Advanced Rolling Stock Condition Monitoring Technologies for Freight Rail Transport

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Overview

- Introduction and Background
- Bearing Condition Monitoring Systems
- Accident Case Studies
- UTCRS Proposed Advanced Condition Monitoring System
- Proof of Concept Validation Testing
- Results and Analysis
  - Laboratory Testing
  - 2015 TTCI Field Test
- Other UTCRS Ongoing Research and Capabilities
- UTCRS Research Group
BEARING ASSEMBLY
Bearing Assembly

Figure 1. Tapered-Roller Bearing Components [2]
BEARING FAILURE MODES
Bearing Failure Modes

Geometric Defects
- Geometric inconsistencies of bearing components
- Out-of-tolerance components due to manufacturing errors

Local Defects
- Spalls
- Pits
- Cracks

Distributed Defects
- Waviness of raceways
- Asperities on multiple bearing components
- Water-etch

Figure 2. Example of a localized defect (left) and distributed defect (right)
BEARING CONDITION MONITORING SYSTEMS
Hot-Box Detectors (HBDs)

- Hot-Box Detectors (HBDs) use infrared sensors to measure the temperature radiated from bearings, wheels, axles, and brakes.
- Over 6,000 in use in the U.S. [3].
- 119 train derailments due to overheated bearings from 2010 to 2016 in the U.S. and Canada [4].

Figure 3, Example of a HBD site [5]
Trackside Acoustic Detector Systems (TADS™)

- Uses microphones to detect high risk defects in components such as “growlers”.
- “Growlers” are severely spalled bearing components containing spalls that occupy more than 90% of bearing component’s contact surface.
- Alerts train operator to stop immediately if a defective bearing is detected.
- 18 systems used in the U.S. and Canada. [7]

Figure 4. TADS™ site and defects detected by TADS™ [6]
ACCIDENT CASE STUDY
Railway Investigation Report R13T0122

- Approximately 10:00 a.m. E.S.T., June 02, 2013.
- Canadian Pacific Railway freight train 119-01, heading north to Sudbury, Ontario, Canada, at 35 mph, had 6 cars derail.
- Some of the cars that derailed struck the bridge, causing for the bridge to collapse, releasing several hazardous materials into the river.
- CP 119-01 did not trigger any of the 6 HBDs between Mactier and Sudbury before derailing shortly before reaching Sudbury.

Figure 5. Travel path of CP 119-01 [8]
Railway Investigation Report R13T0122

Figure 6. Photograph of CP 119-01 derailment [9]
Figure 7. Photographs of the burnt-off axle journal stub (left), cup (center), and outboard cone assembly (right) [8]
UTCRS PROPOSED ADVANCED CONDITION MONITORING SYSTEM
Proposed Method Using On-board Sensors

1. Trigger Accelerometer at 40 MPH
   - Collect 20,000 Data Points (4 seconds of data at 5 kHz)
   - Generate RMS

2. Level 1
   - Is the Bearing Defective? (i.e., RMS > Preliminary Thld.)
     - YES
     - Generate PSD
     - Is it a Local Defect? (i.e., track fundamental frequencies)
       - YES
       - The Bearing Most Likely Contains a Distributed or Geometric Defect
     - NO
     - Is the RMS Value Higher than the Defect-Free Bearing Maximum Threshold?
       - NO
       - Continue to Monitor

3. Level 2
   - The Bearing Most Likely Contains a Distributed or Geometric Defect

4. Level 3
   - What is the Defect Size? (Use library of defects along with the developed correlations)
Instrumentation Setup

Figure 8. Modified bearing adapter showing sensor locations
Figure 9. Adapter Sensor Insert Flex Circuit

Figure 10. Load Sensor Insert Assembly

Figure 11. Smart Adapter Machined for Load Insert Capability
Fundamental Frequencies

ω₀ = angular speed of axle in Hz

ω_{cone} = ω₀

ω_{cage} = \left( \frac{R_{cone}}{R_{cone} + R_{cup}} \right) ω_{cone}

ω_{in} = 23(ω_{cone} - ω_{cage})

ω_{roller} = \left( \frac{R_{cone}}{D_{roller}} \right) ω_{cone}

ω_{rolldef} = \left( \frac{R_{cup}}{R_{roller}} \right) ω_{cage}

R_{cone} = 3.578367 \text{ in.}

R_{cup} = 4.408067 \text{ in.}

D_{roller} = 0.8425 \text{ in.}
Level 2 Analysis: Generate PSD

Figure 12. Examples of PSD plots for healthy and defective bearings
PROOF OF CONCEPT
VALIDATION TESTING
UTCRS Bearing Test Rigs

Figure 13. Four Bearing Test Rig (4BT)
UTCRS Bearing Test Rigs

Figure 14. Single Bearing Test Rig (SBT)
Instrumentation Setup

Figure 15. Top and rear views of 4BT including sensor locations
Test Speeds

Table 1. Typical speeds used to perform the experiments in this study

<table>
<thead>
<tr>
<th>Axle Speed [RPM]</th>
<th>Track Speed [km/h] / [mph]</th>
</tr>
</thead>
<tbody>
<tr>
<td>280</td>
<td>48 / 30</td>
</tr>
<tr>
<td>327</td>
<td>56 / 35</td>
</tr>
<tr>
<td>373</td>
<td>64 / 40</td>
</tr>
<tr>
<td>420</td>
<td>72 / 45</td>
</tr>
<tr>
<td>467</td>
<td>80 / 50</td>
</tr>
<tr>
<td>498</td>
<td>85 / 53</td>
</tr>
<tr>
<td>514</td>
<td>89 / 55</td>
</tr>
<tr>
<td>560</td>
<td>97 / 60</td>
</tr>
<tr>
<td>618</td>
<td>106 / 66</td>
</tr>
<tr>
<td>699</td>
<td>121 / 75</td>
</tr>
<tr>
<td>799</td>
<td>137 / 85</td>
</tr>
</tbody>
</table>
Field Test Railcar Setup at TTCI

Figure 16. A picture of the business car and the freight railcar being instrumented for the field test at TTCI
Field Test Railcar Setup at TTCI

Figure 17. Test Railcar Setup at TTCI
Laboratory Testing

RESULTS AND ANALYSIS
Experiment 201A: Pre-Test Information

Pre-Test Defect Size:
14.2 cm²
(2.2 in²)

Figure 18. Starting cup spall for Experiment 201A
A steady increase in bearing RMS is an indication of spall growth.

Figure 19. Vibration and temperature profiles for Experiment 201A [13]
**Level 1 Analysis RMS Values**

<table>
<thead>
<tr>
<th></th>
<th>Exp. 201A</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Load [%]</strong></td>
<td>17 17 17 17 17 17 17 100</td>
</tr>
<tr>
<td><strong>Speed [MPH]</strong></td>
<td>53 53 53 53 53 53 53 53</td>
</tr>
<tr>
<td><strong>IB-SA</strong></td>
<td>3.8 3.6 3.4 3.3 3.2 3.2 2.6</td>
</tr>
<tr>
<td><strong>IB-M</strong></td>
<td>5.5 2.6 2.6 4.8 6.1 6.1 5.4</td>
</tr>
<tr>
<td><strong>OB-SA</strong></td>
<td>6.4 4.2 4.3 6.0 7.1 7.1 5.2</td>
</tr>
<tr>
<td><strong>OB-M</strong></td>
<td>3.7 3.1 3.1 3.5 3.7 3.7 4.4</td>
</tr>
<tr>
<td><strong>Avg. Thld.</strong></td>
<td>2.3 2.3 2.3 2.3 2.3 2.3 2.3</td>
</tr>
<tr>
<td><strong>Max. Thld.</strong></td>
<td>4.9 4.9 4.9 4.9 4.9 4.9 4.9</td>
</tr>
</tbody>
</table>
## Level 1 Analysis RMS Values

<table>
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</tr>
<tr>
<td><strong>OB-M</strong></td>
</tr>
<tr>
<td><strong>Avg. Thld.</strong></td>
</tr>
<tr>
<td><strong>Max. Thld.</strong></td>
</tr>
</tbody>
</table>
## Level 2 Analysis

<table>
<thead>
<tr>
<th></th>
<th>IB-SA</th>
<th>IB-M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load [%]</td>
<td>17 17 17 17 17 17 17 100</td>
<td>17 17 17 17 17 17 17 100</td>
</tr>
<tr>
<td>Max/Sum [%]</td>
<td>98 92 94 96 92 92 92 97</td>
<td>85 92 94 82 61 61 61 93</td>
</tr>
<tr>
<td>Highest Magnitude</td>
<td>Cup Cup Cup Cup Cup Cup Cup Cup</td>
<td>Cup Cup Cup Cup Cup Cup Cup Cup</td>
</tr>
</tbody>
</table>

- IB-SA
- IB-M
# Level 2 Analysis

<table>
<thead>
<tr>
<th></th>
<th>IB-SA</th>
<th></th>
<th>IB-M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load [%]</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Speed [MPH]</td>
<td>53</td>
<td>53</td>
<td>66</td>
</tr>
<tr>
<td>Max/Sum [%]</td>
<td>99</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>Highest Magnitude</td>
<td>Cup</td>
<td>Cup</td>
<td>Cup</td>
</tr>
</tbody>
</table>
Experiment 201A: Post-Test Information

Post-Test
Defect Size:
20.9 cm$^2$
(3.24 in$^2$)

Distance traveled:
32,955 km
(20,477 miles)

Figure 20. Ending cup spall for Experiment 201A
RESULTS AND ANALYSIS

2015 TTCI Field Test
Laboratory Data vs. Field Data

Figure 21. Difference between laboratory data and field data
# Field Test Data Collected

Total Number of Sample Windows (SW) used for analysis for each speed and load

<table>
<thead>
<tr>
<th>Day 1 &amp; 2 (100% of Full-Load)</th>
<th>Day 3 (17% of Full-Load)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed [mph]</td>
<td>End A</td>
</tr>
<tr>
<td>30</td>
<td>109</td>
</tr>
<tr>
<td>40</td>
<td>58</td>
</tr>
<tr>
<td>50</td>
<td>111</td>
</tr>
<tr>
<td>55</td>
<td>97</td>
</tr>
<tr>
<td>57</td>
<td>-</td>
</tr>
<tr>
<td>60</td>
<td>-</td>
</tr>
</tbody>
</table>
2015 Field Test: Pre-Test Information

L1 Cone Defect
Max Area: 2.2 in²
Represents 2.5% of Combined Cone Raceway Area

R2 Cup Defect
Max Area: 5.3 in²
Represents 4.7% of Combined Cup Raceway Area
## Level 1: Defect Detection

Percentages of SWs with RMS values greater than the Maximum Threshold at End A

<table>
<thead>
<tr>
<th>End A</th>
<th>17% Load</th>
<th>100% Load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L1 (Cone Defect)</td>
<td>R2 (Cup Defect)</td>
</tr>
<tr>
<td>Speed [mph]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>97%</td>
<td>100%</td>
</tr>
<tr>
<td>50</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>55</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>57</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>60</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>
Level 2: Defect Type

Percentages of SWs having the corresponding defective component’s normalized defect energy (NDE) greater than 50% at End A

<table>
<thead>
<tr>
<th>End A</th>
<th>17% Load</th>
<th>100% Load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L1 (Cone Defect)</td>
<td>R2 (Cup Defect)</td>
</tr>
<tr>
<td>Speed [mph]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>3%</td>
<td>47%</td>
</tr>
<tr>
<td>50</td>
<td>43%</td>
<td>80%</td>
</tr>
<tr>
<td>55</td>
<td>72%</td>
<td>100%</td>
</tr>
<tr>
<td>57</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>60</td>
<td>100%</td>
<td>92%</td>
</tr>
</tbody>
</table>
Smallest Spall Size Detected

U.S. Penny
Diameter: 0.75"
Area = 0.442 in²

Smallest Spall Detected
L_{\text{max}} = 0.144"
W_{\text{max}} = 0.791"
Area = 0.114 in²
% of cup raceway = 0.1%

President Lincoln’s Head on a Penny
L_{\text{max}} = 0.2"
W_{\text{max}} = 0.5"
Area = 0.1 in²
Conclusions

- Current wayside condition monitoring systems are reactive and inefficient.
- Temperature measurements alone are not a reliable or effective metric for quantifying bearing health.
- Onboard condition monitoring techniques utilizing vibration and temperature sensors provide a more reliable and proactive approach to tracking the health of railroad bearings in service.
- Accurately identifying bearing defects at an early stage, and tracking these defects as they develop and worsen can assist railroads in scheduling appropriate maintenance cycles, and avoid costly and unnecessary train stoppages and delays, not to mention preventing severe damages to the rail infrastructure that can result if defects progress undetected leading to catastrophic derailments.
123,744 miles
22 round trips from N.Y.C. to L.A.

Size [in²]: 0.114
RMS [g]: 8.0
Absolute Temperature [°C]: 74
Temp. Above Ambient [°C]: 55
Control Temp. [°C]: 85

Size [in²]: 3.24
RMS [g]: 18.3
Absolute Temperature [°C]: 78
Temp. Above Ambient [°C]: 53
Control Temp. [°C]: 85
OTHER UTCRS ONGOING RESEARCH AND CAPABILITIES
Assessing Performance of Reconditioned Bearings

![Graph showing RMS vs. time and temperature profile](image-url)
Assessing Performance of Reconditioned Bearings

94,000 miles of service operation after bearing was reconditioned
Dynamic test utilizing the second order correlation

Dynamic test utilizing the multivariate correlation
Conductive Adapter Steering Pad

- The polymer adapter steering pad is used to reduce stress of axle and wear of surrounding components experienced by railcar during daily operation.
- Cyclic loading and wear of pad causes copper studs inserted in pad to lose contact and render it non-conductive.
- UTCRS created a conductive nanocomposite made of Carbon Nano Fibers (CNFs) and Thermoplastic Polyurethane (TPU) to replace current material.
Current Results

- Worked with BASF to develop a nanocomposite with microstructural properties suited for injection molding conductive inserts
- Currently studying the electrical, thermal, mechanical, and fatigue properties of the injection molded parts
UTCRS RESEARCH GROUP
UTCRS Research Group

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- Expertise: Experimental Heat Transfer and Fluid Mechanics; Thermal and Dynamic Analysis of Railroad Rolling Stock; Advanced Bearing Condition Monitoring Systems; and Acoustics and Vibrations.
- 14 Years of Experience Conducting Railroad Research.
Ongoing Research Projects

• Assessing the Efficacy of Railroad Bearing Reconditioning through Service Life Performance Testing. Transportation Technology Center, Inc. (TTCI)
• Low Power Wireless Sensors for Railroad Bearing Health Monitoring. [USDOT]
• Prototyping and Testing of Electrically Conductive Thermoplastic Polyurethane (TPU) Railroad Suspension Pad. [USDOT]
• Development of Predictive Models for Spall Growth in Railroad Bearing Rolling Elements. [USDOT]
• Radiative Heat Transfer Analysis of Railroad Bearings Using a Single Bearing Test Rig for Wayside Thermal Detector Optimization. [USDOT]
• Demonstration of Magnetostrictive Materials for Self-Powered Monitoring of Rail Vehicle Suspension Components. [USDOT]
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- Expertise: Mechanical behavior of materials and components; Polymer and Composite Processing, Structure, and Performance; Fracture and Failure of Materials and Components; Dental Materials and Structures
- 13 Years of Experience Conducting Railroad Related Research.
Ongoing Research Projects

• Prototyping and Testing of Electrically Conductive Thermoplastic Polyurethane (TPU) Railroad Suspension Pad. [USDOT]
• Development of Predictive Models for Spall Growth in Railroad Bearing Rolling Elements. [USDOT]
• Evaluation of Lubricant Life by Differential Scanning Calorimetry. [USDOT]
• Characterization and Testing of Composite Manhole Covers for Commercial Service. [Private Industry]
Materials Laboratory Resources

• Mechanical Testing (22 kip dynamic, 70k, & 400k Universal Test Machines, Enviro Chamber -40° to 200°C)
• Impact (Charpy, Izod, Instrumented Impact)
• Hardness (Brinell, Rockwell, Shore, Vickers)
• Thermal Analysis (DSC, DMA, TMA, TGA)
• Specialized (Salt Fog, Taber Abraser, RR Moor Fatigue, Sheet Metal Fatigue, Polymer Creep)
• Microscopy (Digital, SEM, AFM)
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- Expertise: Experimentally Validated Stress, Vibration, and Heat Transfer Finite Element Analysis; Condition-Based Monitoring Systems.
- 10 Years of Experience Conducting Railroad Research.
Relevant Research Projects

- Railroad Bearing Thermal Management including Hysteresis Heating of Railroad Bearing Thermoplastic Elastomer Suspension Pad. [USDOT]
- Development of Predictive Models for Spall Growth in Railroad Bearing Rolling Elements. [USDOT]
- Vibration-Based Defect Detection for Freight Railcar Tapered-Roller Bearings in Field and Laboratory Testing. [USDOT]
- Structural Integrity and Fatigue Life Estimation of Railroad Bearing Adapters for Onboard Monitoring Applications. [USDOT]
- Identifying and Understanding Temperature Trending in Railroad Tapered-Roller Bearings. [USDOT]
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- Expertise: Microwaves; RF Circuits; Electromagnetics; Wireless Sensor Devices; Low Power Electronics.
- 25 Years Experience in Antennas, Wireless, and Sensor Electronics, including 8 Years Experience with Railway Safety Group.
Relevant Research Projects

• Low-power wireless sensors for railway suspension monitoring [Ongoing, USDOT through UTCRS]
• Energy harvesting using magnetostrictive materials. [USDOT through UTCRS]
• Reconfigurable antennas for vehicular communications. [DARPA, ITT]
UTCRS Research Group

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- Expertise: Applied Statistics; Design of Experiments; Reliability; Time Series Analysis; Operations Research; Information Technology; Data Science/Analytics
- 25 Years Experience in Applied Statistics and Data Science, including 6 years with Railway Safety Group.
Relevant Research Projects

- Models for the Residual Life of Railroad Bearing Grease in Laboratory and Industry Applications. [USDOT through UTCRS]


- Study of Processing Variables on the Electrical Resistivity of Conductive Adhesives.
UTCRS Research Group

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- Expertise: Computer Vision; Artificial Intelligence; Intelligent Transportation Systems; Autonomous Driving.
- 8 Years of Experience Conducting Cross-Domain Research in Computer Vision, Artificial Intelligence and Transportation.
Relevant Research Projects

- Traffic Data Collection for Multiple Vehicle Types from Drone Videos. [On going]
- Integrated Feature Detection and Tracking from Microscope Images of Composite Materials. [Air Force Research Lab]
- Algorithm Development for Reconstruction of Design Elements. [NSF]
- Robust Feature Tracking through Serial Section Microstructural Image Data. [Air Force Research Lab]
References


References


Questions?