Optimizing Tank Car Safety Design to Reduce Hazardous Materials Transportation Risk

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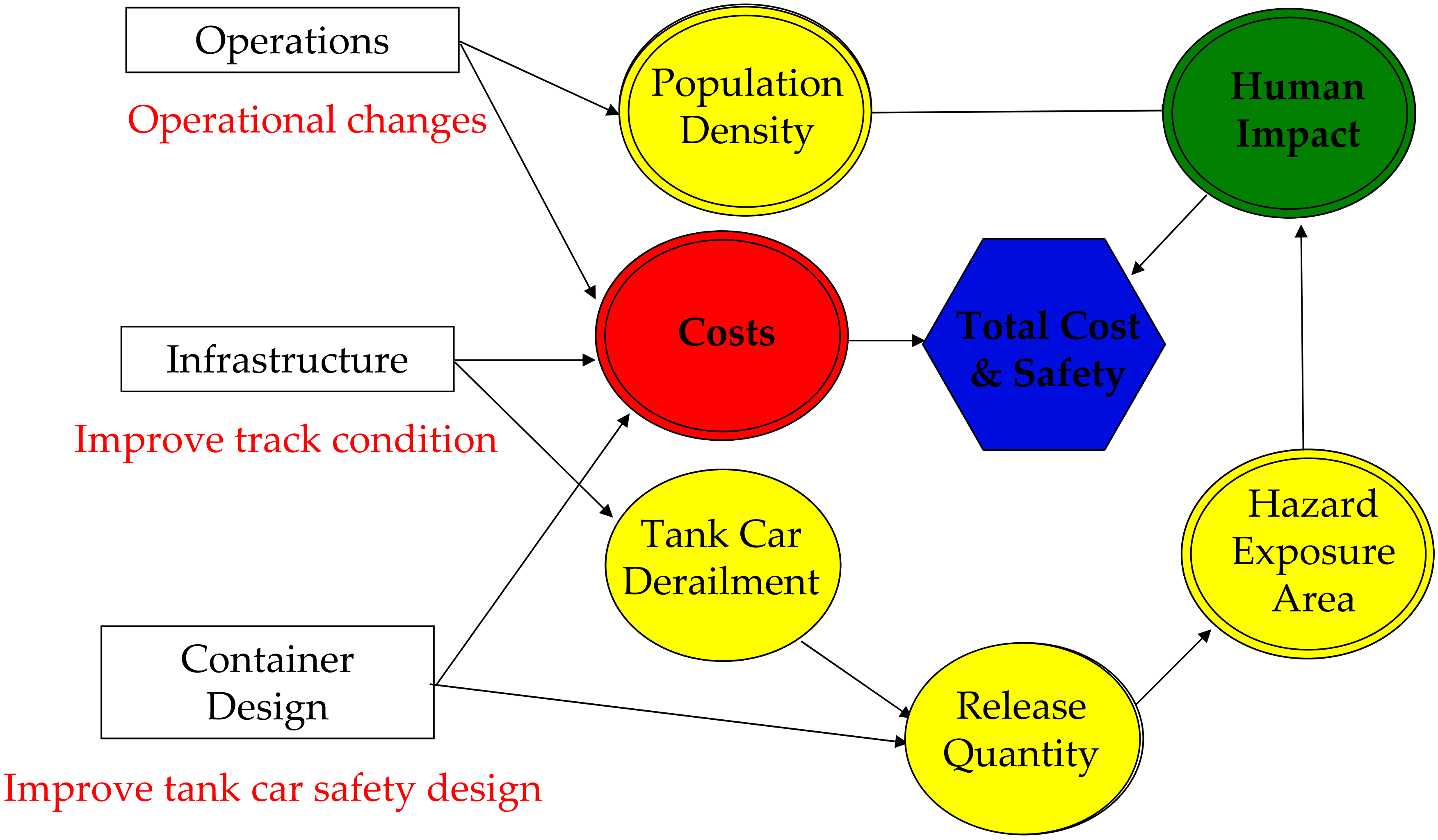
ILLINOIS
RAILROAD ENGINEERING PROGRAM

Outline

- Overview of elements involved in reducing hazardous materials transport risk by rail
- Tank Car Design Optimization Model
    - Tank car weight and capacity model
    - Metrics to assess tank car performance
    - Illustration of the optimization model
- Application in Toxic Inhalation Hazards (TIH) Risk Analysis
- Future Work

Reducing Hazardous Materials Transportation Risk



Multi-Objectives, Multi-Attributes Decision Analysis

Tank Car Safety Design Optimization

Tank Car Safety Performance Model

- RA-05-02 Statistical Model

Risk Consequence Model

-TIH ERG Exposure Model
-ESH Exposure Model

Mathematical Optimization Model
Mixed-Integer Programming

$F_{risk, cost} \propto RRO$

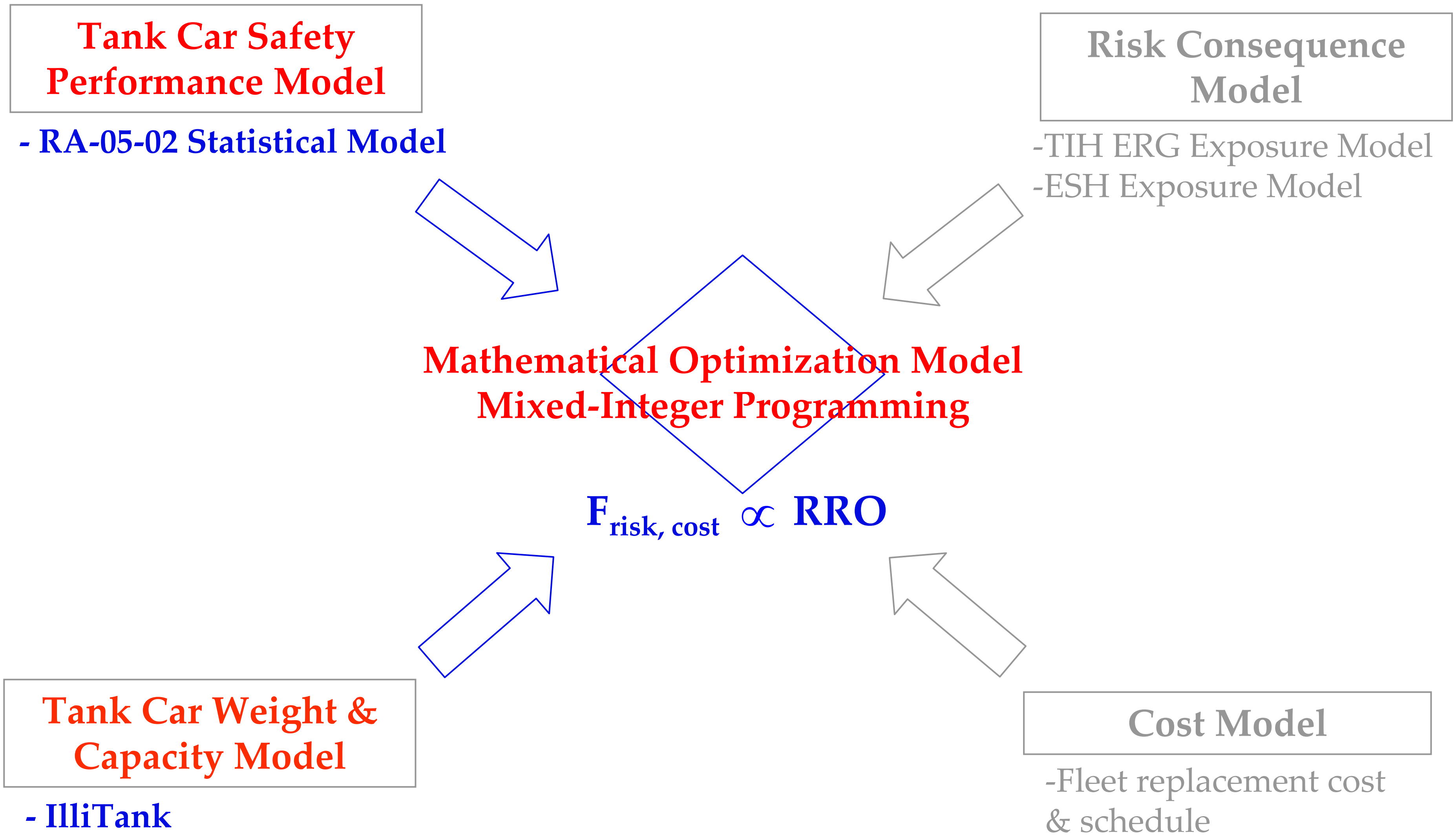
Tank Car Weight & Capacity Model

- IlliTank

Cost Model

-Fleet replacement cost & schedule

Tank Car Safety Design Optimization



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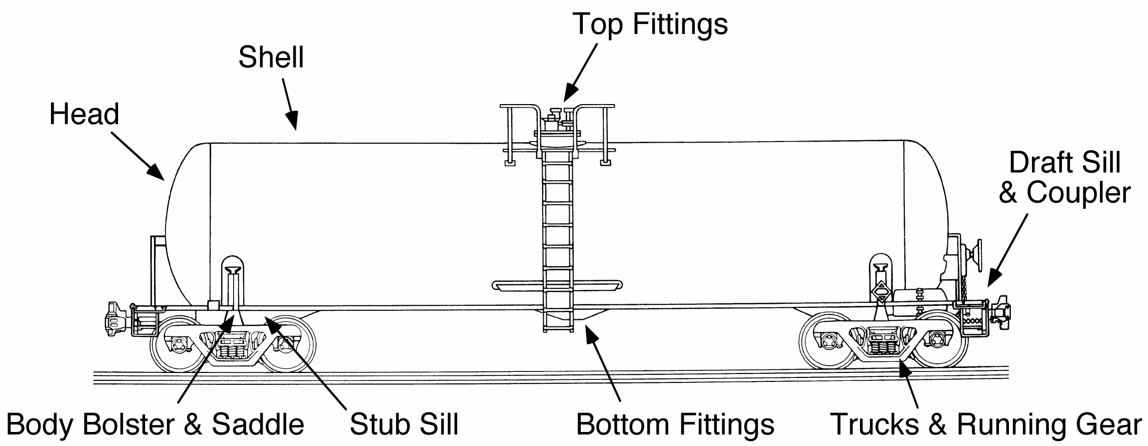
Tank car sizes are optimized for different density ladings

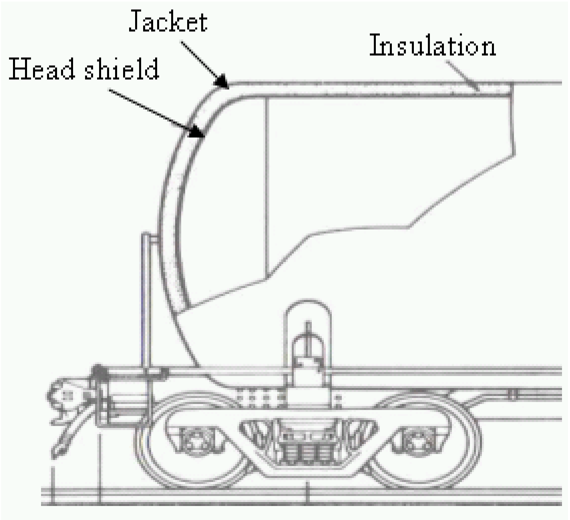
Sulfuric Acid

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

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

IlliTank: Tank Car Weight & Capacity Program





$$Cap + LW \leq GRL$$

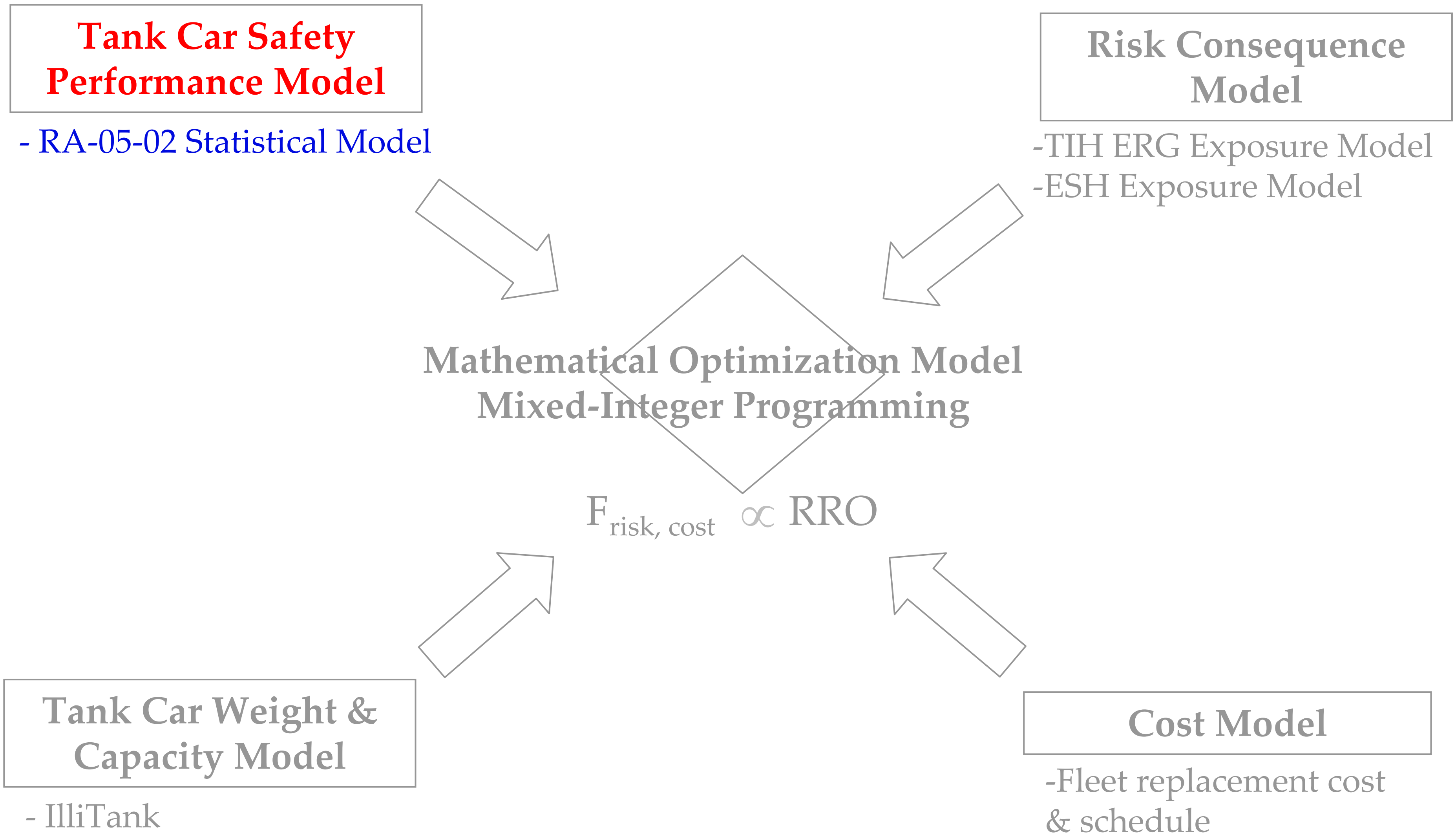
where:

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 + additional weight

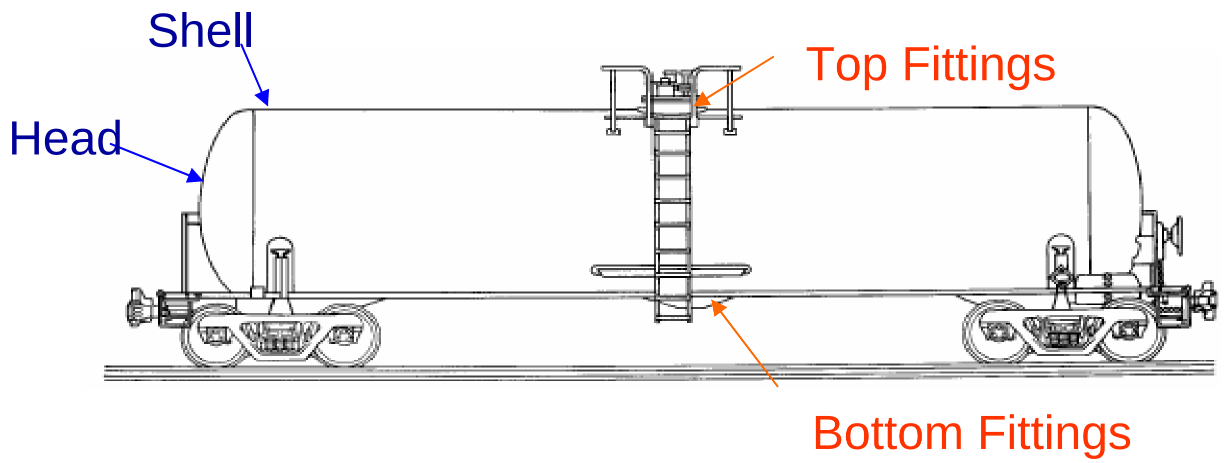
IlliTank: Tank Car Weight & Capacity Program

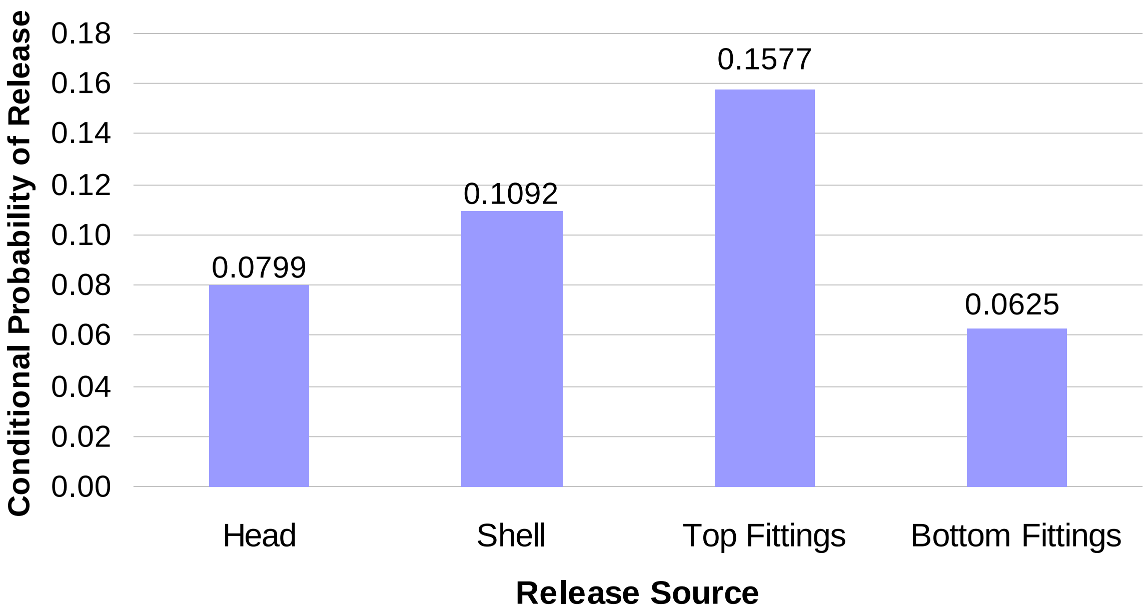
Variable	Description	Input Range	Unit
GRL	maximum gross rail load	Positive number, typically 263,000	lbs
productDensity	product density	Positive decimals	lbs/gallon
outage	tank outage	Positive number, typically 2 or 5	%
insideDia	tank inside diameter	Positive decimals	in.
headThick	tank head thickness	Positive decimals	in.
shellThick	tank shell thickness	Positive decimals	in.
insulate1Thick	ceramic fiber insulation thickness	Positive decimals	in.
insulate2Thick	fiberglass insulation thickness	Positive decimals	in.
jacket	tank jacket constant	0 = none, 1 = jacketed	-
headShield	head shield constant	0 = none, 1 = half-height, 2 = full-height	-
bottomFit	bottom fittings constant	0 = none, 1 = equipped	-
topFitProtect	top fittings protection constant	0 = none, 1 = equipped	-
addWeight	additional weight increase/reduction	Positive/negative number	lbs

Tank Car Safety Design Optimization



Tank Car Release Sources in Accidents





Accident-Caused Release Rate

$$P_R = \sum_j P_{Rj|A} Z$$

where:

P_R = accident-caused release rate

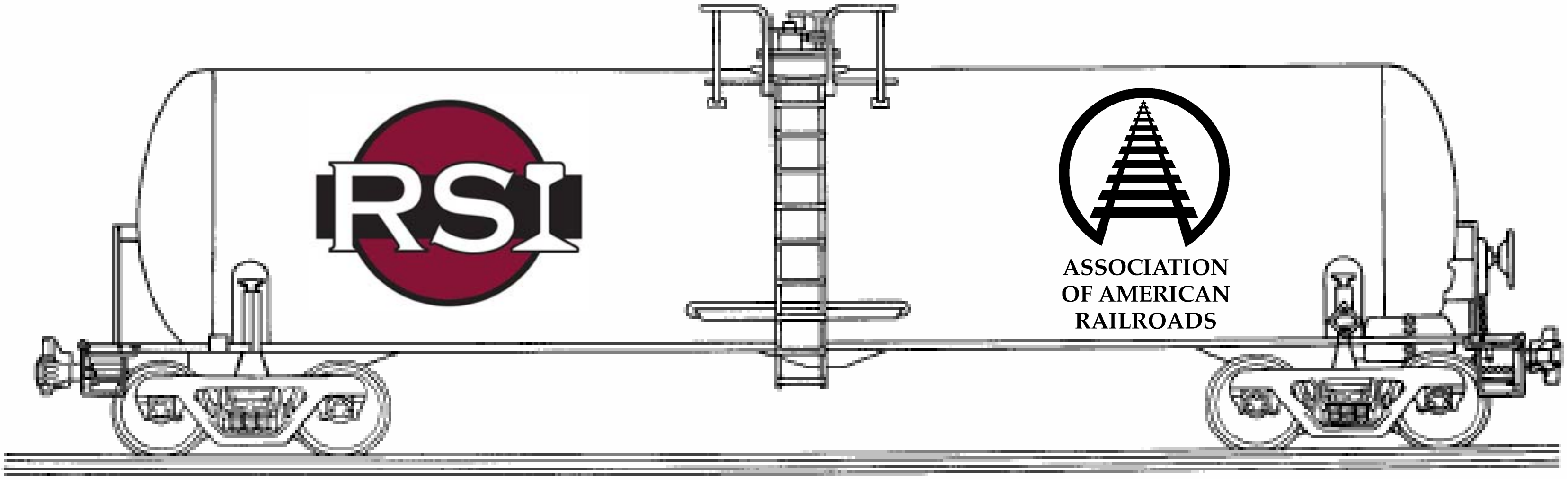
$P_{Rj|A}$ = conditional probability of release from source *j* given the car is derailed in an accident

Z = $P_A M$ = accident exposure

P_A = tank car derailment probability per mile traveled

M = number of car-miles

Railway Supply Institute - Association of American Railroads: Railroad Tank Car Safety Research and Test Project



- Formed in 1970
- Cooperative effort of tank car and railroad industries to improve tank car safety
- Comprehensive database of over 40,000 tank cars and the accidents they were involved in
- Provides a robust basis for quantitative analysis of tank car safety design

Conditional Probability of Release

- From the database, Wen and Simpson (*Treichel et al. 2005*) presented a logistic regression model to estimate tank car safety performance

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

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

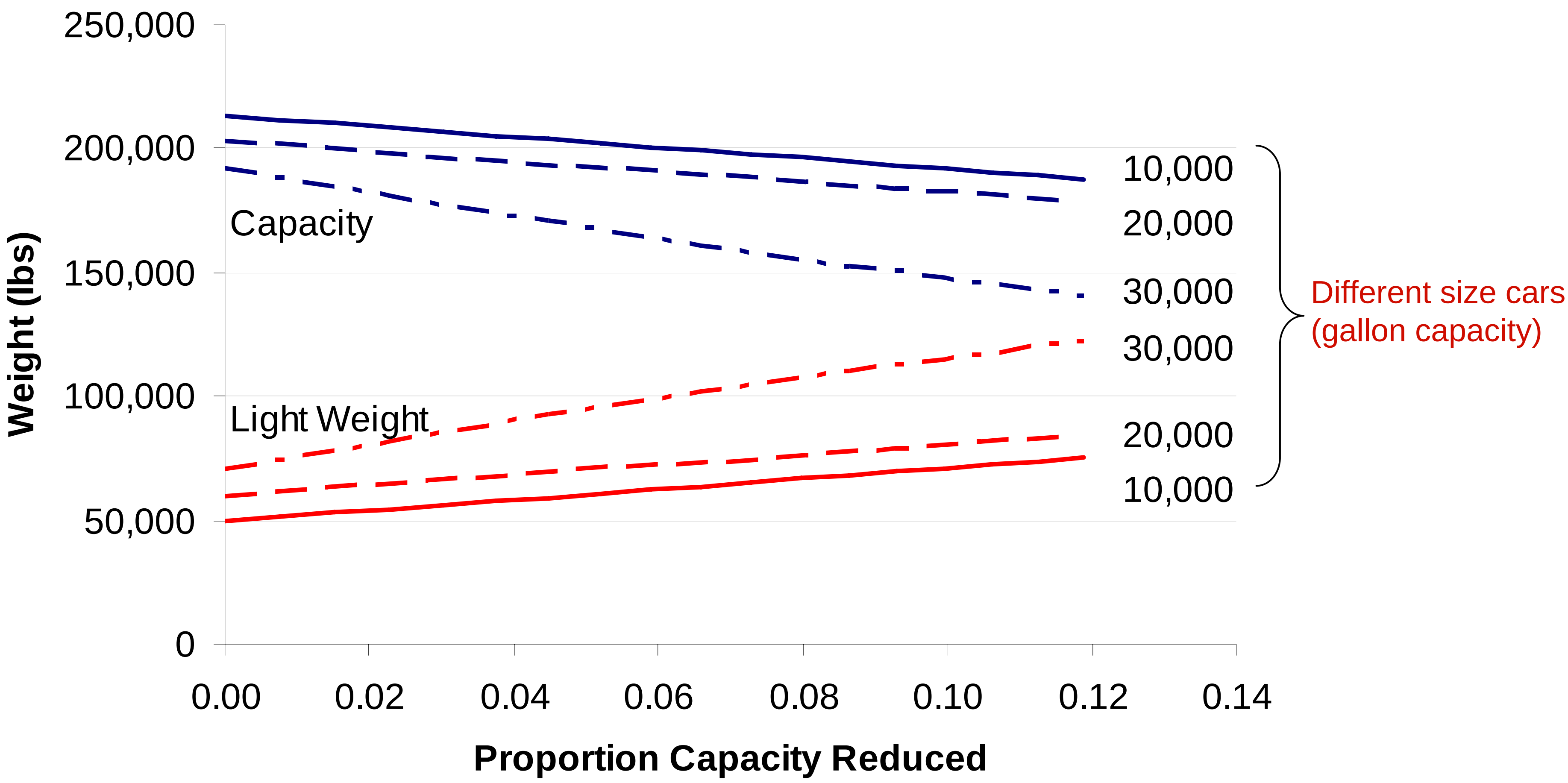
L(HEAD) = - 0.4492 - 1.1672 HST - 1.9863 HMT - 0.9240 INS - 0.4176 SHELF- 0.4905 YARD

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

Relationship Between More Robust Tank Cars, Capacity, and Number of Shipments



Capacity + Light Weight = Gross Rail Load (GRL) = 263,000 lbs

Relationship Between More Robust Tank Cars, Capacity, and Number of Shipments

- The change in the light weight/capacity changes the exposure term as follows:

$$Z \quad = P_A \, M \, S$$

where:

P_A = tank car derailment probability per mile traveled

M = number of car-miles

S = shipment multiplier = Cap/Cap′

Cap = nominal gallon capacity of a baseline tank car

Cap′ = nominal gallon capacity of a tank car with improved safety design

Accident-Caused Release Rate

$$P_R = \sum_j P_{Rj|A} P_A M S$$

where:

P_R = accident-caused release rate

$P_{Rj|A}$ = conditional probability of release from source j given the car is derailed in an accident

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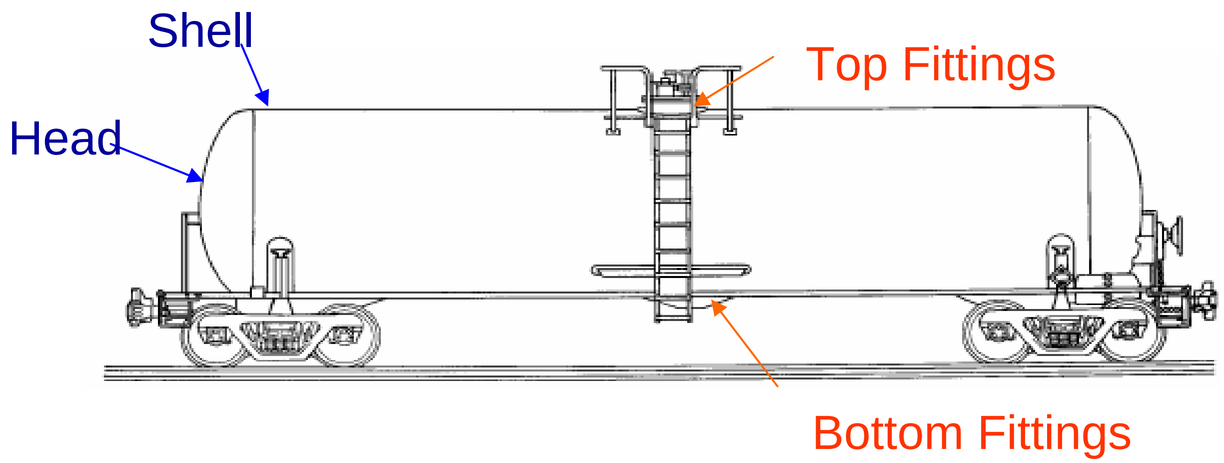
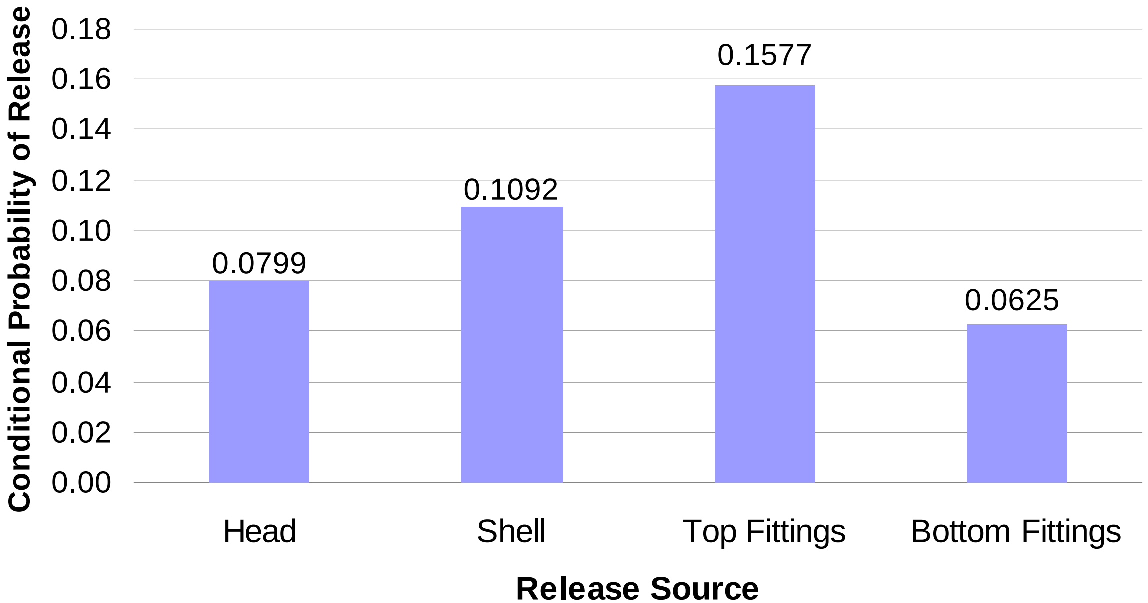
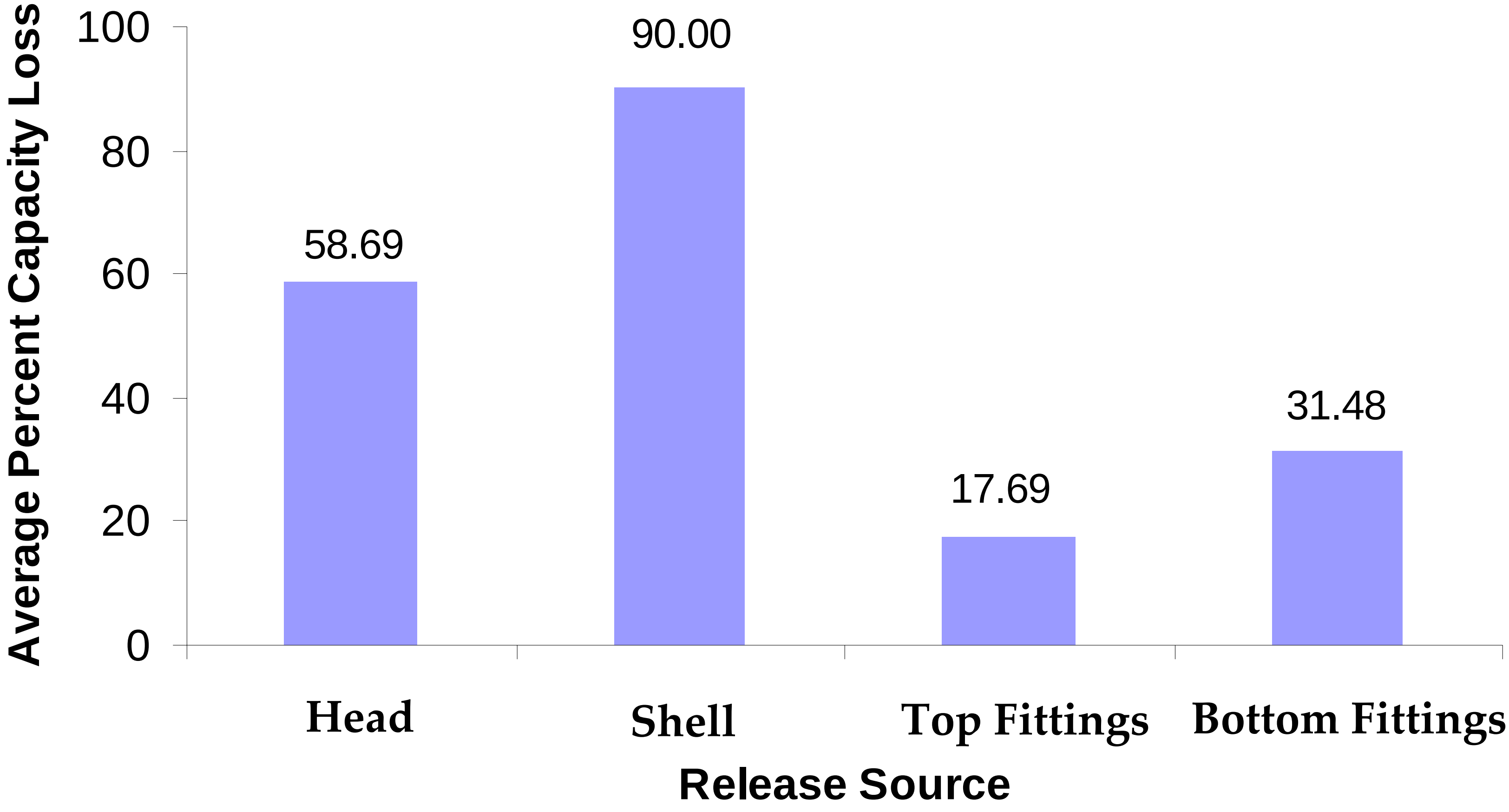
Tank Car Release Sources in Accidents





Tank Car Release Size Distribution



Expected Quantity of Release

$$R_R = \frac{P_R}{P_{R|A}} E_{Gal_{R|R}}$$

where:

R_R = expected gallon capacity lost

$$E_{Gal_{R|R}} = Cap \sum_i \hat{P}_{R_i|A} Q_i$$

where:

$E_{Gal_{R|R}}$ = expected gallon capacity lost given a tank car release

Q_i = average percent tank capacity lost from source *i*

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

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

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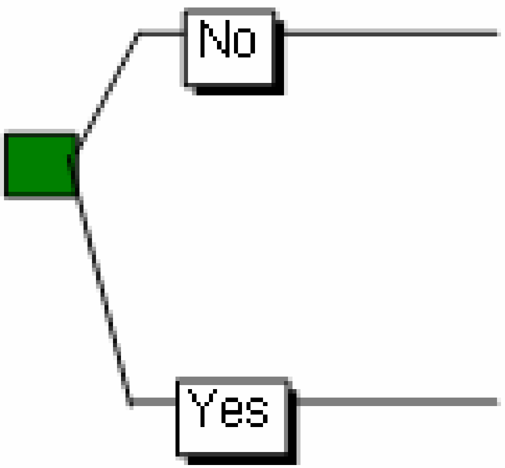
Baseline Tank Car Safety Design

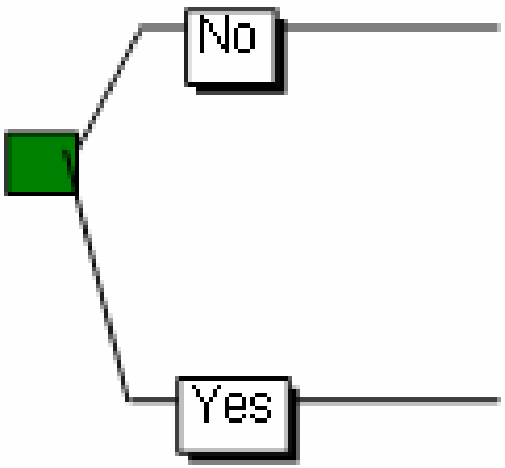
- Example of a commonly used tank car design
  - Class DOT 111A100W1
  - Non-pressure, non-insulated car used for transporting liquids
  - Various top fittings for loading, pressure relief, gauging, etc.
  - Bottom outlet for gravity unloading
  - 7/16" A-516 steel tank

Considered as a baseline safety design for improvement

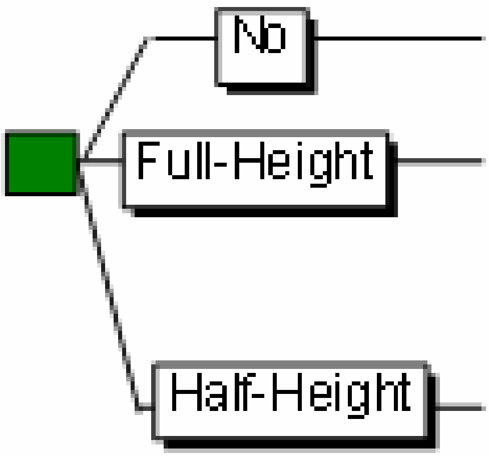
Non-Pressure Tank Car Risk Reduction Options



Bottom Fittings Removal
BFR



Top Fittings Protection
TFP



Head Protection
HHP/FHP

Generic Decision Tree Representing RRO Combinations

Notation

RRO	Definition
H	Increasing tank head thickness
S	Increasing tank shell thickness
HHP	Using half-height head protections
FHP	Using full-height head protections
BFR	Removing bottom fittings
TFP	Adding top fittings protection

Possible Risk Reduction Option Combinations

RRO Combination	Descriptions
H S	Improved head and/or shell thicknesses
H S HHP	Improved head and/or shell thicknesses with 0.5"-half-height head protection
H S FHP	Improved head and/or shell thicknesses with 0.5"-full-height head protection
H S TFP	Improved head and/or shell thicknesses with top fittings protection
H S BFR	Improved head and/or shell thicknesses with removed bottom fittings
H S TFP BFR	Improved head and/or shell thicknesses with top fittings protection and removed bottom fittings
H S HHP TFP	Improved head and/or shell thicknesses with 0.5"-half-height head protection and top fittings protection
H S FHP TFP	Improved head and/or shell thicknesses with 0.5"-full-height head protection and top fittings protection
H S HHP BFR	Improved head and/or shell thicknesses with 0.5"-half-height head protection and removed bottom fittings
H S FHP B	Improved head and/or shell thicknesses with 0.5"-full-height head protection and removed bottom fittings
H S HHP TFP BFR	Improved head and/or shell thicknesses with 0.5"-half-height head protection, top fittings protection and removed bottom fittings
H S FHP TFP BFR	Improved head and/or shell thicknesses with 0.5"-full-height head protection, top fittings protection and removed bottom fittings

Tank Car Safety Design Optimization Model

Vector of objective functions:

$$F_{m,n} \propto RRO_j$$

where:

m = percent reduction in capacity
n = percent reduction in the release rate

$Cap + LW \leq GRL$ ← Weight-capacity constraint

$LW \propto RROj$ ← Effect of improving tank car design to its weight

RRO_{BFR} = Yes, No

RRO_{TF} = Yes, No

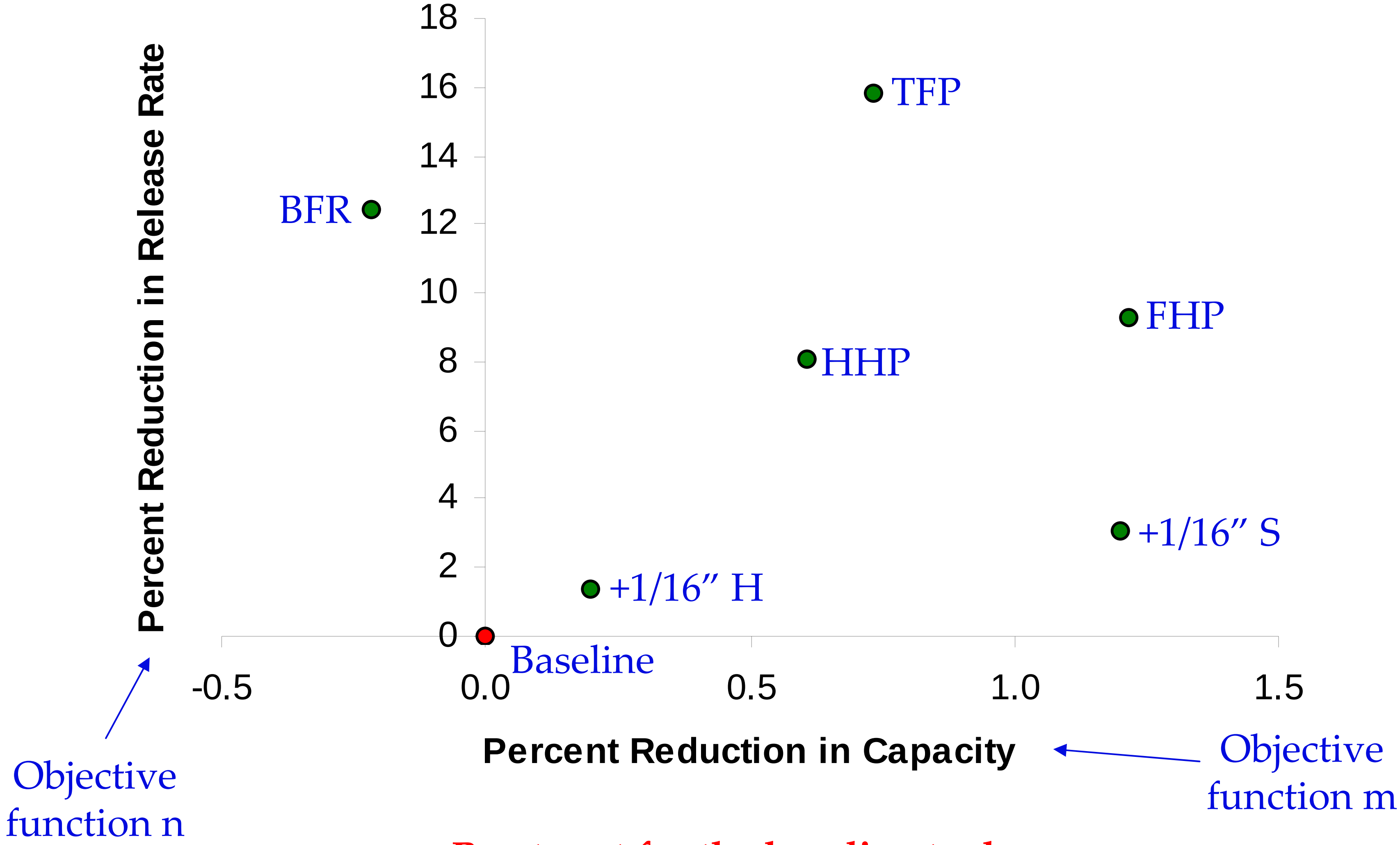
RRO_{HP} = HHP, FHP, No

RRO_{H} = 7/16″-3″ with 1/16″-increment

RRO_{S} = 7/16″-3″ with 1/16″-increment

} Options to improve tank car safety design

Tank Car Safety Design Optimization Model



Pareto set for the baseline tank car

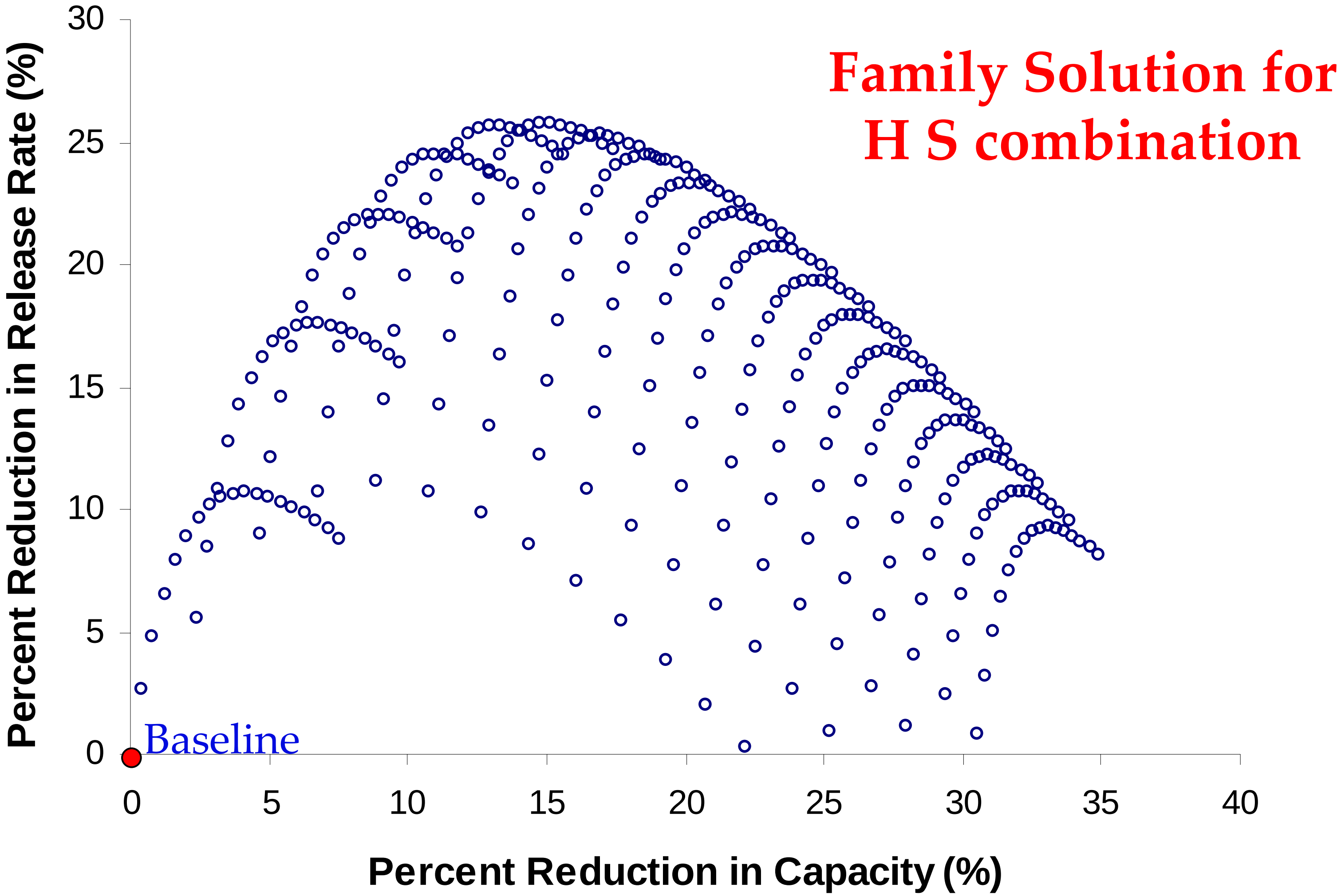
Release Rate Enumeration

Head Thickness (inch)

Shell Thickness (inch)	0.4375	0.5000	0.5625	0.6250	0.6875
0.4375	4.41%	4.35%	4.29%	4.24%	4.19%
0.5000	4.27%	4.21%	4.15%	4.10%	4.05%
0.5625	4.16%	4.10%	4.03%	3.98%	3.93%
0.6250	4.08%	4.01%	3.94%	3.89%	3.84%
0.6875	4.01%	3.94%	3.88%	3.82%	3.76%

- For each of the risk reduction option combination, the release rate is enumerated with incremental head and shell thicknesses, up to 3”

Tank Car Safety Design Optimization Model



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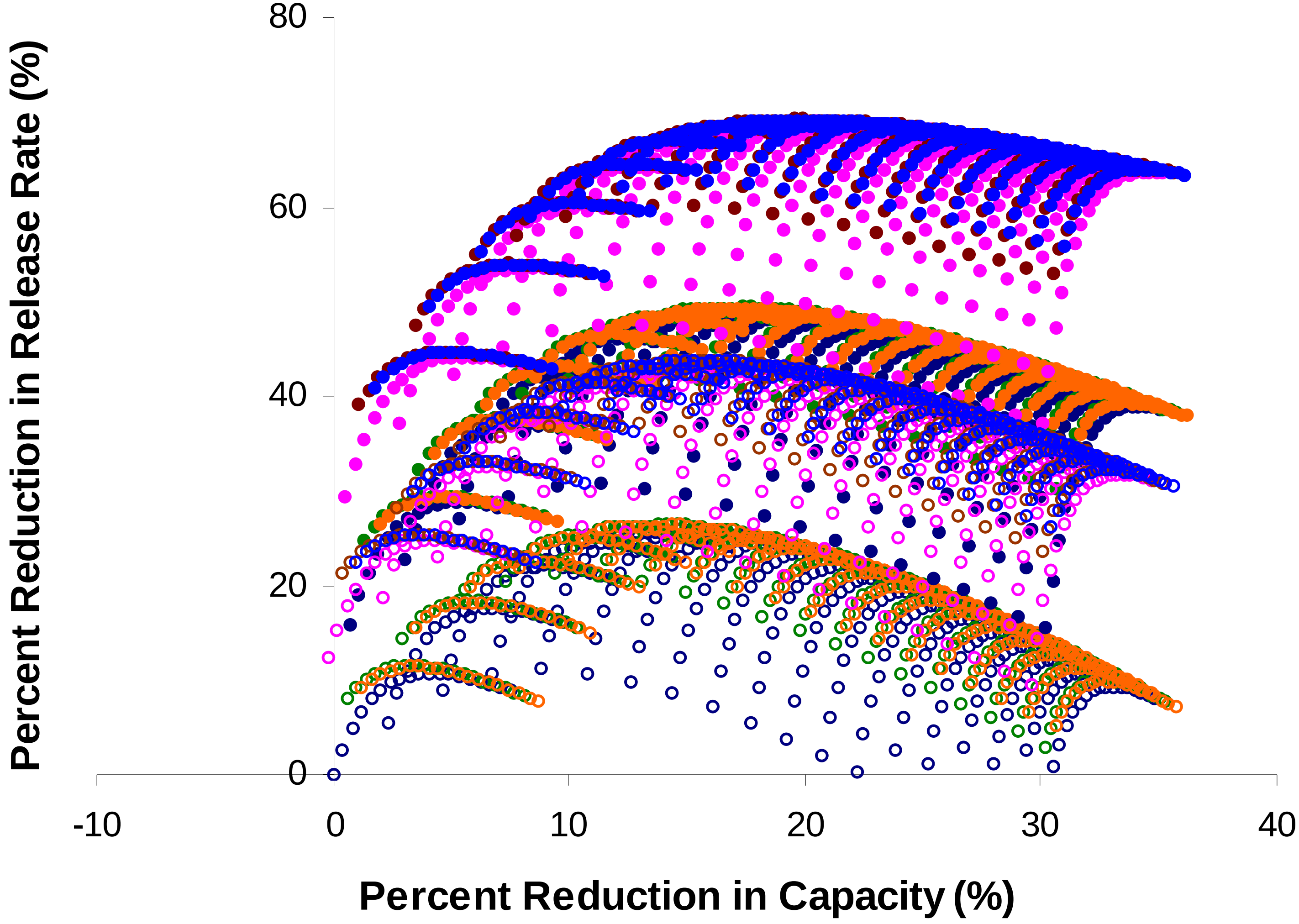

Pareto set for the baseline tank car

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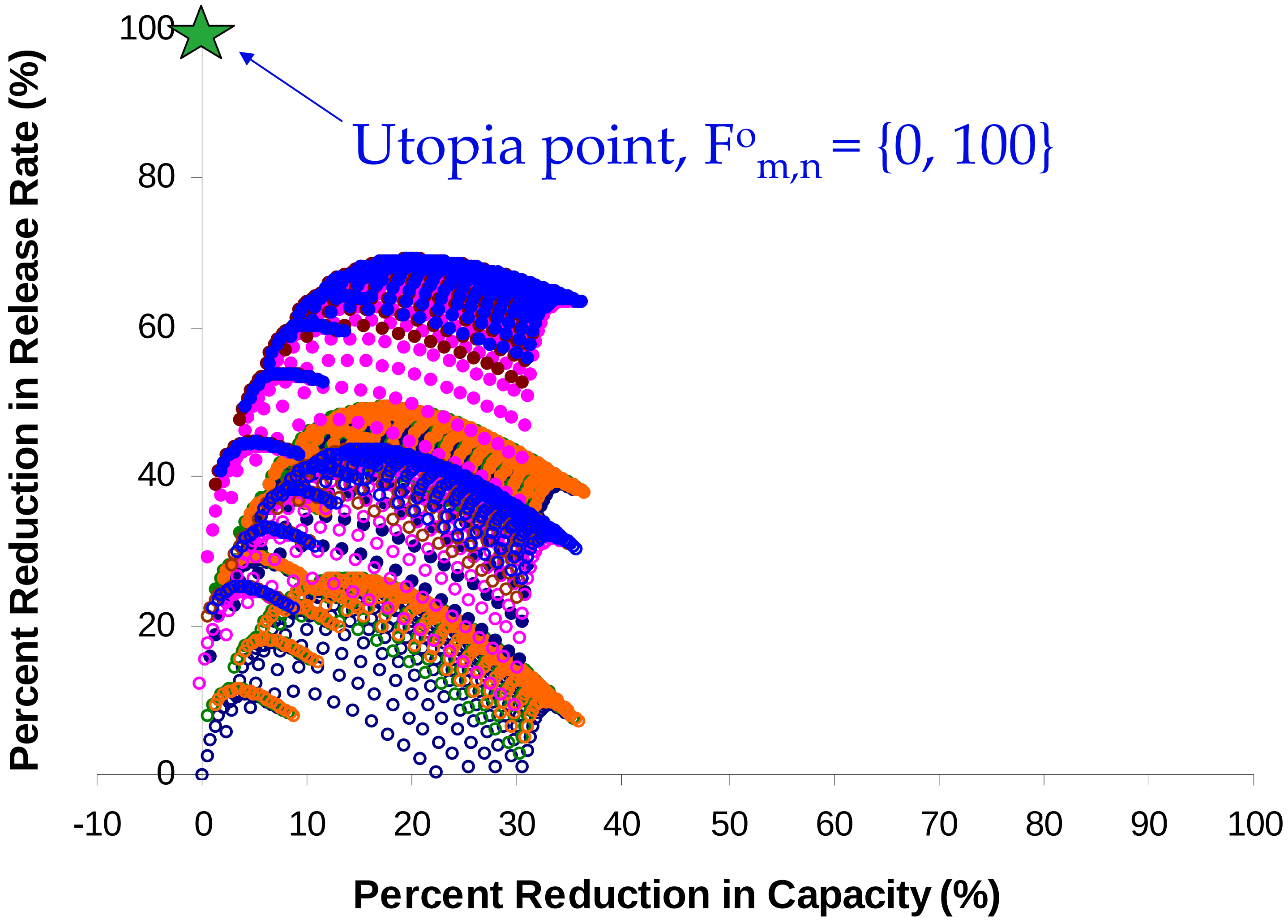


Pareto set for the baseline tank car

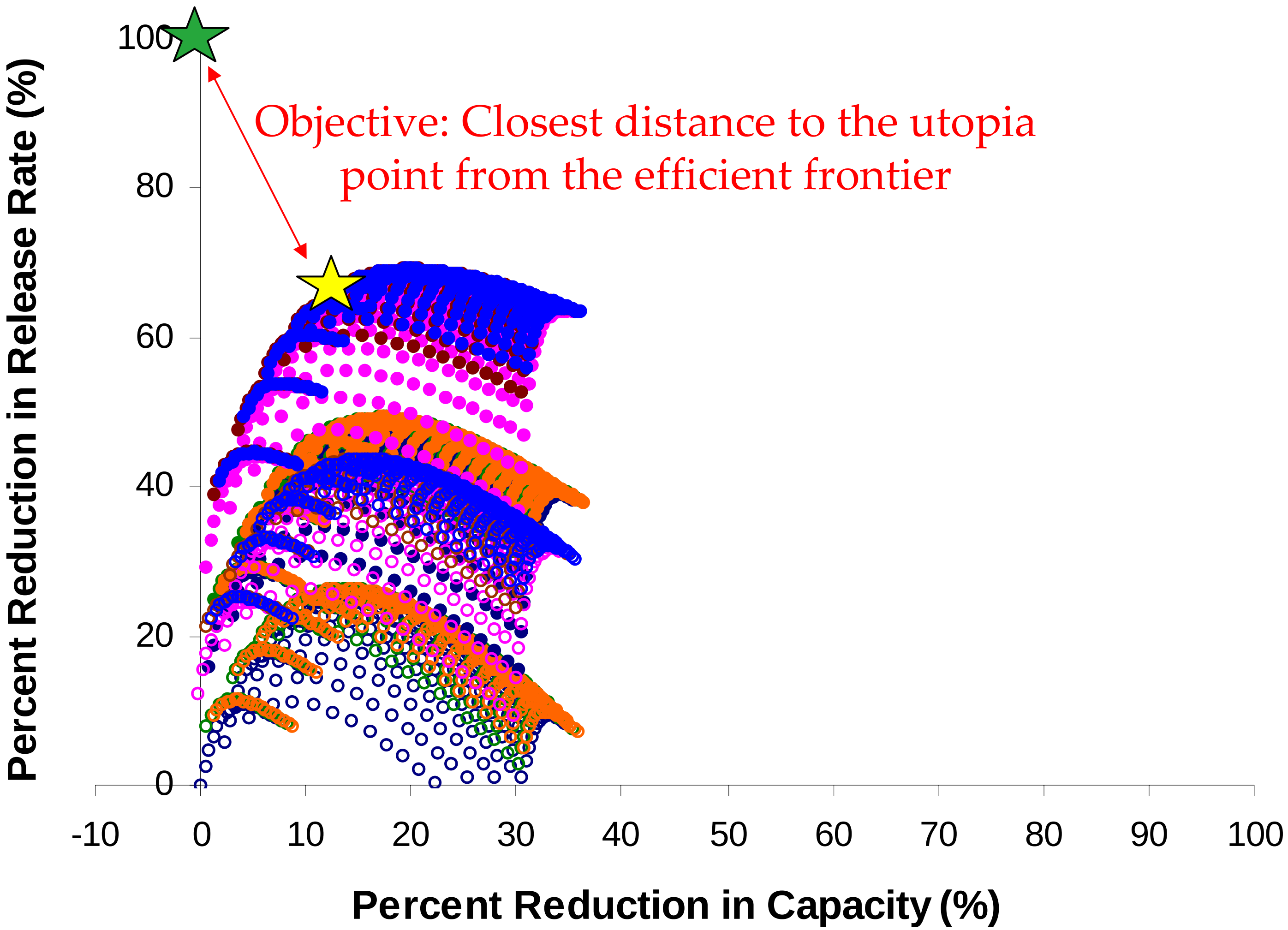
Tank Car Safety Design Optimization Model

Minimize $N(x) = |F(x) - F^o| = \left\{ \sum_{m,n}^{i} [F_i(x) - F_i^o]^2 \right\}^{1/2}$

where:

N(x) = Euclidean distance
F(x) = objective functions vector
$F^o_{m,n}$ = utopia point vector
x = feasible design space

Tank Car Safety Design Optimization Model



Pareto set for the baseline tank car

Tank Car Safety Design Optimization Model

RRO Combination	Min Distance to Utopia Point	% Reduction in Capacity	% Reduction in Release Rate	Head Thickness (in.)	Shell Thickness (in.)
H S	75.46	12.89	25.65	1.8125	0.9375
H S HHP	74.69	11.94	26.27	1.3125	0.9375
H S FHP	74.80	12.12	26.19	1.1875	0.9375
H S TFP	53.66	15.77	48.71	1.9375	1.0625
H S BFR	58.68	14.93	43.25	1.9375	1.0625
H S TFP BFR	35.78	15.58	67.79	1.9375	1.0625
H S HHP TFP	53.01	14.83	49.11	1.4375	1.0625
H S FHP TFP	53.11	15.01	49.06	1.3125	1.0625
H S HHP BFR	58.00	13.99	43.71	1.4375	1.0625
H S FHP BFR	58.10	14.17	43.65	1.3125	1.0625
H S HHP TFP BFR	35.18	15.01	68.18	1.5625	1.0625
H S FHP TFP BFR	35.27	15.19	68.17	1.4375	1.0625

Possible solution set for the baseline tank car

Future Work

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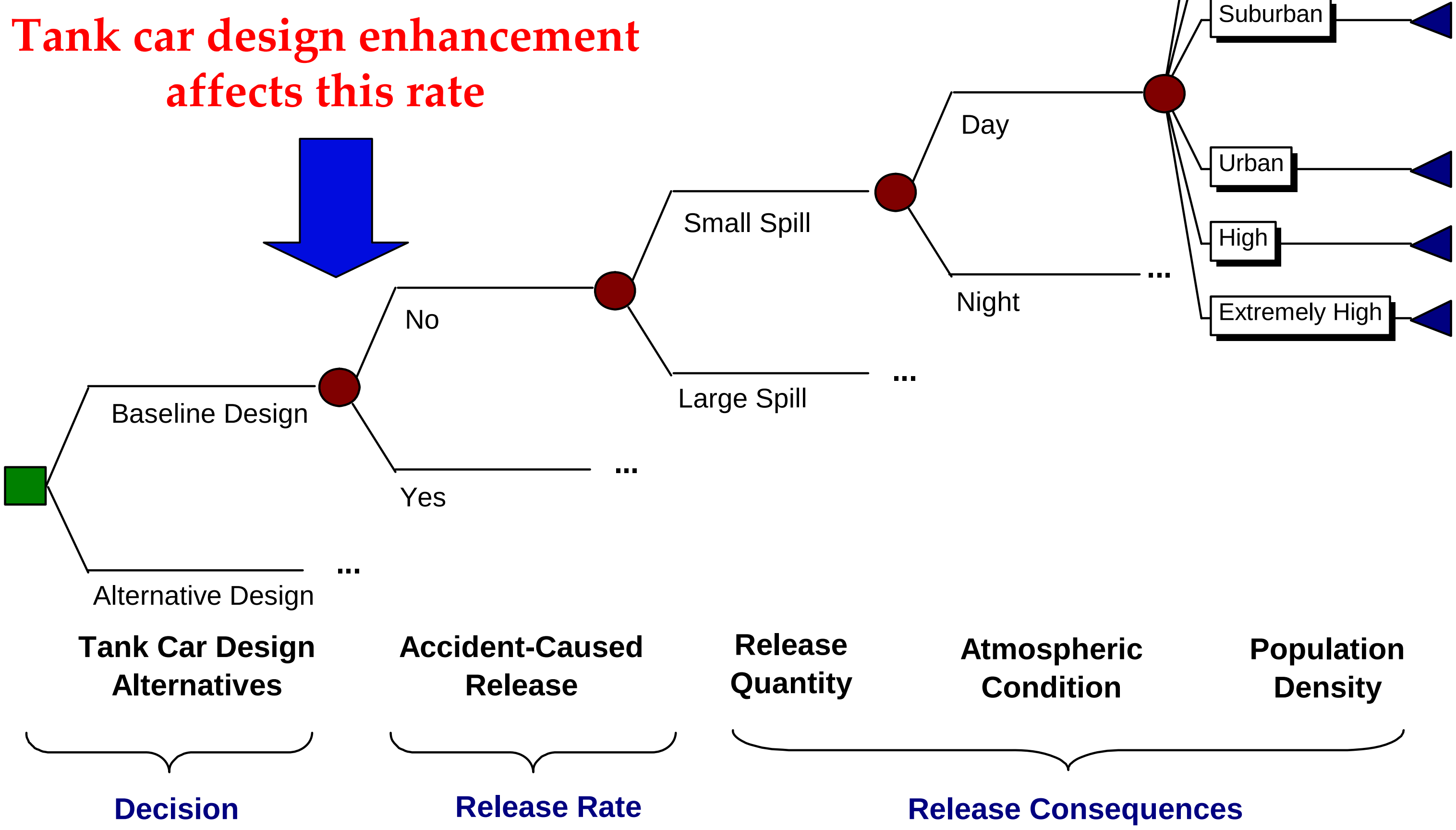
Risk-Based Decision Making

$$R = P \times C$$

Risk = probability of an event multiplied by the consequence of that event

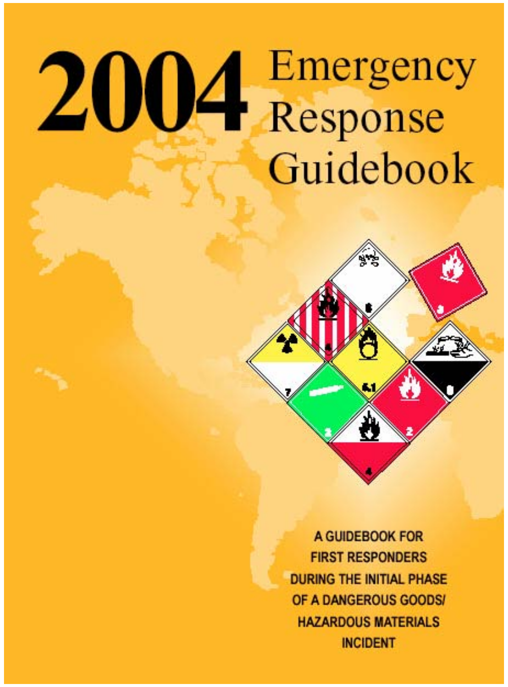
Toxic Inhalation Hazards (TIH) Risk Analysis Decision Tree



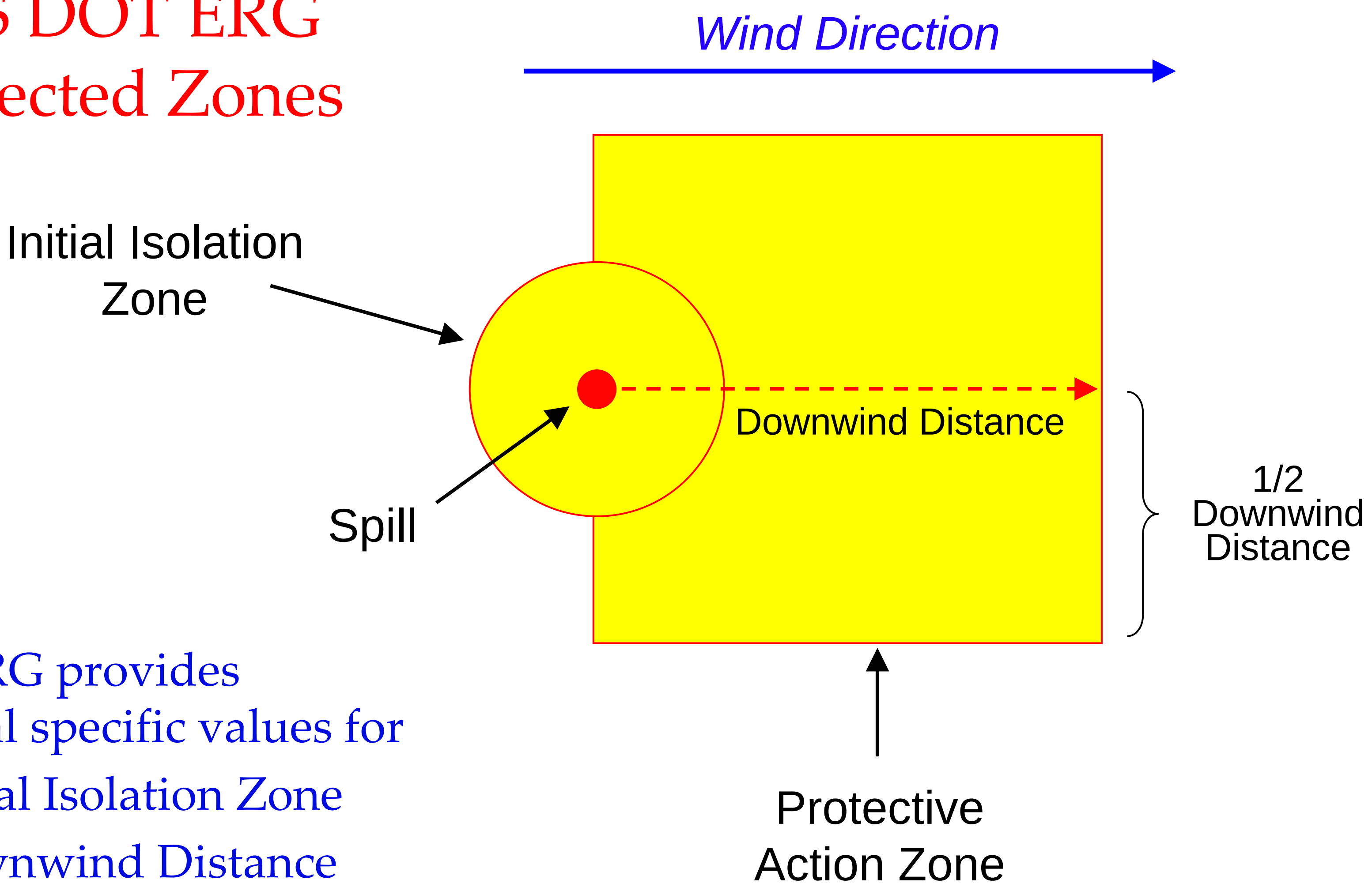
Consequence Estimation using US DOT ERG

- Affected by the behavior and toxicity of the chemical spilled
  - amount released
  - exposure of humans in the direction of the plume
  - weather conditions affecting plume formation and behavior

- ERG provides guidelines for area that should be evacuated in the event of a spill of most hazardous materials, including chlorine and ammonia
  - Good general guide to likely impact of a spill event
  - Familiar to railroads and widely used by emergency response community
  - Government figures
  - Based on nationwide, average meteorological conditions



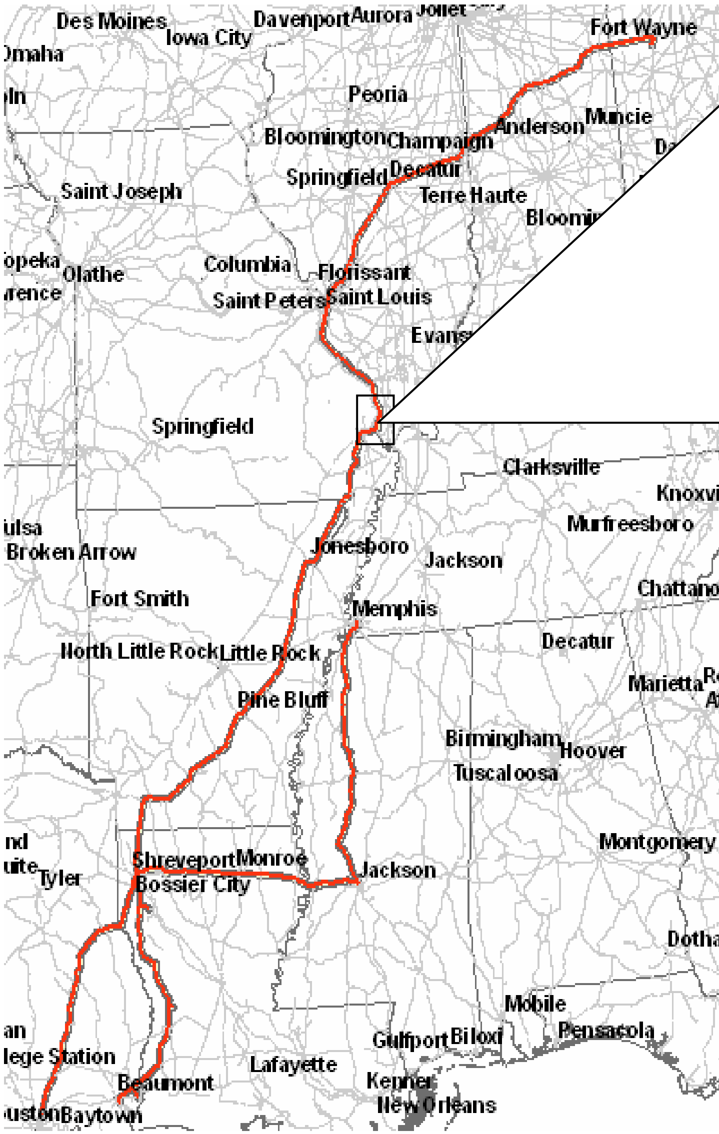
US DOT ERG Affected Zones

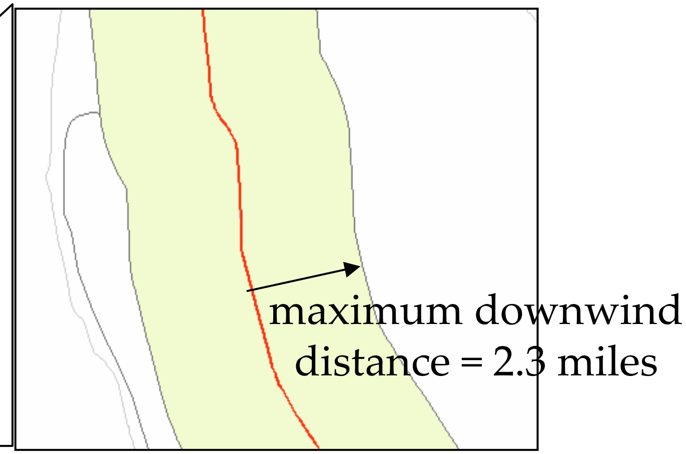


- DOT ERG provides chemical specific values for
  - Initial Isolation Zone
  - Downwind Distance
- These can be used to calculate an "*Affected Zone*" for each chemical
- *Affected Zone* = *Protective Action Zone* + 1/2 of *Initial Isolation Zone*

Example of population exposure along rail line

- Population distribution along chemical-specific routes was determined for micro-level risk exposure analyses

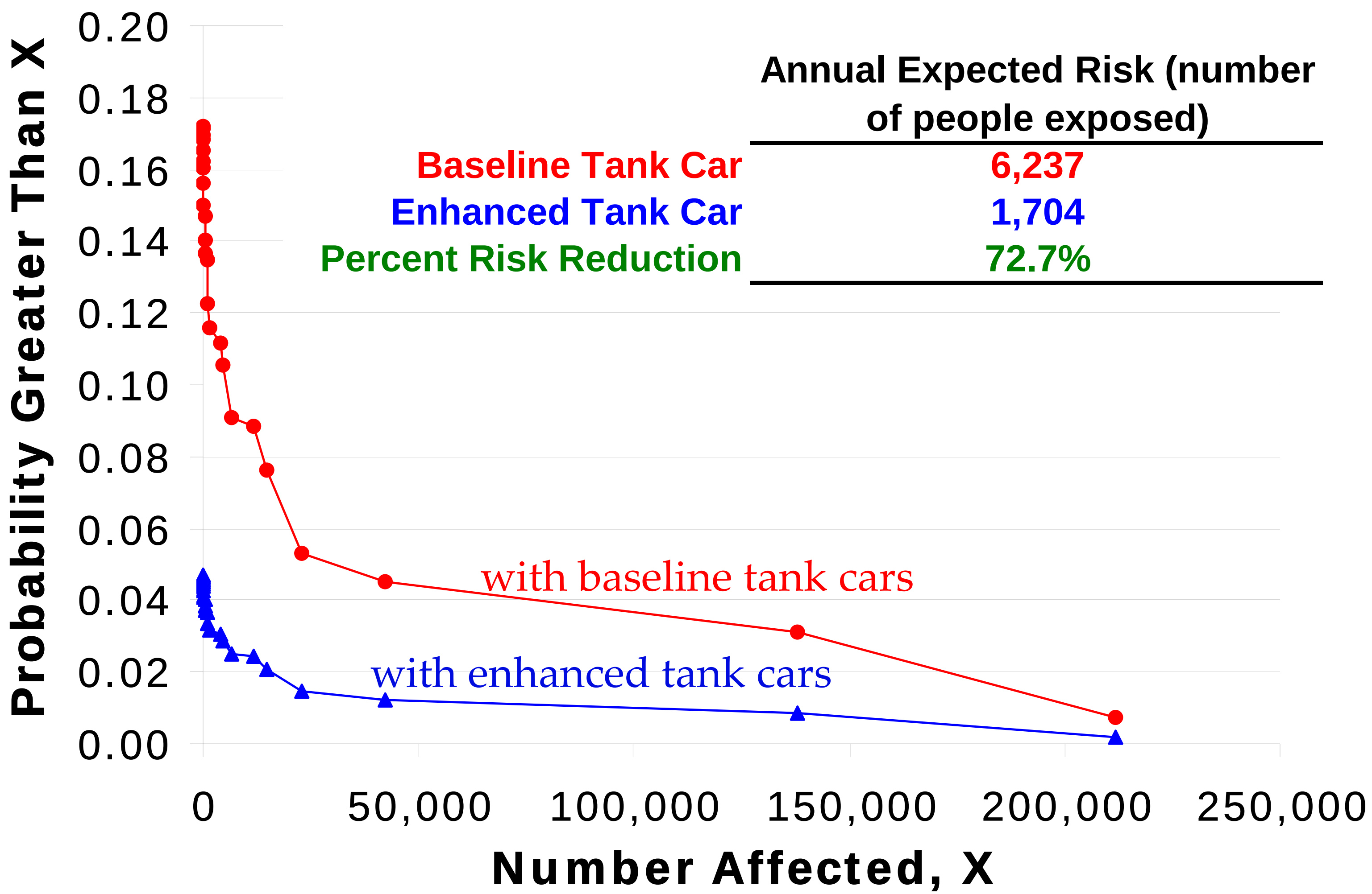




Population density (average people per square mile)	Percentage of Rail Mileage
Remote (10)	7.63%
Rural (60)	12.04%
Suburban (550)	24.27%
Urban (2,000)	29.25%
High (6,500)	26.70%
Very High (=10,000)	0.12%

Population exposure for a TIH

Annual Expected Risk & Risk Profile



	Annual Expected Risk (number of people exposed)
Baseline Tank Car	6,237
Enhanced Tank Car	1,704
Percent Risk Reduction	72.7%

Annual Risk for a TIH Rail Transport

Future Work

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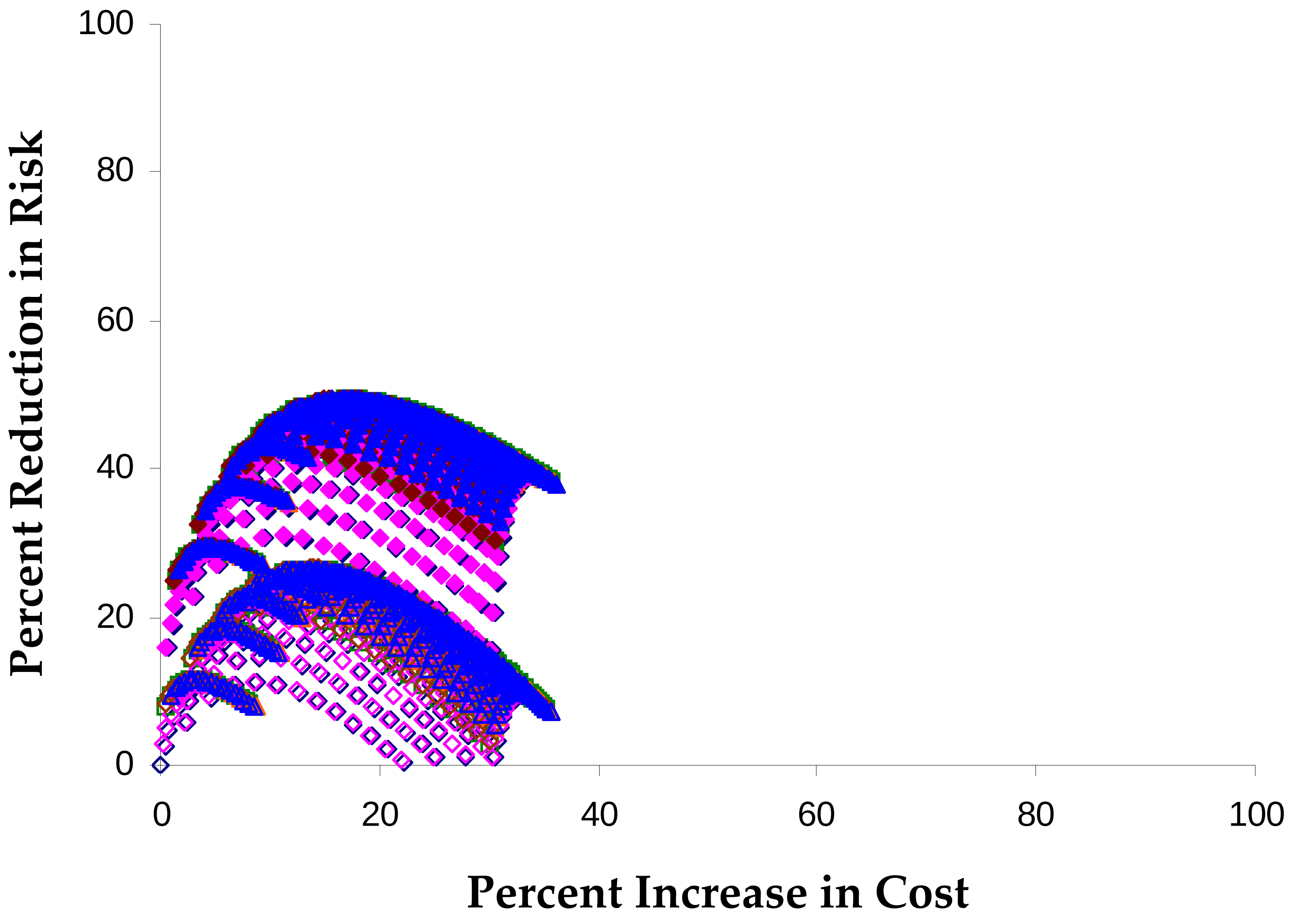
Consider cost-benefit implicitly



Future Work

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Decision Analysis Model
Multi-Attribute Utility Technique

Preference & Risk Tolerance Levels

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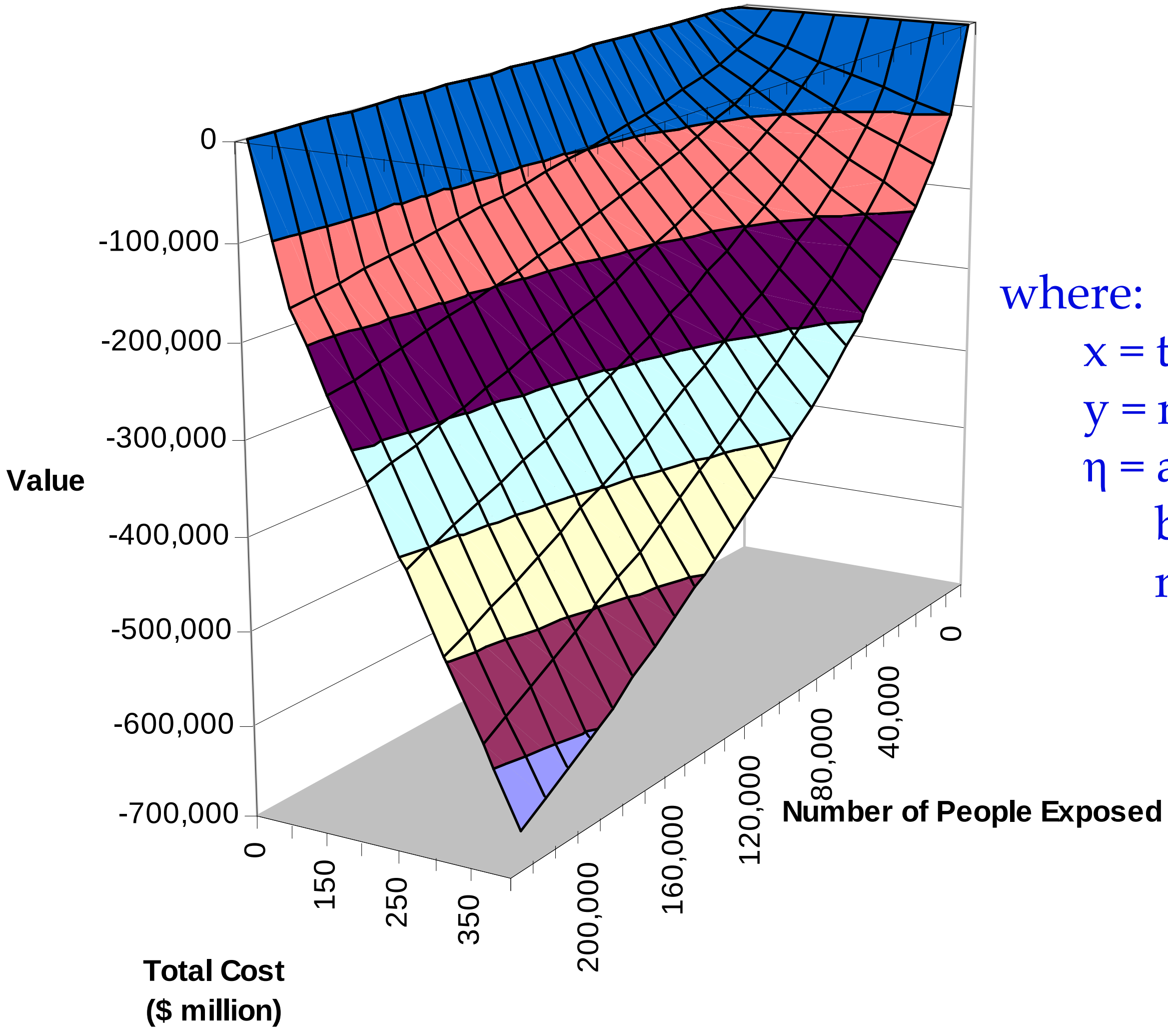
Incorporate Utility/Value Function in Decision Making



$V(x, y) = -x\, y^{\eta}$

where:

x = total cost

y = number of people exposed

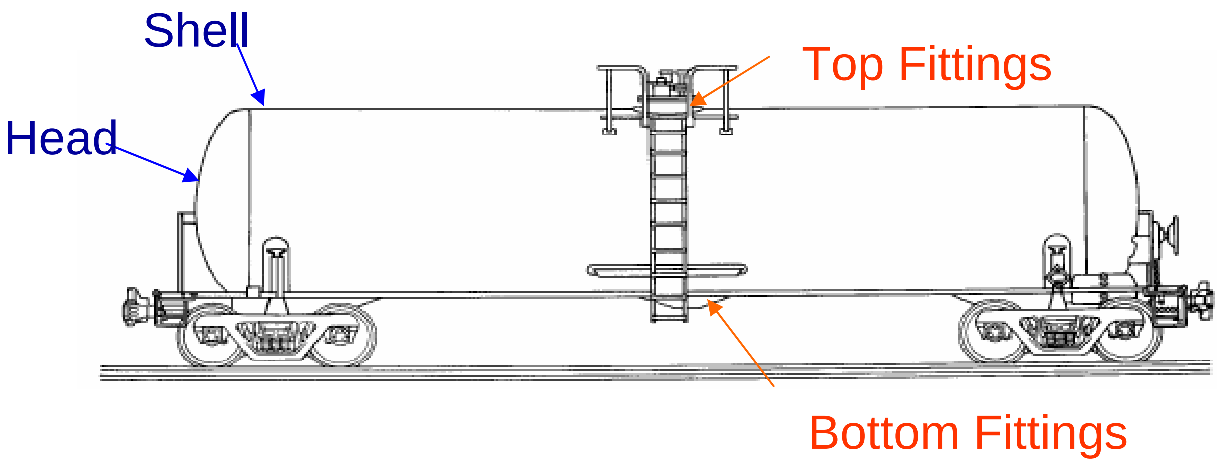
η = a measure of the tradeoff between total cost and number of people exposed

Summary

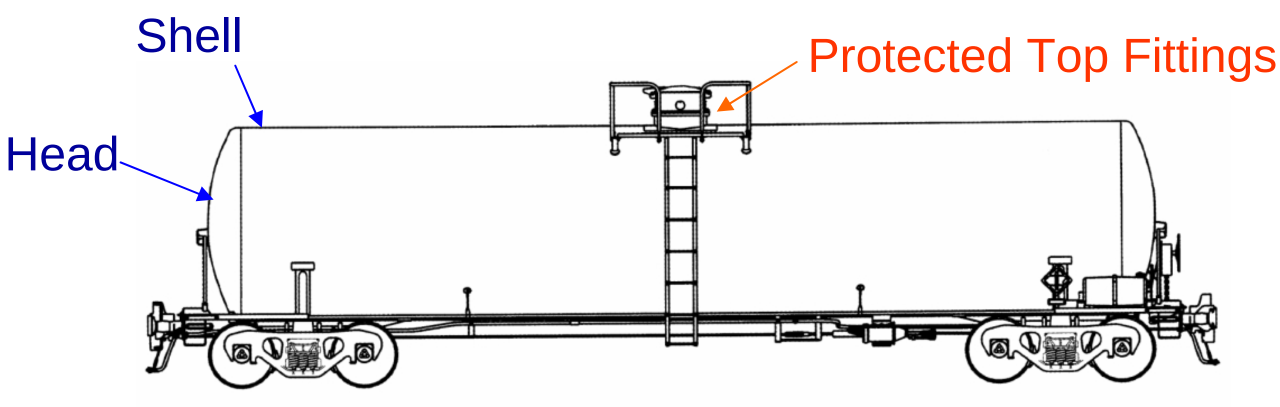
- Presented Tank Car Design Optimization Model
- Future work
  - incorporate cost and consequence models
  - develop model using the multi-attribute utility technique
  - application in Environmentally Sensitive Chemical (ESC) tank cars
  - consider non-conventional tank car safety design enhancement

QUESTIONS?

Non-Pressure vs. Pressure Tank Cars



Non-Pressure



Pressure