Railroad Hazardous Materials Transportation Risk Management Framework

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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

Hazardous materials, including TIH materials, are a small percentage of rail traffic but are responsible for a major share of rail insurance costs and liability risks.

Source: AAR analysis of 2008 STB Waybill Sample
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

**INPUT**
- Infrastructure Data
- Accident Data
- Traffic & Shipment Data
- Cost Data
- Other Data

**Analytical framework**

**OUTPUT**
- Optimal strategies to improve hazmat transportation safety
  - What to do
  - Where to do it
  - How to do it
Analytical models for risk management

- Accident Analysis
  - Train accident frequency and severity
  - Train accident causes

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

- Decision Analysis
  - Optimizing risk reduction strategies
Analytical models for risk management

Analytical Framework

Accident Analysis
- Train accident frequency and severity
- Train accident causes

Risk Analysis
- Risk modeling
- Evaluation of risk reduction strategies

Decision Analysis
- 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

- Track: 41%
- Equipment: 33%
- Human Factors: 14%
- Misc.: 11%
- Signals: 0.4%

Data source: FRA Rail Equipment Accident (REA) database, 2001 to 2010
Class I mainline freight-train derailment frequency by cause, 2001-2010

Top 10 causes account for 56% of derailments
Frequency-severity graph of Class I mainline freight-train derailments, 2001-2010

Average frequency = 89

Broken Rails or Welds

Average severity = 8.6
Freight-train derailment severity by cause, Class I mainlines, 2001-2010

**Broken Rails or Welds**
- Sample size: 458
- Mean: 14.2
- Standard deviation: 9.5
- 25% quantile: 7
- 50% quantile (median): 12
- 75% quantile: 19

**Bearing Failures**
- Sample size: 197
- Mean: 7.0
- Standard deviation: 9.6
- 25% quantile: 1
- 50% quantile (median): 1
- 75% quantile: 10

*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

Analytical Framework
Chain of events leading to hazmat car release

This study focuses on hazmat release rate

**Accident Cause**
- Track defect
- Equipment defect
- Human error
- Other

**Influencing Factors**
- Track quality
- Method of operation
- Track type
- Human factors
- Equipment design
- Railroad type
- Traffic exposure etc.

**Train is involved in a derailment**
- Number of cars derailed

**Number of cars derailed**
- Speed
- Accident cause
- Train length etc.

**Derailed cars contain hazmat**
- Number of hazmat cars in the train
- Train length
- Placement of hazmat car in the train etc.

**Hazmat car releases contents**
- Hazmat car safety design
- Speed, etc.

**Release consequences**
- Chemical property
- Population density
- Spill size
- Environment etc.
Modeling hazmat car release rate

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

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)

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

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

\( P(R_{ij} | H_{ij}, D_i, A) \) = 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)

![Non-Signaled Territory Graph]

- Class I Mainline Train Derailment Rate per Billion Gross Ton-Miles

![Signaled Territory Graph]

- Class I Mainline Train Derailment Rate per Billion Gross Ton-Miles

FRA Track Class
Car derailment probability by position-in-train

\[ P(D_i | A) \]

Source: FRA Rail Equipment Accident (REA) database, 2000-2009, Class I Mainline Derailment, All Accident Causes
Probability of a hazmat car derailed

\[ P(H_{ij} | D_i, A) \]

- 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, $P(R_{ij} | H_{ij}, D_i, A)$

- 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.
- 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

Analytical Framework

Accident Analysis
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- Accident causes

Risk Analysis
- Risk modeling
- Evaluation of risk reduction strategies

Decision Analysis
- 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

Risk

Baseline risk

Dominated
Non-Dominated

Pareto frontier

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

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

Present  Year 1  Year 2  Year 3  Year n

Benefit of a risk reduction strategy ($)

Cost of a risk reduction strategy ($)
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 $B$ ($) $\sim$ Normal $(1000,100)$
  - annual cost $C$ ($) $\sim$ Normal $(900,100)$
  - annual discount rate: 5% in 40 years study period

Number of simulations: 1,000,000
Mean: 4,101
Standard Deviation: 906
25% quantile: 3,490
50% quantile (median): 4,101
75% quantile: 4,711
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

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

<table>
<thead>
<tr>
<th>Tank Car</th>
<th>Product</th>
<th>Accident Rate</th>
<th>Conditional Probability of Release</th>
<th>Hazard Consequence</th>
<th>Risk</th>
<th>Cost (Inspection, Detection, Maintenance, Upgrade, Operational Cost etc.)</th>
<th>Capacity</th>
<th>Demand</th>
</tr>
</thead>
</table>

Source: modified based on Lai et al. (2010)
Example integrated optimization model

Model Formulation

\[
\min \sum_{(i,j) \in A} \sum_{v \in V} \sum_{q \in Q} H_{ij}^{vq} y_{ij}^{vq} + \sum_{(i,j) \in A} \sum_{k \in K} \sum_{t \in T} C_{ij}^{kt} x_{ij}^{kt} + \sum_{(i,j) \in A} \sum_{v \in V} \sum_{q \in Q} R_{ij}^{vq} y_{ij}^{vq}
\]

Maintenance cost \hspace{1cm} Transportation cost \hspace{1cm} Risk cost

Subject to:

1. \[\sum_{k \in K} \sum_{t \in T} (x_{ij}^{kt} + x_{ji}^{kt}) \leq \sum_{v \in V} \sum_{q \in Q} U_{ij}^{vq} y_{ij}^{vq} \quad \forall (i, j) \in A, (i < j)\]
   - Capacity constraint

2. \[\sum_{v \in V} y_{ij}^{vq} = 1 \quad \forall (i, j) \in A, (i < j)\]
   - Track class and car composition constraint

3. \[\sum_{k \in K} (x_{ij}^{kt} + x_{ji}^{kt}) \leq \sum_{v \in V} \sum_{q \in Q} N_{i}^{vq} y_{ij}^{vq} \quad \forall (i, j) \in A, (i < j), t \in T\]
   - Linking constraint for decision variables

4. \[\sum_{j \in S(i)} x_{ij}^{kt} - \sum_{j \in S'(i)} x_{ji}^{kt} = \begin{cases} D_{kt} z_{ki} & \text{if } i \in s_{kt} \\ -D_{kt} z_{ki} & \text{if } i \in e_{kt} \\ 0 & \text{otherwise} \end{cases} \quad \forall i \in N, k \in K, t \in T\]
   - Flow conservation constraint

5. \[\sum_{i \in T} z_{ki} = 1 \quad \forall k \in K\]
   - Car type constraint

6. \[x_{ij}^{kt} \in \text{positive integer}, \quad \forall (i, j) \in A, k \in K, t \in T,\]
   - Decision Variables Constraint

7. \[y_{ij}^{vq} \in \{0, 1\}, \quad \forall (i, j) \in A, v \in V, q \in Q,\]

8. \[z_{ki} \in \{0, 1\}, \quad \forall k \in K, t \in T\]

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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