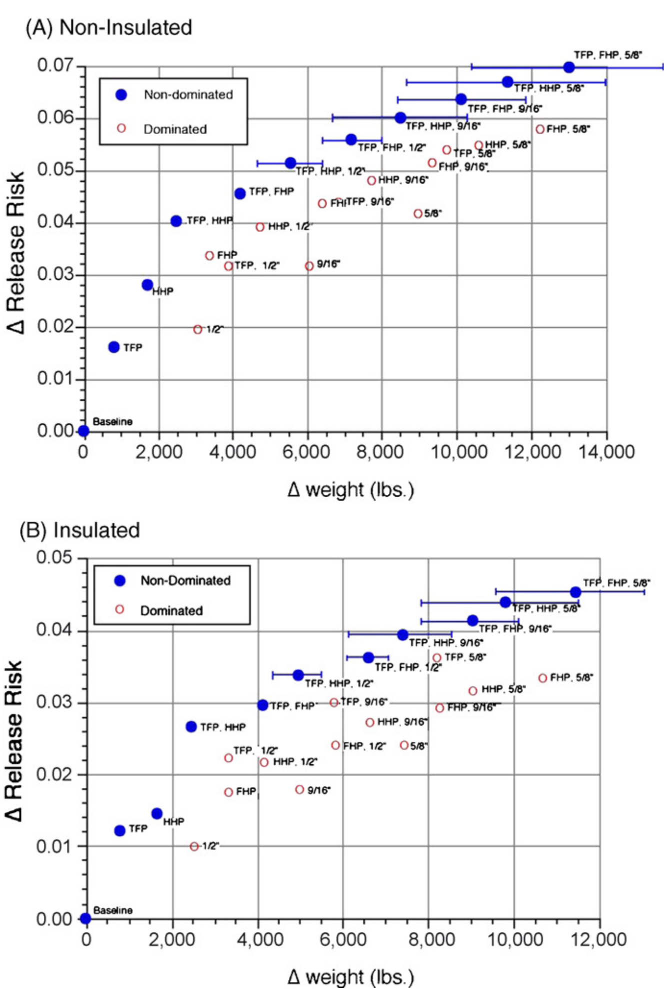

Fig. 8. Reduction in release risk versus increase in weight for the set of risk-reduction-option combinations considered for non-insulated (A) and insulated (B) tank cars. Horizontal bars indicate range from 13,000-gallon to 30,000-gallon cars as above.

5. Discussion and conclusions

The analysis presented here provided the railroad, tank car and chemical industries and U.S. and Canadian regulators with quantitative estimates of how the safety of higher-capacity railroad tank cars would be enhanced by all of the different combinations of risk-reduction options under consideration. The data and methodology employed helped identify the best set of solutions to choose from so that safety improvement was maximized within the specified limit in weight increase.

The “one third” criterion for the portion of incremental weight allocated to safety turns out to have been a good choice in terms of maximizing benefit for the non-insulated car. As weight increases, there are considerable diminishing returns among the non-dominated set of solutions (Figs. 5 and 6). The Tank Car Committee selected the combination of TFP, HHP, 1/2 in. for the non-insulated car and TFP, FHP for the insulated car. For the non-insulated car these combinations represented the maximum reduction in conditional probability of release possible without exceeding the agreed upon one-third weight threshold for any size tank car. For the insulated car the 1/8 in. jacket provides enhanced safety much the same as a thicker tank would, consequently it was decided that it was not necessary to increase tank thickness for the 286,000-lb. specification. Although the relative reduction in release probability was higher for the non-insulated car than the insulated, the resulting $P_{R|A}$ is similar for the two cars (0.2324 for the non-insulated and 0.2165 for the insulated). Incorporating quantity released into the analysis in the form of the parameter release risk slightly changed the make-up of the Pareto optimal set; however, it did not alter the optimal combination of RROs determined using the algorithm.

The agreed upon solution for the non-insulated car resulted in a nearly 32% reduction in $P_{R|A}$ (0.3407 to 0.2324) and for the insulated car, a 24% reduction (0.2899 to 0.2165). These safety improvements had a relatively modest impact on the potential increase in transportation capacity, which was diminished by about 2.5% for the non-insulated car, and about 1.1% for the insulated car.

It is evident that the differences between the dominated and non-dominated solutions were substantial in a number of cases. Consequently selecting from the dominated solutions could have provided much less benefit per unit of weight increase. For example, increasing tank thickness is beneficial, but it was clearly not the most efficient means of enhancing safety by itself. Comparison of the 9/16 in. option for non-insulated cars in Fig. 5 with the TFP, HHP, 1/2 in. solution selected by the Tank Car Committee shows that although the weight increase for the two options was about the same (ca. 6000 lb for a 21,000-gal car), the reduction in release probability was more than twice as large for the solution chosen.

Additionally, the new specification called for tanks to be constructed of normalized, TC-128B steel, which is tougher and has higher tensile strength than the A-516 grade that is the standard for non-pressure tank cars. As a consequence these cars will be less susceptible to both brittle and ductile failure in accidents. Because the density of TC-128B is virtually the same as the A-516, this provided additional benefit [51] with no extra weight penalty. Another benefit not formally considered is that the higher-capacity tank cars will mean fewer shipments and consequently lower exposure to accidents [50].

Another result that is apparent from the tank size and weight sensitivity analysis (Fig. 7A and B) is that for the smallest cars (left side of the bars), some of the solutions involving increased thickness are nearly the same in terms of weight increase, but offer a relative reduction in release probability (for example TFP, FHP, 1/2 in. versus TFP, HHP, 9/16 in. and TFP, FHP, 9/16 in. versus TFP, HHP, 5/8 in.). Although all of these cases are above the agreed-upon weight criterion, some hazardous materials shippers might still opt for the added measure of safety. In these specialized cases there is little weight penalty associated with selecting the tank car with the lower release probability. These cases are more the exception than the rule and are on the diminishing returns portion of the curve. Nevertheless, it is worthwhile to be cognizant of these choices when they are available. It is also worth noting that in the unusual case of a tank car less than 13,000 gal, the make-up of the Pareto Optimal Set might be slightly different.

In conclusion, the availability of a comprehensive database enabled detailed quantitative analysis of the accident performance of each component of the tank car. This was combined with detailed engineering analysis of the implications for tank weight and transportation efficiency of each possible design change being considered. Use of these data together with application of operations research methodology helped guide the Tank Car Committee to an informed, rational selection of the most efficient set of options to improve the safety of higher-capacity tank cars. The methods developed here can be applied to other problems regarding optimization of tank car safety design. The key information needed would be the effect of design changes on release probability and severity, combined with the effect of these changes on weight and cost for the tank car components being considered in the analysis.

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