Railroad Safety & Risk Analysis Using North American Accident Database Systems

Chris Barkan
克禮思・巴肯
Professor

George Krambles Director
Rail Transportation and Engineering Center (RailTEC)

29 November 2018

3rd Workshop on Railway Operation for Safety and Reliability

RAILTEC
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
Thank you for the invitation!

The 3rd Workshop on Railway Operation for Safety and Reliability

29 November 2018, City University of Hong Kong
Supporters of RailTEC Safety & Risk Research

- and various petroleum, chemical and refining companies
Acknowledgements

- Research conducted by a number of talented and dedicated students, past and present
  - Ph.D.
    Samantha Chadwick
    Athaphon Kawprasert
    Chen-Yu Lin
    Xiang Liu
    M. Rapik Saat
    Brandon Wang
  - M.S.
    Jesus Aguilar
    Weixi Li
    Manuel Martin
    Kaiyu Wang
    Lijun Zhang
  - B.S.
    Jaemin Kim
    Sam Pal
    Max Potvin
    Geordie Roscoe
Outline of Presentation

- Introduction to North American rail safety trends
- Types of data needed for railroad safety and risk analysis
- Review several projects:
  - Optimizing Tank Car Safety Design
  - Multiple Tank Car Release Risk
  - Analysis of Train Derailment Rates, Causes, and Changes
  - Loaded versus Empty Unit Train Derailment Cause Analysis
  - Adjacent Track Accident Risk Model Development
Substantial decline in major North American railroads’ mainline derailment rate: 2006 - 2015

- 50% reduction in mainline derailment rate in this time period
- However, this improvement occurred at the same time as an even more dramatic increase in hazardous dangerous goods traffic
Decline in railroad derailment rate coincided with increase in flammable liquid traffic

- Beginning in the mid-2000s flammable liquid traffic, notably ethanol and petroleum crude oil grew more than 10-fold
- Most of this traffic was moving in large unit trains rather than single carload shipments
Safety paradox, derailments were declining but serious incidents were increasing

- Substantial increase in rail transport of ethanol and petroleum crude oil led to a corresponding increase in derailments involving these products

New Brighton, PA
Cherry Valley, IL
Lac-Mégantic, QC

Casselton, ND
Aliceville, AL
Mt. Carbon, WV

... and a number of others
Decline in accidents part of a longer-term trend, but shows evidence of diminishing returns

- Eliminating the remaining accident causes is an increasingly stubborn problem
- Requires more sophisticated data and analytical techniques to prioritize investment in most effective risk reduction strategies

Train accident rate dropped steeply following deregulation in 1980, then leveled off, but has been declining again over the past decade:
- 79% since 1980, and
- 42% since 2005

FRA Data
Railroad freight train risk reduction strategies

**Infrastructure**
- e.g. Track upgrade
  Reduce accident occurrence

**Railcar/Container**
- e.g. Tank car safety design
  Reduce incidence and severity of releases

**Operational**
- e.g. Speed reduction
  Reduce accident severity

**Routing**
- e.g. Alternative routings
  Reduce impact of releases
Railroad data systems needed for safety and risk analysis

- Accidents and incidents – what, when, where, why & how occurred
- Operations and traffic – type, routing and exposure
- Infrastructure – routes and characteristics
- Rolling stock – safety design characteristics
Railroad accident and incident data

- **US DOT Federal Railroad Administration**
  - Highway-rail grade crossing accident/incident (58 variables + narrative)
  - Rail equipment accident/incident (80 variables + narrative)
  - Death, injury, or occupational illness (>40 variables + narrative)

- **US DOT Pipeline and Hazardous Materials Administration**
  - Hazardous materials incident report (90 variables + narrative)

- **RSI-AAR Railroad Tank Car Safety Research and Test Project**
  - Railroad tank car accident database
    - Train accident characteristics (37 variables and >30,000 records)
    - Damage and performance of tank cars involved in accidents (34 variables and >48,000 records)
Railroad operations and traffic

- **Association of American Railroads**
  - TRAIN II – Detailed records of railcars, lading transported, and routing of most rail shipments in North America
  - Analysis of Class 1 Railroads – Detailed annual summary of railroad operating statistics

- **US Surface Transportation Board**
  - Waybill Sample – Statistically robust sample of rail shipment movements over US rail network

- **Major North American railroads**
  - Operating data – Detailed data on train makeup, movements, routing, schedules, traffic composition and volume, railcars, and commodities transported (proprietary)
Railroad infrastructure route characteristics

- **Association of American Railroads**
  - Analysis of Class 1 Railroads – Annual summary of certain railroad infrastructure characteristics

- **US DOT Federal Railroad Administration**
  - Grade crossing inventory file – Data on all US grade crossings

- **Major North American railroads**
  - Detailed data on track characteristics, train control systems, and numerous other characteristics (proprietary)

- **Geographic Information System (GIS) databases**
  - Various other GIS databases on numerous features of interest including environmental characteristics, waterways, etc.

* Topologically Integrated Geographic Encoding and Referencing
Railroad rolling stock design characteristics

- **Association of American Railroads**
  - UMLER (Universal Machine Language Equipment Register)
    Detailed data on nearly all rail rolling stock operating in North America

- **RSI-AAR Railroad Tank Car Safety Research and Test Project**
  - Car design properties and lading transported for tank cars involved in accidents (40 variables)
Examples of recent and current research

- Optimizing Tank Car Safety Design
- Multiple Tank Car Release Risk
- Analysis of Train Derailment Rates, Causes, and Changes
- Loaded versus Empty Unit Train Derailment Cause Analysis
- Adjacent Track Accident Risk Model Development
Optimizing Tank Car Safety Design

M. Rapik Saat, Ph.D.
Graduate Research Assistant

now
Director - Operations Analysis
Policy & Economics Department
Association of American Railroads
Fundamental tradeoff in tank car design: Safety versus efficiency

- Principal approaches 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 transportation efficiency

- Thus there is a tradeoff between enhanced safety and transport efficiency
Change in light weight and probability of release for each tank car safety design modification

Example: 263,000-lb maximum GRL for 30,000-gallon baseline 111 tank car
Pareto optimal set of flammable liquid tank car design options

- BASELINE
  Non-Jacketed
  7/16” Tank

- Non-Jacketed
  CPC-1232
  1/2” Tank, Half-Height Head Shields

- Jacketed
  CPC-1232
  7/16” Tank, Full-Height Head Shields

- Jacketed
  1/2” Tank, Full-Height Head Shields

- Jacketed
  9/16” Tank, Full-Height Head Shields
Multiple Tank Car Release Risk

Xiang Liu, Ph.D.
Graduate Research Assistant
now
Assistant Professor
Rutgers University
Previous tank car safety research focused on single car performance

- Optimization techniques and tank car data used to quantitatively identify combinations of design features that maximized tank car safety performance*
- This approach alone was successful when focused on single-car release incidents such as environmentally sensitive chemicals (ESC) or toxic inhalation hazard materials (TIH)
- Substantial growth in unit-trains transporting petroleum and alcohol suggested need to consider probability of multiple-car release events†
Safety performance of flammable liquid tank cars derailed in accidents

* CPR(100) = Probability that a tank car derailed in an FRA-reportable accident releases ≥100 gallons due to the impacts it receives in the derailment
Events leading to a release incident

**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

**Train involved in a derailment**
- speed
- accident cause
- train length

**Number of cars derailed**
- number of HM cars in the train
- train length
- placement of HM cars in the train

**Derailed cars contain hazmat (HM)**
- HM car safety design
- operating speed
- accident characteristics

**HM car releases contents**
Analytical framework for estimating probability distribution of number of tank cars releasing

**Input**
- Train Characteristics
- Track Characteristics

**Train Derailment**
- Point of Derailment (POD)

**Probability of Multiple-Car Release**
- Number of All Types of Cars Derailed
- Number of Tank Cars Derailed

**Output**
- Distribution of Tank Cars Releasing per Train Shipment

**Distribution of Tank Cars Releasing per Train Shipment**

**Distributions**
- Poisson Distribution
- Beta Distribution
- Truncated Geometric Distribution
- Multivariate Hyper-geometric Distribution
- Poisson Binomial Distribution
Effect of tank car safety design on estimated interval* between multiple-car release incidents

* Assuming 2012 levels of crude oil and alcohol tank car traffic (ca. 550,000 carloads)

*Ceteris paribus*, the estimated intervals will be reduced in proportion to increases in traffic
Analysis of Train Derailment Rates, Causes, and Changes

Brandon Wang
Graduate Research Assistant
Frequency vs Severity of Mainline Derailments

- 2006 to 2010
- 2011 to 2015

- Other rail and joint defects
- Extreme weather
- Buckled track
- Broken rails or welds
- Track geometry (excluding wide gauge)
- Track geometry (excluding wide gauge)
- 80 iso-car line

Average Number of Cars Derailed vs Number of Derailments / Trillion Ton-Miles

- Broken rails or welds showed the most reduction, followed by track geometry
- Derailments due to extreme weather increased

![Graph showing changes in derailment rate by cause](image-url)
Loaded versus Empty Unit Train Derailment Cause Analysis

Weixi Li
Graduate Research Assistant

Geordie Roscoe
Undergraduate Research Assistant
Summary statistics for loaded vs. empty unit train derailments

- Loaded unit trains were five times more frequent than empty unit trains
- Loaded unit trains weighed over four times more than empty trains
- Similar train length and speed for both loading conditions
- Loaded trains tended to derail more cars
- Position of first derailed (POD) car was farther back in loaded trains than empty

<table>
<thead>
<tr>
<th>Loading Condition</th>
<th>Number of Accidents</th>
<th>Tons (1,000s)</th>
<th>Train Length †</th>
<th>Average Speed †</th>
<th>Average Number of Cars Derailed *</th>
<th>Average POD *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loaded</td>
<td>1,536</td>
<td>14.2</td>
<td>106.9</td>
<td>25.1</td>
<td>11.5</td>
<td>54.4</td>
</tr>
<tr>
<td>Empty</td>
<td>303</td>
<td>3.0</td>
<td>106.8</td>
<td>24.8</td>
<td>8.9</td>
<td>41.8</td>
</tr>
<tr>
<td>Other</td>
<td>4,180</td>
<td>7.1</td>
<td>77.9</td>
<td>22.5</td>
<td>8.3</td>
<td>34.2</td>
</tr>
</tbody>
</table>

* Denotes that significant difference for loaded and empty train derailments
† Denotes no significant difference between loaded and empty train derailments
Substantial difference in most frequent causes for loaded & empty unit train derailments

<table>
<thead>
<tr>
<th>Rank</th>
<th>Loaded Train Causes</th>
<th>Number</th>
<th>Empty Train Causes</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Broken Rails or Welds</td>
<td>288</td>
<td>Severe Weather</td>
<td>33</td>
</tr>
<tr>
<td>2</td>
<td>Broken Wheels (Car)</td>
<td>175</td>
<td>Broken Rails or Welds</td>
<td>31</td>
</tr>
<tr>
<td>3</td>
<td>Other Axle/Journal Defects (Car)</td>
<td>127</td>
<td>Track Geometry (excl. Wide Gauge)</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>Bearing Failure (Car)</td>
<td>122</td>
<td>Other Wheel Defects (Car)</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>Buckled Track</td>
<td>93</td>
<td>Buckled Track</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>Track Geometry (excl. Wide Gauge)</td>
<td>80</td>
<td>Lading Problems</td>
<td>13</td>
</tr>
<tr>
<td>7</td>
<td>Wide Gauge</td>
<td>74</td>
<td>Other Brake Defect (Car)</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>Roadbed Defects</td>
<td>44</td>
<td>All Other Car Defects</td>
<td>10</td>
</tr>
<tr>
<td>9</td>
<td>Turnout Defects - Switches</td>
<td>41</td>
<td>Train Handling (excl. Brakes)</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>Other Rail and Joint Defects</td>
<td>36</td>
<td>Non-Traffic, Weather Causes</td>
<td>8</td>
</tr>
</tbody>
</table>

Causes in **red** are unique to loaded unit trains, causes in **blue** are unique to empty unit trains and causes in **black** are shared by the two loading conditions.
Adjacent Track Accident Risk Model Development

Chen-Yu Lin
Graduate Research Assistant

RAILTEC
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
Adjacent track accidents (ATA)

- ATAs refer to train accident scenarios where derailed railroad equipment intrudes upon adjacent tracks, causing operational disruptions and potential subsequent collisions on the adjacent track(s).

- Other ATA scenarios include collisions between trains on adjacent tracks (raking collisions), turnouts, and railroad crossings (side collisions).

- A typical adjacent track accident scenario:

```
Normal Operation
Derailment
Intrusion
Collision
```

Clearance envelope
Equipment loading gauge
Integrated ATA risk assessment model

- Combine probability models for initial accident, intrusion and train presence on adjacent tracks to develop a holistic risk assessment model for ATA
- Account for common affecting factors in different probability models

**Diagram:**

- **Initial Derailment** → **Intrusion** → **Train Presence**

**Event Tree Analysis**

**Fault Tree Analysis**

**Basic Event Probability Assessment**
ATA model application: hypothetical shared rail corridor

\[ R = P(D) \times P(I|D) \times P(T|I|D) \times C \]
Calculate segment-specific ATA risk

\[ R_i = P(D)_i \times P(I|D)_i \times P(T|I|D)_i \times C_i \]
Identify high ATA risk segments

**Risk Hotspots**

- Freight Yard
- Freight RR F
- Passenger Terminal A
- MP 000 - 002
  Terminal Tracks (Passenger Only)
- Mainline Commuter RR C
- Mainline Freight RR K
- Terminal Tracks
- Passenger Terminal B
- R₁, R₂, R₃, …, Rₙ
Conclusion: Efficient investment in train safety is essential

- Continued decline in derailment rates benefits the rail industry and the public
- Continued pressure, both internally and externally, for further improvement
- Most effective means of improving train safety becomes less obvious (and often more costly) as incident rate declines
- Industry (and government) must stay focused on identifying the most effective means for improvement
- Increasingly sophisticated data and analytical methods can be used to understand the most efficient ways to invest in safety improvements
Thank you very much! Questions?
Current RailTEC Safety and Risk Research Topics

**Derailment analysis**
- Factors affecting downward trend and rate
- Effect of train length on derailment occurrence
- Quantitative assessment of impact of speed restrictions
- Early detection of changes in derailment rate
- Loaded vs empty train unit-train derailment occurrence and causes

**Hazardous materials transportation safety and risk**
- Unit vs manifest train risk of hazardous materials transport
- Risk assessment tools for multiple railroad tank car releases
- Risk analysis of toxic inhalation hazard tank car implementation

**Grade crossing risk to railroads**
- Derailment probability due to grade crossing incidents
- Consequences of grade crossing incidents

**Passenger train derailments**
- Causal analysis and comparison to freight trains
- Quantitative risk analysis of adjacent-track train accident risk
Three-factor model of mainline freight train derailment rate: track class, method of operation & traffic density

Analysis indicates that *ceteris paribus*:
1) Higher track classes have lower derailment rates
2) Signaled tracks have lower derailment rates
3) Higher density trackage has lower derailment rates

*Liu et al 2017 Freight-train derailment rates for railroad safety and risk analysis. Accident Analysis and Prevention*
How did the distribution of derailments change between 2006-2010 and 2011-2015?

### Number of Derailments: 2006 - 2010

<table>
<thead>
<tr>
<th>Traffic Density (MGT)</th>
<th>Method of Operation (MO)</th>
<th>FRA Track Class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>&lt;20</td>
<td>Non-Signaled</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>Signaled</td>
<td>17</td>
</tr>
<tr>
<td>≥20</td>
<td>Non-Signaled</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Signaled</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>105</td>
</tr>
</tbody>
</table>

### Number of Derailments: 2011 - 2015

<table>
<thead>
<tr>
<th>Traffic Density (MGT)</th>
<th>Method of Operation (MO)</th>
<th>FRA Track Class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>&lt;20</td>
<td>Non-Signaled</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Signaled</td>
<td>17</td>
</tr>
<tr>
<td>≥20</td>
<td>Non-Signaled</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Signaled</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>77</td>
</tr>
</tbody>
</table>

*Gross Ton-Miles: 2006 to 2010 = 16.7 trillion, 2011 to 2015 = 17.2 trillion*
Change in Estimated Derailment Rate by FRA Track Class

- **2006 - 2010**
- **2011 - 2015**

<table>
<thead>
<tr>
<th>Track Class</th>
<th>2006-2010 Rate</th>
<th>2011-2015 Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-16%</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-30%</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-34%</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-26%</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-26%</td>
<td></td>
</tr>
</tbody>
</table>
Change in Estimated Derailment Rate by Method of Operation

- Non-Signaled: 44% decrease
- Signaled: 12% decrease
Change in Estimated Derailment Rate by Traffic Density

- 18% for <20 MGT
- 24% for ≥20 MGT
Did Derailment Causes Show Uniform Rates of Change?

- Was the decline in accident causes proportional to their frequency or did some decline at a rate greater (or less) than average?

- Statistical analysis of the change in cause-specific derailment frequency

![Graph showing the change in number of derailments over the number of derailments.](image)
Estimated Probability Distribution and Actual Number of Cars Releasing

Number of Tank Cars Releasing
Cumulative Frequency Distribution of Loaded, Empty and Other Type Train Derailments

- **Empty**
- **Loaded**
- **Other**

![Graph showing cumulative frequency distribution of train derailments](image)

- Number of Derailments
- Number of Cars Derailed
- Cumulative Percentage