Impact of Automated Condition Monitoring Technologies on Railroad Safety and Efficiency

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Presentation Outline

- Objective & Motivation
- Impact of ACMT on Safety
- Impact of ACMT on Efficiency
  - Terminal Performance Using Lean Production Methods
  - Mainline Efficiency Using Dispatch Simulation Software
- Future Work
Research Objective

To determine the safety and economic implications of using Automated Condition Monitoring Technology (ACMT) to monitor the condition of freight cars.
Automated Condition Monitoring Technology (ACMT)

- Reactive Maintenance:
  - Dragging Equipment Detectors
  - Hot Bearing Detector
- Condition-Based Maintenance:
  - Acoustic Bearing Detectors
  - Wheel Impact Load Detectors
  - Hunting Truck Detectors
  - Truck Performance Detectors
  - Wheel Temperature Trending
  - Wheel Profile Monitoring
  - Warm Bearing Trending
  - Machine Vision (MV) Inspection

Increased Implementation of ACMT

Increased Implementation of ACMT

Objectives Driving Condition Monitoring Improvements

Improved Condition Monitoring → Reduced Derailments → Reduced Terminal Dwell → Reduced In-Service Failures

- Reduced Track & Equipment Damages
- Reduced Employee Injuries
- Reduced Mainline Delay
Cost of Equipment-Caused Derailments

- Over 1,340 equipment-caused, reportable mainline derailments from 1999-2008 for four largest US Class I railroads
- $350 million in track and equipment damages
- 78% of all damages resulted from failures to wheels, journal bearings, or truck components
- 49 injuries during this time frame (< 5 per year)
Cost of Equipment-Caused Derailments

1999-2008 ~ $38.4 M / yr

Source: Federal Railroad Administration (FRA) Office of Safety Analysis
Cost of Equipment-Caused Derailments

- Wheels: $33.0 M / yr
- Journal Bearings
- Truck Components
- Axles
- Couplers & Draft System
- Brakes
- Car Body
- Other

Source: Federal Railroad Administration (FRA) Office of Safety Analysis
Objectives Driving
Condition Monitoring Improvements

- Reduced Derailments
- Reduced Terminal Dwell
- Reduced In-Service Failures

- Improved Condition Monitoring
- Reduced Track & Equipment Damages
- Reduced Employee Injuries
- Reduced Mainline Delay
Terminal Performance

- “Cars spend most of their time in terminals, and that’s where the service battle is won or lost for carload business”
- Terminal Dwell = the average time a car resides at a specified yard or terminal (measured in hours)
- Terminal Dwell is directly related to average train velocity
- A 15% reduction in systemwide average terminal dwell could result in an increase of 2 mph in carload velocity
- Terminal performance directly affects unit train operations directly due to FRA-required 1,000-mile (Class IA) air brake inspections

Lean Railroading

- In 1990 “Lean Manufacturing” was first introduced at MIT based on a study of the Toyota Production System
  - *Lean* is defined as the production of goods or services using minimal buffering costs
  - Sources of excessive buffering include *direct waste* and *variability*
- Dirnberger developed steps for applying *lean* to terminals
- Applying Lean Railroading over a one-year period, Canadian Pacific Railway (CPR) saw average terminal dwell drop by over 28%, average terminal capacity increase by 40%, and average train speed increase by 3.6 mph
- CPR, UP, BNSF, NS, Belt Railway of Chicago, and GE Yard Solutions are now applying aspects of Lean Railroading

Lean Railroading (cont.)

- Steps for Implementing Lean Railroading in Terminals:
  - Eliminate Direct Waste
  - Modify Buffers
  - Reduce Variability
  - Perform Continuous Improvement

- Applied to humping and switching activities to improve efficiency in classification yards

- Lean techniques can also be applied to railcar maintenance practices to improve yard efficiency
Autonomation and Inspection

- Autonomation is “automation with a human touch”
- Train inspection can be likened to quality control in the railyard “production system”
- There are various inspection types used for quality control:

<table>
<thead>
<tr>
<th>System</th>
<th>Search</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure human inspection</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Computer-search human decision</td>
<td>C</td>
<td>H</td>
</tr>
<tr>
<td>Human-computer decision-making</td>
<td>C</td>
<td>H + C</td>
</tr>
<tr>
<td>Pure automated inspection</td>
<td>C</td>
<td>C</td>
</tr>
</tbody>
</table>

H = Human, C = Computer

*Adapted from Hou et al. (1993)

- Hybrid systems typically perform better than either humans or machines alone
Eliminate Direct Waste

- Direct waste comes from operations that are unnecessary
- Examples include: rework, accidents, in-service failures, injuries, car damage, and unnecessary motion or information collection

- Two Types of Direct Waste:
  - Type I: Inherent but Unavoidable
    - Tagging of bad order cars
  - Type II: Immediately Avoidable
    - Manual railcar inspection
      - Implementation of Electronically Controlled Pneumatic (ECP) brakes
      - Integration of ACMT
Type I Waste

*Each bad order adds approx. ten minutes of Type I waste

\[ y = 0.17x + 2.25 \]
\[ R^2 = 0.89 \]
Eliminate Direct Waste

- Direct waste comes from operations that are unnecessary
- Examples include: rework, accidents, in-service failures, injuries, car damage, and unnecessary motion or information collection

- Two Types of Direct Waste:
  - **Type I: Inherent but Unavoidable**
    - Tagging of bad order cars
  - **Type II: Immediately Avoidable**
    - Manual railcar inspection
      - Implementation of Electronically Controlled Pneumatic (ECP) brakes
      - Integration of ACMT
Type II Waste

Average Train Inspection Times

*Trains equipped with ECP brakes require fewer Class IA inspections*
Modify Buffers

- Buffers result from uncertainty and lead to indirect waste
- Common buffers
  - **Inventory**: reserve supplies of fuel, railcars, or wheelsets
  - **Capacity**: excess storage tracks, car inspectors, or repair personnel
  - **Time**: “slack time” in the train schedule
- Buffers can be modified, or swapped, to reduce indirect waste
- Example: decrease the time buffer due to excess inspection time and increase the capacity buffer by shifting labor from inspection to repair activities
- ACMT will affect all three types of buffers
Reduce Variability

- Variability is a fundamental source of waste, as it necessitates buffering in the form of extra inventory, capacity, or time

<table>
<thead>
<tr>
<th>Buffer</th>
<th>Inventory</th>
<th>Capacity</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Variability</td>
<td>Fueling requirements</td>
<td>Train arrivals</td>
<td>Train arrivals</td>
</tr>
<tr>
<td></td>
<td>Amount of rolling stock requiring maintenance</td>
<td>Amount of rolling stock requiring maintenance</td>
<td>Inspection or repair times</td>
</tr>
<tr>
<td></td>
<td>Severity of required maintenance</td>
<td>Severity of required maintenance</td>
<td>Labor availability</td>
</tr>
</tbody>
</table>

- Variability can be reduced by regulating work-in-process (WIP), or the amount of unfinished product in the system at a given time

- ACMT can help regulate WIP through the use of “windows of opportunity” (e.g. opportunistic wheelset replacement)
Reduce Variability (cont.)

Repair Time vs. No. of Wheelset Replacements

\[ y = 0.03x^2 + 0.01x + 0.64 \]

\[ R^2 = 0.97 \]
Perform Continuous Improvement

- Variability will always exist in the production system
- Managers should work to actively manage buffers:
  - Predictive maintenance can result in reduced inventory buffers
  - Improved railcar maintenance will lead to increased railcar utilization and can result in decreased capacity buffers
  - Time buffers should be closely monitored and appropriately reduced as technology permits
- Improvements in terminal efficiency can impact efficiency across a railroad’s entire network
Data Analysis

- Long distance unit trains are required to stop for FRA Class IA, 1,000-mile air brake inspections.
- Operational waste was estimated using inspection data for an example Class I railroad terminal.

<table>
<thead>
<tr>
<th>Train Type</th>
<th>Coal</th>
<th>Grain</th>
<th>Automotive</th>
<th>Intermodal</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Inspection Time (hrs)</td>
<td>2.31</td>
<td>1.96</td>
<td>1.62</td>
<td>1.33</td>
<td>2.16*</td>
</tr>
<tr>
<td>Number of Trains Inspected per year</td>
<td>10,600</td>
<td>650</td>
<td>770</td>
<td>1,320</td>
<td>13,340</td>
</tr>
<tr>
<td>Percent of Trains Inspected per year (%)</td>
<td>79</td>
<td>5</td>
<td>6</td>
<td>10</td>
<td>100</td>
</tr>
</tbody>
</table>

*Weighted average

- Savings were determined by subtracting the estimated hybrid inspection costs from the current cost of manual inspections.
Manual Inspection Cost

\[ C_{\text{manual}} = 2 \times T_{\text{manual}} \times N \times S \]

where,

- \( C_{\text{manual}} \) = total annual labor cost for manual inspections, in $(USD)
- \( T_{\text{manual}} \) = average inspection time (weighted by train type) for manual inspections, in hours
- \( N \) = number of 1,000-mile inspections per year
- \( S \) = average hourly compensation for car inspectors, including benefits in $(USD)

\[ C_{\text{manual}} = 2 \times 2.16\text{hrs} \times 13,340 \times $39.13/\text{hr} \]
Manual Inspection Cost

\[ C_{\text{manual}} = 2 \times T_{\text{manual}} \times N \times S \]

where,

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\[ C_{\text{manual}} = $2,255,300 \]
Hybrid Inspection Cost

\[ C_{\text{hybrid}} = (D \times A_{\text{automated}} + F_{\text{automated}}) \times T_{\text{hybrid}} \times N \times S \]

where,

- \( C_{\text{hybrid}} \) = total annual labor cost for hybrid inspections, in US dollars
- \( D \) = average number of detectable FRA defects per train inspection
- \( A_{\text{automated}} \) = average correct identification percentage for automated wayside detectors (i.e. accuracy)
- \( F_{\text{automated}} \) = average false alarm rate for automated wayside detectors
- \( T_{\text{hybrid}} \) = average inspection time to verify a single component defect, in hours

\[ C_{\text{hybrid}} = (2 \times 0.95 + 0.10) \times 0.25 \text{hrs} \times 13,400 \times $39.13/\text{hr} \]
Hybrid Inspection Cost

\[ C_{\text{hybrid}} = (D \times A_{\text{automated}} + F_{\text{automated}}) \times T_{\text{hybrid}} \times N \times S \]

where,
- \( C_{\text{hybrid}} \) = total annual labor cost for hybrid inspections, in US dollars
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- \( T_{\text{hybrid}} \) = average inspection time to verify a single component defect, in hours

\[ C_{\text{hybrid}} = \$261,000 \]
Results

Net Savings: \[ C_{\text{manual}} - C_{\text{hybrid}} = $1,994,300 \]

- Results suggest that a single Class I railroad terminal could recover approximately $2 million per year through the use of hybrid inspection practices.
- This is a conservative estimate, since only labor costs for Class IA inspections have been included.
- Additional savings would result from reducing variability.
- These costs are sensitive to both the number of inspections considered, \( N \), and the overall condition of the railcar fleet, represented in this model by \( D \).
Sensitivity Analysis

N = 250,000

N = 50,000

N = 10,000

* N = annual Class IA inspections
Summary of Terminal Performance Analysis

- Railroad terminals can benefit substantially from lean principles.
- A methodology has been presented for the application of Lean Railroading to railcar inspection and maintenance practices.
- Results from this analysis:
  - Single Terminal: ~$2 million estimated annual savings
  - US Railroad Industry: ~$35 million estimated annual savings
- To realize these benefits:
  - ACMT capable of monitoring all safety-critical railcar components must be fully developed and integrated
  - New operational practices must be approved and adopted
- As technology integration advances, the distances between inspections may be increased, resulting in additional savings.
Future Terminal Related Research

- Evaluate the entire railcar maintenance process to understand additional sources of waste (e.g. value stream mapping)
- Examine sources of variability and develop techniques to better quantify variability
- Apply lean production methods to other areas such as intermodal terminals

http://assets.bizjournals.com/story_image/111314-600-0-2.jpg
Objectives Driving Condition Monitoring Improvements

- Improved Condition Monitoring
  - Reduced Derailments
  - Reduced Terminal Dwell
  - Reduced In-Service Failures

- Reduced Track & Equipment Damages
- Reduced Employee Injuries
- Reduced Mainline Delay
Analysis of Train Delay

- Train delay is a metric often used for mainline capacity.
- Rail Traffic Controller (RTC) from Berkeley Simulation Software is the de facto industry standard for measuring train delay.
- The University of Illinois at Urbana-Champaign (UIUC) recently used RTC to analyze effects of train type heterogeneity.
- In the current study, we assess the effects of equipment-caused mainline in-service failures (ISFs).
- We consider the amount and variability of train delay for various lengths of ISF and traffic volumes.

http://www.berkeleysimulation.com/rtc/location.html
**RTC Dispatch Simulations**

<table>
<thead>
<tr>
<th>Route Characteristics</th>
<th>Train Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>260 miles long</td>
<td>Unit coal trains</td>
</tr>
<tr>
<td>10 miles between control points</td>
<td>115 cars, 6,325 ft. long</td>
</tr>
<tr>
<td>8,000 ft. signaled sidings</td>
<td>16,445 tons per train (loaded)</td>
</tr>
<tr>
<td>2.5-mile signal spacing</td>
<td>3,795 tons per train (empty)</td>
</tr>
<tr>
<td>3-block, 4-aspect signaling</td>
<td>0.78 HP / trailing ton</td>
</tr>
<tr>
<td>0% grade and curvature</td>
<td>3 SD70 4,300 HP locomotives</td>
</tr>
<tr>
<td></td>
<td>Maximum speed: 50 mph</td>
</tr>
</tbody>
</table>

- Simulations consisted of unit coal traffic on single and double-track routes
- 1, 3, and 5-hour train stops were initiated to represent equipment-caused in-service failures (ISFs)
- Train delay was determined by subtracting delay time for the base case from the delay time for an ISF
Delay Cost Calculation

Total Cost = Total Delay Time × Delay Cost

- Delay cost figure involves five components:
  - freight car ownership cost
  - locomotive ownership cost
  - fuel idling cost
  - crew labor cost
  - lading delay cost

- For the current study, we assume a delay cost of $662 per train-hour

- The lading delay cost was estimated at $430 per train hour

Train Delay Costs

Average Delay Cost ($1000)

Traffic Volume (Trains Per Day)

Single Track
R² = 0.99

Double Track
R² = 0.98
R² = 0.99
R² = 0.94
R² = 0.96
Estimation of Industry-Wide Costs

<table>
<thead>
<tr>
<th>Average ANMGT</th>
<th>Single-Track</th>
<th></th>
<th>Double-Track</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Delay Cost ($)</td>
<td>Ton-Miles (%)</td>
<td>Delay Cost ($)</td>
<td>Ton-Miles (%)</td>
</tr>
<tr>
<td>&lt;40 (~37)</td>
<td>1,250</td>
<td>31.3</td>
<td>990</td>
<td>0.9</td>
</tr>
<tr>
<td>40-60</td>
<td>1,600</td>
<td>17.9</td>
<td>1,000</td>
<td>2.3</td>
</tr>
<tr>
<td>60-100</td>
<td>2,190</td>
<td>18.7</td>
<td>1,040</td>
<td>6.2</td>
</tr>
<tr>
<td>&gt;100 (~110)</td>
<td>4,640</td>
<td>5.5</td>
<td>1,160</td>
<td>16.3</td>
</tr>
<tr>
<td>Total</td>
<td>--</td>
<td>73.5</td>
<td>--</td>
<td>25.6</td>
</tr>
</tbody>
</table>

- **Assumptions:**
  - 15,000 to 20,000 ISFs on US class I mainlines per year
  - Average delay time of 1.5 hours per ISF
  - Delay costs are negligible for routes with more than two main tracks

- **Results:**
  - Annual failure costs range from $24 million to $33 million for US Class I railroads

Train Delay Variability

- Variability is a fundamental source of operational waste because it necessitates buffering (e.g. added slack time in train schedules)

- Based on RTC simulations, train delay variability increases with both traffic volume and length of ISF

- Length of ISF ranged from 0 to 5 hours

- Traffic volumes ranged from 16 to 52 trains per day (T/D) on single-track (ST) and from 64 to 126 T/D on double-track (DT)

- Frequency diagrams were created for both single and double-track routes
Various Lengths of ISF (ST, 52 T/D)
Various Lengths of ISF (DT, 126 T/D)
Various Traffic Volumes (ST, 5 hr ISF)
Various Traffic Volumes (DT, 5 hr ISF)
Summary of Variability Analysis

- Train delay variability increases with both ISF length and traffic volume
- Variability is much more evident on single-track routes
- Mechanical ISFs affect variability on double-track routes, but only at very high traffic volumes
- Increased variability results in a higher probability that trains will experience longer delays, resulting in indirect waste in the form of increased time buffers
- Although costs are more difficult to quantify, variability negatively impacts the level of service that railroads can offer customers
Future Mainline Efficiency Research

- Develop a metric to determine the effectiveness with which critical railcar components can be monitored:
  - A function of ACMT accuracy and the statistical probabilities for equipment-caused ISF
  - Requires extensive data collection and analysis
  - Can be used to determine the proportion of ISF costs that could be recovered using ACMT

- Quantification of train delay costs associated with major derailments
  - Performing RTC simulations for 24-48 hour ISFs is not practical
  - Empirical analysis using historical derailment data may be the best approach
Summary

Improved Condition Monitoring

- Reduced Derailments: Average: $38 million
- Reduced Terminal Dwell: Estimated: $35 million
- Reduced In-Service Failures: Estimated: $29 million

Total Potential Savings of over $100 million per year
Additional Future Research

- Include estimates of environmental clean-up and litigation costs due to equipment-caused derailments.
- Develop a methodology for determining what proportion of equipment-caused derailments and ISFs can be prevented using ACMT.
- Apply six sigma and statistical process control (SPC) methods to improve maintenance efficiency and reduce operational variability.

[Source: http://wayzata.com/2010/06/30/train-derails-in-wayzata/]
Acknowledgements

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Questions / Comments?