EVALUATING NEW TECHNOLOGIES FOR RAILWAY TANK CAR SAFETY THROUGH COOPERATIVE RESEARCH

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SUMMARY

Transportation of chemical and petroleum products is the second largest source of revenue for North American railroads and is a vital element in all facets of the continent's economy. In 1997 over 200 million tons of these products were shipped by rail in the US and Canada, mostly in railroad tank cars. Safe and efficient transportation of these products has long been a vital interest of the railroads, chemical shippers, tank car companies and government agencies. As the volume and diversity of this traffic has expanded, increased attention has been directed to the potential hazards posed by the products and the safety of the cars used to transport them. In recognition of the need for reliable engineering and statistical data regarding the implementation of new technologies for tank car safety design, the railroads and tank car manufacturers formed the Railway Progress Institute-Association of American Railroads: Railroad Tank Car Safety Research and Test Project to develop the needed information. In the 28 years since its formation, extensive testing on many aspects of tank car safety have been conducted. Data on over 36,000 tank cars damaged in accidents have been collected and analyzed. The performance of the damaged tank cars and the benefits of new tank car safety technologies in preventing releases of hazardous materials have been evaluated.

In this paper we review the formation of the Tank Car Safety Project and describe some of the key research programs that have contributed to the improvement in North American tank car safety over the past two decades. From its inception, the Project's engineering and testing aspects and its statistical analysis aspects have played complementary roles. Analysis of tank car accident data was the initial step in identifying and prioritizing the key features of the tank car that needed improvement. This led to the engineering and testing of design modifications to tank cars. In the ensuing years since these design changes were adopted, statistical analyses by the Tank Car Safety Project have provided quantitative evaluation of their effect on tank cars' performance in accidents. Recent interest in more sophisticated approaches to analyzing hazardous materials transportation safety have led to new uses for the Project's data that provide additional insight into further, cost-effective improvements in chemical transportation safety.

KEY WORDS: tank car safety, engineering and design, chemical transportation, hazardous materials, dangerous goods, risk analysis

1 Introduction

The railroad tank car has played a vital role in the development of the North American manufacturing economy since the latter part of the 19th century. Tank cars were originally developed primarily for petroleum transport and there were no specifications for these cars (Heller 1970). However, several disastrous accidents in the first years of the 20th century awakened the industry to the need for improvements in tank car safety design. In 1903 a Committee on Tank Cars was formed composed of mechanical officers from various railroads and a representative from the major owner of tank cars at the time, the Union Tank Line. This committee which was part of the Master Car Builders' Association established a set of recommended practices for construction and repair of tank cars. These recommended practices were soon established as industry standards and adopted by the American Railway Association, and later its successor, the Association of American Railroads. They were also adopted as the basis for federal regulations.

By involving both railroad and tank car company representatives, the original Committee on Tank Cars established an important precedent that has proved beneficial to this day, that of cooperation between the railroads, the companies that transport tank cars, and the tank car companies that build and own them. The first half of the 20th century saw numerous enhancements to tank car design, perhaps most notable being the development and acceptance of fusion-welding techniques for tank car fabrication. This single innovation had a major impact on the US economy over the second half of the century by enabling safe, economical transportation of the wide variety of chemicals used by industrialized society. The rate of tank car construction doubled twice in the three decades following the war, resulting in the construction of almost 200,000 new tank cars between 1945 and 1975, nearly all of them employing the new fusion-welding technology [1].

In the early 1970s the railroad and tank car industries again found themselves confronted by a tank car safety problem. Recognition of the need for improvement was again prompted by a series of accidents involving flammable petroleum products. However, in this case the problems were more complex and the answers less obvious. Amidst clamor for a wide range of unproven "solutions", the railroad and tank car industries once again cooperated, this time to conduct the research necessary to understand the problem and develop a factual basis for effective solutions. The research would focus on ways to improve the damage resistance of tank cars involved in accidents, and in particular on how to prevent the most serious causes of failure [2]. The Railway Progress Institute (RPI) - Association of American Railroads (AAR): Railroad Tank Car Safety Research and Test Project (Tank Car Safety Project) was formed to conduct and oversee these investigations. It comprised two principal elements: statistical analysis, and engineering design and testing. In the ensuing 28 years the RPI-AAR Tank Car Safety Project has yielded invaluable information on improving the safety of railroad tank cars.

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1 This figure is an estimate based on the number of applications for construction submitted to the AAR Tank Car Committee from 1945-1975. Applications for approximately 1,500 riveted cars were submitted during this interval, all of them in the first 10 years after 1945.

2 The tank car research was one part of a two-pronged approach. The other part addressed the prevention of train derailments, by developing a better understanding of why they occurred and how they could be prevented. This program focused on improving the understanding of track/train dynamics and led to substantially better understanding of the relationship between track structure and rail vehicle performance. This program continues to yield important insights on train safety through the AAR and Federal Railroad Administration research programs conducted by the Transportation Technology Center, Inc.

2 Early Work of the RPI-AAR Tank Car Safety Project

Statistical analyses conducted by the RPI-AAR Tank Car Safety Project shortly after its formation identified two types of event in tank car accidents that tended to have serious consequences: the puncture of a tank by a coupler from another car in the train, and thermally induced weakening and subsequent rupture of tanks carrying highly flammable liquefied petroleum gas (Pasternak & Barkan 1998). It was also learned that bottom outlet fittings were particularly susceptible to damage in derailments. Thus, means of preventing tank head puncture, thermally induced tank ruptures and releases from bottom outlets became the initial focus of the Tank Car Safety Project's early engineering and testing activities.

2.1 Tank Car Head Protection

In order to understand the effectiveness of protecting the tank head, testing was conducted in which an impact car was equipped with a coupler attached to an elevated ram (Figure 1). The ram was adjustable and backed up by heavy structural beams internal to the ramming car. One fifth scale tanks were used to develop and refine the experimental design for the final full scale tests. Full-scale testing was conducted at the US Department of Transportation Test Center (TTC) in Pueblo, Colorado, (now operated by the Transportation Technology Center, Inc.) It was found that when the head of a DOT specification 112A340W pressure tank car loaded with water pressurized to 689 kilopascals was rammed at 20.4 km per hour (kph), the head would be punctured. A similar car, equipped with a 1.3 cm thick steel shield over the head of the tank, was hit at 24.1 kph without suffering a head puncture.

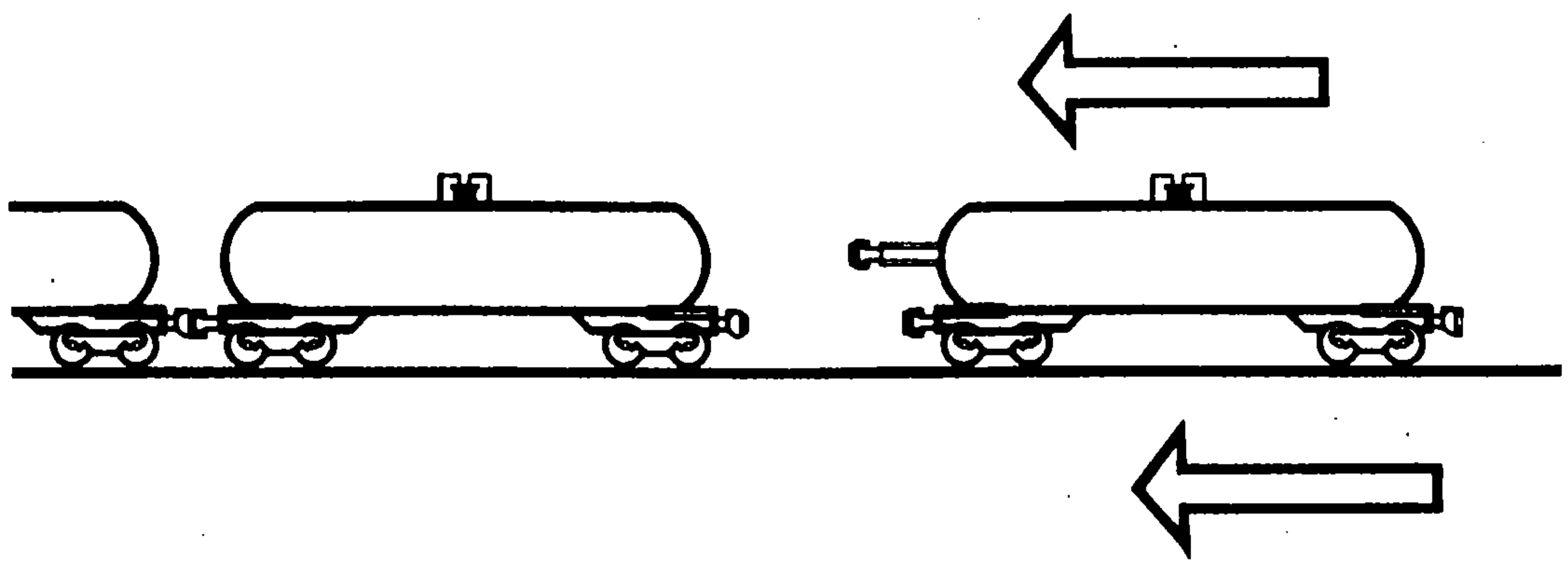

Figure 1. Tank car head puncture resistance testing

2.2 Tank Car Shelf Couplers

Although head shields would protect the end of the tank from puncture, it was less obvious how to protect the sides of the tank. Evidence from the accident analyses suggested that the couplers of adjacent cars often disengaged in accidents and acted as a ram that would puncture the shell of a tank car. If couplers were equipped with top and bottom "shelves", their likelihood of becoming disengaged might be reduced. An extensive series of full-scale impact tests of cars equipped with shelf couplers were conducted at TTC. A test car was equipped with shelf couplers and it was impacted by another car. The shelf couplers held firmly together, then broke off at the shank. This action eliminated the projecting coupler heads and rendered the coupler assembly less capable of puncturing the tank car head. In less severe impacts the shelf-couplers remained engaged and did not break.

2.3 Tank Car Thermal Protection

A study of the cause of violent rupture found that if an undamaged tank car containing liquefied petroleum gas (LPG) was in a fire, the LPG was heated, its pressure rose, and it vented through the pressure relief valve. However, as the liquid level inside the tank dropped, the flame encountered unwetted tank surface and the temperature of the this portion of the tank shell quickly rose to approximately 650° C. Thermally induced internal pressure acted on the weakened tank, causing it to burst and resulting in a Boiling Liquid Expanding Vapor Explosion or "BLEVE". Studies on the effectiveness of insulating LPG cars to protect them from external heat sources were undertaken. Tests showed that an LPG tank car engulfed in a pool fire would rupture in about seven minutes after unwetted surfaces of the tank were exposed. Testing also determined that in a fire, a typical LPG car could vent its entire contents through its pressure relief valve in about 45 minutes. Thus, if the tank could be sufficiently insulated to prevent it from reaching critical temperature in the 45 minutes it took to completely vent the car, the tank would not rupture violently. As a result, thermal protection standards were developed for tank cars transporting LPG and similar volatile materials, under both pool fire and torch fire conditions.

2.4 Tank Car Bottom Outlet Protection

Tank car bottom outlet valves used for gravity unloading of liquids are vulnerable to damage in derailments. The RPI-AAR Tank Car Safety Project undertook a series of tests to evaluate the effectiveness of systems to protect these valves. The tank car companies designed protective skids and applied them to their tank cars. The design of the protective systems varied, but in each case the bottom outlet valve was protected within the profile of the applied skid. Thus, if a car was grounded in a derailment, the outlet leg (which is below the valve and the bottom of the skid) might be broken off at its shear groove, but the valve itself would remain intact and sealed.

These skid designs were tested and evaluated using a special ram and test arrangement (Figure 2). An impacting anvil was located at one end of the ram immediately adjacent to the skid. The ram was struck at the far end by a loaded hopper car causing the anvil to impact the skid. In most tests the skids protected the bottom outlet valve from damage and leakage.

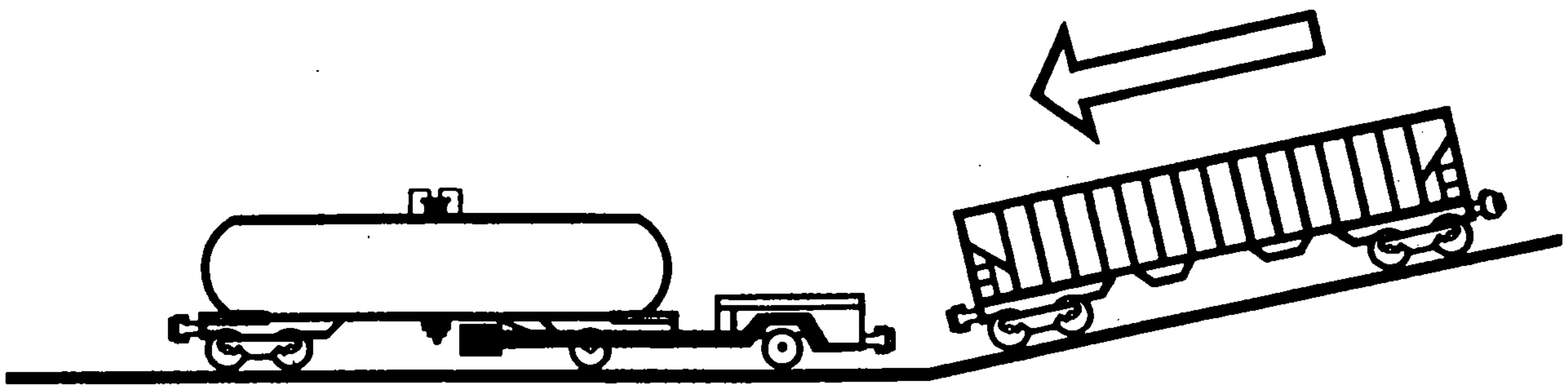

Figure 2. Tank car bottom outlet protection testing

3 Statistical Analyses of Tank Car Safety

Over the 28 years since the RPI-AAR project's formation, data on over 36,000 tank cars damaged in accidents have been collected. This database includes extensive information about the conditions of the accident, as well as detailed data on the nature and severity of the damage to the tank cars involved. The testing described in the preceding sections provided evidence that the design changes would be effective in reducing losses from tank cars in accidents, but they did not allow quantification of their degree of effectiveness under actual service conditions. Consequently, after tank cars with the enhancements described had been in service for a number of years, statistical analyses of their performance in accidents were conducted.

One such analysis showed that half-height head shields have reduced the likelihood of head puncture on the type of tank car that transports LPG by approximately 68%, and that full-height head shields result in a reduction of 81% (Phillips et al. 1995). Another analysis showed that bottom outlet protection reduces the likelihood of losing lading through a damaged bottom outlet by 55%, and that even if there is a release, the expected quantity lost is 42% lower than for unprotected bottom fittings (Griger & Phillips 1992). These types of results are important for a variety of reasons including: understanding the adequacy of the changes made, the justification for further investment in changes, and for risk management decisions. For these reasons the statistical element of the RPI-AAR Tank Car Safety Project's activities has proved to have lasting value. Development of the database is ongoing, and provides an up-to-date source of reliable information on the accident performance of North American railroad tank cars.

3.1 Safety and risk analysis of hazardous materials transportation

Over the 16-year period 1982 through 1997 the rate of accident-caused release of hazardous materials shipped by rail in the United States has been reduced by an order of magnitude (Figure 3). This impressive accomplishment has been achieved by prevention of derailments through improved design and maintenance of track and vehicles, and through enhancements in tank car design and components that make them more resistant to damage in the event that they are involved in an accident (Phillips & Role 1989). Analyses of the RPI-AAR Tank Car Safety Project database have helped to document and understand why these improvements have been effective and provided justification for the investments in enhanced safety features.

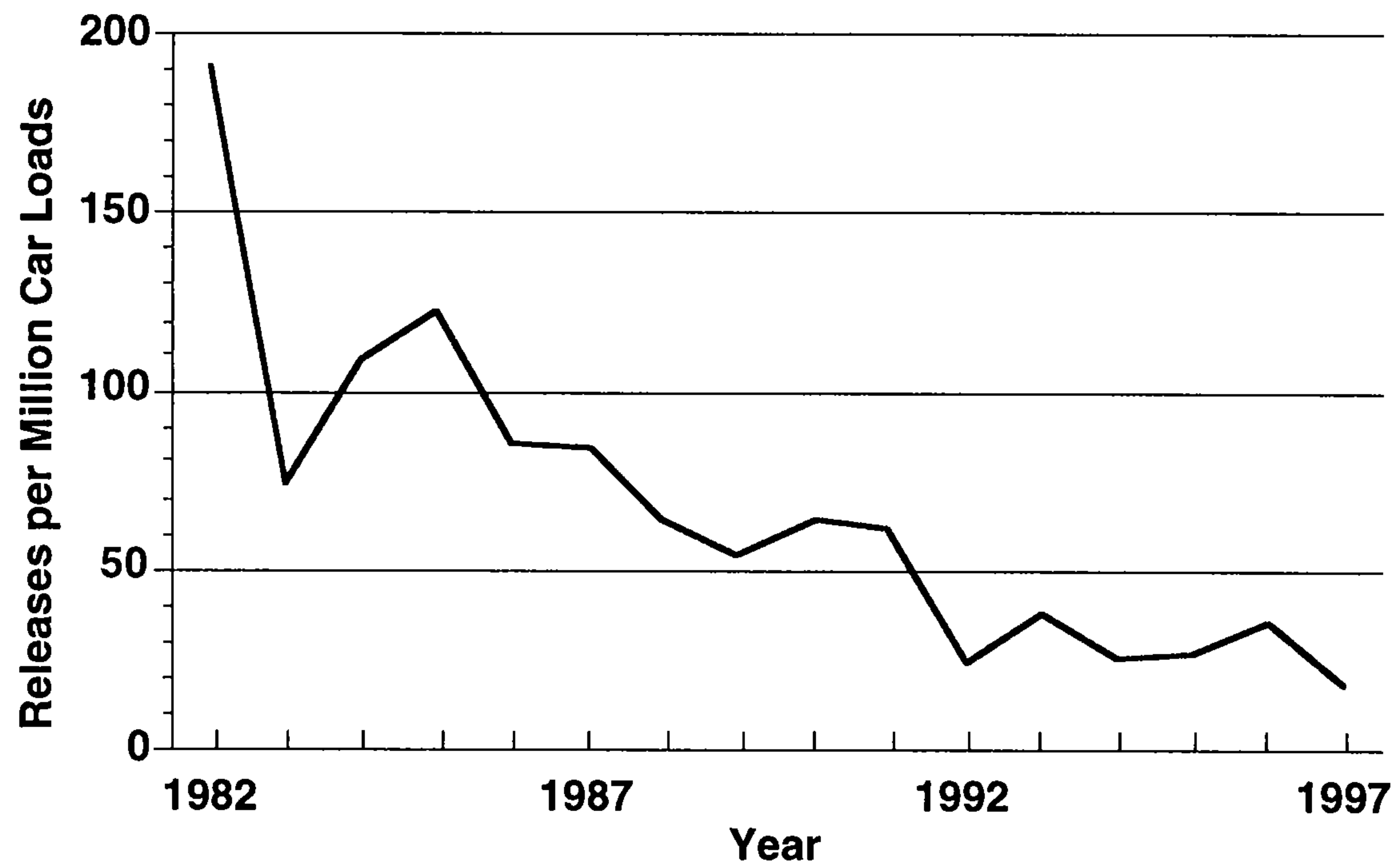

Figure 3. Accident-caused releases per carload of hazardous materials: 1982-1997

However, this improvement in safety has made the job of the risk manager more difficult. Although the safety of railroad transportation of hazardous materials in North America has never been better, a serious accident is still possible. The risk manager at a railroad, tank car or chemical company is faced with the task of trying to understand what circumstances can lead to such an accident. Because these accidents are so infrequent it is not obvious what the most effective steps to enhance safety will be. The difficulty in answering these types of questions has led to new uses for the data. Here again cooperation between railroads and tank car companies enables a better understanding of when and how to most cost-effectively improve safety.

The likelihood that a tank car might suffer a release in an accident can be combined with probability estimates of train accidents to develop a statistical estimate of the overall likelihood of a release accident. Such information is useful to chemical shippers, railroads and tank car companies who can use this information to manage the risk of hazardous materials transportation in a more informed manner (Barkan et al.

1992, Burke 1999, O'Toole 1999). Such analyses are useful at two different levels. At the macro level, such analyses enable management to determine the risk associated with various business activities and whether such risk is prudent or tolerable. At a micro level, the underlying details of the analysis can help the risk manager understand which steps may be the most effective in reducing the risk. These may include changes in tank car design, railroad maintenance or operating practices, or chemical distribution practices.

Phillips et al. (1995) developed estimates of the conditional probability that different specification tank cars will release lading if they are derailed in an accident (Table 1). The data also enable the development of probability distributions of the percentage of a tank's capacity that will be lost. Federal regulations specify the types of tank car permissible for each type of hazardous material, with requirements that the most hazardous products be transported in the tank cars least likely to release in accidents. However, chemical manufacturers are interested in understanding the risk associated with their shipments and the benefit that might be achieved through use of tank cars that exceed the minimum requirements. Taken in their proper context, data such as these can help shippers make better-informed decisions about the packaging for their products (Burke 1999) and provide reliable statistics for industry and government as they move toward a more performance-based approach to regulation of safety.

Table 1. Estimated Conditional Probability of Release for Tank Cars in Accidents

Tank Car Type (1)	Conditional Probability of Release in an Accident (2)	Percentage of Tank Capacity Released		
		1 - 5%	>5 - 80%	>80 - 100%
1) 111A100W1	0.341	0.116	0.099	0.126
2) 111A100W3 (3)	0.290	0.099	0.084	0.107
3) 105A300W	0.098	0.035	0.013	0.050
4) 112J340W (4)	0.086	0.031	0.011	0.044
5) 105A500W	0.038	0.014	0.005	0.019

(1) Tank cars 1 & 2 are for non-pressurized liquids and are assumed to have a bottom outlet, cars 3 - 5 are for liquefied, pressurized gases.

(2) From Phillips et al. 1995 for tank cars in mainline accidents. In this context these statistics are primarily useful for relative comparisons rather than absolute probabilities.

(3) Same as preceding car except it is insulated and has a steel jacket.

(4) With half-height head shield.

The detailed nature of the database and its resultant capability to support such fine-grained assessment of the tank car and its components, is one of its greatest strengths. In addition to understanding the overall performance of various types of tank car, the database enables one to compute the probability of a release from a particular part of the tank car, and the average percentage of the tank's capacity lost due to damage to each (Phillips et al. 1995, Treichel 1996). The tank car can thus be "statistically" disassembled and each of its components evaluated to understand how much it contributes to the overall likelihood of release in an accident. Taken together these data can be used to develop quantitative estimates of how much benefit will be achieved from modifications to various aspects of a tank car's design.

3.2 Application of Tank Car and Railroad Accident Statistics for Safety Analysis

It is beyond the scope of this paper to present a complete mathematical development of the process for using these types of statistics for risk analysis purposes. However, a recent analysis for a North American railroad provides an example of their utility when combined with statistics on the probability of derailment. The results indicate that the probability that a typical tank car of anhydrous ammonia (a commonly used agricultural chemical) would derail and release at a typical location along a railroad mainline was 1.09×10^{-8} (0.0000000109). Furthermore, in many accidents even if there is a release, less than 5% of the tank car's lading is actually lost (Table 1). Thus the probability of a release greater than 5% is even lower (6.99×10^{-9} or 0.00000000699). Even when the total annual traffic of almost 1,000 carloads at the particular location was taken into account, the probability of a release is minimal.

4. Conclusion

The estimate in the preceding paragraph indicates the exceptional safety of railroad transportation of hazardous materials in North America. Yet, it is not really surprising when one considers that in 1997 over one million loaded tank cars of hazardous materials were transported in the United States an average distance of 1,395 km each. Of these, only 38 cars (not all of them tank cars) released lading in accidents (FRA 1998). The cooperative research of the RPI-AAR Tank Car Safety Project has had a great deal to do with achieving this impressive safety record. By pooling technical expertise, resources, data, and research funds, the railroad and tank car industries have developed a solid basis of knowledge upon which to design safe and efficient tank cars. As the industry enters the next century and moves from 100 to 110 ton capacity tank cars, the RPI-AAR Tank Car Safety Project will continue to be an important resource for further improvements in the safe, economical transportation of hazardous materials in North America.

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