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Tank Car Safety Design Optimization to Reduce Hazardous Materials Transportation Risk

M. Rapik Saat, Ph.D.

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Outline

- Overview of hazardous materials transport risk by rail

- Background on vehicle structural design optimization & railroad hazardous material transportation

- A Two-Phase Tank Car Safety Design Optimization Process

  - Generalized Bicriteria Model for Optimizing Railroad Tank Car Safety Design

  - Risk-Based Tank Car Safety Design Optimization Model

- Application of tank car safety design optimization to reduce the environmental risk

- Future research

- Summary

Influence diagram showing relationships of factors affecting hazardous materials transportation safety

Legend:
- Decision Node
- Uncertainty Node
- Deterministic Node
- Value/Objective Node
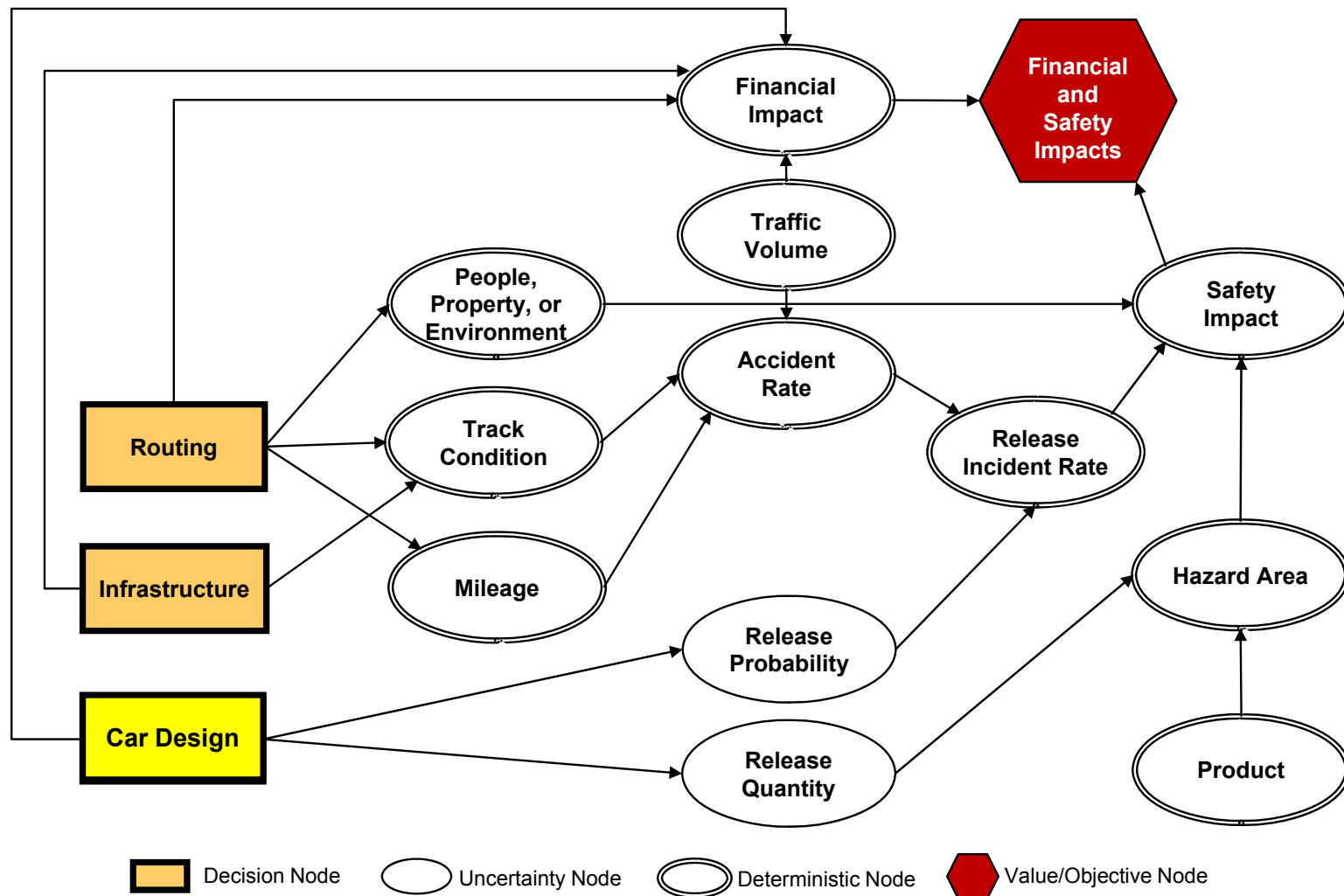
Structural optimization in vehicle design

- Vehicle structural designs are subject to both performance requirements and cost constraints

- For aircraft and most other aerospace systems, conceptual design optimization has typically been based on achieving efficient aerodynamics while minimizing weight configuration subject to structural requirements

- With regard to automotive design, crashworthiness criteria to maximize vehicle structural integrity for occupant safety in the event of a crash has been considered together with the objectives to minimize noise, vibration, harshness (NVH), and weight or other cost constraints

Tank car weight vs. capacity tradeoff

Maximum Gross Rail Load (GRL) = Lading Capacity + Light (Empty Weight)

Sulfuric Acid

Density = 14.26 lbs./gallon
ca. 13,000 gallon tank

Alcohol

Density = 6.58 lbs./gallon
ca. 29,000 gallon tank

- Tank cars can be made safer by increasing tank thickness and adding various protective features, but these increase the weight and cost of the car and reduce its capacity and consequent transportation efficiency

- Formal consideration of this tradeoff between tank car safety and transportation efficiency, and use of optimization techniques to address this tradeoff represent the first phase involved in tank car safety design optimization

Railroad hazardous materials transportation
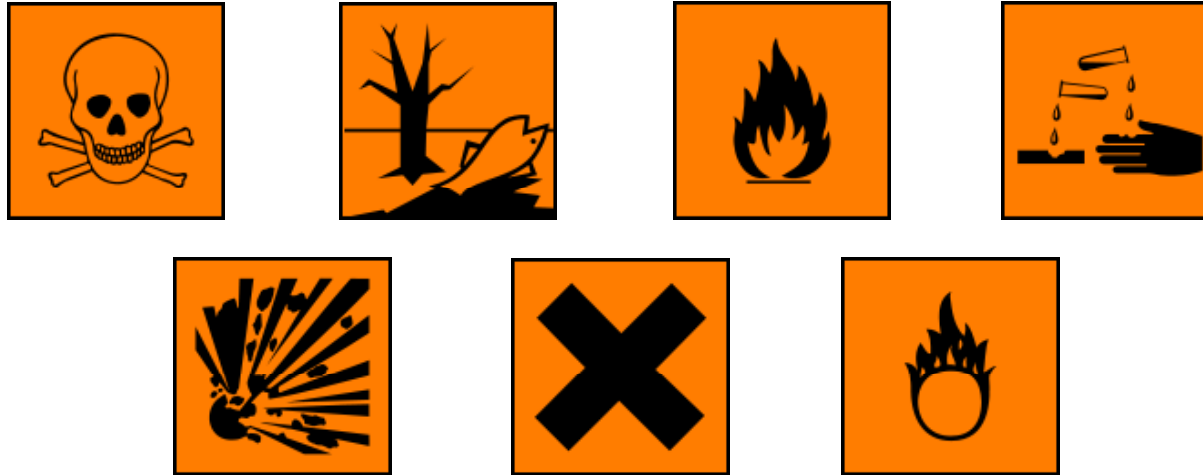
- More than 70% of about 2 million annual rail shipments of hazardous materials in the U.S. & Canada are transported in tank cars

- Actual hazard posed by these materials varies widely in terms of both the nature and magnitude of the hazard

- In order to allocate safety enhancement resources in the most efficient manner possible requires quantitative understanding of the consequent risks and benefits

- The second phase of the tank car safety design optimization model addresses chemical-specific hazard and its consequent risks and benefits

Tank car safety design optimization model

- Phase 1: A Generalized Bicriteria Model for Optimizing Railroad Tank Car Safety Design

  - Addresses the tradeoff between safety and transportation efficiency

- Phase 2: Risk-Based Tank Car Safety Design Optimization

  - Accounts for chemical-specific hazard levels and the consequent benefits and costs

A generalized bicriteria model for optimizing railroad tank car safety design

- To identify a Pareto-optimal set of tank car designs, based on the tradeoff between safety and transportation efficiency

  - Consideration of Risk Reduction Options (RROs)

    - tank car safety design features

  - Use of a statistical model to estimate tank car safety performance

  - Development of a tank car weight & capacity model

  - Enumeration of tank car weight and safety performance metric

  - Identification of a set of Pareto-optimal solutions

Tank car risk reduction options (RROs)
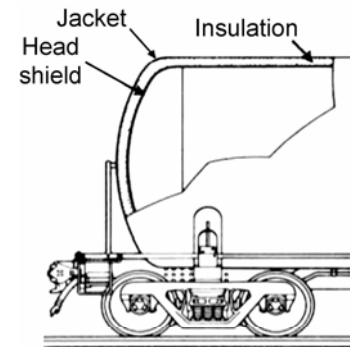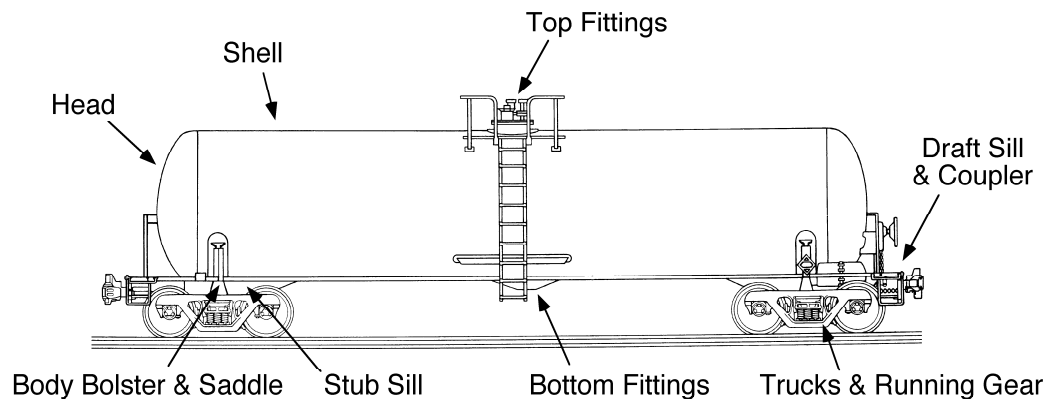
- Principal approaches considered to enhance tank car safety design:
  - Thicker/stronger head and/or head shield
  - Thicker/stronger shell
  - Adding top fittings protection
  - Removing bottom fittings
- Stronger tank and better-protected fittings *improve accident performance*
- Also increase weight and cost, thereby *reduce transport efficiency*
- Thus there is a *tradeoff* between enhanced safety and transport efficiency

Estimating tank car safety performance

- More than 40 thousand records of tank cars involved in accidents have been recorded since 1970 in the RSI-AAR Tank Car Accident Database

- Resultant database provides a robust source of information for quantitative analysis of tank car safety design

- Treichel et al (2006) developed a logistic regression model to estimate tank car conditional probability of release

$$P_{Ri|A} = 0.533\,e^{\,L(i)} / (1 + e^{L(i)})$$

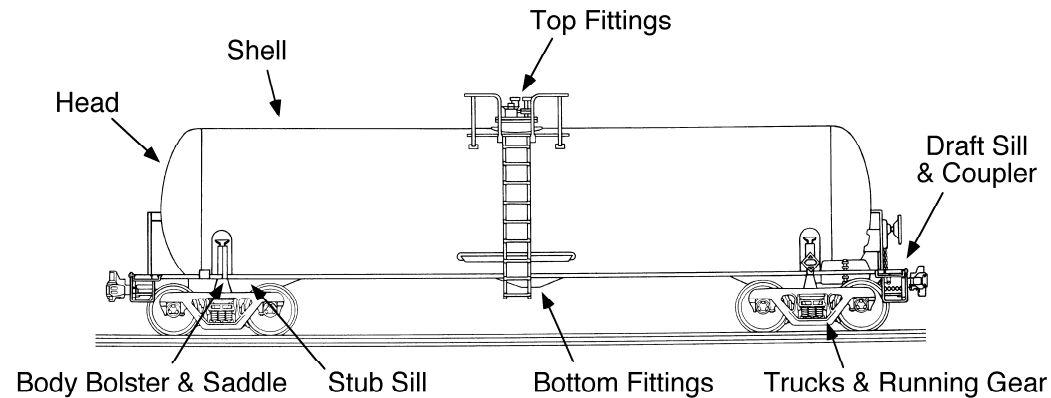- The calculated regression equations for the four release sources are:

L(HEAD) = - 0.4492 - 1.1672 HST - 1.9863 HMT - 0.9240 INS - 0.4176 SHELF- 0.4905 YARD

L(SHELL) = 0.4425 - 0.6427 INS - 4.1101 STS - 1.5119 YARD

L(TOP FITTINGS) = - 1.0483 - 0.8354 PRESS - 0.8388 INS + 0.1809 SHELF - 0.3439 YARD

L(BOTTOM FITTINGS) = - 1.4399 - 0.3758 INS - 0.5789 SHELF - 1.4168 YARD

IlliTank: Tank car weight & capacity program

$$\text{Cap} + \text{LW} \leq \text{GRL}$$

where:

GRL = gross rail load

Cap = tank car maximum lading capacity in lbs

LW = tank car empty weight

= tank head and shell assembly + head shields + insulation + jacket + top fittings protection + bottom fittings + non-tank components
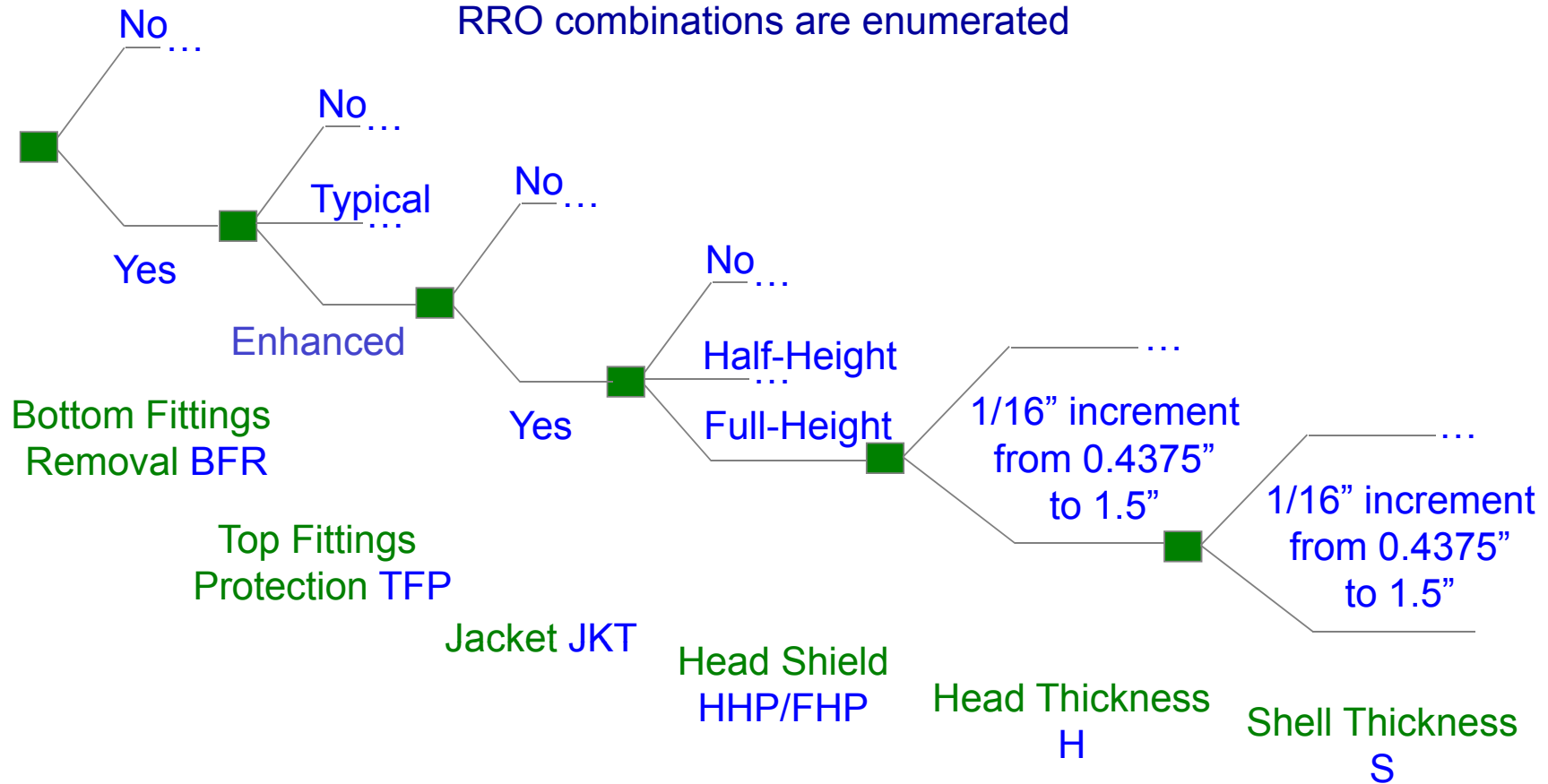
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IlliTank list of variables

Variable Description	Input Range	Unit
Maximum Gross Rail Load	Numeric Value, typically 263,000	lbs
Product Density	Numeric Value	lbs/gallon
Tank Outage	Numeric Value, typically 2 or 5	%
Tank Inside Diameter	Numeric Value	in.
Tank Head Thickness	Numeric Value	in.
Tank Shell Thickness	Numeric Value	in.
Ceramic Fiber Insulation Thickness	Numeric Value	in.
Fiberglass Insulation Thickness	Numeric Value	in.
Tank Jacket Constant	None or Jacketed	-
Head Shield Constant	None, Half-height or Full-height	-
Bottom Fittings Constant	None or Equipped	-
Top Fittings Protection Constant	None or Equipped	-
Additional Weight Increase/Reduction	Numeric Value	lbs

Enumeration of all tank car RROs

The safety performance and weight for all possible
RRO combinations are enumerated

No …

No …

Typical …

No …

Yes

No …

Enhanced

Half-Height …

Yes

…

Full-Height

1/16" increment
from 0.4375"
to 1.5"

…

1/16" increment
from 0.4375"
to 1.5"

Bottom Fittings
Removal BFR

Top Fittings
Protection TFP

Jacket JKT

Head Shield
HHP/FHP

Head Thickness
H

Shell Thickness
S

2 x 3 x 2 x 3 x 18 x 18 = 11,664 combinations

Enumeration of the conditional probability of release

- The conditional probability of release were enumerated with 1/16" incremental head and shell thicknesses, up to 1.5"

Head Thickness (inch)

| Shell Thickness (inch)	0.4375	0.5000	0.5625	0.6250	0.6875	. . .
0.4375	0.3090	0.3051	0.3014	0.2981	0.2951	
0.5000	0.2981	0.2940	0.2901	0.2867	0.2835	
0.5625	0.2889	0.2846	0.2806	0.2770	0.2737	
0.6250	0.2813	0.2769	0.2728	0.2690	0.2657	
0.6875	0.2751	0.2705	0.2663	0.2625	0.2590	
:						

14

Pareto optimization

- Once all possible RRO combinations have been considered, the decision space is searched for a set of Pareto optimal solutions, from which the final design will be chosen from

- A set of solutions is called Pareto optimal if there is no other feasible solution that would improve some objective function without causing a simultaneous decline in at least one other objective function

- This approach has its roots in mathematical consumer economics as considered by Pareto (1896)

- Pareto optimization has been used extensively in vehicle safety and crashworthiness design problems (Kasprzak et al 1998, Andersson & Redhe 2003, Hamza & Saitou 2005, Lee et al 2006, Cristello & Kim 2007, Sinha 2007, Sinha et al 2007)

# Stepwise algorithm used to identify the Pareto-optimal (non-dominated) solutions
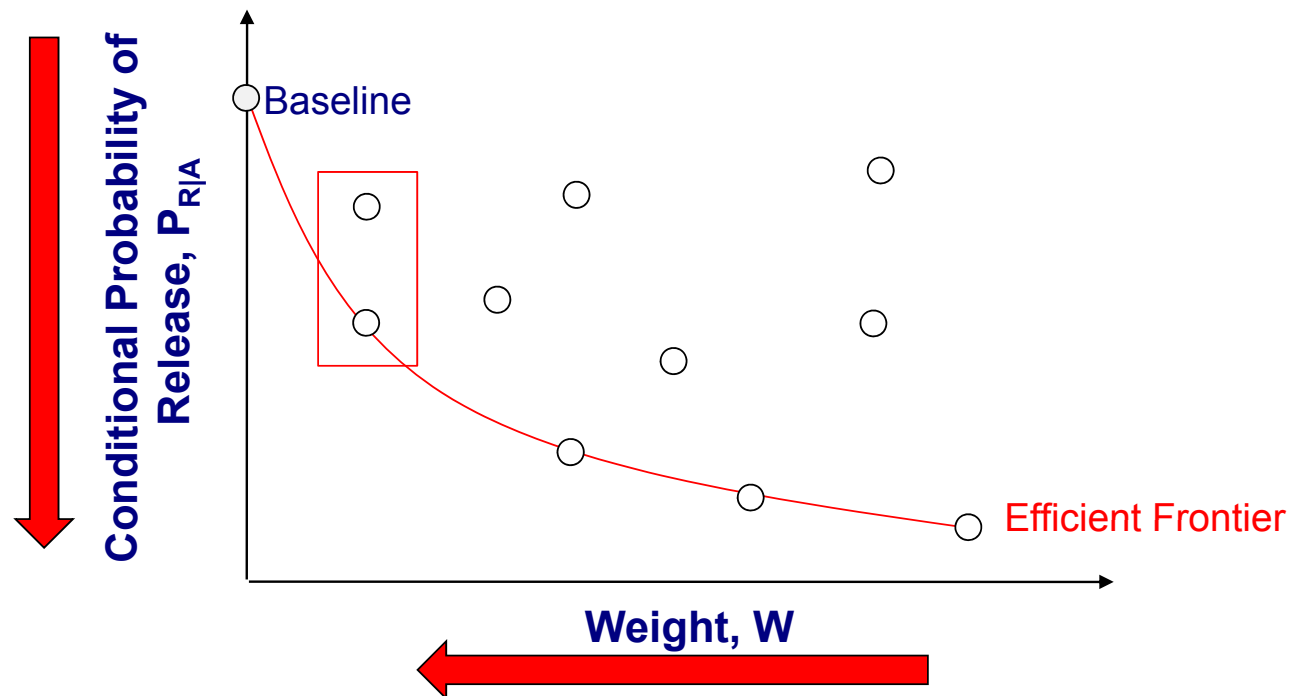
1) Compute **W**, $P_{R|A}$ and **ΔW** for all **RRO**$_i$; set $i = 0$ (base case);

2) From **RRO**$_i$, find **RRO** with the smallest **ΔW** and lower $P_{R|A}$ than current $P_{R|Ai}$

3) Insert solution **RRO**$_{i+1}$ that has the minimum $P_{R|A}$ among **RRO** identified in step 2 to the set of Pareto-optimal solutions, **S**

4) Repeat steps 2 and 3 for all feasible solutions

Trade-off between $P_{R|A}$ and tank car weight

Enumerated all possible RRO combination design solutions
(263,000-lb maximum GRL for 20,000-gallon baseline tank car)
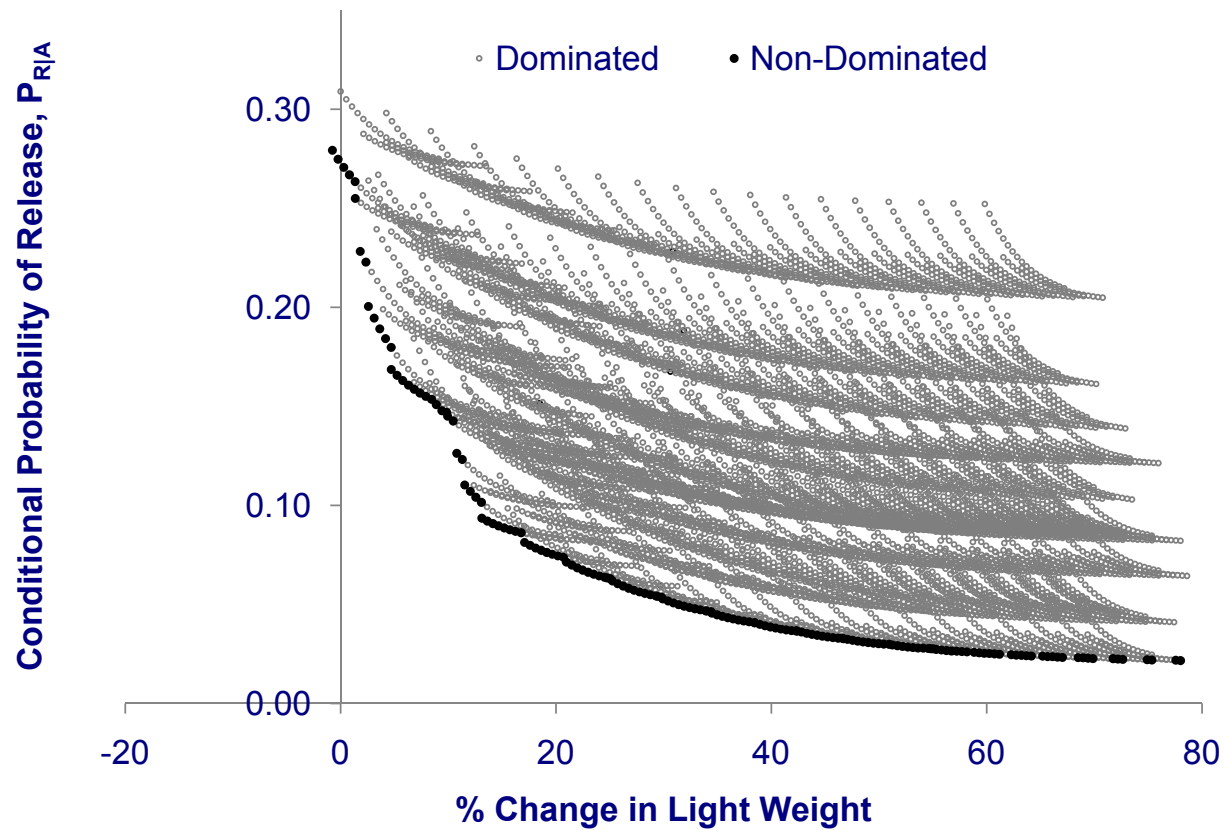
Expected quantity lost
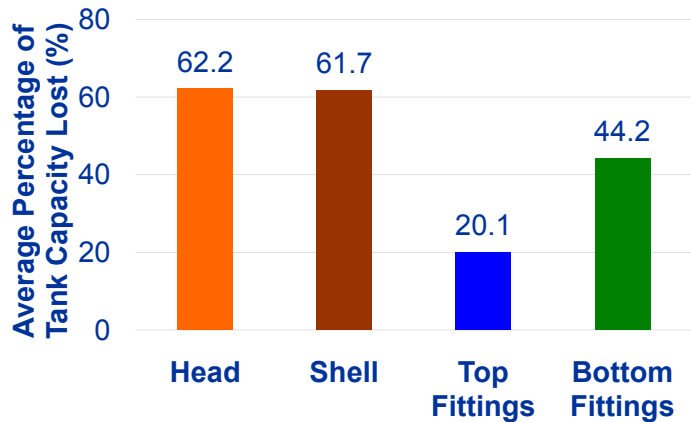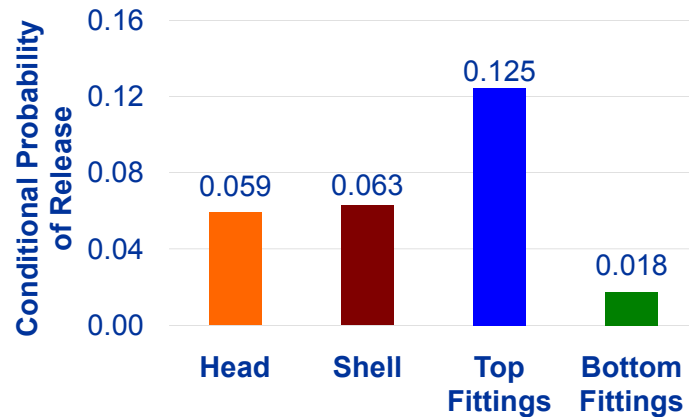
(DOT-111 Non-Insulated Tank Car)

- Account for source-specific conditional probability of release and average release size

$$E_{Gal_R} = Cap \sum_i \left(\overline{P}_{R|A} \times Q_i \right)$$

where:

E_{Gal_R} = expected gallon capacity lost given a tank car is derailed in an accident

Cap = tank car gallon capacity

$\overline{P}_{R|A}$ = mutually-exclusive and collectively-exhaustive conditional probability of release from source i given a tank car is derailed in an accident

Q_i = average percent tank capacity lost from source i

i = tank head (H), tank shell (S), top fittings (T), bottom fittings (B), and multiple causes (M)

Trade-off between expected quantity lost and tank car weight

Enumerated all possible RRO combination design solutions
(263,000-lb maximum GRL for 20,000-gallon baseline tank car)
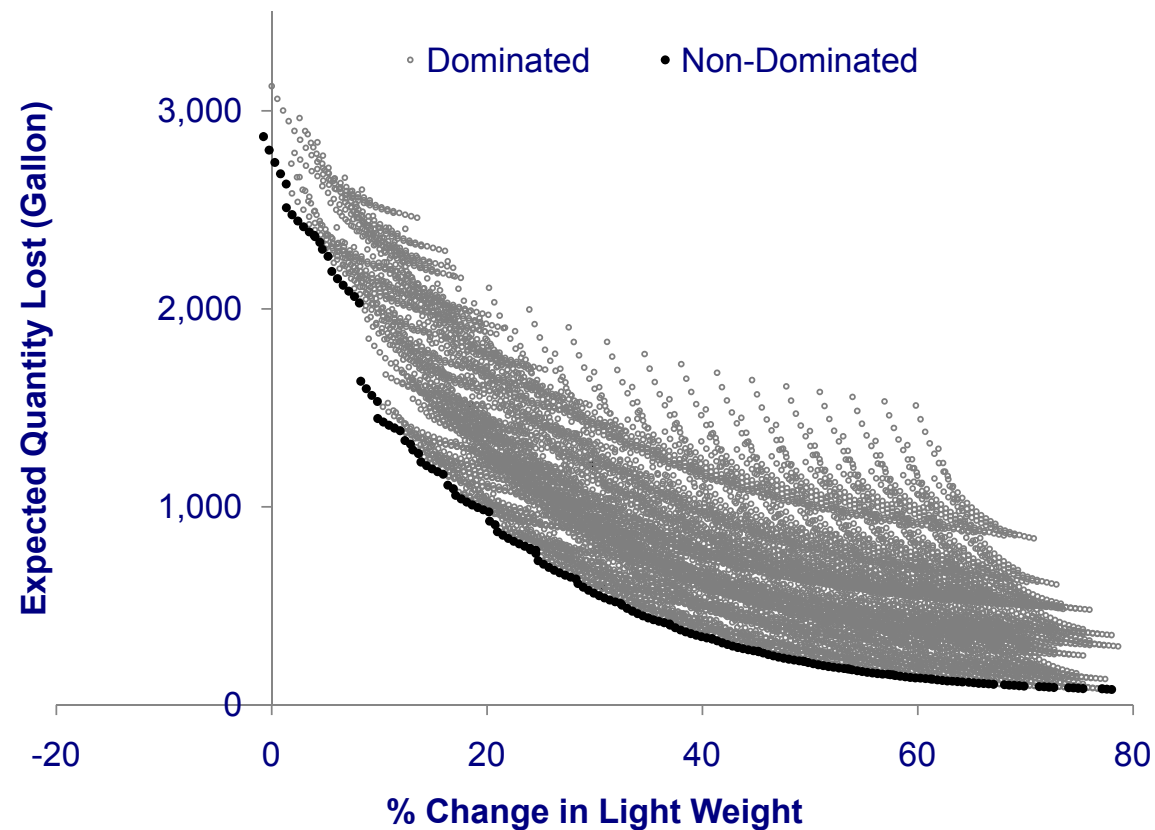
Identification of a compromise solution using the utopia point method
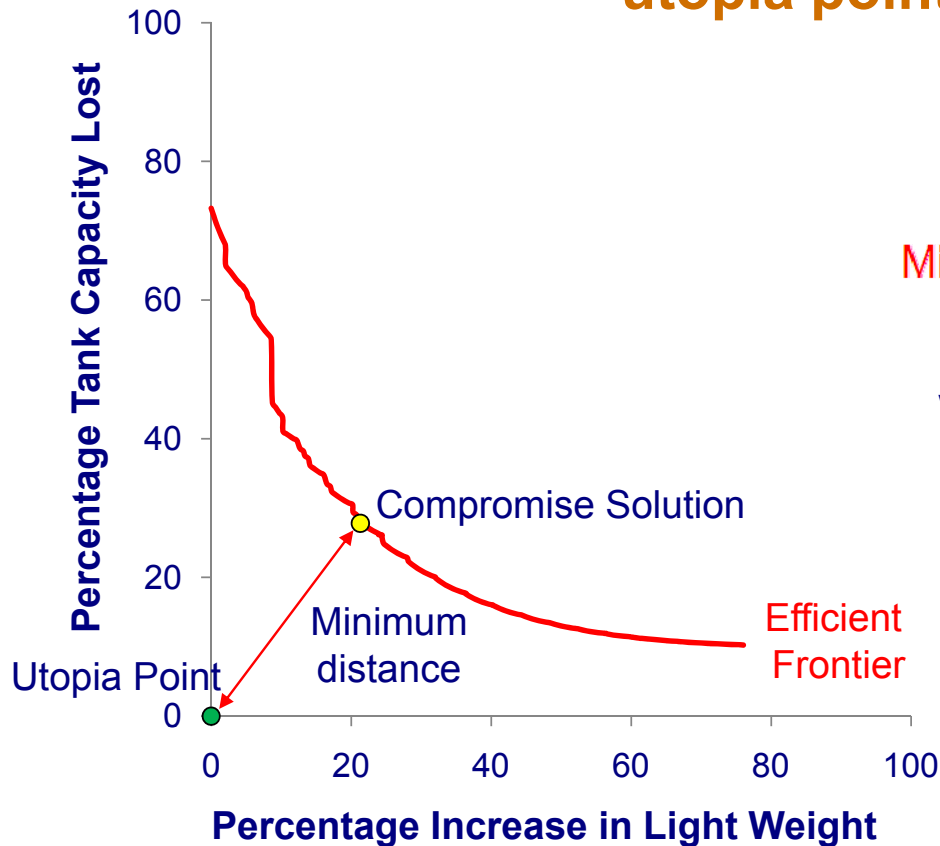
$$\text{Min } N(x) = \left| F(x) - F^O \right| = \left\{ \sum_{a,b} \left[F_{a,b}(x) - F^O_{a,b} \right]^2 \right\}^{1/2}$$

where:

N(x) = Euclidean distance

F(x) = objective functions vector

$F^O_{a,b}$ = utopia point vector

x = feasible design space

References:

Vincent, T.L. 1983, Game theory as a design tool. *J. Mech. Transm. Autom. Des.* 105, 165–170

Kämpke, T. 2007, The Reference Point Method in Primer Design, *Methods in Molecular Biology,* Yuryev, A., ed.

Examples of the applications of Phase I conceptual approach

- Risk Analysis of Toxic Inhalation Hazard (TIH) Materials' Transportation on U.S. Railroad Mainlines

  - The utopia point method was used to select among the Pareto-optimal set of combinations to identify candidate designs for enhanced tank cars for TIHs

  - Safety and transportation efficiency were assumed equally weighted, in part because that is what the Association of American Railroads (AAR) specified, but largely because no explicit information on how to differentially assign the preference level or weight on safety performance versus railcar capacity or cost was available

- Barkan, C.P.L. 2008, Improving the design of higher-capacity railway tank cars for hazardous materials transport: Optimizing the trade-off between weight and safety, *Journal of hazardous materials*, vol. 160, no. 1, pp. 122-134.

  - A goal programming approach was used to identify the optimal safety design combinations for higher GRL (total weight) tank cars for the AAR

  - The industries had agreed a-priori that one third of the incremental weight would go toward enhanced safety and the remaining two thirds to extra capacity

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Limitations in the Phase I approach

- The bicriteria tank car safety design optimization model enables identification of a specific, Pareto-optimal set that represents the most efficient combinations of tank car safety design options

- However, that model does not provide a means of determining what the optimal level of safety or performance is for any particular product

- The utopia point method or a goal programming formulation, can provide an objective approach to identify the optimal solution

- However, the underlying assumption of equal preference in the utopia point method, or a decision maker's specification to allocate a specific weight increment for safety, leaves an element of subjectivity in the process of identifying the final decision for individual car designs

- Phase II of the tank car safety design optimization process gives an advancement to the work that has already been done by considering explicit chemical-specific hazard and the consequent benefits and costs to identify the optimal solution using the net present value approach

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Net present value (NPV) analysis

- Benefit and cost streams generally extend into the future from some decision point

- The NPV method accounts for the future benefits and costs, and the time value of money within a specific analysis period

- Provides an objective means for decision makers to compare the cost-effectiveness of different feasible alternatives

Fleet replacement schedule

- An important variable in the NPV analysis that determines how fast the full benefit and cost would be realized

- Immediate Replacement

  - Chemicals with extremely high hazard may justify an immediate fleet replacement with enhanced-design tank cars

  - With this scenario, the full benefit and cost would be accrued immediately

- Attrition-Based Replacement

  - Tank cars are replaced with enhanced designs at the end of their normal service life, typically between 30 to 40 years

  - With this scenario, the full benefit and cost are accrued proportionally over the life-span of a tank car

- Accelerated Replacement

  - 1/n of the fleet is replaced annually

  - The benefit and cost would be accrued proportionally over the n-year period after which the benefit and cost would be fully realized

Risk-based tank car safety design optimization

- I develop a quantitative model that combines the bicriteria optimization method with a benefit-cost approach based on maximizing the NPV

- Enables chemical-specific hazard and risk to be used with the NPV approach to objectively determine the optimal tank car safety design for each material

- The risk-based tank car safety design optimization concept will be illustrated by using idealized benefit and cost curves

- The first step involved is to define a set of Pareto-optimal solutions, then consider how chemicals with different hazard levels affect the optimality
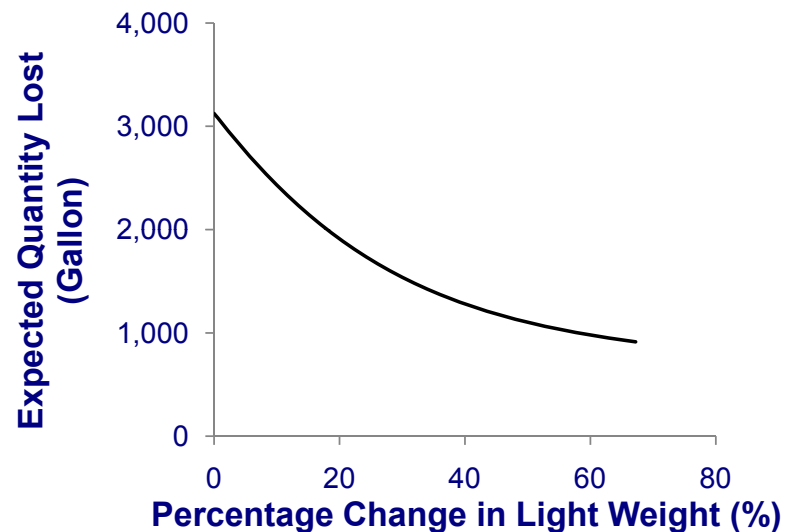
Risk analysis framework

- For a set of Pareto-optimal solutions identified, the accident-caused release risk can be estimated as follows:

$$R_{R_j} = P_{R_j} \times P_{Q_i|R} \times Q_i \times C_j$$

where:

R_{R_j} = accident-caused risk for transporting chemical j

P_{R_j} = accident-caused release rate for a tank car transporting chemical j

$P_{Q_i|R}$ = probability of release size i given a tank car released its content
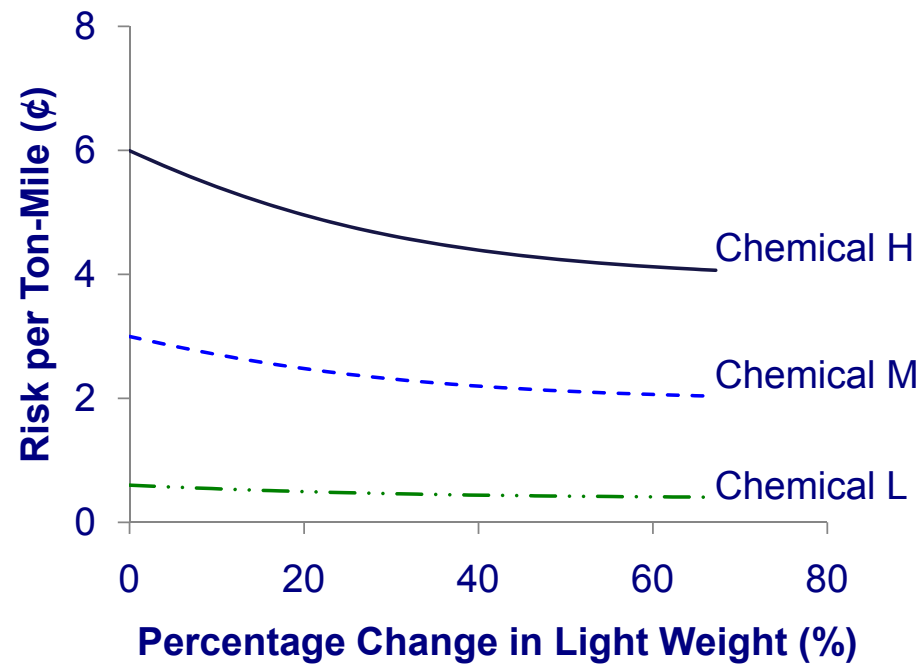
Q_i = average release quantity

= average percentage tank capacity lost for release size i × tank car capacity

C_j = chemical j release consequence

Risk per ton-mile

Assuming $C_L < C_M < C_H$, where $C_M = 5\,C_L$ and $C_H = 10\,C_L$

- The higher the hazard level, the higher the risk for all weight increments

Estimating risk reduction or benefit

$$\text{Benefit}_t = \left(\hat{R}_R - R_R\right) \times \rho_t$$

where:

Benefit_t = risk reduction or benefit at year t

$\hat{R}_R$ = accident-caused risk when baseline tank car design is used

R_R = accident-caused risk when enhanced tank car design is used

ρ_t = proportion of total tank car fleet replaced at year t

$= (t + 1)/\theta$ if $(t + 1) \leq \theta$, else $\rho_t = 1$

θ = phase-in period based on tank car fleet replacement schedule

- Net benefit over a certain present-value analysis period can be estimated as follows:

$$PV_{\text{Benefit}} = \sum_{t=0}^{Y} \frac{\text{Benefit}_t}{(1+d)^t}$$

where:

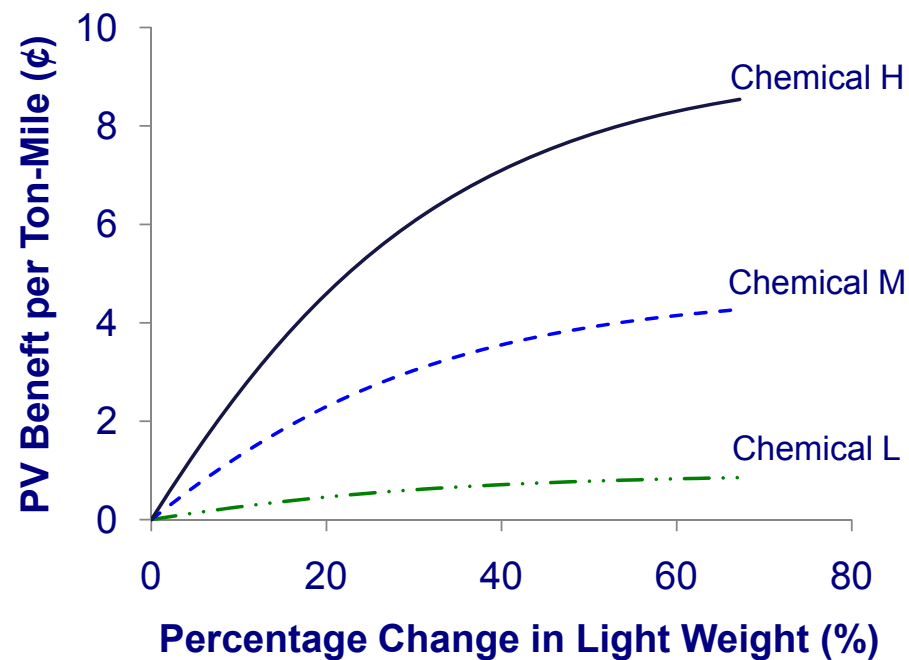PV_{Benefit} = present-value benefit or risk reduction

Y = present-value analysis period

d = discount rate

Benefit per ton-mile

Assuming $C_L < C_M < C_H$, where $C_M = 5\ C_L$ and $C_H = 10\ C_L$

- At any specific weight increment the benefits are higher for chemicals with higher hazards

Estimating costs related to fleet replacement

- Tank car replacement incurs incremental increases in both capital and operating costs

- Capital includes tank car life-cycle cost, i.e. the cost of buying a new car, maintenance costs, salvage value and other expenses throughout the life-span of a car

- It must also account for the total number of tank cars required to replace a fleet, and the replacement schedule

- Operating cost accounts for the total number of shipments and the cost per trip

- Total cost is the sum of capital and operating costs for any particular design

Identifying minimum tank car fleet size

$$N = \frac{S \times Cap/Cap'}{T}$$

where:

N = minimum total enhanced-design tank cars in a fleet

S = annual number of shipments with baseline tank cars

Cap = nominal gallon capacity of a baseline tank car

Cap' = nominal gallon capacity of an enhanced-design tank car

T = tank car utilization rate (annual trips per car)

Tank car fleet replacement or capital cost estimation

$$PV_{Fleet} = \sum_{t=0}^{Y} \frac{LC_{TankCar} \times m_t}{(1+i)^t}$$

where:

PV_{Fleet} = present value of total fleet replacement cost

$LC_{TankCar}$ = life-cycle cost of a tank car

m_t = total number of enhanced-design tank cars entering the fleet in year t

$= N/\theta$

Operating cost estimation

$$PV_{Opr} = \sum_{t=0}^{Y} \frac{M \times C_{Opr}}{(1+i)^t}$$

where:

PV_{Opr} = present value of total fleet operating cost

M = number of car miles

C_{Opr} = operating cost per mile

Incremental cost estimation

$$PV_{Incremental\ Cost} = [PV_{Fleet} + PV_{Opr}] - [\widehat{PV}_{Fleet} + \widehat{PV}_{Opr}]$$

where:

$PV_{Incremental\ Cost}$ = present value of total incremental cost

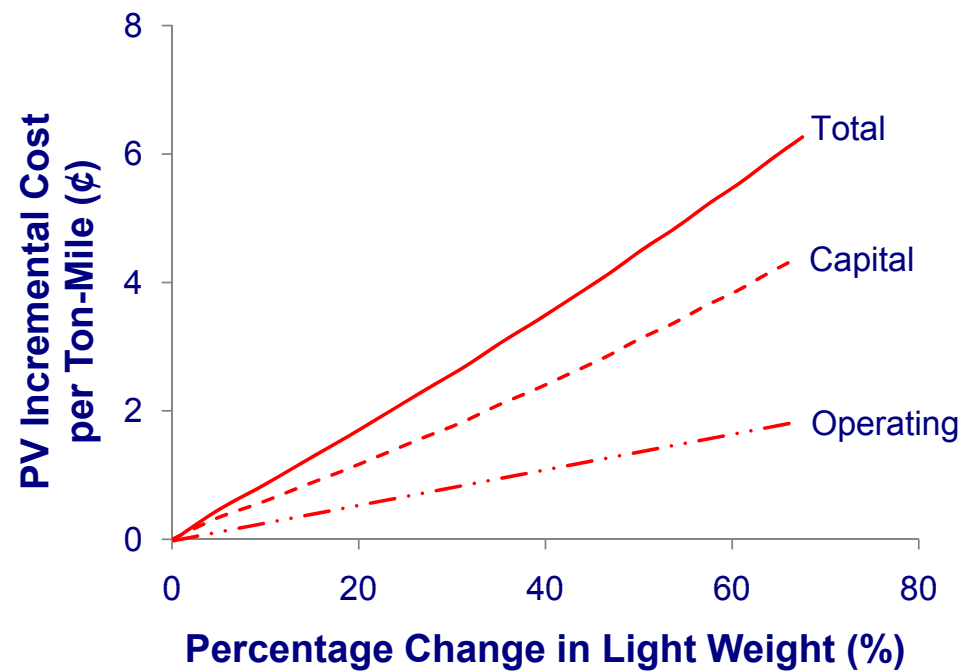PV_{Fleet} = present value of fleet replacement cost with enhanced-design tank cars

PV_{Opr} = present value of operating cost with enhanced-design tank cars

$\widehat{PV}_{Fleet}$ = present value of fleet replacement cost with baseline tank cars

$\widehat{PV}_{Opr}$ = present value of operating cost with baseline tank cars
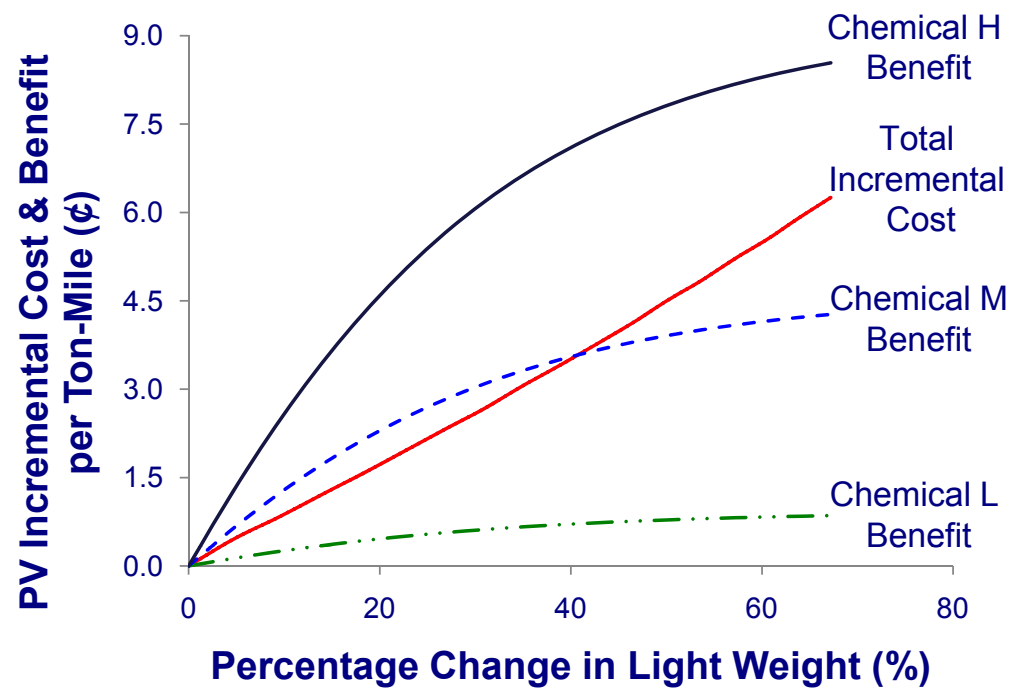
Incremental present-value capital, operating & total costs per ton-mile
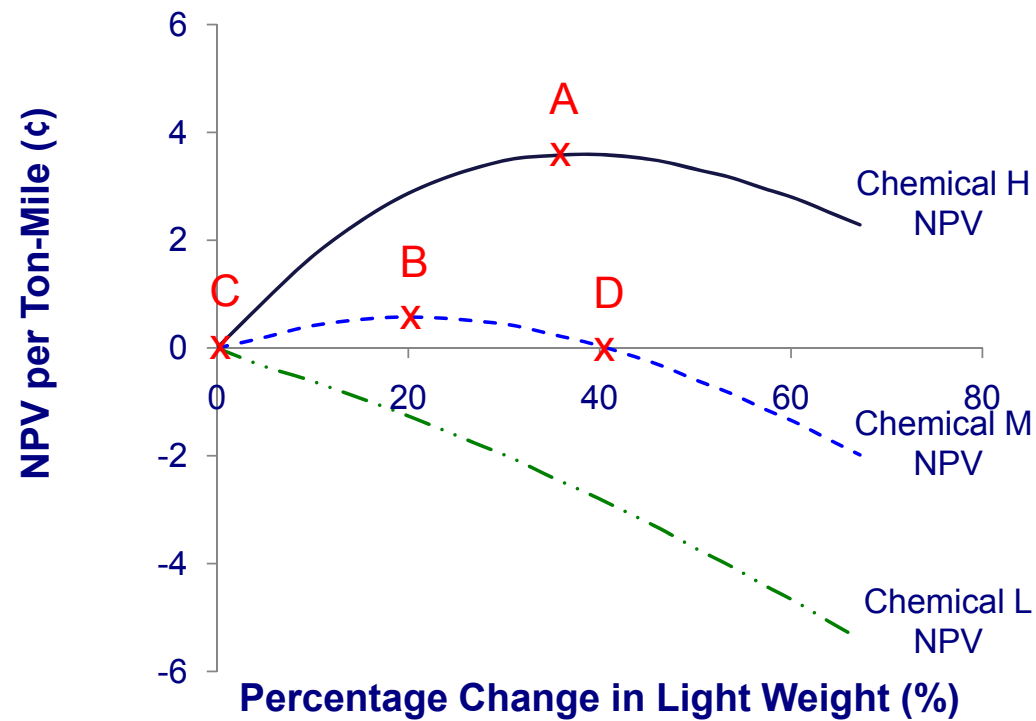
Cost effectiveness evaluation – PV benefits & cost

$$\text{Max NPV} = \text{PV}_{\text{Benefit}} - \text{PV}_{\text{Incremental Cost}}$$

# Cost effectiveness evaluation - NPV

Application of the risk-based tank car safety design optimization model

- Summarize a risk analysis of rail transportation involving a group of chemicals that pose hazard to the environment

- Use the risk analysis results to evaluate cost-effectiveness of tank car safety design enhancements

Decision & risk analyses framework
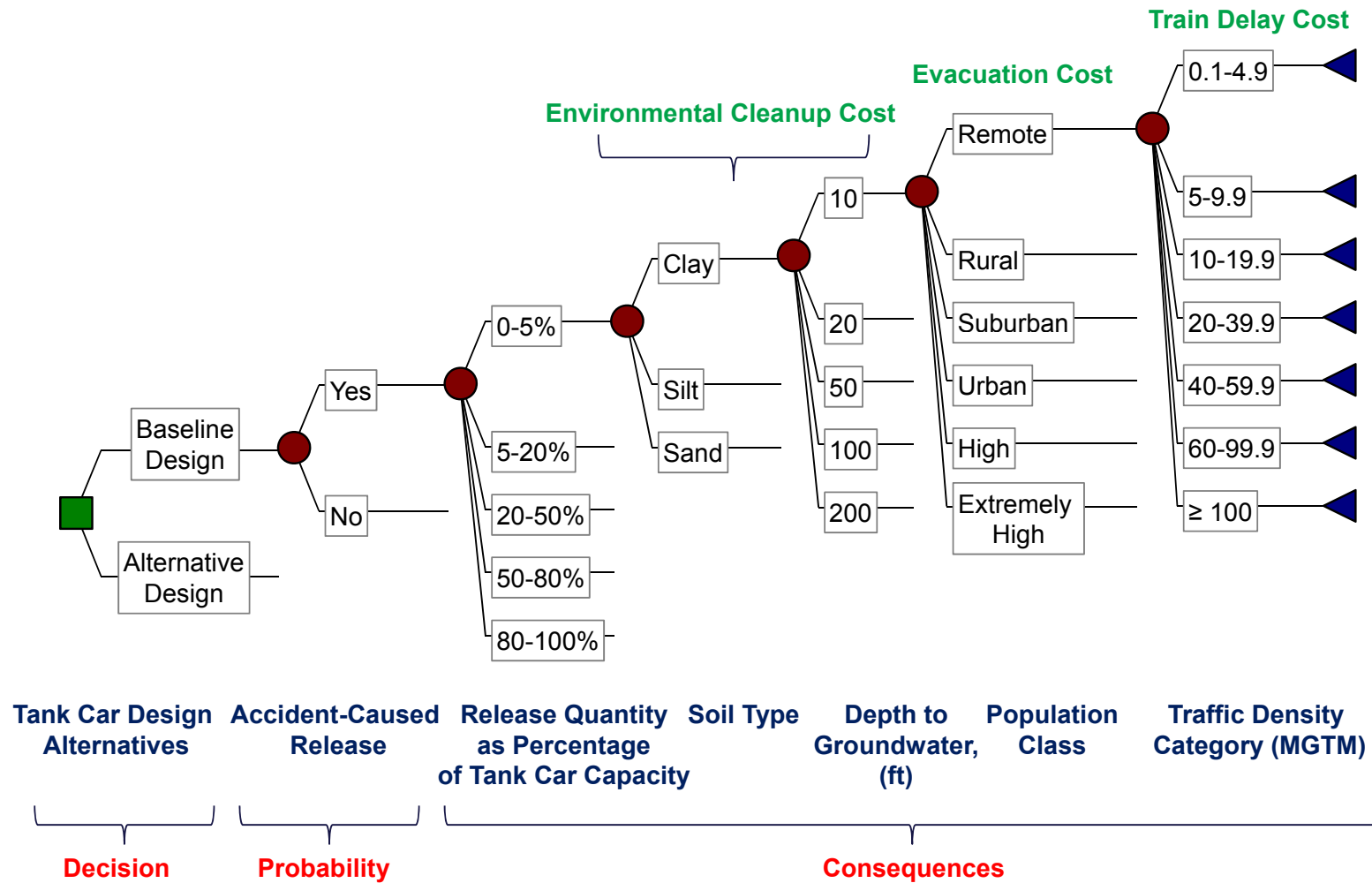
Probability analysis

- Accident-caused release rate metric was used to estimate the rate of a release event:

$$P_R = P_A \times P_{R|A} \times M \times Cap/Cap'$$

where:

P_A = tank car derailment rate

$P_{R|A}$ = tank car conditional probability of release
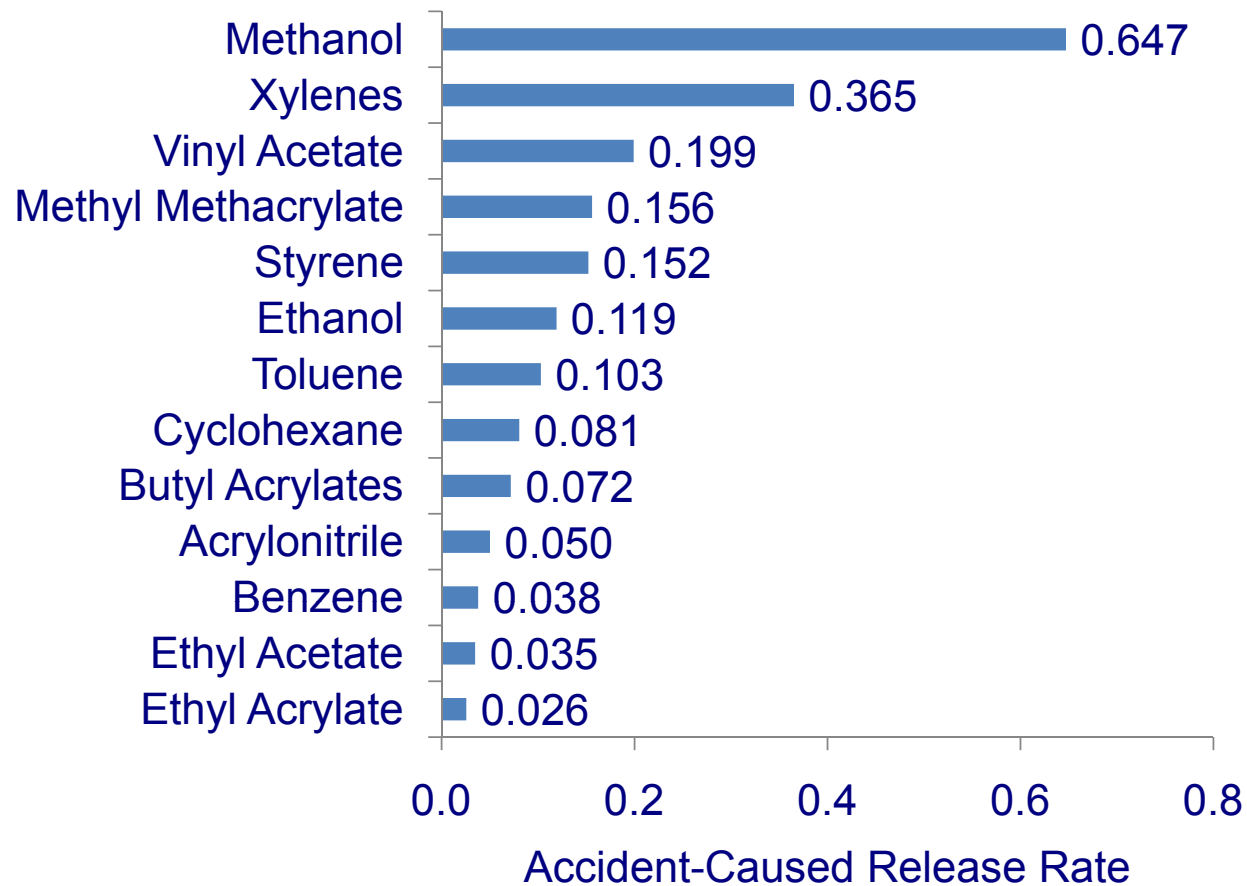
M = total number of car miles

Cap = nominal gallon capacity of a baseline tank car

Cap' = nominal gallon capacity of an alternate-design tank car

Accident-caused release rate summary

(The "probability" or frequency term in the risk definition)

Consequence analysis

- Impacts to Soil and Groundwater

  - Hazardous Materials Transportation Environmental Consequence Model (HMTECM) was used to estimate soil and groundwater cleanup cost

  - Accounts for physicochemical properties, soil type and depth to groundwater

- Population Exposure

  - US Emergency Response Guidebook (ERG) was used to determine hazard area

  - Impact in terms of evacuation cost was estimated

- Train Delay

  - Estimate impact due to additional costs related to locomotives, railcars, fuel and labor

 - Accounts for traffic density to estimate total number of trains delayed

References:

Yoon, H., Werth, C.J., Barkan, C.P.L., Schaeffer, D.J. & Anand, P. 2009, "An environmental screening model to assess the consequences to soil and groundwater from railroad-tank-car spills of light non-aqueous phase liquids", Journal of hazardous materials, vol. 165, no. 1-3, pp. 332-344.
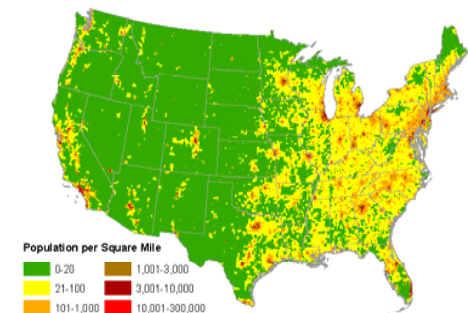
Schafer, D.H. & Barkan, C.P.L. 2008, "A prediction model for broken rails and an analysis of their economic impact", *Proceedings of the AREMA Annual Conference, Salt Lake City, UT.*
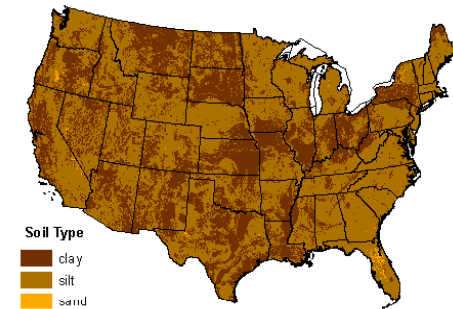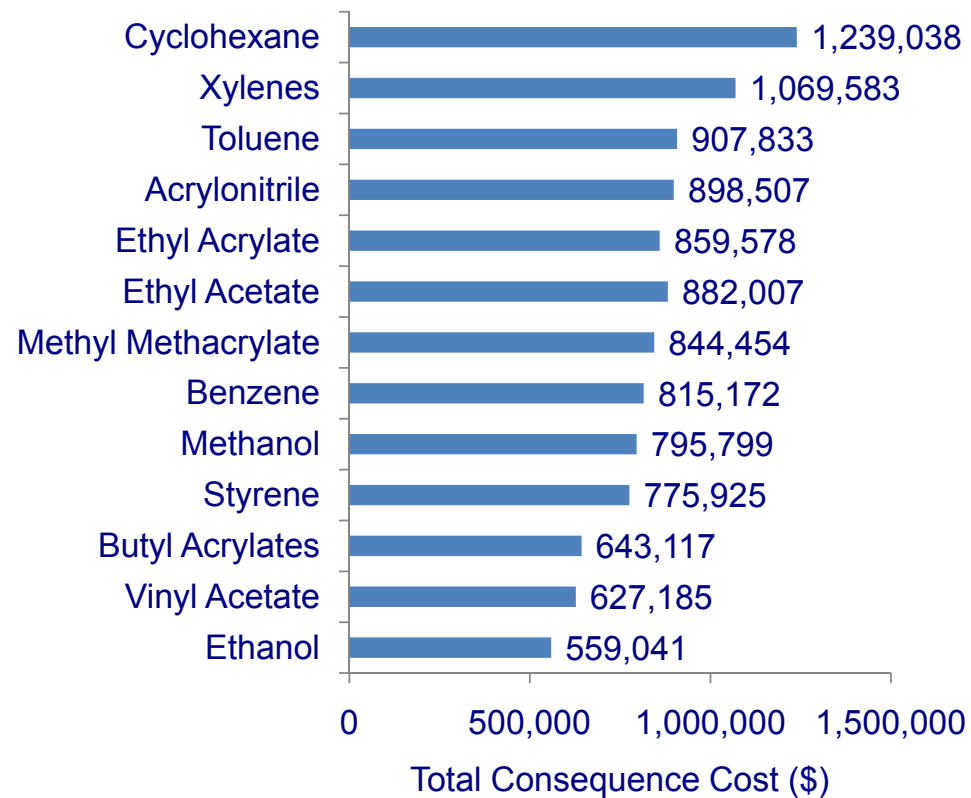
Soil Type
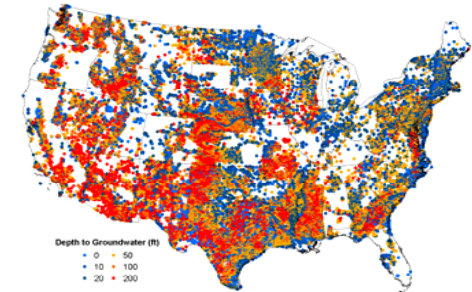
Depth to Groundwater

Population Density

Total expected consequence cost

- Expected Cleanup Cost + Evacuation Cost + Train Delay Cost

(The consequence term in the risk definition)

Chemical	Total Consequence Cost ($)
Cyclohexane	1,239,038
Xylenes	1,069,583
Toluene	907,833
Acrylonitrile	898,507
Ethyl Acrylate	859,578
Ethyl Acetate	882,007
Methyl Methacrylate	844,454
Benzene	815,172
Methanol	795,799
Styrene	775,925
Butyl Acrylates	643,117
Vinyl Acetate	627,185
Ethanol	559,041

Total Consequence Cost ($)

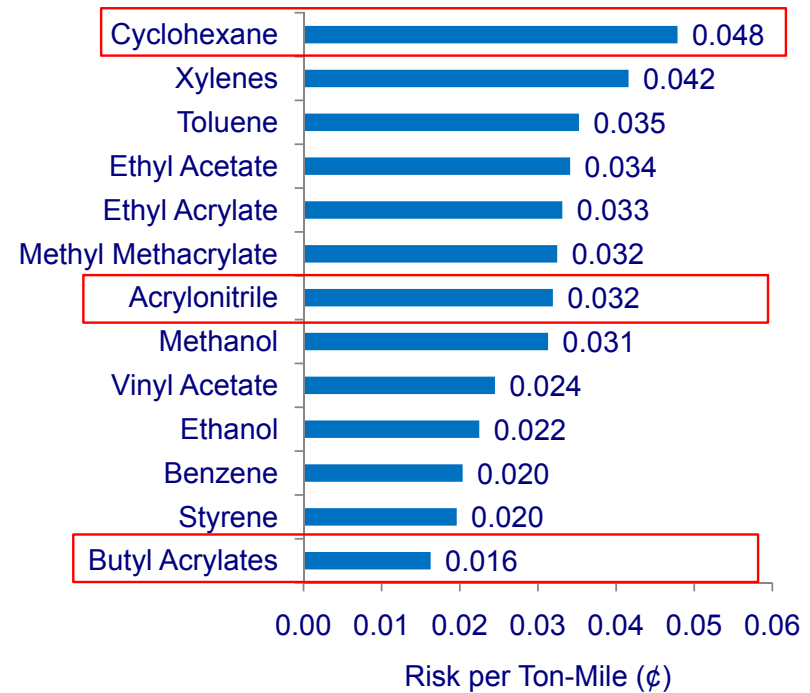# Risk estimation

- Accident-Caused Release Rate x Total Expected Consequence Cost

Annual Release Risk ($)	
Methanol	515,051
Xylenes	390,711
Methyl Methacrylate	131,756
Vinyl Acetate	124,871
Styrene	118,081
Cyclohexane	99,801
Toluene	93,545
Ethanol	66,641
Butyl Acrylates	46,187
Acrylonitrile	45,168
Benzene	30,998
Ethyl Acetate	30,744
Ethyl Acrylate	22,075

Risk per Ton-Mile (¢)	
Cyclohexane	0.048
Xylenes	0.042
Toluene	0.035
Ethyl Acetate	0.034
Ethyl Acrylate	0.033
Methyl Methacrylate	0.032
Acrylonitrile	0.032
Methanol	0.031
Vinyl Acetate	0.024
Ethanol	0.022
Benzene	0.020
Styrene	0.020
Butyl Acrylates	0.016

Annual Risk

Risk per Ton-Mile

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44

Considering tank car safety design enhancements

No …

Typical …

Enhanced

No …

Yes

No …

Half-Height …

Full-Height

1/16" increment
from 0.4375"
to 1.5"

…

1/16" increment
from 0.4375"
to 1.5"

…

Top Fittings
Protection TFP

Jacket JKT

Head Shield
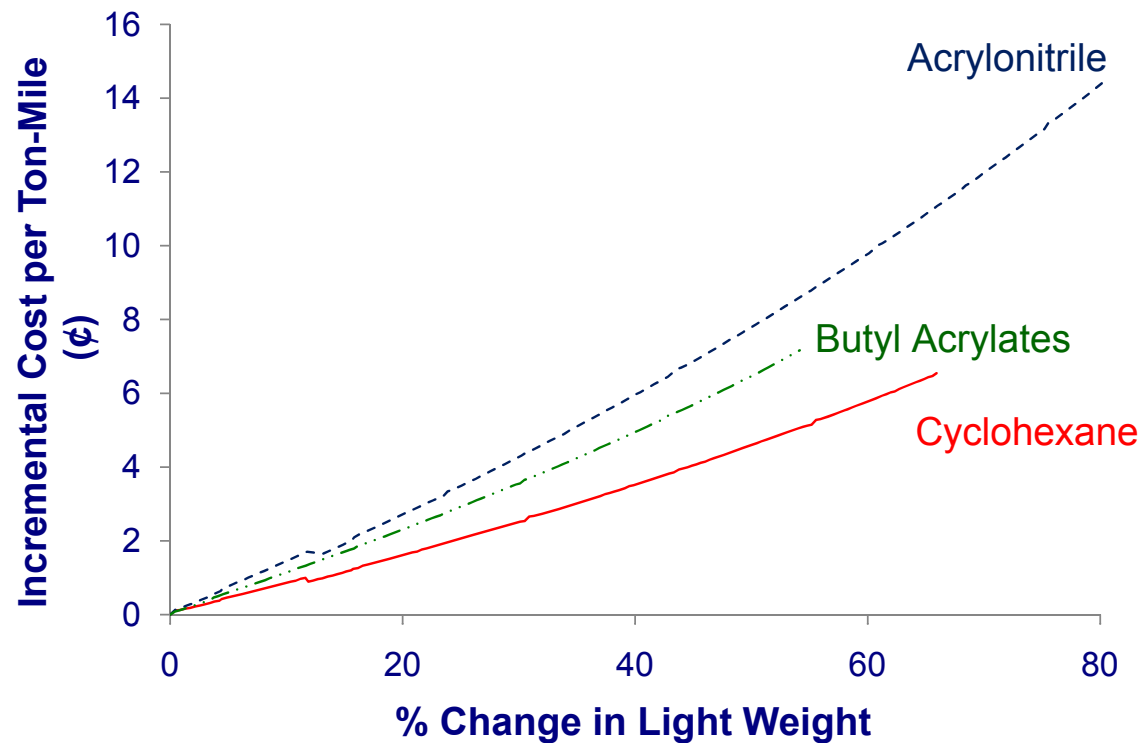HHP/FHP

Head Thickness
H

Shell Thickness
S
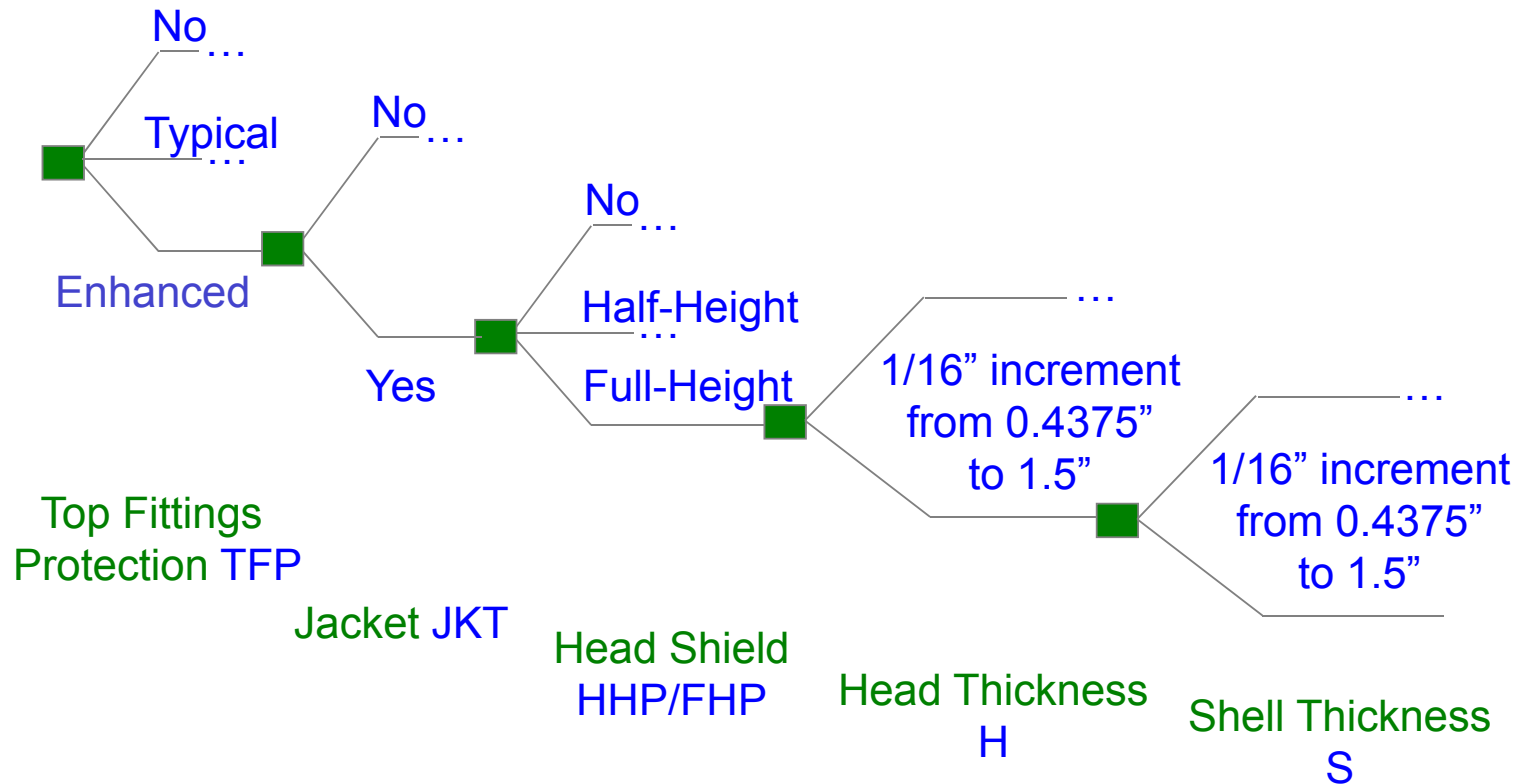
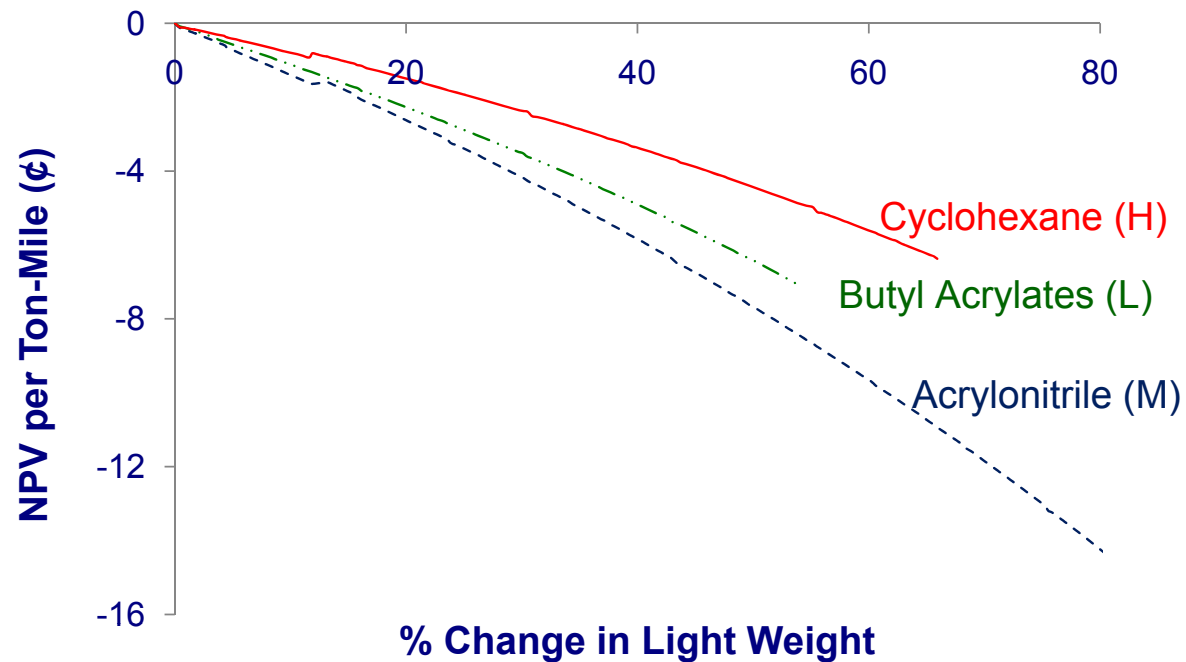# Identifying Pareto-optimal solutions
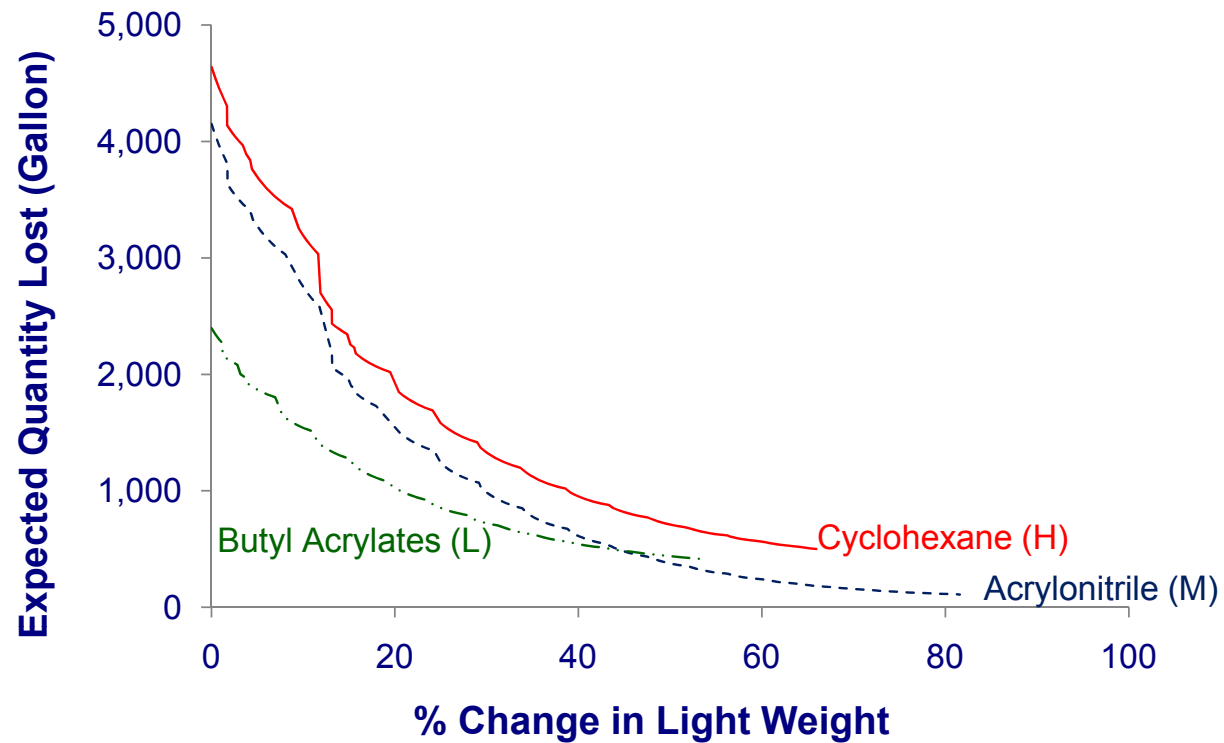
Estimating the benefit for Pareto-optimal solutions
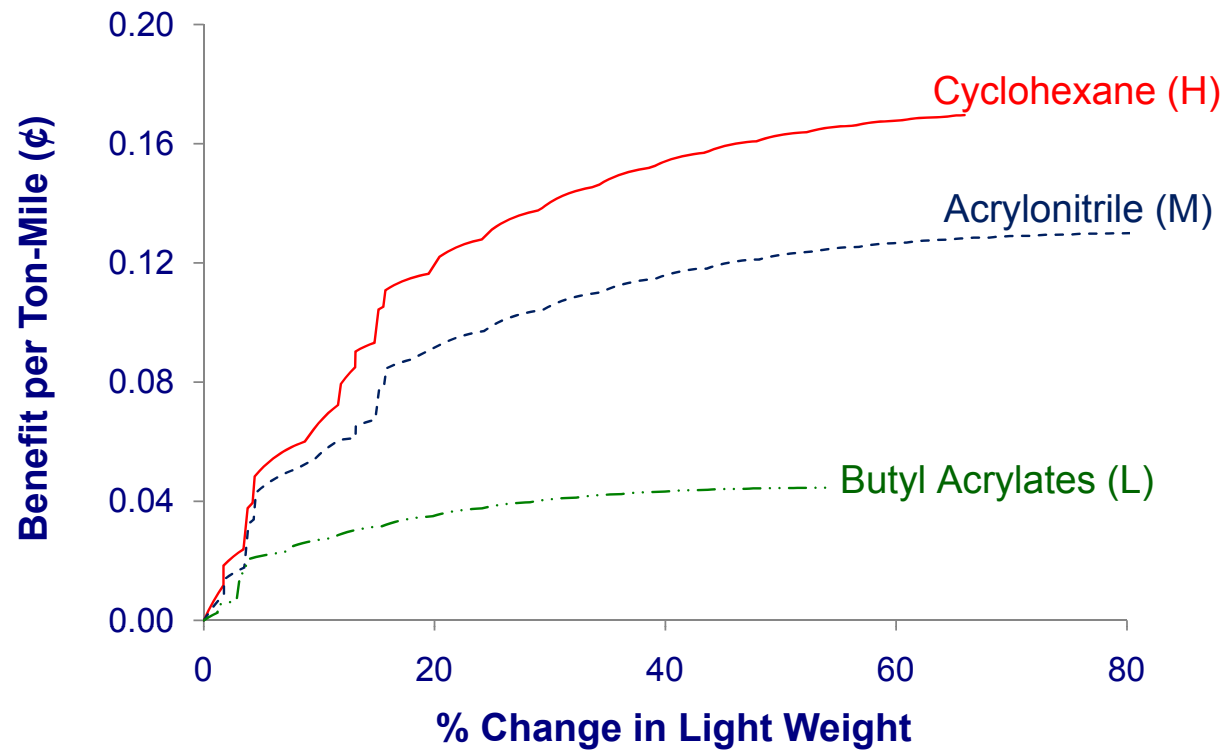
# Estimating the incremental cost for Pareto-optimal solutions

Estimating the NPV for Pareto-optimal solutions

On the basis of the NPV, it is not cost justified to replace the fleets of any of the chemicals of interest with enhanced-design tank cars

Minimum risk-cost multiplier to attain positive NPV solutions

Risk-Cost Multiplier, μ

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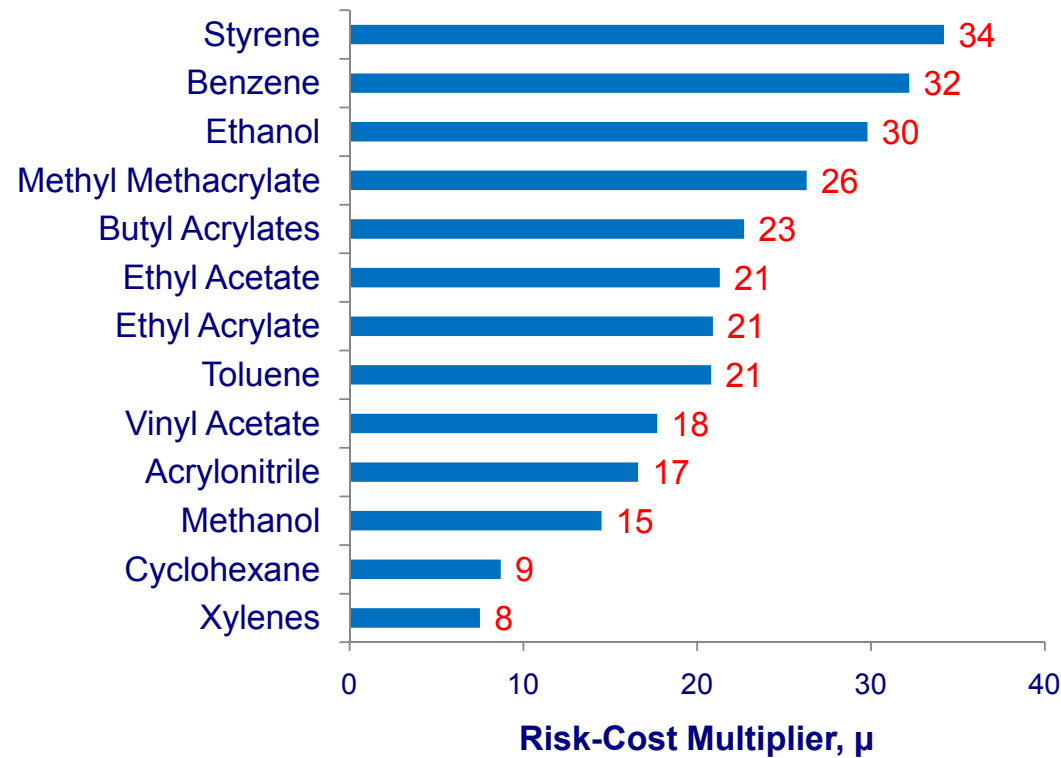
Future research

- Addressing Constraints in Existing Work

  - Considering Multiple-Car Derailments and Multiple-Car Releases

  - Considering Varying Transportation Demand (i.e. shipments over 10-40 years)

  - Improving Chemical-Specific GIS Route Creation Process

  - Considering Other Decision Making Techniques

  - Developing a More Detailed Uncertainty Analysis

- New Research Directions

  - Evaluating Unconventional Tank Car Designs' Performance

  - Considering Multiple Hazards and Risk Impacts

  - Considering Transportation Security

  - Considering Other Strategies to Reduce Hazardous Materials Transportation Risk

Summary

- Tank car safety design optimization is presented in my dissertation as a two-phase process

- The first phase addresses the tradeoff between safety and transportation efficiency by using Pareto optimization to identify the most efficient non-dominated design combinations of safety performance and weight

- The second phase involves incorporating chemical-specific hazard level and the consequent benefit and cost to determine the optimal level of protection for different hazardous materials

- My dissertation research provides decision tools and parametric models to assess hazardous materials transportation risk, identify optimal tank car safety design, and estimate potential risk reduction options and their associated benefit and cost

- The framework presented in this research is intended to assist industry and government policy makers to make better-informed decisions for safer transportation of hazardous materials

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QUESTIONS?