Environmental Risk Analysis of Chemicals Transported in Railroad Tank Cars

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Summary: This study assesses the risk to soil and groundwater in the event of a spill of hazardous materials transported in railroad tank cars. Tank cars are designed to be resistant to damage in accidents to reduce the probability of a spill. For safety and economic reasons, the damage-resistant design of tank cars is commensurate with the degree of hazard posed by the product they are intended to transport. The second objective of the research was to analyse the cost-effectiveness of replacing current tank cars used for the chemicals under consideration with more robust tank car alternatives.

Index Terms: hazardous material, transportation risk, environmental impact, cost-benefit analysis, tank car, chemical spill.

Each year a large volume of hazardous materials is transported by rail in the United States. Although hazardous materials are shipped in various kinds of rail cars e.g. tank cars, covered hoppers, boxcars, intermodal equipment etc., tank cars carry the major portion of the traffic. The safety of rail transportation of hazardous materials has improved dramatically over the past two decades, firstly, due to the decline in the US railroad mainline accident rate [1] and secondly due to improvements in the safety design of tank cars used to transport hazardous materials, including changes in the packaging regulations for certain hazardous chemicals being transported in tank cars.

Until the 1980s hazardous material transportation risk was considered primarily in terms of the danger posed to human health and property damage. In the 1980s tank car spills of a group of chemicals referred to as "environmentally sensitive chemicals" were responsible for a series of expensive environmental clean ups. Many of these chemicals were suspected carcinogens. Furthermore because of their physical and chemical properties they were particularly difficult to remove from soil and groundwater. A study conducted by Association of American Railroads (AAR) [2] found that much of the risk was due to a limited group of halogenated hydrocarbons and that when the overall costs were accounted for, the extra expense of using a more robust tank car for these products was more than offset by the reduced environmental liability. As a result an agreement was reached between the chemical and railroad industries that the old cars would be phased out and new more robust cars used for these chemicals. These changes were later promulgated as regulations by the US Department of Transportation (DOT) in 1995 and marked the expanded focus with respect to railroad accident risks [3].

The AAR research raised a question as to whether other hazardous materials that were still permitted to be shipped in the minimum specification, non-pressure, 111 tank car were also a potential source of high environmental risk. Several accidents in the late 1990s led to renewed interest in the topic. We conducted research investigating the risk to soil and groundwater due to rail transport of the most common hazardous materials authorized for shipment in non-pressure specification cars in the U.S. The analysis also considers the cost-effectiveness of using more robust tank car specifications in place of the ones currently used.

METHODOLOGY

Risk is calculated as the product of probability of an event occurring and its consequence (Equation 1).

$$R = P \times C \qquad (1)$$

where,

R = Risk from an event
P = Probability of occurrence of the event
C = Consequence of the event

In the context of hazardous material transportation risk, we are interested in the probability of an accident resulting in a release of a hazardous material, and the consequence of that release. The consequence of a hazardous materials release can be measured in a number of ways but in the context of this study, we were primarily interested in the consequences as measured by the cost to clean up the spilled chemical as expressed in Equation 2.

$$R_c = FP_cC_c \qquad (2)$$

where,

R_c = Risk of a release in "$ per car-mile", for a commodity 'c'

F = Railcar derailment rate per car-mile (initiating event)

P_c = Probability of release of the group of tank cars used to transport commodity 'c'

C_c = Expected clean up cost for commodity 'c' in $

Chemicals for Consideration

The group of chemicals considered in this study was drawn from the 125 most commonly shipped hazardous materials that were authorized for shipment in non-pressure specification tank cars (Table 1). A large percentage of the carloads of these materials are transported in non-pressure specification cars, and more than 50% of them are transported in the most commonly used tank car, the 111A100W1 (Figure 1).

Table 1 59 Commodities Authorized for Transport in Non Pressure Tank Cars

Acetaldehyde
Acetic Acid, Glacial
Acetic Anhydride
Acetone
Acrylonitrile, Inhibited
Acrylic Acid, Inhibited
Alcoholic Beverages
Ammonium Nitrate, Liquid
Benzene
Butanols
Butyl Acrylates, Inhibited
Combustible Liquid, N.O.S.
Compounds, Cleaning Liquid
Cyclohexane
Denatured Alcohol
Diesel Fuel
Elevated Temperatures Liquid, Flammable, N.O.S.
Elevated Temperatures Liquid, N.O.S.
Environmentally Hazardous Substances, Liquid, N.O.S.
Ethanol
Ethyl Acetate
Ethyl Acrylate, Inhibited
Ferric Chloride, Solution
Ferrous Chloride, Solution
Flammable Liquids N.O.S.
Formaldehyde, Solutions
Fuel Oil
Fuel, Aviation, Turbine Engine
Gasoline
Hexamethylenediamine, Solid
Hydrocarbons, Liquid, N.O.S.
Hydrochloric Acid
Hydrogen Peroxide, Stabilized
Isopropanol
Kerosene
Maleic Anhydride
Methanol
Methyl Methacrylate Monomer, Inhibited
Methyl Tert Butyl Ether
Nitric Acid
Other Regulated Substances, Liquid
Other Regulated Substances, N.O.S.
Petroleum Crude Oil
Petroleum Distillates, N.O.S.
Phenol, Molten
Phosphoric Acid
Phosphorus, White, Dry
Potassium Hydroxide, Solution
Propylene Oxide
Sodium Chlorate, Aqueous Solution
Sodium Hydroxide Solution
Styrene Monomer, Inhibited
Sulfur Molten
Sulfuric Acid
Sulfuric Acid, Spent
Toluene
Toluene Diisocyanate
Vinyl Acetate, Inhibited
Xylenes

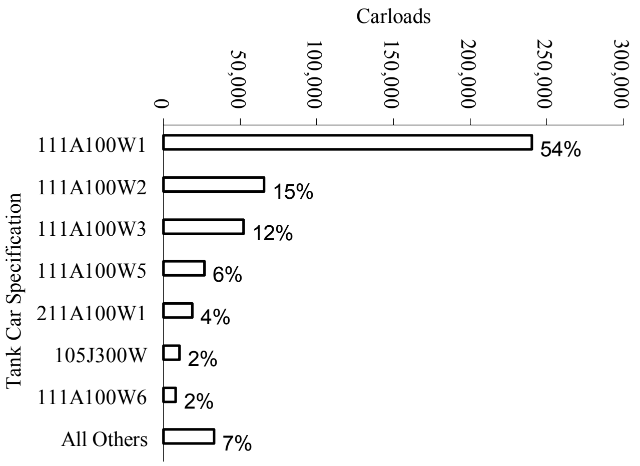

Figure 1 Annual Number of Carloads Transported by Top Ten Tank Car Specifications for Products of Interest

PROBABILITY ANALYSIS

Train accident rate or accident frequency is a key parameter in determining the risk associated with transport of hazardous material by rail. Basic train accident rate statistics can be calculated using Federal Railroad Administration (FRA) data. FRA and AAR statistics for the interval 1992-2001 were used to compute an industry average, per-car-mile derailment rate statistic [4]. This rate is 0.000000126 derailments per car, per mile, or one derailment for every 7,911,198 miles traveled.

The second important parameter for probability analysis is the probability of release from a tank car that has been derailed in accidents. Tank car classes differ in their damage resistance. Consequently the conditional probability of release depends on the class of the derailed tank car. Different chemicals are transported in different tank car classes; therefore, the conditional probability of release varies from one chemical to another. Therefore, an analysis on a chemical-by-chemical basis is necessary. Another aspect in release probability calculation is that, in general, more than one type of tank car class is used to transport a chemical. Data from the RSI-AAR Railroad Tank Car Safety Research and Test Project [5, 6] were used to estimate the conditional release probability of tank cars (Table 2) used for the products listed in Table 1. A merge of the AAR Universal Machine Language Equipment Register (UMLER) database and AAR TeleRail Automated Information Network (TRAIN II) database was used to obtain information on traffic volume for all materials. However, only the tank car carrying the maximum carloads was used for all the chemicals. For all the chemicals transported in carbon steel cars 111A100W1 is the most commonly used car except for sulfuric acid for which the maximum carloads were transported in 111A100W2.

Table 2 Conditional Release Probabilities, given Derailment for Tank Cars used for Products of Interest

Car Class	Release Probability of a Derailed Tank Car	Car Class	Release Probability of a Derailed Tank Car
105A100W	11.44	111A100W6 - NI	10.45
105J100W -1/2 HS	9.17	111J100W3 -1/2 HS	26.67
105A300W	9.80	111A100ALW2 - NI	51.26
105J300W- 1/2 HS	8.26	111A60W7	10.05
105A500W	3.82	111A60ALW1 - NI	53.08
105J500W - 1/2 HS	3.16	111A60ALW2 - NI	51.26
111A100W1 – NI	34.07	111S60ALW1 – NI	53.08
111A100W2 – NI	32.32	111S60ALW2 – NI	51.26
111A100W3	28.99	114A340W - NI	14.24
111A100W5 - NI	32.32	211A100W1 - NI	34.07

CONSEQUENCE ANALYSIS

The extent of contamination of the environment following a hazardous material spill depends on the properties of the chemical spilled as well as the environmental characteristics of the spill site.

Chemical Characteristics

Different chemicals interact differently with the environment because of differences in their physical and chemical properties e.g. toxicity, mobility, recalcitrance etc. There was little or no spill history for many of the chemicals under consideration. For those that had been spilled, the differences in environmental features at one site compared to another meant that generalization of the restoration costs was not possible. Therefore something more than a strictly empirical approach was needed. We needed a modeling process that could simulate a hazardous material spill of any chemical in a variety of prescribed environmental conditions.

The AAR Quantitative Risk Assessment Environmental Module (QRAEM) was used for the environmental consequence modeling. The model allows the user to specify the chemical, the soil type and the groundwater depth for simulating the spill. Therefore, before carrying out the simulations we needed to generate a set of environmental scenarios consisting of soil-type groundwater-depth combinations occurring over the contiguous U.S.

Environmental Characteristics

Rail lines traverse a variety of different terrains. The extent of damage caused to the environment in the event of a chemical spill varies from one environmental scenario to another due to their varying susceptibilities to the same chemical. The efficiency of site remediation methods also depends on the characteristics of the site. Thus the location of a spill is a key variable in the analysis of the environmental risk. Soil type and groundwater depth are the two parameters considered to be the most important environmental attributes affecting cleanup cost.

We used a comprehensive geographic information system (GIS) based database on the soil characteristics called State Soil Geographic Database (STATSGO) for each of the 48 contiguous states [7]. We characterized the soil into three categories, sand, silt, and clay based on the relevant parameters for each and developed a soil map for the contiguous United States (Figure 2).

We conducted an overlay analysis using the GIS data for soil type and rail lines. This allowed us to quantify the distribution of soil types over which the rail network is located (Table 3).

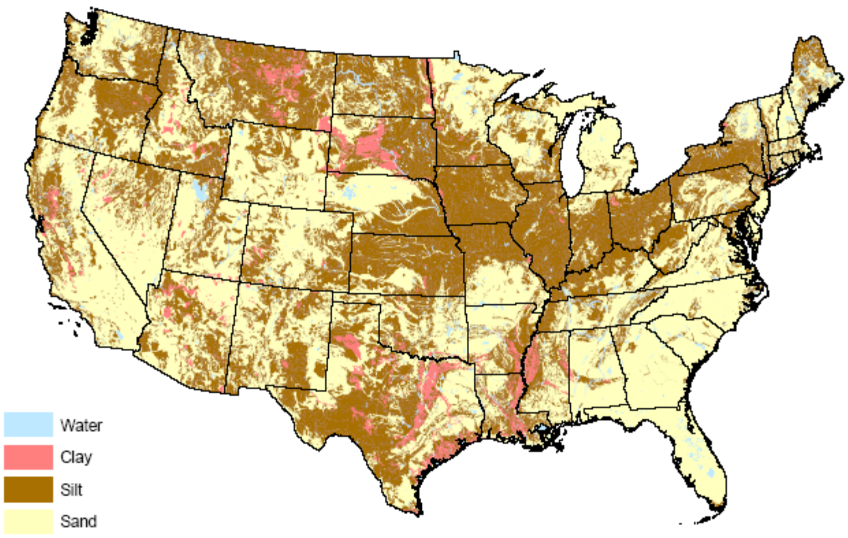

Figure 2 Surface Soil Types in the United States

Table 3 Probability of Occurrence of Three Soil Types near Rail Lines

Soil Type 's'	Length of Railroad on soil type 's' *(miles)* L_k	Probability of occurrence of a soil type P_k
Clay	6,781	0.035
Silt	100,585	0.528
Sand	81,500	0.428
Water	1,359	0.007

Unfortunately, there is no satisfactory GIS database for depth to groundwater comparable to the soil type data. Consequently, we used information from a US Geological Survey database [8] that provides real-time data for groundwater monitoring wells located in the US to develop information on the distribution of depths to groundwater (Table 4).

Table 4 Distribution of Groundwater Depths

Groundwater Depth Range (feet) 'g'	Probability of Occurrence of a GW Depth Range P_j
>5 to ≤15	0.1902
>15 to ≤25	0.1542
>25 to ≤75	0.2776
>75 to ≤125	0.1028
>125	0.2751

Using these two sources of environmental data, we generated a probabilistic matrix of three soil types and five groundwater depths, for a set of fifteen scenarios over which the simulations were conducted using the QRAEMdiscussed above. It should be noted that the model could be run successfully only for 27 of the 59 hazardous materials due to incomplete data for some chemicals. Complete analysis could be conducted on only 24 chemicals for reasons discussed below.

Risk Calculation

Assuming that soil type and groundwater depth are independent of each other, the expected cost of clean up for each chemical was calculated using Equation 3.

$$C_c = \sum_{j=1}^{g} \sum_{k=1}^{s} P_j P_k C_{cjk} \qquad (3)$$

where,

C_c = Expected value of clean up of a spill for chemical 'c' ($)

g = Number of types of groundwater regions considered

s = Number of types of soils considered

P_j = Probability of occurrence of a groundwater region 'g' at a spill location

P_k = Probability of occurrence of soil type 's' at a spill location

C_{cjk} = Average cost of clean up of a spill on groundwater region 'g' and soil type 's' for chemical 'c', obtained from the QRAEM simulations ($)

Having obtained all the parameters, the risk per car-mile could be calculated for each chemical using Equation 2. Annual risk for all the chemicals was calculated by multiplying the risk per car-mile by the annual car-mile data for each chemical. The annual car-mile data were developed by obtaining the information on the annual number of shipments from AAR TRAIN II database and average shipment distance from US Surface Transportation Board (STB) waybill sample for each chemical. The annual number of shipments, average shipment distance and annual car-mile data are tabulated for the 24 chemicals in Table 5. The expected clean up cost, risk per car-mile and annual risk are tabulated in Table 6.

Table 5 Average Shipment Distance, Carload and Car-mile Data for Products of Interest

Chemical	Average Shipment Distance (car-miles per car)	Annual Carloads	Annual Car-miles
A	1,047	1,735	1,817,008
B	986	457	450,516
C	896	4,200	3,763,534
D	1,059	740	783,463
E	569	3,163	1,799,349
F	374	2,940	1,099,251
G	1,103	2,138	2,358,120
H	1,368	4,179	5,716,993
I	434	4,439	1,927,121
J	939	4,062	3,812,718
K	1,186	1,422	1,685,813
L	1,326	1,490	1,976,449
M	938	2,364	2,216,964
N	763	27,194	20,741,476
O	1,121	2,418	2,710,194
P	1,706	7,479	12,756,182
Q	575	11,496	6,610,315
R	717	4,854	3,480,267
S	560	80,503	45,062,338
T	1,230	18,244	22,448,144
U	573	65,595	37,597,318
V	860	3,132	2,693,760
W	1,301	6,236	8,115,576
X	606	5,323	3,223,650

Table 6 Conditional Release Probability, Expected Clean up Cost, Risk per car-mile, Annual Risk Data for Products of Interest

Chemical	Expected Clean up Cost ($) C_c	Risk of a Major Clean-up ($ per car-mile)	Annual Risk of a Major Clean-up ($)
A	7,681,086	0.1852	240,558
B	5,994,267	0.1446	65,127
C	8,389,792	0.2023	761,491
D	6,469,324	0.1560	122,235
E	8,547,617	0.2061	163,823
F	9,995,480	0.2411	235,150
G	7,369,142	0.1777	419,084
H	6,404,303	0.1545	443,926
I	5,402,908	0.1303	251,104
J	6,331,707	0.1527	582,202
K	8,565,875	0.2066	348,256
L	9,844,603	0.2374	301,074
M	6,066,440	0.1463	324,347
N	7,394,838	0.1783	3,699,016
O	7,624,777	0.1839	498,363
P	2,885,746	0.0696	887,762
Q	4,801,821	0.1158	510,934
R	2,017,976	0.0487	127,153
S	1,882,066	0.0454	1,571,097
T	10,314,995	0.2488	5,185,142
U	1,724,155	0.0394	1,483,031
V	9,309,515	0.2245	604,789
W	7,070,101	0.1705	1,383,767
X	9,688,601	0.2337	534,463

RISK REDUCTION OPTIONS

The second objective of the research was to assess the extent to which risk could be reduced by using tank car specifications different from the currently used specifications. The alternatives were either to equip the currently used cars with risk reduction features like top fittings, head shields, jacket etc. or to use different tank car specifications with more damage resistant features. For example a 105 specification tank car has tanks ranging in thickness from 1/2" to nearly 1" thickness made of normalized TC-128 steel, an additional 1/8" thick steel jacket, no bottom fittings and top fittings housed within a steel bonnet made of 3/4" steel. This is in contrast to the 111 specification tank car that typically has a 7/16" tank shell and head made of A-516 steel and no extra protection of top fittings. We analyzed the following enhancements to the current car:

1. Top Fittings Protection
2. Half/Full Height Head Shield
3. Jacket

Among tank car specifications, we analyzed the 105A300W and 105A500W consistent with the previous AAR research on ESCs [2]. Apart from these specifications one other important alternative we considered was an enhanced safety 111 car with Gross Rail Load (GRL) equal to 286,000 lbs (286K). All the other tank car specifications in this analysis have a GRL of 263,000 lbs (263K). GRL is defined as the total weight of the tank car and its lading. As a result, the enhanced safety 286K 111 car actually provides the benefit of greater capacity as well as improved safety performance. The risk reduction options for this car are as follows:

1. Top Fittings Protection
2. Half Height Head Shields
3. 1/2" Thick TC-128 Steel Tank

COST BENEFIT ANALYSIS

Net Present Value Calculation

Determination of the cost-effectiveness of replacing tank cars used for transportation of potential ESCs requires a net present value (NPV) approach. This is because the benefit stream extends far into the future and the NPV provides a better basis for decision-making than a simple payback period. The future benefits and costs must be discounted so that they are consistently valued throughout the analysis. This is primarily due to the effects of inflation and to some degree other sources of uncertainty regarding the actual value of future benefits. It was assumed that a tank car has a life span of 30 years. The NPV was calculated based on the general formula as given by Equation 4.

$$\mathrm{NPV} = \sum_{i=1}^{Y} \frac{B_i - C_i}{(1+d)^i} \qquad (4)$$

where,
Y = time span over which NPV is calculated (= 30 years),
B*i* = benefit from enhanced tank car in year *i*,
C*i* = extra cost of enhanced tank car in year *i*,
d = discount rate (= 16%).

It should be noted that the discount rate of 16% is conservatively high. It assumes that the investment in safer tank cars is being considered in a manner comparable to any other business investment. However, investments for safety or environmental protection purposes are often considered using a lower discount rate. This will have the effect of increasing the NPV.

Benefit Estimation

Benefit is estimated as the reduction in risk due to replacement or retrofitting of the current tank car types. The reduction in risk is calculated by determining the difference in release probability between the current car and the proposed car. This translates directly to a reduction in expected cost due to a spill of the particular chemical being transported and further on to a reduction in the risk per car-mile reduction. Therefore, reduction in clean up cost risk is calculated as the benefit achieved as a result of replacement. The difference in conditional release probability of tank cars and also those of the individual enhancements was calculated using Phillips et al [6] that has data for carbon steel cars. Comparable data are not available for alloy or aluminum tank cars and therefore, among the 27 chemicals, further analysis could not be carried out for acetic acid, hydrogen peroxide and nitric acid that are transported in such tank cars.

Cost Estimation

Tank car replacement incurs capital cost and changes in operating cost. There is capital cost involved in making any modification to the tank car or buying a new tank car. More damage resistant designs generally add to the cost of the car as well as its weight. The maximum GRL of railcars is limited by AAR, and in the case of hazardous materials tank cars, by DOT regulations as well. Consequently the lading capacity of the tank car is reduced as a result of any increase in the car's light weight. This means that more shipments, and possibly more cars are required to carry the same quantity of chemical. As a consequence the operating cost and generally the capital cost of transporting the chemical increases.

Replacement Schedule

The time frame over which the current fleet of tank cars is replaced and the manner of replacement is important for the cost-benefit analysis. Depending on the degree of risk posed by the chemical, three plausible scenarios were considered as follows: a chemical could be so hazardous to the environment that immediate upgrade to an enhanced car is warranted thereby implying immediate replacement, a chemical might pose so little risk that no change to the current fleet is justified, or, there could be chemicals that pose a risk somewhere in between these two extremes such that a slower continuous replacement of the fleet would be appropriate. Three replacement schedules were considered for this analysis, as follows:

1. Attrition Based Replacement – Each year 1/30th of the cars would be retrofitted or replaced. Capital costs, additional operating costs and benefits would all accrue proportionally over the 30-year period.
2. Immediate Replacement - All cars would be replaced or retrofitted in the first year. Capital cost, increase in operating cost and full benefits would accrue immediately.
3. Ten-year Retrofit/Replacement – Each year 1/10th of the cars would be retrofitted or replaced. Capital costs, additional operating costs and benefits would all accrue proportionally over the ten-year period after which full benefits and ongoing operating costs would be realized.

Results

All the alternatives led to risk reduction compared to the current scenario for all the chemicals, however, none were cost effective using the immediate replacement schedule or the 10-year retrofit/replacement schedule. This is because the reduction in expected clean up cost of the chemical is not large enough to compensate for the extra capital and operating costs incurred due to replacement.

For the attrition-based replacement schedule neither of 105A300W or 105A500W or the individual enhancements were cost effective. Only enhanced safety 286K 111 tank car yielded a positive NPV with this schedule because there is no capacity penalty paid with this car. In fact it leads to an increase in capacity and hence a reduction in the operating cost. Nineteen of the twenty four chemicals showed a positive net present value (Figure 3).

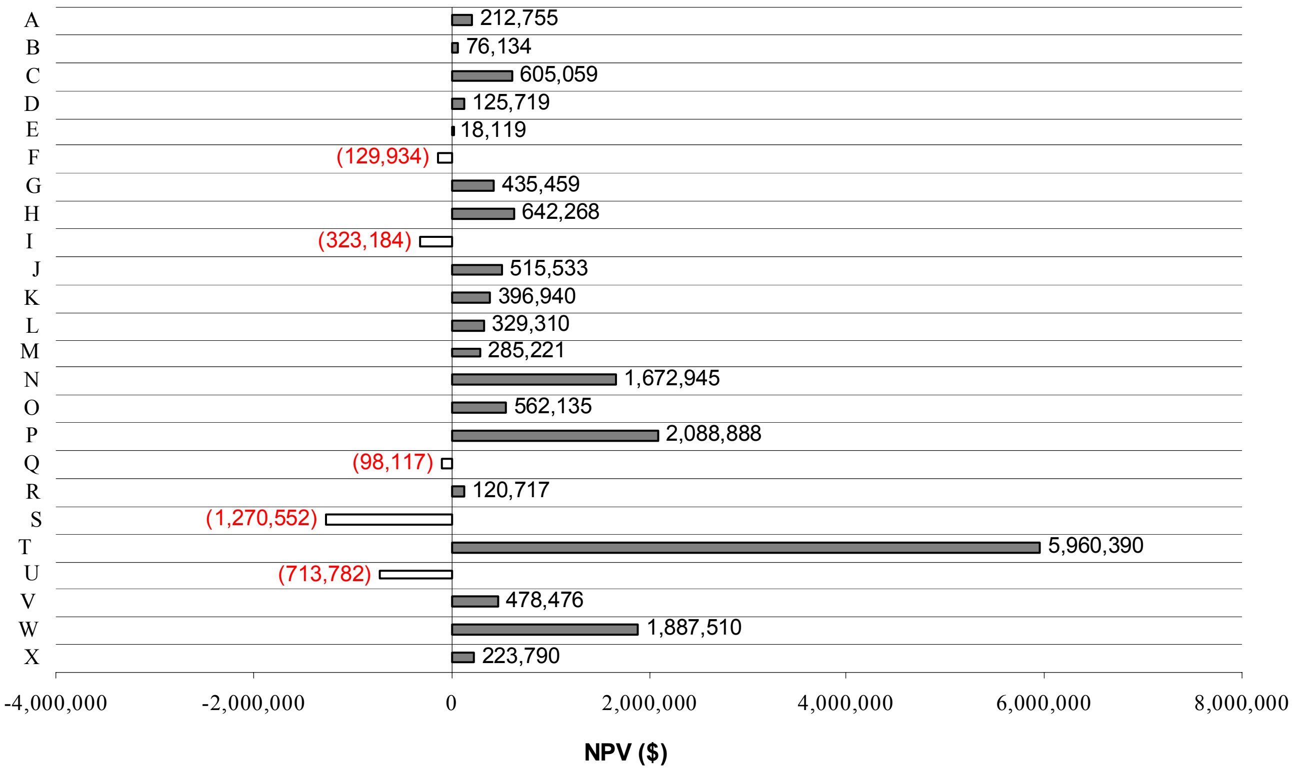

Figure 3 Net Present Value for Products of Interest using Attrition based Replacement Schedule with 286K Enhanced Safety 111 Car

CONCLUSIONS

The research determined that the estimated annual clean up risk associated with the chemicals under consideration ranged from $1.7 to 9.7 million dollars and the cost risk per car-mile ranged from 4 to 23 cents. Cost risk per carload is a useful indicator of the liability incurred by railroads while transporting these products. The cost benefit analysis shows that the enhanced safety 286K 111 is a feasible alternative for 19 of the 24 chemicals.

As discussed above, use of a lower discount rate would increase the NPV and might increase the number of chemicals with a positive NPV. Additionally, the capital cost could be reduced if cars were used more efficiently, further improving the NPV [2]. Finally the benefits presented here are conservative in that they only consider the reduced risk to soil and groundwater. In fact costs due to a number of other sources of risk would also be reduced, further enhancing the NPV. In conclusion the results presented here indicate that the majority of the chemicals considered here could be cost-effectively transported in the enhanced safety 286K car and environmental liability of railroads would be reduced.

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