Railroad Hazardous Materials Transportation Risk Management Framework






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William W. Hay Railroad Engineering Seminar

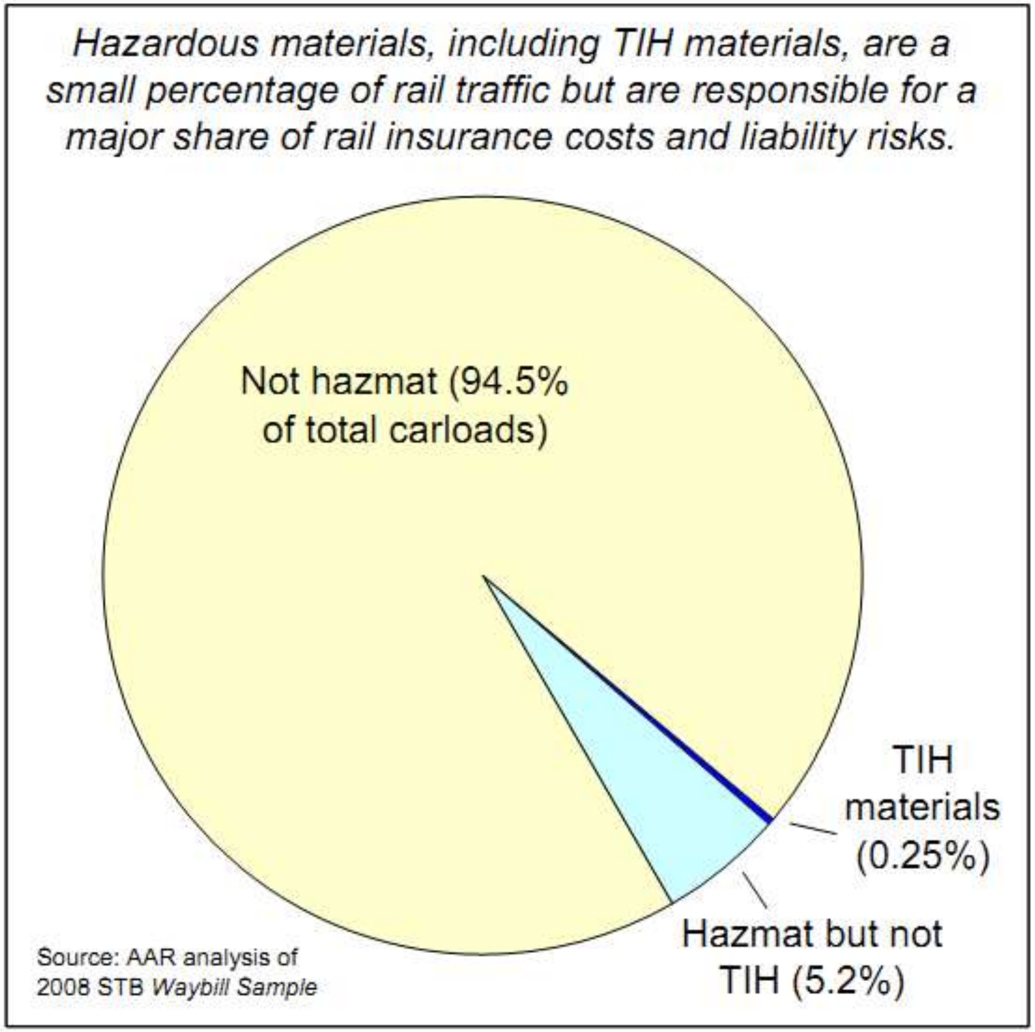
Rail Transportation and Engineering Center (RailTEC)

Outline

- Overview of hazardous materials transportation by rail
- Analytical framework for risk management
  - Accident analysis
    - train accident frequency and severity
    - accident causes
  - Risk analysis
    - modeling of hazardous materials release risk
    - evaluation of risk reduction strategies
  - Decision analysis
    - Optimization of risk reduction strategies
- Proposed dissertation research

Overview of railroad hazardous materials transportation

- There were 1.7 million rail carloads of hazardous materials (hazmat) in the U.S. in 2010 (AAR, 2011)
- Hazmat traffic account for a small proportion of total rail carloads, but its safety have been placed a high priority



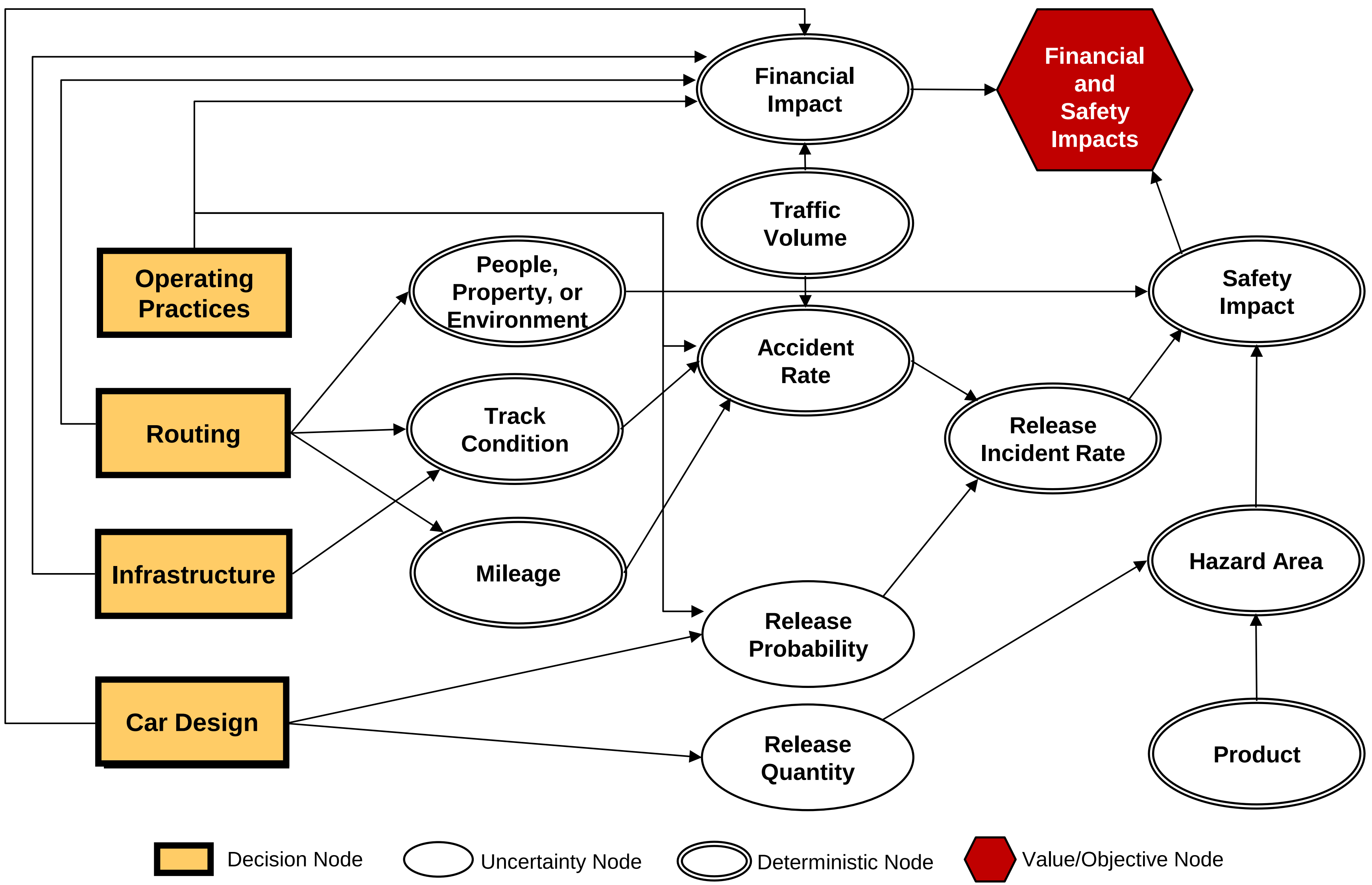
Safety of railroad hazmat transportation

- 99.998% of rail hazmat shipments reached their destinations without a train-accident-caused release in 2008 (AAR, 2011)

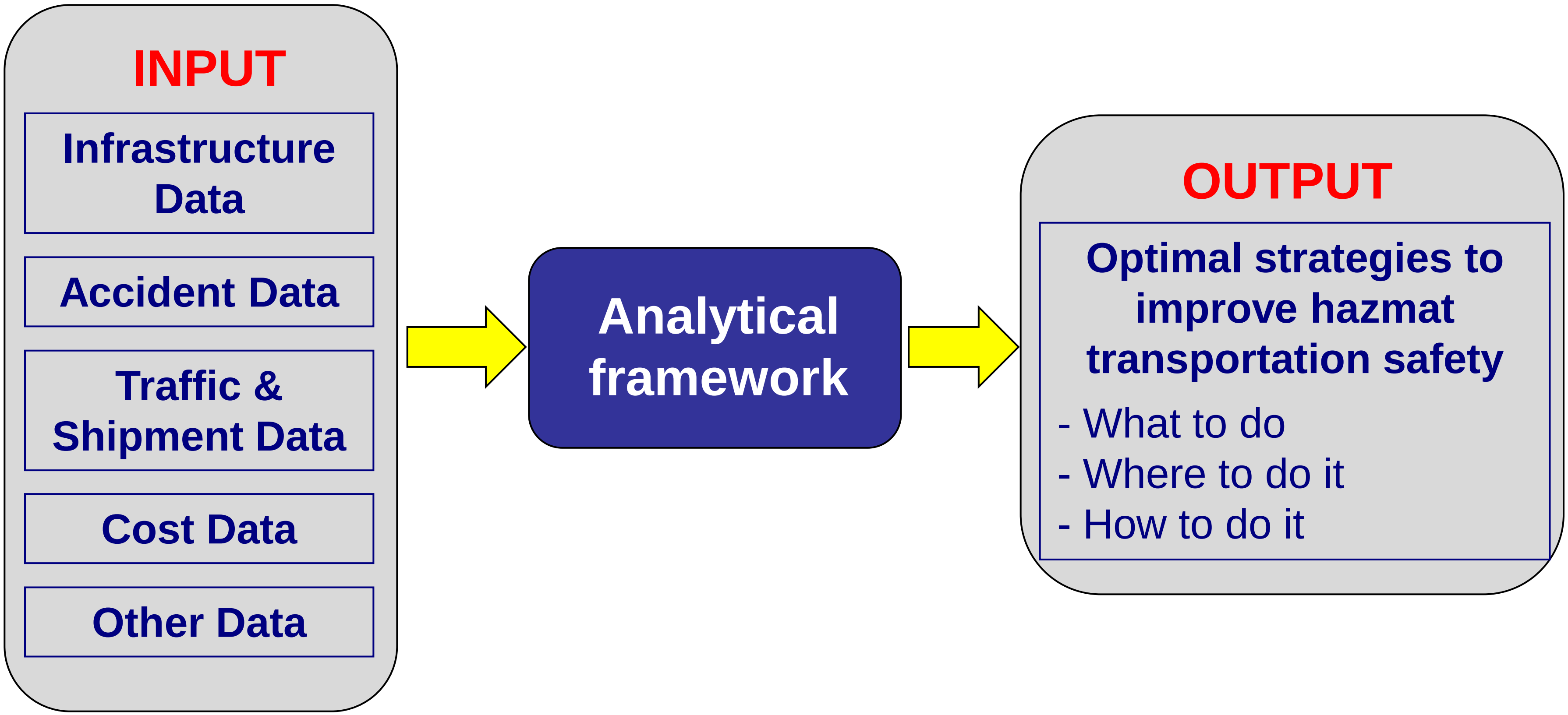
- Train-accident-caused hazmat release rates have declined by about 90% since 1982
  - about 200 cars released per million carloads in 1982
  - about 21 cars released per million carloads in 2010

- Further improvement in the transportation safety remains a high priority of the rail industry and government

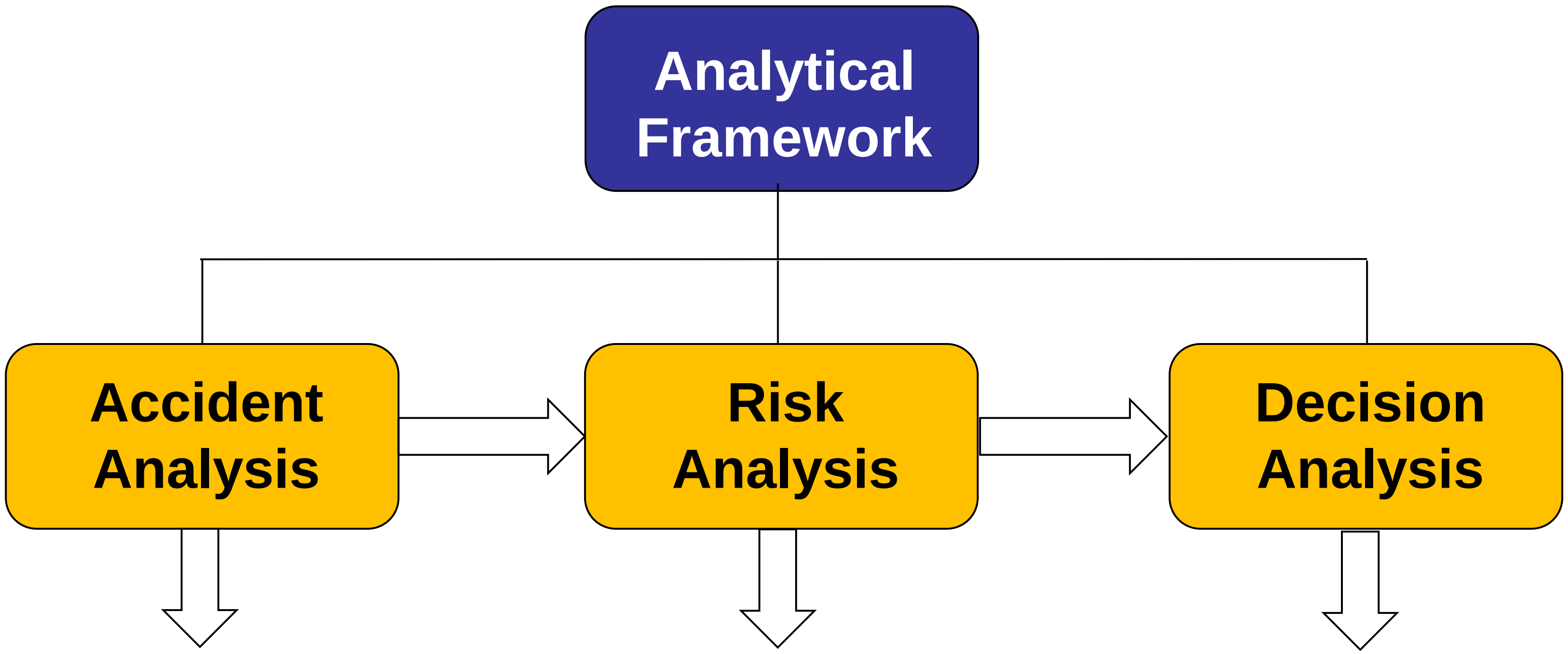
Influence diagram showing relationships of factors affecting hazardous materials transportation safety



Railroad hazardous materials transportation risk management framework



Analytical models for risk management

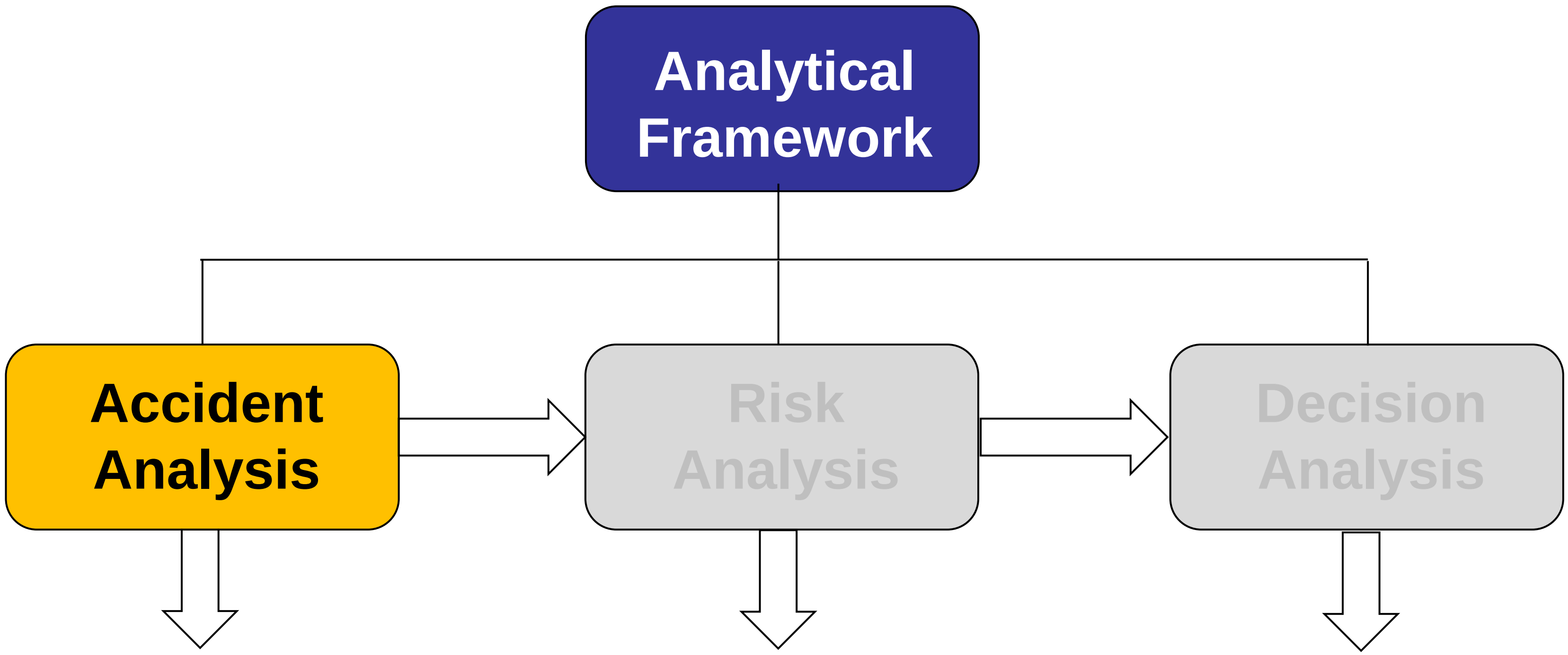


- Train accident frequency and severity
- Train accident causes

- Risk modeling
- Evaluation of risk reduction strategies

- Optimizing risk reduction strategies

Analytical models for risk management



- **Train accident frequency and severity**
- **Train accident causes**

- Risk modeling
- Evaluation of risk reduction strategies

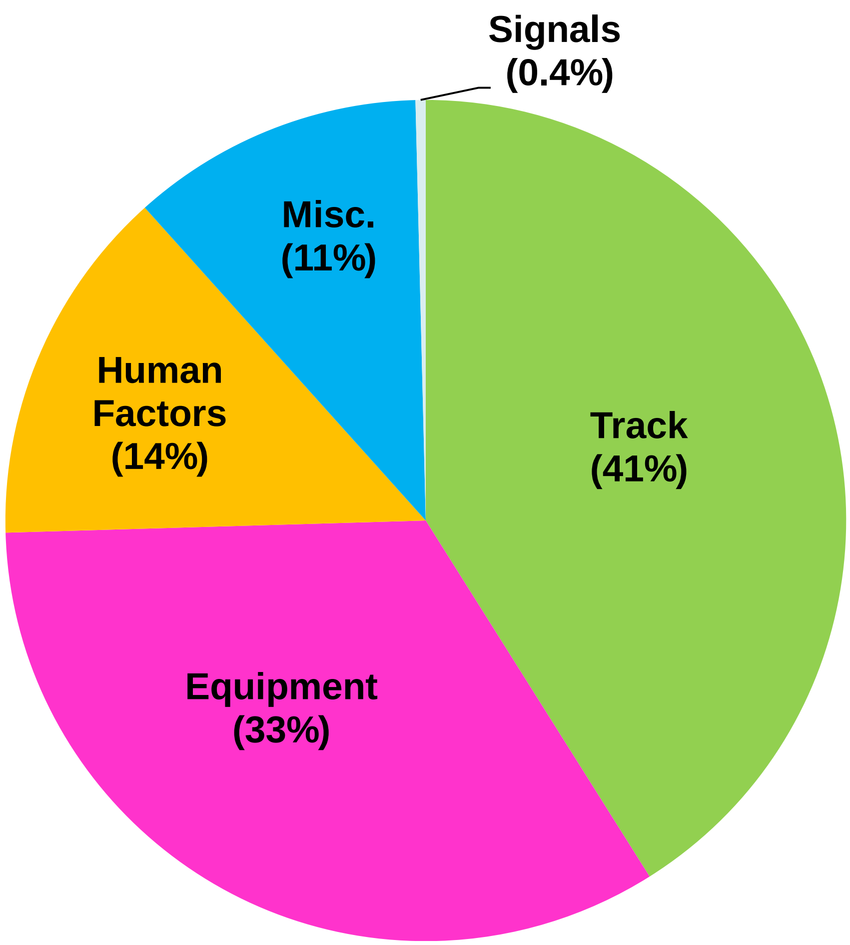
- Optimizing a combination of risk reduction strategies

FRA Rail Equipment Accident (REA) database

- The U.S. Federal Railroad Administration (FRA) Rail Equipment Accident (REA) database records all accidents that exceeded a monetary threshold of damages*
- The REA database records railroad, accident type, location, accident cause, severity and other information important for accident analysis and prevention
- This study focuses on Class I freight railroads (operating revenue exceeding $378.8 million in 2009), that account for
  - 68% of U.S. railroad route miles
  - 97% of total ton-miles
  - 94% of total freight rail revenue

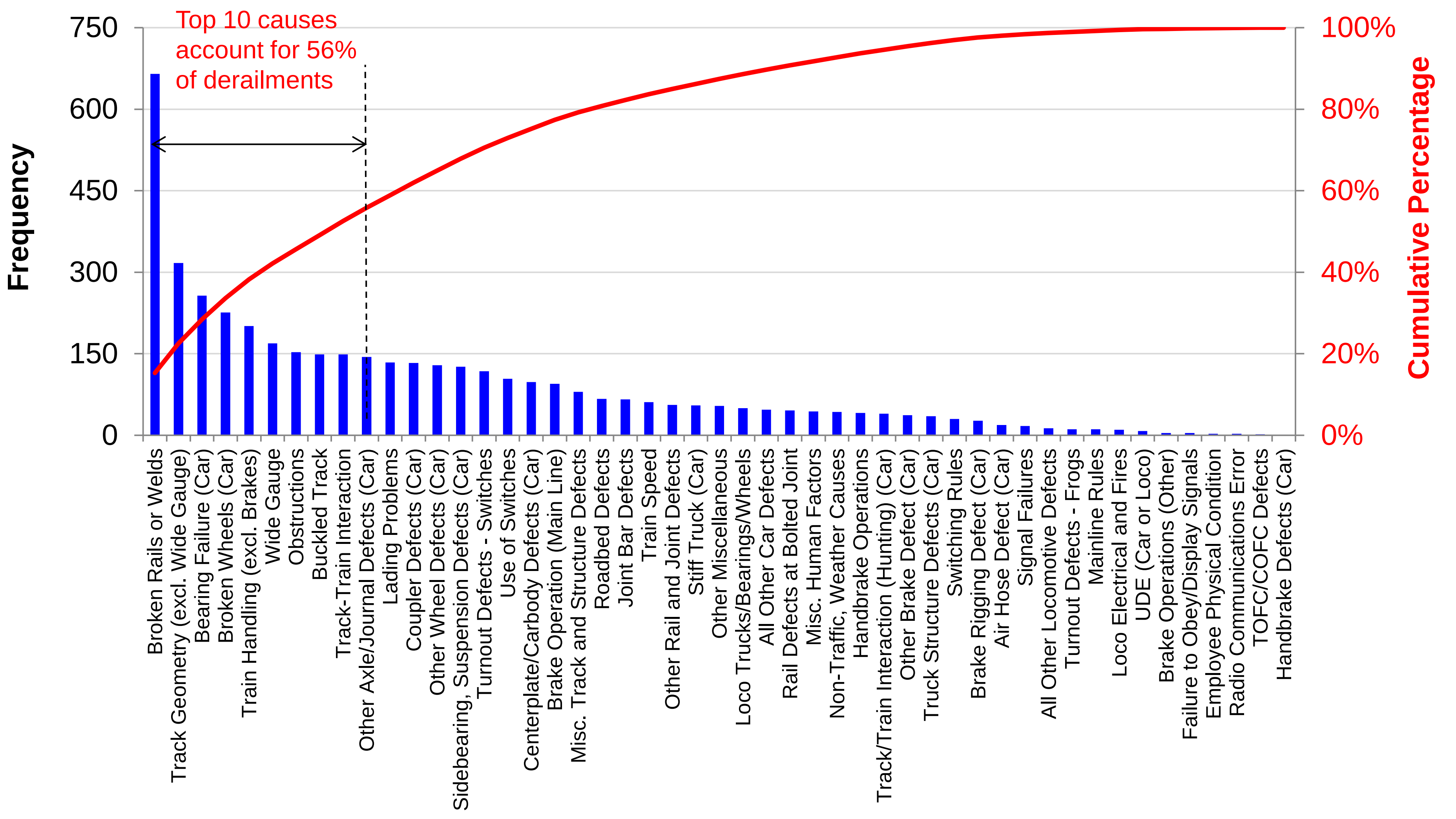
It accounts for damage to on-track equipment, signals, track, track structures, and roadbed. The reporting threshold is periodically adjusted for inflation, and has increased from $7,700 in 2006 to $9,400 in 2011.

Freight-train derailments on Class I mainlines by accident cause group: 2001-2010

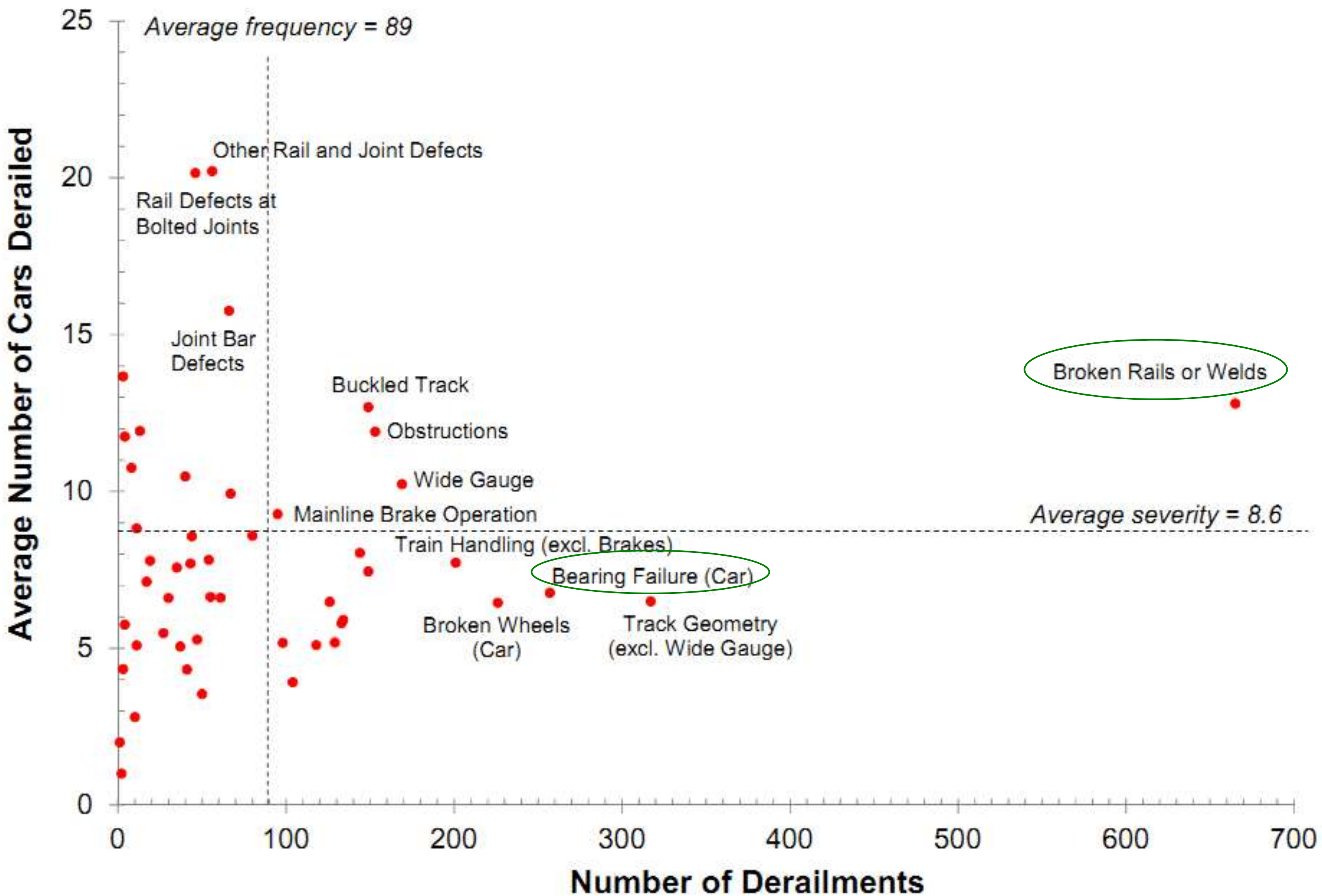


Data source: FRA Rail Equipment Accident (REA) database, 2001 to 2010

Class I mainline freight-train derailment frequency by cause, 2001-2010

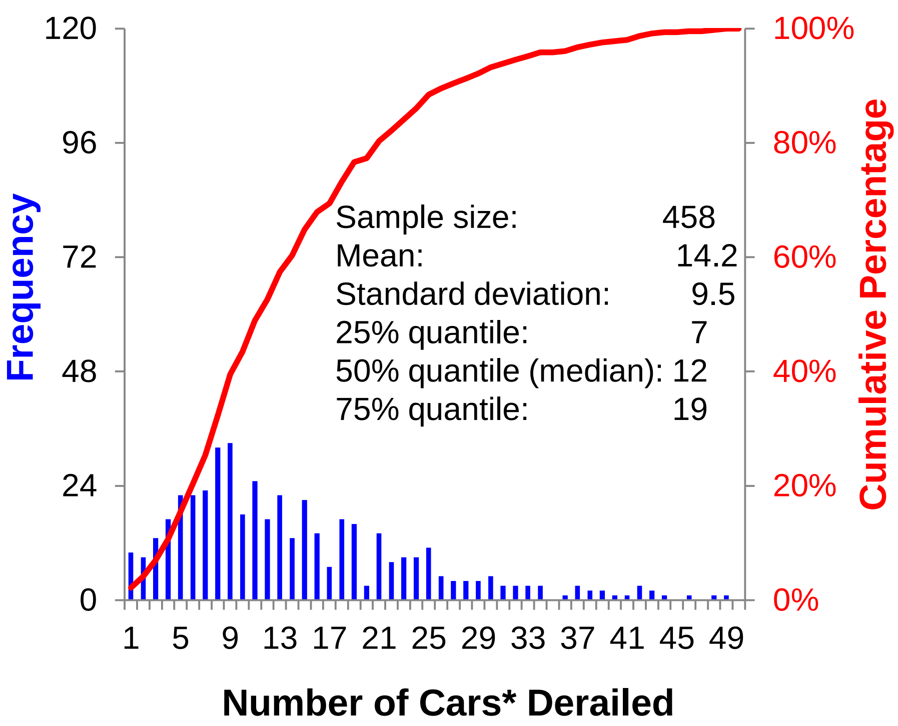


Frequency-severity graph of Class I mainline freight-train derailments, 2001-2010

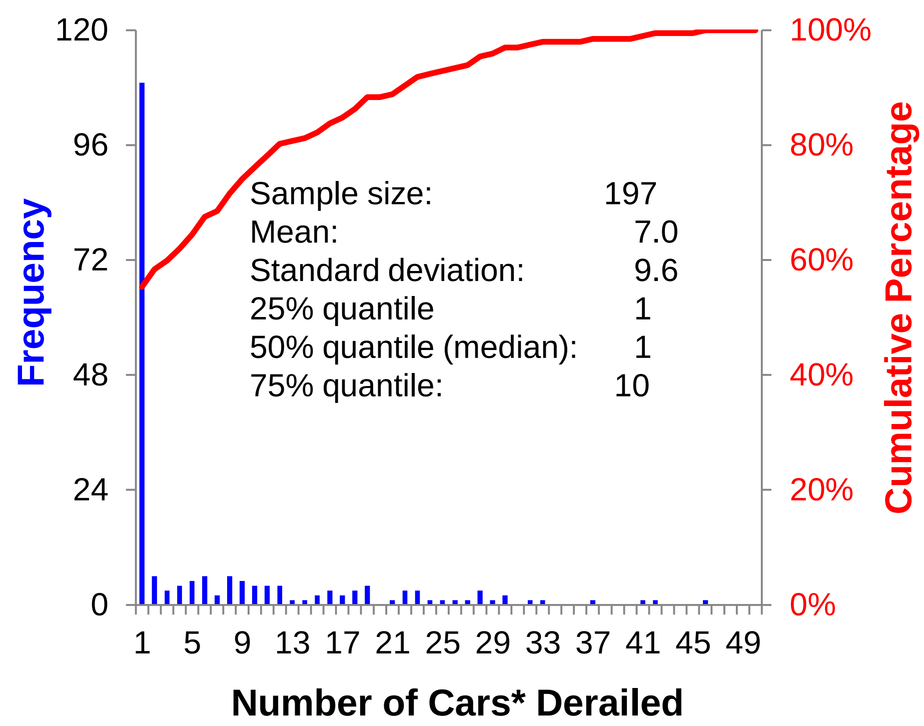


Freight-train derailment severity by cause, Class I mainlines, 2001-2010

Broken Rails or Welds



Bearing Failures



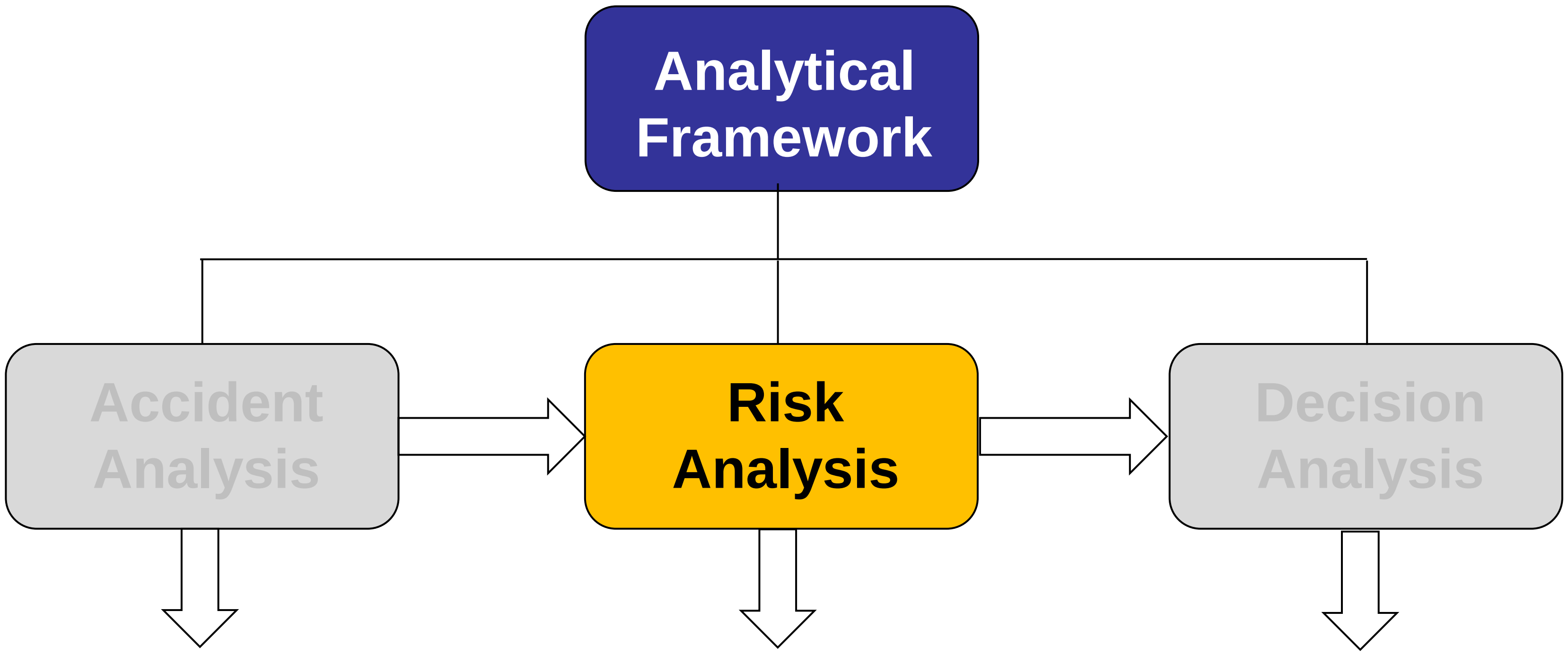
**Include number of locomotives derailed*

Proposed dissertation research in train accident analysis

- Modeling accident-cause-specific accident rate and severity
  - Develop a logistic regression model to estimate the probability that a train accident is due to a specific accident cause
  - Develop a negative binomial regression model to estimate the mean of number of cars derailed
  - Develop a quantile regression model to estimate the quantile distribution (e.g., median) of number of cars derailed

- Evaluate the effectiveness of specific accident prevention strategies

Analytical models for risk management

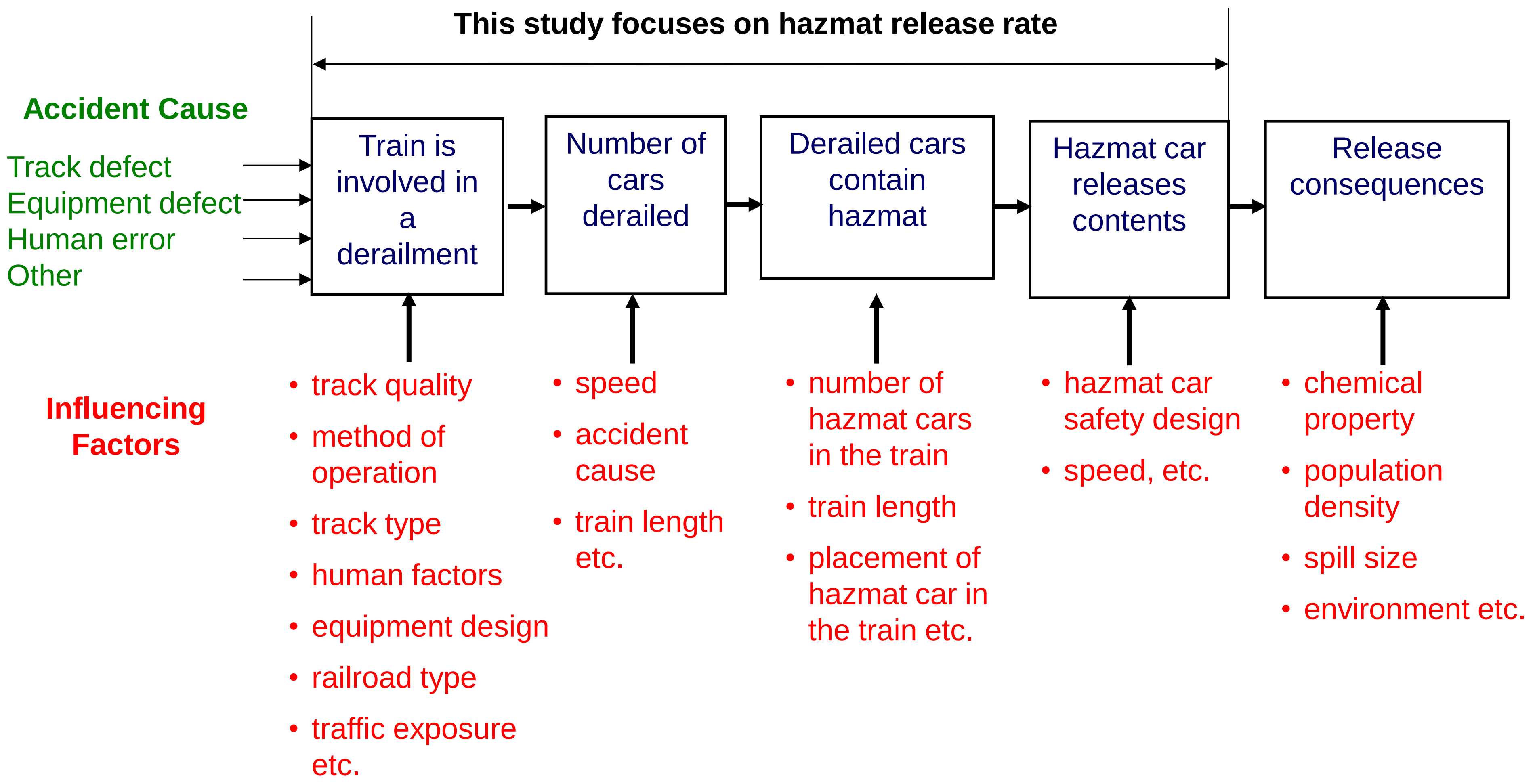


- Train accident frequency and severity
- Train accident causes

- **Risk modeling**
- Evaluation of risk reduction strategies

- Optimizing risk reduction strategies

Chain of events leading to hazmat car release



Modeling hazmat car release rate

$$P(R) = P(A) \times \left\{ \sum_{i=1}^{L} P(D_i \mid A) \times \left\{ \sum_{j=1}^{J} [P(H_{ij} \mid D_i, A) \times P(R_{ij} \mid H_{ij}, D_i, A)] \right\} \right\}$$

Where:

$P(R)$ = release rate (number of hazmat cars released per train-mile, car-mile or gross ton-miles)

$P(A)$ = derailment rate (number of derailments per train-mile, car-mile or gross ton-mile)

$P(D_i \mid A)$ = conditional probability of derailment for a car in i^{th} position of a train

$P(H_{ij} \mid D_i, A)$ = conditional probability that the derailed i^{th} car is a type j hazmat car

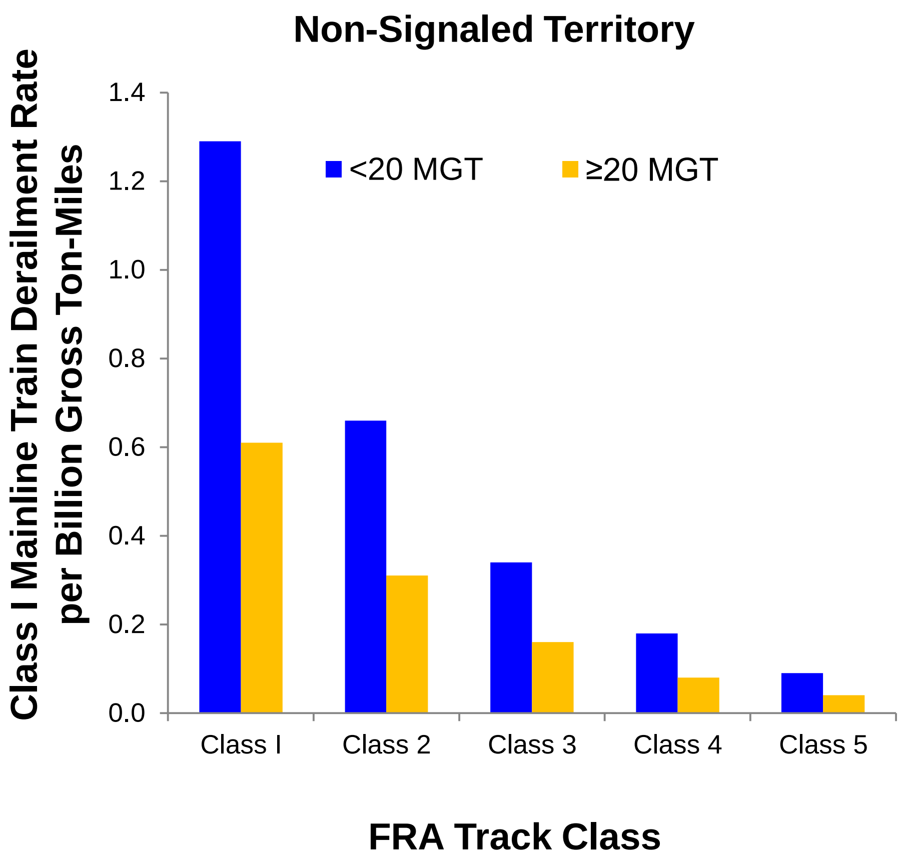
$P(R_{ij} \mid H_{ij}, D_i, A)$ = conditional probability that the derailed type j hazmat car in i^{th} position of a train released

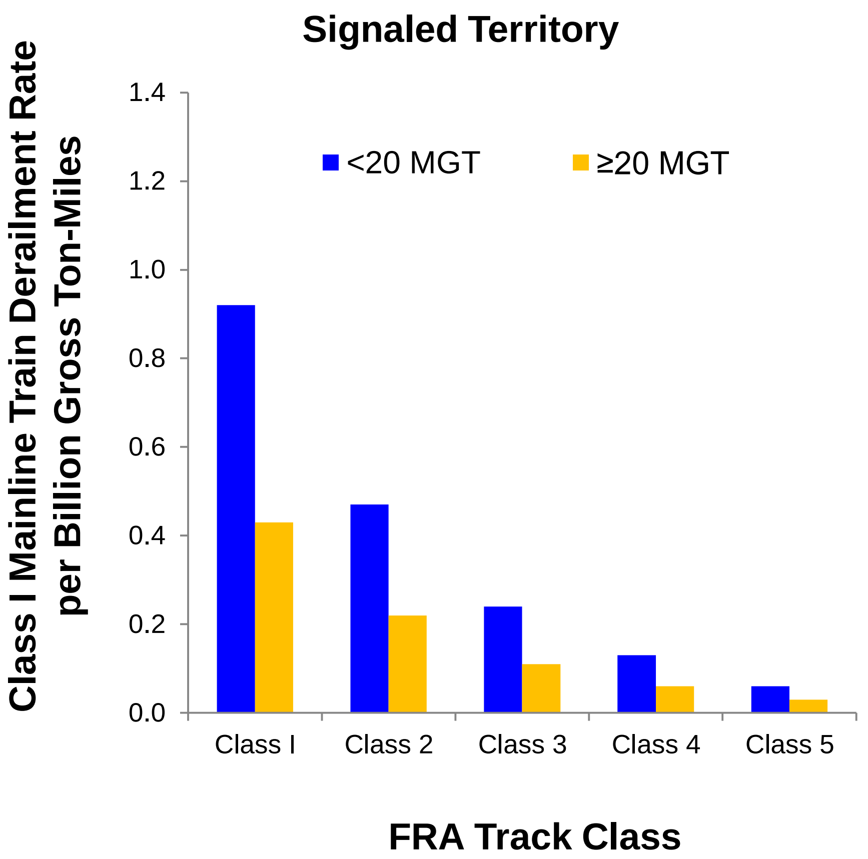
L = train length

J = type of hazmat car

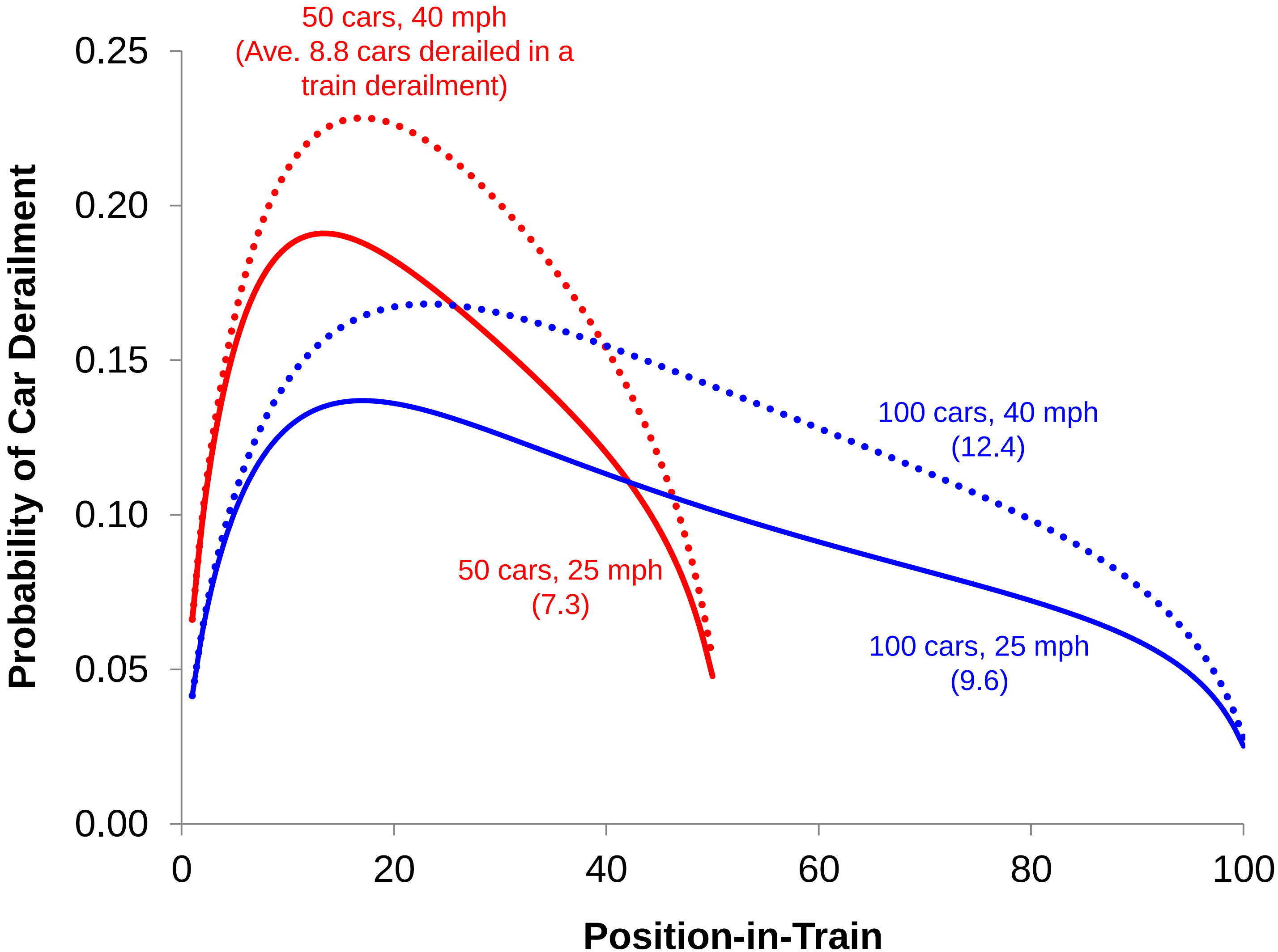
Mainline train derailment rate, P(A)

- Derailment rate varies by FRA track class, method of operation and annual traffic density (MGT)





Car derailment probability by position-in-train $P(D_i \mid A)$



Source: FRA Rail Equipment Accident (REA) database, 2000-2009, Class I Mainline Derailment, All Accident Causes

Probability of a hazmat car derailed $P(H_{ij} \mid D_i, A)$

- The probability that a derailed car contains hazardous materials depends on train length, number of hazmat cars in the train and hazmat car placement
- Given train length and number of hazmat cars in a train, the "worst-case-scenario" is that hazmat cars are placed in the train positions most prone to derailment

Conditional probability of release when a tank car* is derailed, $P(R_{ij} \mid H_{ij}, D_i, A)$

- Conditional probability of release (CPR) of a tank car reflects its resistance to the kinetic energy inflicted on it
- Treichel et al. (2006) developed a logistic regression model to estimate tank car conditional probability of release given tank car configuration
- Kawprasert & Barkan (2010) extended Treichel et al.'s model by accounting for the effect of derailment speed
- Our analysis uses Kawprasert and Barkan's model to estimate the conditional probability of release given tank car type and derailment speed

**The majority (73% in 2010) of hazardous materials movements occur in tank cars.*
In this study, tank car is used as an example to assess hazmat release rate.

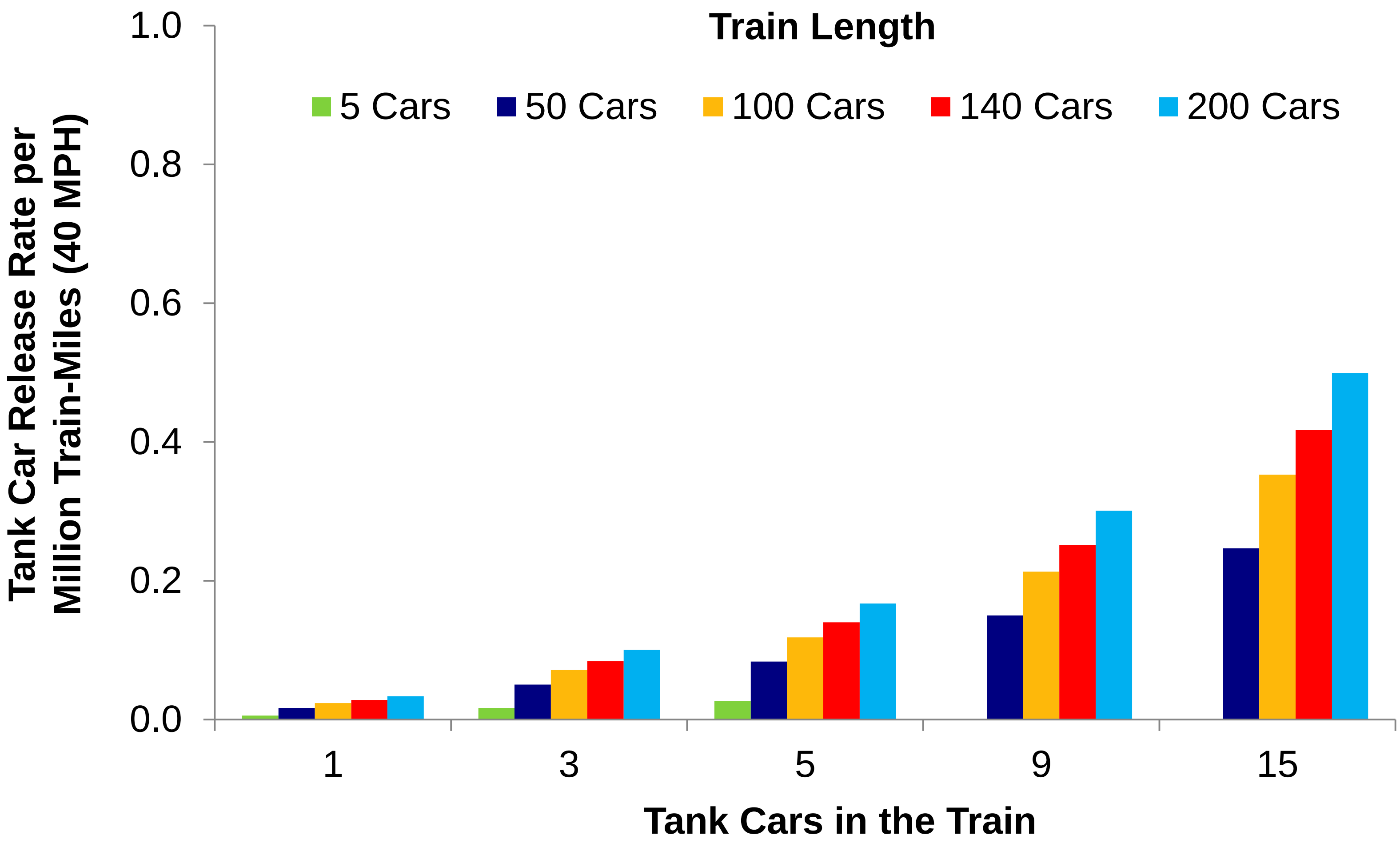
Application to segment-specific risk analysis

- The model can be used to evaluate segment-specific hazmat release rate and aid to develop and prioritize risk reduction strategies

- Sensitivity analyses were performed to analyze the relationship between tank car release rate and several train-related factors:
  - Train length
  - Number of tank cars in the train
  - Derailment speed

Estimated tank car release rates by train length and number of tank cars

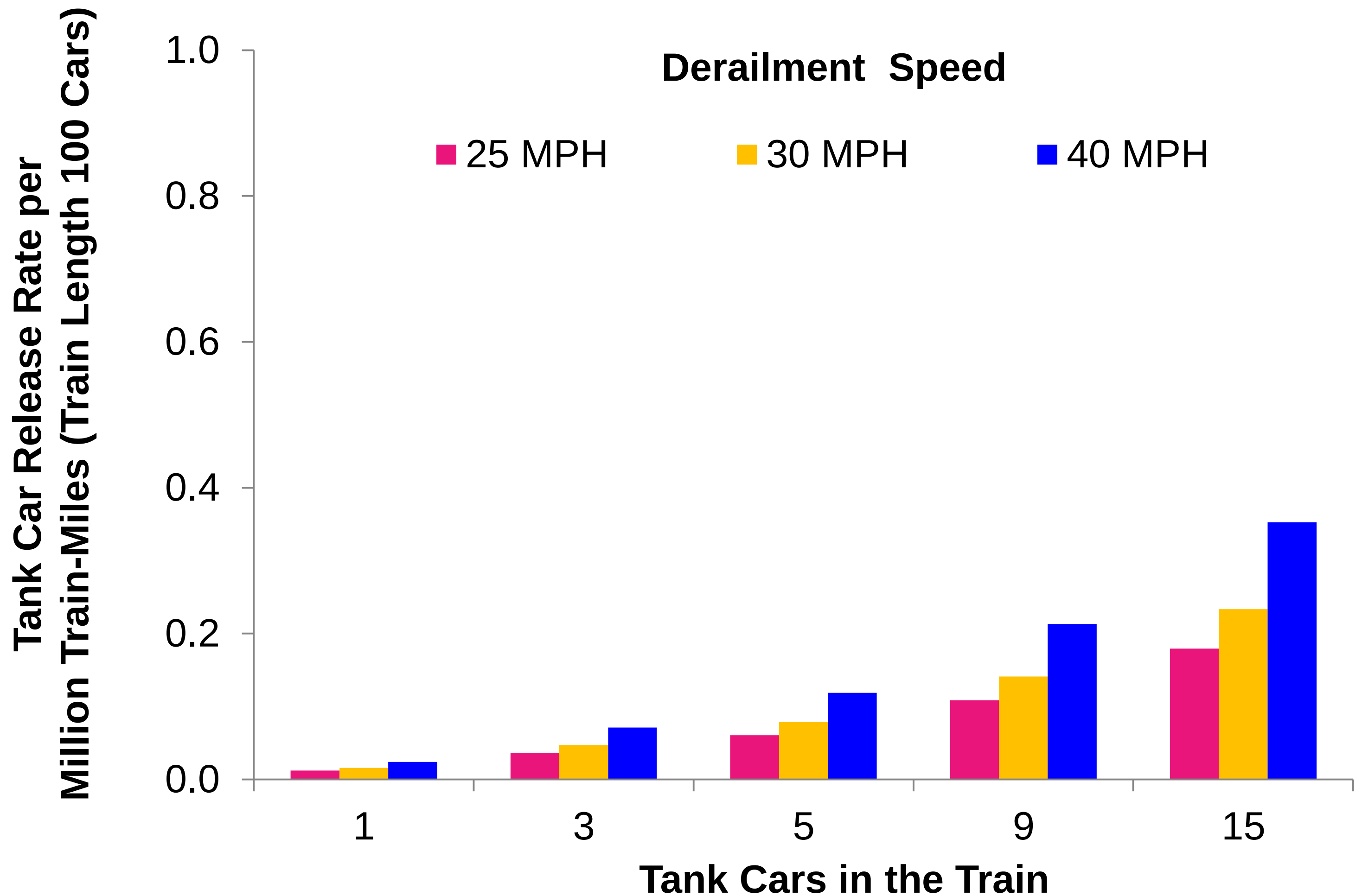
Class 3 Track, Non-Signaled, Annual Traffic Density 5-20 MGT



Tank car type was assumed to be 105J500W

Estimated tank car release rates by number of tank cars and derailment speed

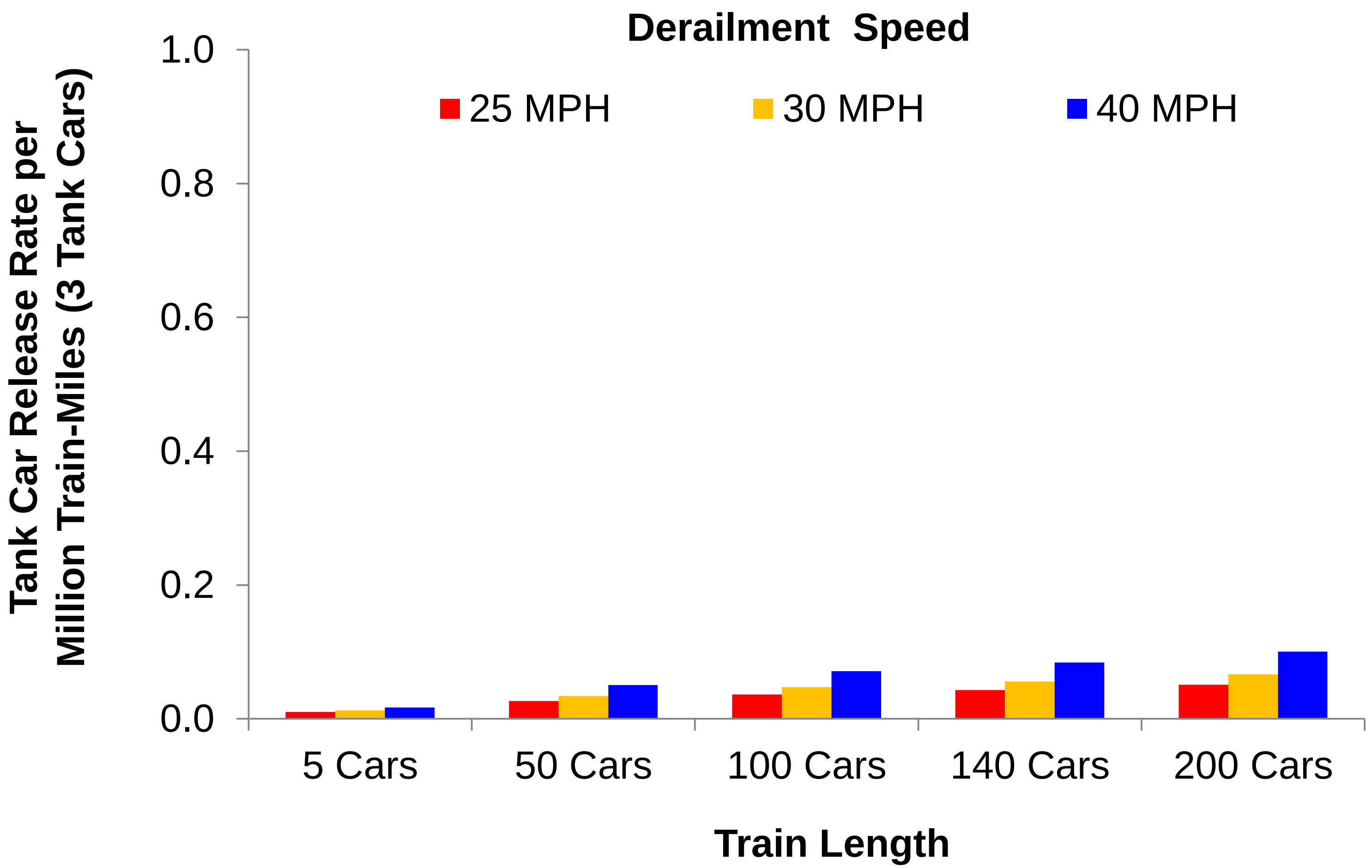
Class 3 Track, Non-Signaled, Annual Traffic Density 5-20 MGT



Tank car type was assumed to be 105J500W

Estimated tank car release rates by train length and derailment speed

Class 3 Track, Non-Signaled, Annual Traffic Density 5-20 MGT



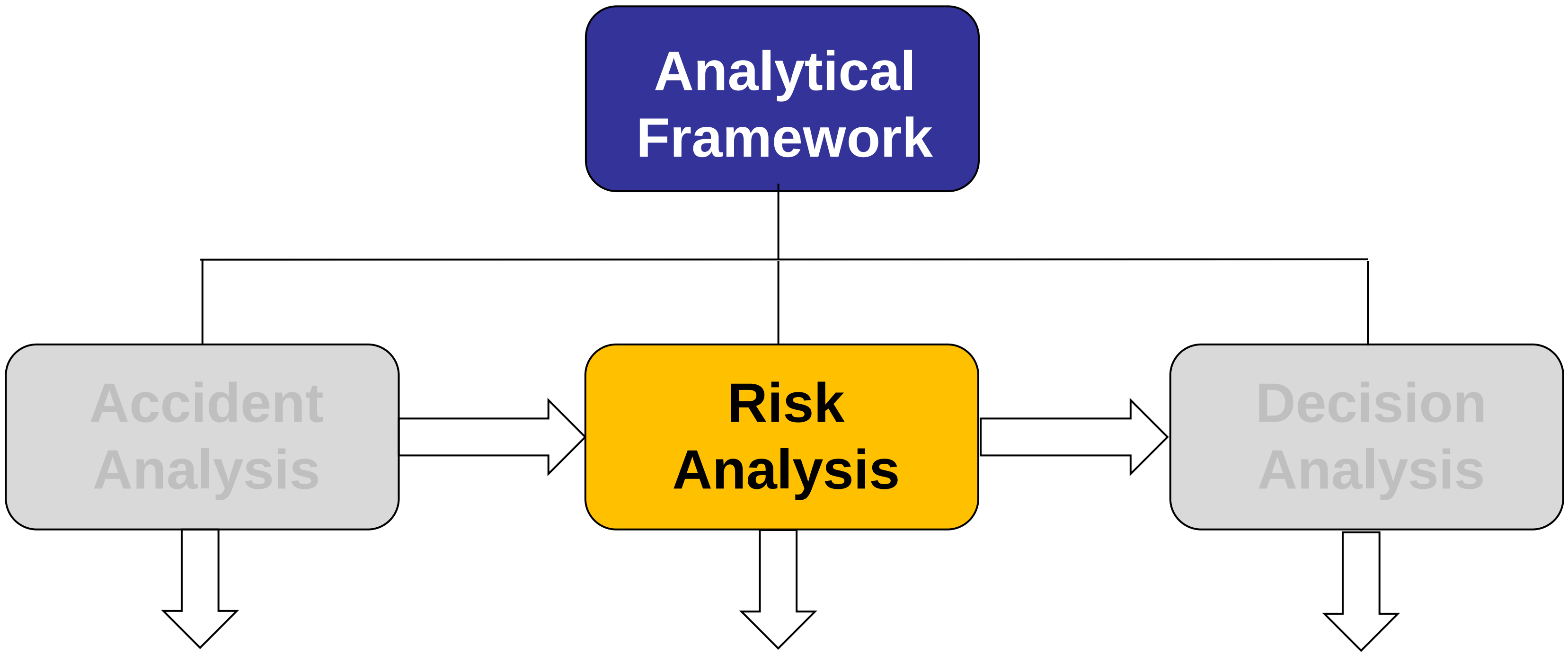
Tank car type was assumed to be 105J500W

Summary of risk modeling

- Train length, derailment speed and number of tank cars affect estimated hazmat release rate per train-mile. When all else is equal,
  - A longer train results in a higher release rate
  - A greater derailment speed results in a higher release rate
  - A larger number of tank cars results in a higher release rate

- The model can be used to assess release rates for a variety of track and rolling stock characteristics

Analytical models for risk management



- Train accident frequency and severity
- accident causes

- Risk modeling
- **Evaluation of risk reduction strategies**

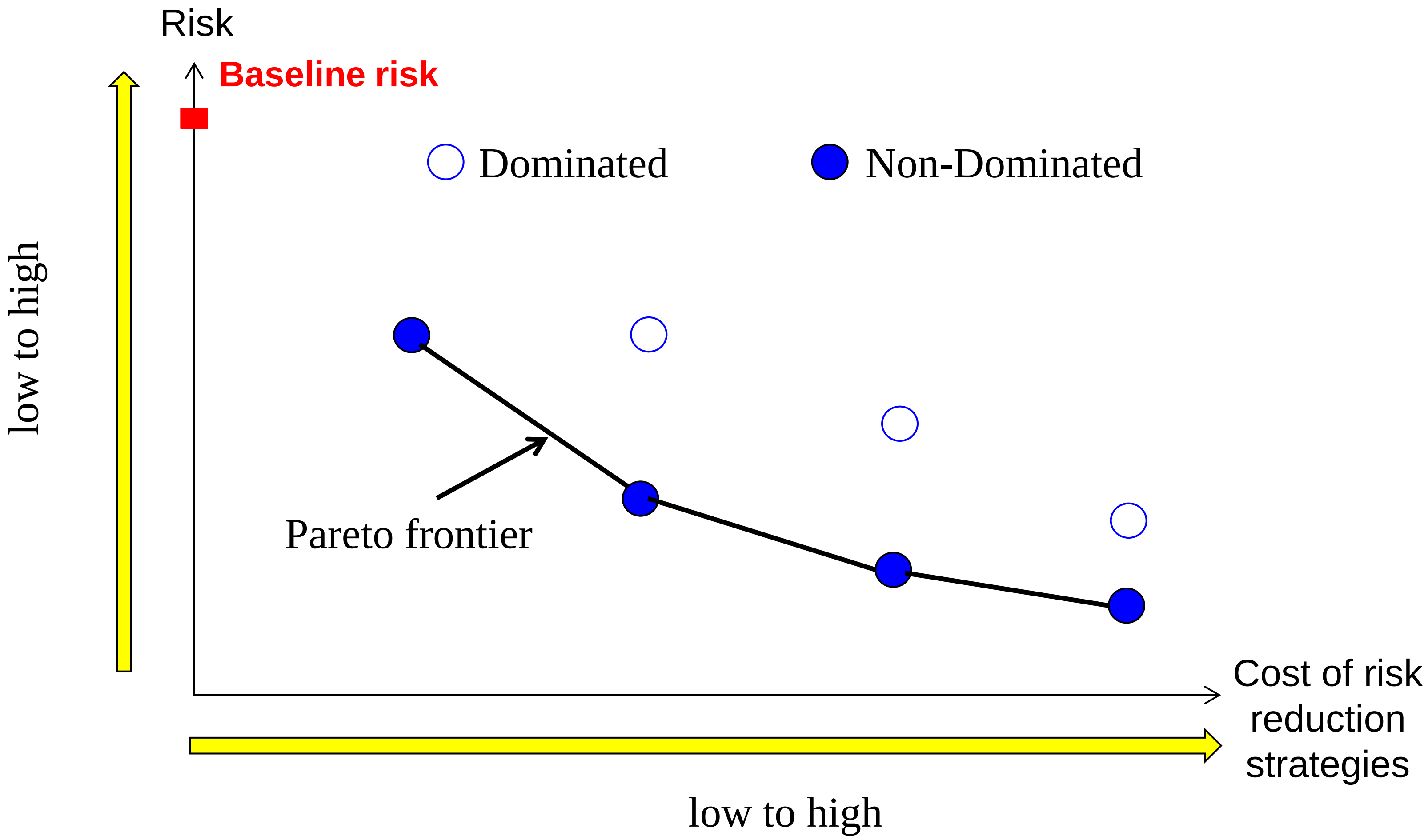
- Optimizing risk reduction strategies

Hazardous materials transportation risk reduction strategies

- Basic strategies for reducing the probability of hazmat release incidents include:
  - Reduce tank car derailment rate by preventing various accident causes
  - Reduce release probability of a derailed tank car by enhancing tank car safety design and/or reducing train speed

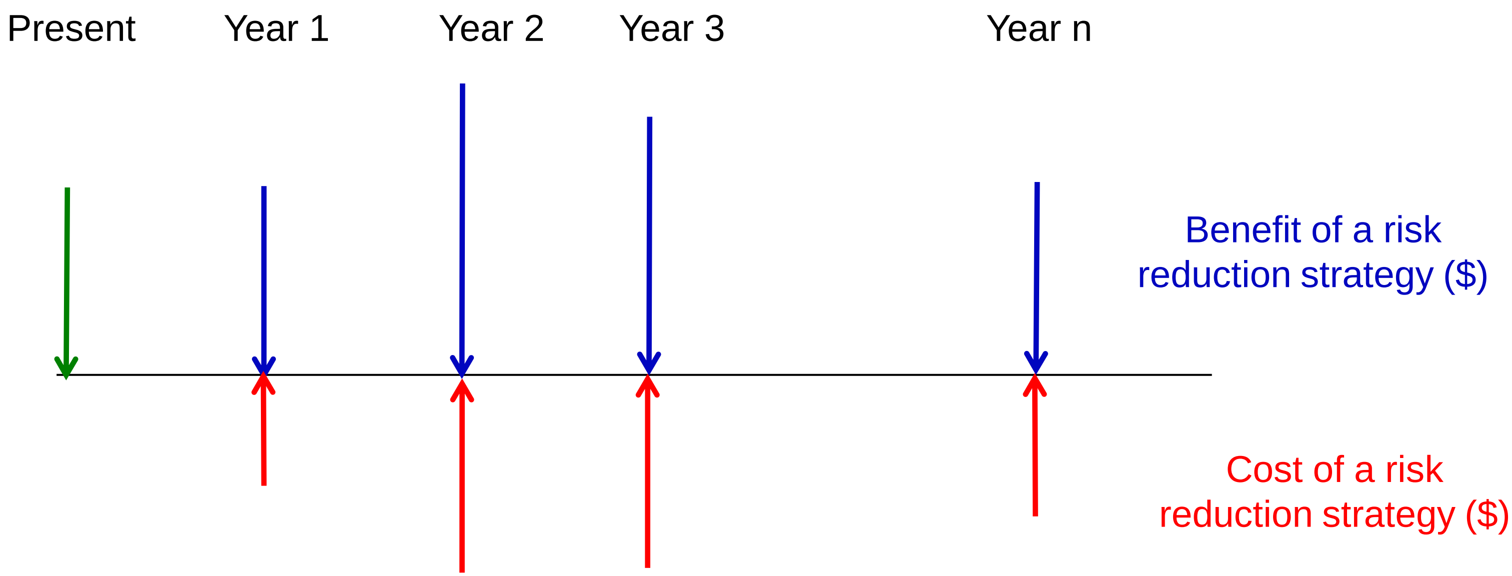


Multi-attribute evaluation of risk reduction strategies using Pareto-optimality



Net present value (NPV) approach to evaluate risk reduction strategies

$$NPV = \sum_{t=0}^{T} \frac{B_t - C_t}{(1+A)^t}$$



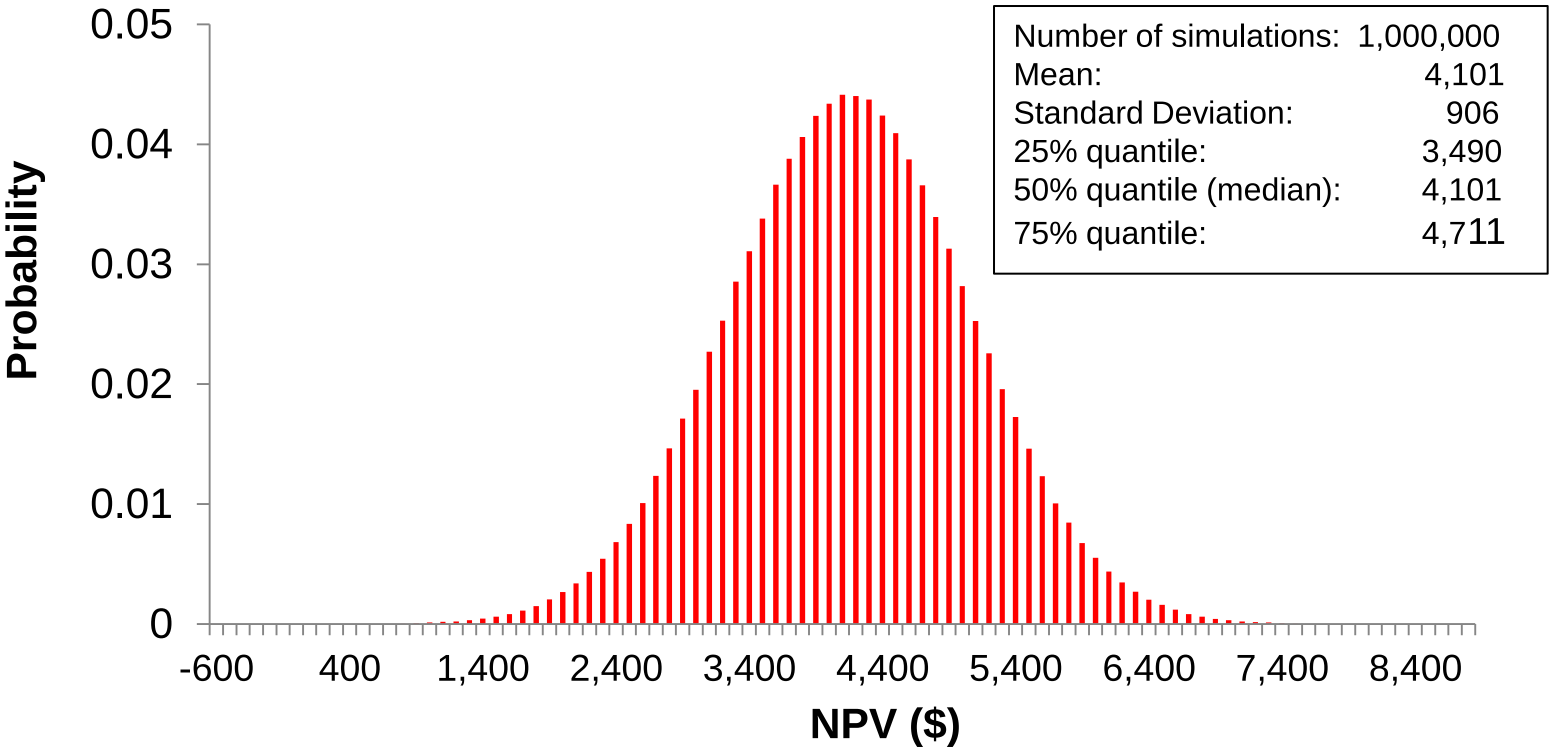
Uncertainty in the NPV approach

- The NPV approach may be subject to uncertainty in terms of:
  - definitions of benefits and costs
  - assessment of the effectiveness of risk reduction strategies
  - estimation of economic benefits of safety improvements
  - discount rates
  - study periods
  - track and rolling stock characteristics on different routes

- Due to the uncertainty, the NPV may follow a random distribution

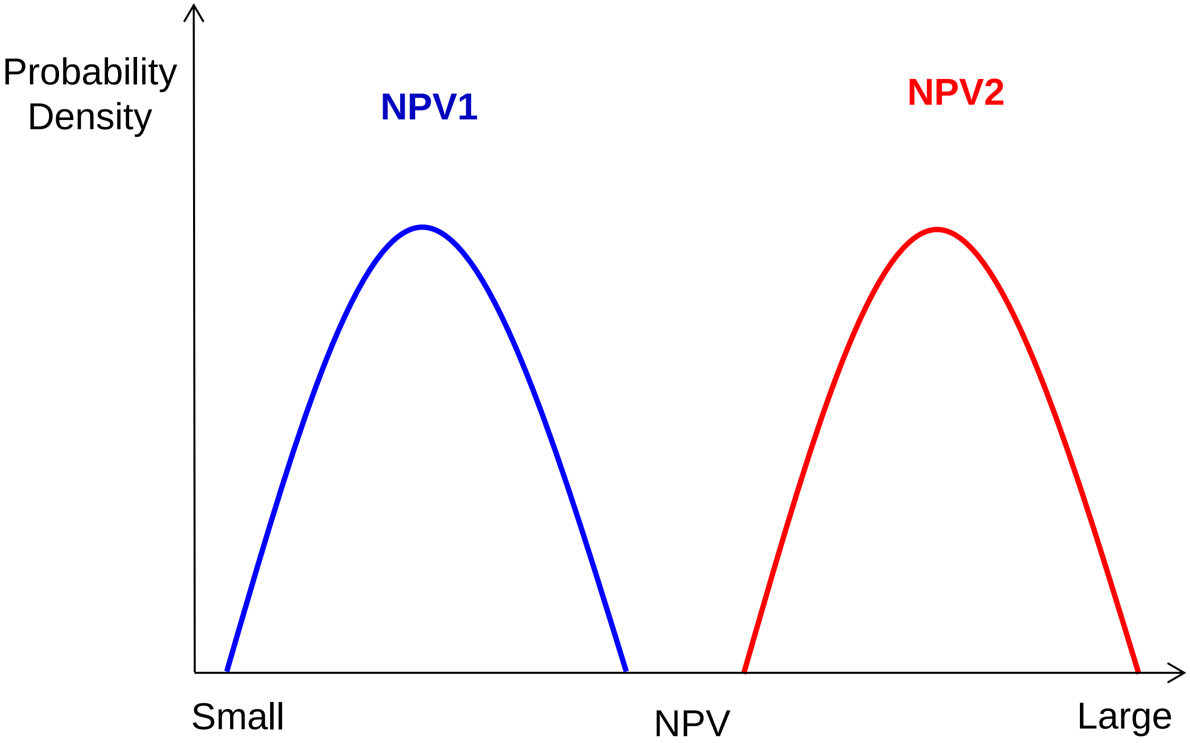
A hypothetical NPV distribution using Monte Carlo simulation

- It is assumed that
  - annual benefit B ($) ~ Normal (1000,100)
  - annual cost C ($) ~ Normal (900,100)
  - annual discount rate: 5% in 40 years study period



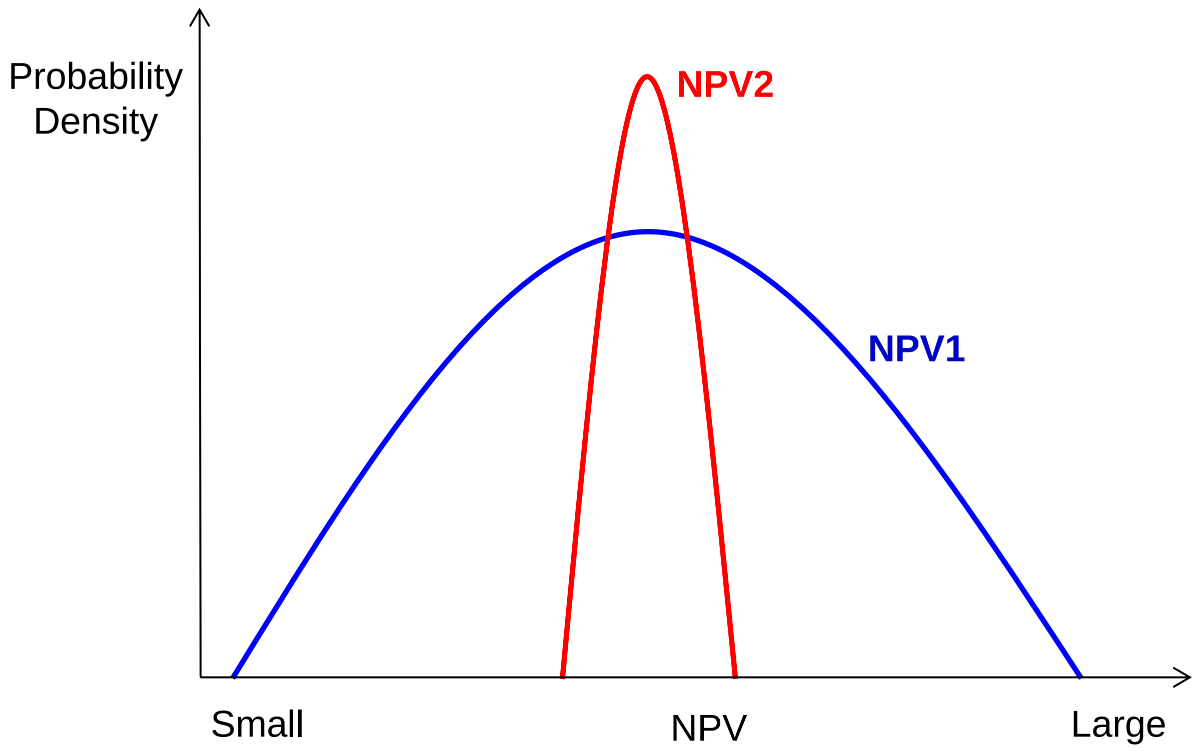
Comparison of risk reduction strategies under uncertainty (scenario 1)

- The NPV2 is always greater than NPV1



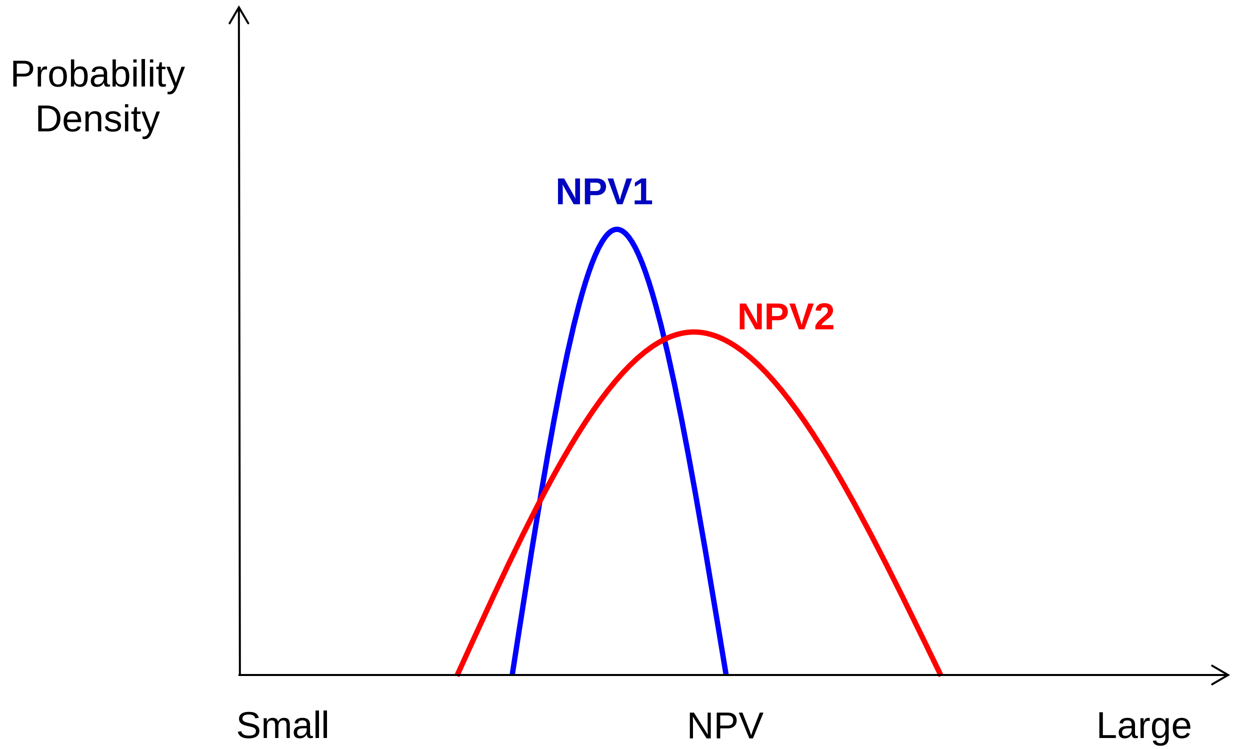
Comparison of risk reduction strategies under uncertainty (scenario 2)

- Both NPV distributions have the same mean, but NPV2 has a smaller variance, thus may be preferred



Comparison of risk reduction strategies under uncertainty (scenario 3)

- NPV2 has a larger mean, also a larger variance. The optimal decision may be based on the consideration of both the mean and variance

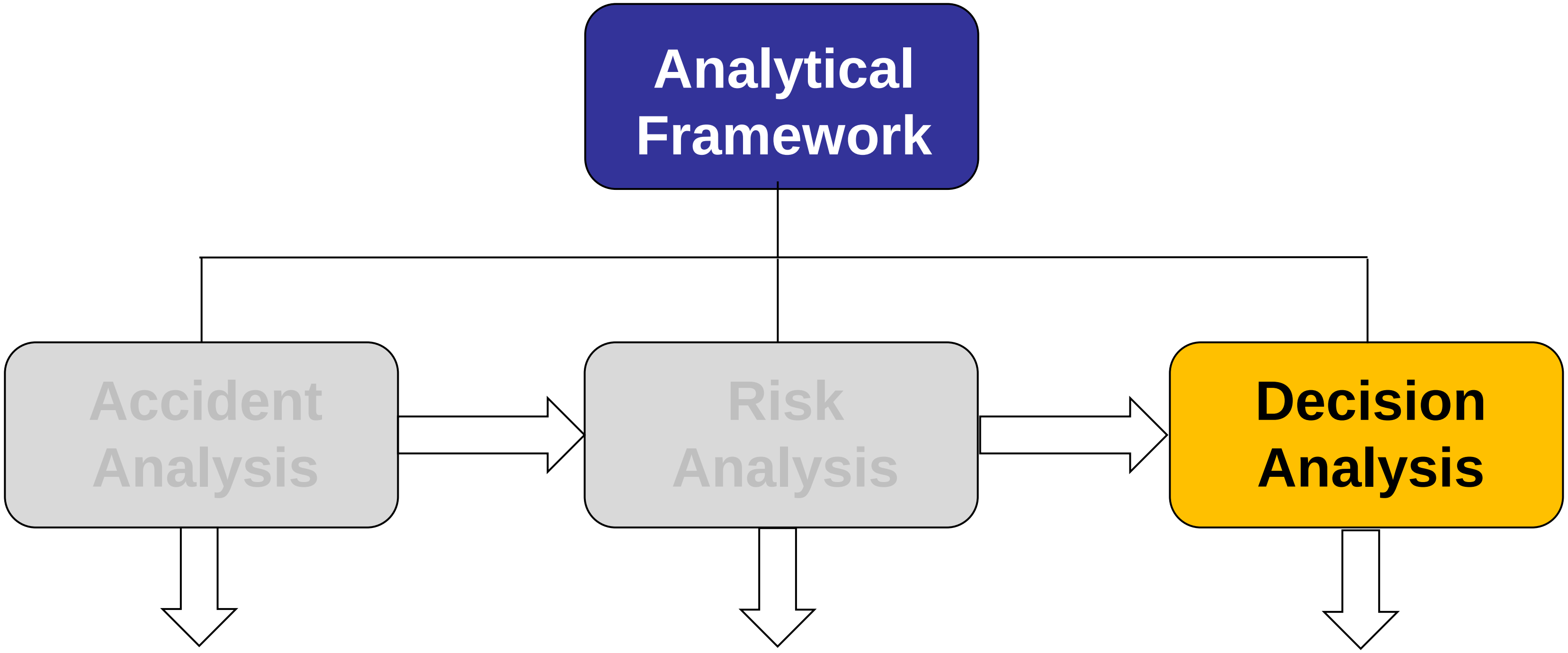


Proposed dissertation research in risk analysis

- Risk modeling
  - Analyze the effect of parameter uncertainty on risk estimation

- Evaluation of risk reduction strategies under uncertainty
  - Consider means to reducing the uncertainty in the cost-benefit analysis
  - Consider the covariance between the benefit and cost estimation

Analytical models for risk management

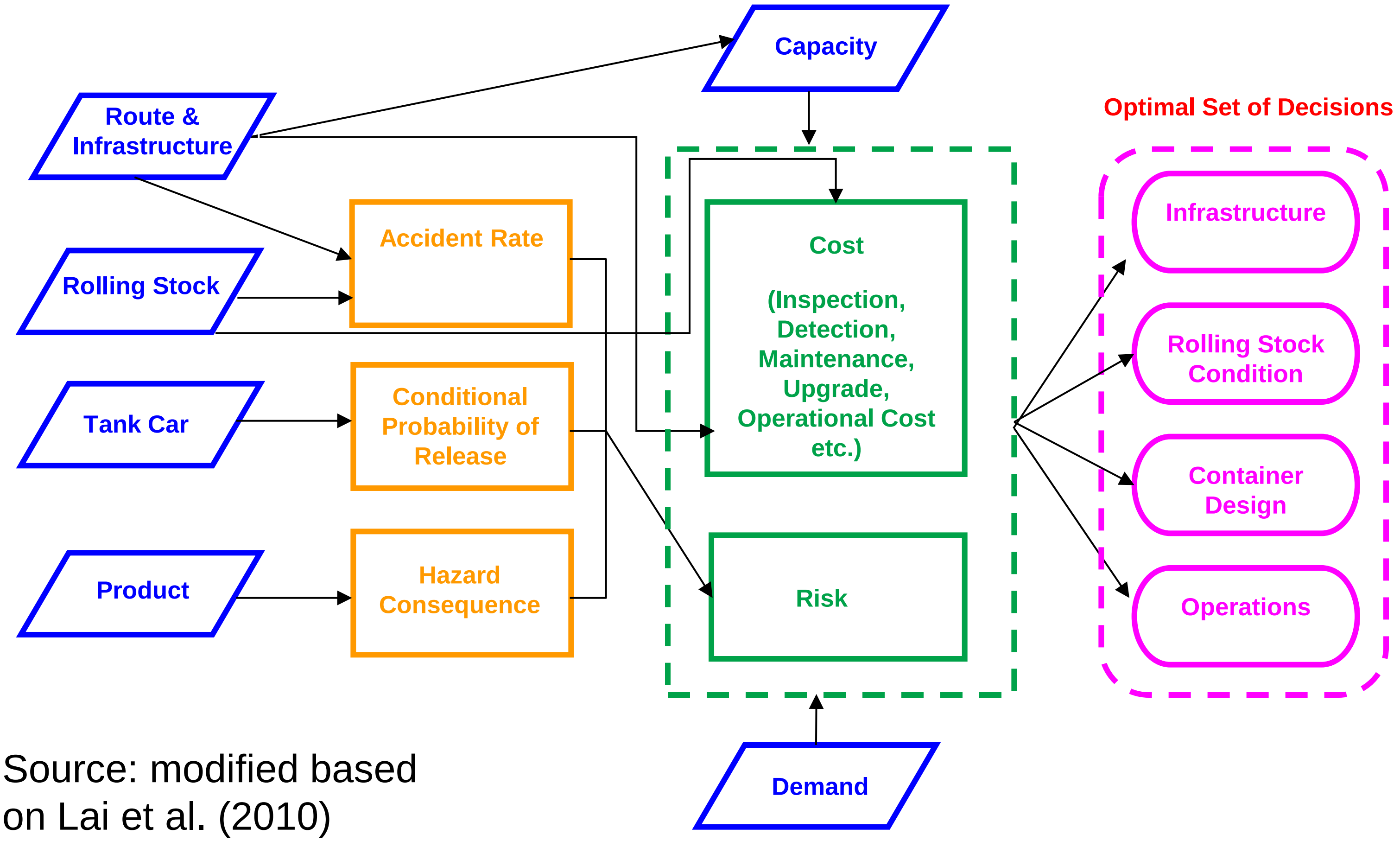


- Train accident frequency and severity
- accident causes

- Risk modeling
- Evaluation of risk reduction strategies

- **Optimizing risk reduction strategies**

An example model to manage the risk of transporting hazardous materials on railroad networks



Source: modified based on Lai et al. (2010)

Example integrated optimization model

Model Formulation

$$\min \underbrace{\sum_{(i,j)\in A}\sum_{v\in V}\sum_{q\in Q} H_{ij}^{vq} y_{ij}^{vq}}_{\text{Maintenance cost}} + \underbrace{\sum_{(i,j)\in A}\sum_{k\in K}\sum_{t\in T} C_{ij} x_{ij}^{kt}}_{\text{Transportation cost}} + \underbrace{\sum_{(i,j)\in A}\sum_{v\in V}\sum_{q\in Q} R_{ij}^{vq} y_{ij}^{vq}}_{\text{Risk cost}}$$

Subject to:

$$\sum_{k\in K}\sum_{t\in T}(x_{ij}^{kt} + x_{ji}^{kt}) \le \sum_{v\in V}\sum_{q\in Q} U_{ij}^{q} y_{ij}^{vq} \qquad \forall\ (i,j)\in A,\ (i<j)$$

Capacity constraint

$$\sum_{v\in V}\sum_{q\in Q} y_{ij}^{Vq} = 1 \qquad \forall\ (i,j)\in A,\ (i<j)$$

Track class and car composition constraint

$$\sum_{k\in K}(x_{ij}^{kt} + x_{ji}^{kt}) \le \sum_{v\in V}\sum_{q\in Q} N_t^{v} y_{ij}^{vq} \qquad \forall\ (i,j)\in A,\ (i<j),\ t\in T$$

Linking constraint for decision variables

$$\sum_{j\in\delta^-(j)} x_{ij}^{kt} - \sum_{j\in\delta^+(j)} x_{ji}^{kt} = \begin{cases} D_{kt} z_{kt} & \text{if } i \in s_{kt} \\ -D_{kt} z_{kt} & \text{if } i \in e_{kt} \\ 0 & \text{otherwise} \end{cases} \qquad \forall\ i\in N,\ k\in K,\ t\in T$$

Flow conservation constraint

$$\sum_{t\in T} z_{kt} = 1 \qquad \forall\ k\in K$$

Car type constraint

$$x_{ij}^{kt} \in \text{positive integer}, \qquad \forall (i,j)\in A,\ k\in K,\ t\in T,$$

$$y_{ij}^{vq} \in \{0,1\}, \qquad \forall (i,j)\in A,\ v\in V,\ q\in Q,$$

$$z_{kt} \in \{0,1\}, \qquad \forall k\in K,\ t\in T$$

Decision Variables Constraint

Source: Lai et al. (2010)

Proposed dissertation research in decision analysis

- Multi-attribute decision making
  - Develop a multi-attribute utility model to consider risk attitudes and trade-offs among conflicting objectives

- Optimization
  - Consider the interactive effects of various risk reduction strategies
  - Develop an analytical model to identify the optimal set of risk reduction strategies under various constraints and uncertainty

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