Telematics Data-driven Prognostics System for Construction Heavy Equipment Health Monitoring and Assessment

Hisham Said, Ph.D.
Santa Clara University

Tony Nicoletti
DPL America

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Outline

- Introduction
- Research Need and Objective
- Telematics Overview – System Architecture And Data
- Telematics-Based Prognostics System
- System Validation
- Conclusion & Future Research
Overview

- Heavy equipment is a vital and expensive asset.
- Effective maintenance program is critical in heavy construction companies.

Types of Equipment Maintenance Programs

- **Reactive (breakdown) Maintenance:** Get the broken machine up and running as quickly as possible. Don’t touch running equipment!

- **Proactive (Preventive) Maintenance:** Periodic inspection, lubrication, and replacement of worn parts, filters, and fluids.

- **Predictive Maintenance:** Schedule maintenance tasks based on the past performance of engine parts. Example: Engine Oil Analysis

Gransberg et al. 2006
Overview

- Preventive Maintenance analysis = Prognostics
- Prognostics is the field of predicting the future health behavior, failure events, and remaining useful life (RUL). (Mesgarpour et al. 2013)

Prognostics

```
Model-Based
Virtual models of the machine behavior under healthy and faulty conditions

Data-Driven
Utilize collected sensor data of the machine’s previous behavior toward failure

Hybrid
Integrating model formulation with sensor data calibration

Prognostics Previous Research:
- Stationary machines health assessment by vibrations monitoring (Dutta and Giurgiutiu 2000; Yan R. and Gao 2007; Da et al. 2011, Thomson 2013)
- Integration of sensors and oil samples for prognostics (Murakami et al. 2002)
```
Research Need and Objective

- Preventive maintenance (data-driven prognostics) is efficient, but requires significant data collection and analysis processes.
- Rich data source …… TELEMATICS!
- Telematics = GPS + machine sensing system + wireless communication.
- Fleet managers are challenged to link telematics data to fleet functions and performance metrics.
- Little research on construction equipment telematics (Monnot and Williams 2011, Aslan and Koo 2012)

Research Objective:

Develop and validate a data-driven prognostics System that utilizes equipment telematics data to estimate its failure probability.
Telematics Overview

- Typical System Architecture

- Telematics installed in equipment by:
  - Original equipment manufacturer (OEM)
  - Third-party service provider (TSP)

User Interface

- Wireless Devices for real time notification
- Web Software 24/7 multi-user access
- Data Download to customer programs

Communication Medium

- Wireless Network

Typical System Architecture

- Transponder Units on Fleet Assets
- GPS Satellites
- Location data
- Utilization, Location, Alarms, CAN-BUS
- Remote shutoff & control

Servers
Telematics Overview

Telematics Data – Types and Collection

J1939 Data (engine speed, check lamps, oil pressure, fluids temperature) received through **CAN-bus Connection**

Basic Data Received (local temperature, battery voltage, engine runtime) through **Main Interface Cables**

Location data Received by **GPS Receiver**

Telematics Data Sent through **Wireless Antenna**
Prognostics System

- **Survival Analysis**: a regression approach to assess the times and probabilities to failure events, in terms of its independent variables.

- **Cox’s proportional hazards function** $h(t)$ to estimate the failure rate at time $t$. (Cox 1972)

\[ h(t) = h_0(t) \times \exp[\beta(t).X(t)] \]

- $h_0(t)$: baseline failure rate (asset decay over time)
- $X(t)$: failure/health parameters
- $\beta(t)$: regression coefficients
Suggested Health Parameters $X(t)$:

1) **Maximum coolant temperature** ($MCT_t$) in degrees Fahrenheit.
2) **Maximum engine oil pressure** ($MOP_t$) in pounds per square inch (psi).
3) **Maximum engine oil temperature** ($MOT_t$) in degrees Fahrenheit.
4) **Maximum engine speed** ($MES_t$), in rounds per minute (rpm).
5) **Maximum engine percent torque** ($MPT_t$).
6) **Maximum fuel rate** ($MFR_t$) in gallons/hour.
7) **Engine working hours** ($HW_t$), which reports the cumulative number of hours the engine run with a speed (rpm) above a specified threshold.
8) **Engine Idling hours** ($HI_t$), which reports the cumulative number of hours the engine ran with a speed (rpm) less than the specified threshold.
Life Intervals and their Hazard Functions

Engine Total Hours (HT)

Survival Life (1)
Survival Life (2)

Right-Censored Data

Failure 1
Failure 2
Failure 3

h(t) = E_t / L

Telematics Health Parameters
1) Max Coolant Temp (MCT_t)
2) Max Oil Pressure (MOP_t)
3) Max Oil Temp (MOT_t)
4) Max Engine Speed (MES_t)
5) Max Percent Torque (MPT_t)
6) Max Fuel Rate (MFR_t)
7) Engine Work Hours (HW_t)
8) Engine Idle Hours (HI_t)

Combine telematics entries of all equipment and assign to their life periods

Apply Data Linearization Regression to Find the Coefficients of Hazard Functions

Life Intervals and their Hazard Functions

h1(t) h2(t) h3(t)

All Fleet Equipment of the Same Type

Equipment (1)

Equipment (2)

Survival Life (2)
Right-Censored Data

Failure 3

E_t

Time (days)

Survival Life (2)

h(t) = E_t / L

RSL

AWL

Left-Censored Data

Failure

Failure

Failure

h(t)

h(t)

h(t)

E_t

L

Time (days)

Prognostics System

Introduction

Need and Objective

Telematics Overview

Prognostics System

System Validation

Future Research
System Validation

- The methodology was applied to:
  - 21 dozers (1836 telematics data entries)
  - 29 backhoes (3315 telematics data entries)
  - 17 trucks (3880 telematics data entries)

- The data is divided into 5 survival intervals:
  1) less than 50 days
  2) between 50 and 100 days
  3) between 100 and 150 days
  4) between 150 and 300 days
  5) more than 300 days

The data of each survival interval is divided into 2 main groups:
- Estimation Data Group (Coeff. Values)
- Prediction Data Group (System Validation)

<table>
<thead>
<tr>
<th>Survival Interval</th>
<th>0 &lt; t &lt; 50</th>
<th>50 &lt; t &lt; 100</th>
<th>100 &lt; t &lt; 150</th>
<th>150 &lt; t &lt; 300</th>
<th>300 &lt; t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimation Data Group</td>
<td>338</td>
<td>185</td>
<td>133</td>
<td>198</td>
<td>24</td>
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<tr>
<td>Prediction Data Group</td>
<td>338</td>
<td>185</td>
<td>133</td>
<td>198</td>
<td>27</td>
</tr>
</tbody>
</table>
## Dozers Hazard Functions

(Estimation Data Group = 878 telematics data entries)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Survival Intervals (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 &lt; t &lt; 50</td>
</tr>
<tr>
<td></td>
<td>Value</td>
</tr>
<tr>
<td>Constant (C)</td>
<td>1</td>
</tr>
<tr>
<td>X1 (MCT)</td>
<td>0</td>
</tr>
<tr>
<td>X2 (MOP)</td>
<td>0</td>
</tr>
<tr>
<td>X3 (MOT)</td>
<td>0.01101</td>
</tr>
<tr>
<td>X4 (MES)</td>
<td>0</td>
</tr>
<tr>
<td>X5 (MPT)</td>
<td>0.02792</td>
</tr>
<tr>
<td>X6 (MFR)</td>
<td>-0.35908</td>
</tr>
<tr>
<td>X7 (HW)</td>
<td>0.00364</td>
</tr>
<tr>
<td>X8 (HI)</td>
<td>0</td>
</tr>
</tbody>
</table>

\[
h(t) = \begin{cases} 
  \exp[-0.04917 \cdot \text{MOP} + 0.01101 \cdot \text{MOT} + 0.02792 \cdot \text{MPT} - 0.35908 \cdot \text{MFR} + 0.00364 \cdot \text{HW}] & 0 \leq t < 50 \\
  \exp[-0.00848 \cdot \text{MCT} - 0.0206 \cdot \text{MOP} + 0.0096 \cdot \text{MOT} + 0.0135 \cdot \text{MPT} - 0.1408 \cdot \text{MFR} + 0.00195 \cdot \text{HW}] & 50 \leq t < 100 \\
  \exp[-0.01491 \cdot \text{MOP} + 0.01336 \cdot \text{MPT} - 0.13776 \cdot \text{MFR} + 0.00193 \cdot \text{HW}] & 100 \leq t < 150 \\
  \exp[-0.00728 \cdot \text{MOP} + 0.00659 \cdot \text{MPT} - 0.09602 \cdot \text{MFR} + 0.00129 \cdot \text{HW}] & 150 \leq t < 300 \\
  \exp[-0.0001 \cdot \text{MES} + 0.00016 \cdot \text{WH} + 0.00101 \cdot \text{HI}] & 300 \leq t
\end{cases}
\]
# System Validation

## Dozers Hazard Functions

*(Estimation Data Group = 878 telematics data entries)*

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Survival Intervals (days)</th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>0 &lt; t &lt; 50</td>
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<td>150 &lt; t &lt; 300</td>
<td>300 &lt; t</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Value</td>
<td>P-Value</td>
<td>Value</td>
<td>P-Value</td>
<td>Value</td>
<td>P-Value</td>
</tr>
<tr>
<td>Observations</td>
<td>338</td>
<td></td>
<td>185</td>
<td></td>
<td>133</td>
<td></td>
</tr>
<tr>
<td>Multiple R</td>
<td>0.80</td>
<td></td>
<td>0.854</td>
<td></td>
<td>0.857</td>
<td></td>
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<tr>
<td>R Square</td>
<td>0.64</td>
<td></td>
<td>0.730</td>
<td></td>
<td>0.735</td>
<td></td>
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<tr>
<td>Adj. R Square</td>
<td>0.633</td>
<td></td>
<td>0.716926</td>
<td></td>
<td>0.721</td>
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<tr>
<td>Significance F</td>
<td>1.054E-72</td>
<td></td>
<td>3.71E-48</td>
<td></td>
<td>1.46E-35</td>
<td></td>
</tr>
</tbody>
</table>

**Estimation**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Observations</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Observations</td>
<td>338</td>
<td></td>
<td>185</td>
<td></td>
<td>133</td>
<td></td>
</tr>
</tbody>
</table>

**Prediction**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>RMSE</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE</td>
<td>0.2967</td>
<td>0.2696</td>
<td>0.223</td>
<td>0.1691</td>
<td>0.0499</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rcorr</td>
<td>0.3896</td>
<td>0.3745</td>
<td>0.4375</td>
<td>0.4965</td>
<td>0.7845</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Observed t-Test</td>
<td>7.707</td>
<td>5.5236</td>
<td>5.6319</td>
<td>8.0085</td>
<td>6.3251</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Critical t-Test</td>
<td>1.64912</td>
<td>1.65304</td>
<td>1.6563</td>
<td>1.65221</td>
<td>1.70562</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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**Increased Function Fit Quality and Prediction Accuracy!**

The failure of assets with longer survival time can be reliably anticipated compared to younger assets with shorter survival time.
# System Validation

## Backhoes Hazard Functions (3315 telematics data entries)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>0 &lt; t &lt; 50</th>
<th>50 &lt; t &lt; 100</th>
<th>100 &lt; t &lt; 150</th>
<th>150 &lt; t &lt; 300</th>
<th>300 &lt; t</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>P-Value</td>
<td>Value</td>
<td>P-Value</td>
<td>Value</td>
</tr>
<tr>
<td>Constant (C)</td>
<td>1</td>
<td>N/A</td>
<td>1</td>
<td>N/A</td>
<td>1</td>
</tr>
<tr>
<td>X1 (MCT)</td>
<td>0</td>
<td>N/A</td>
<td>0</td>
<td>N/A</td>
<td>0</td>
</tr>
<tr>
<td>X2 (MOP)</td>
<td>-0.03958</td>
<td>0</td>
<td>-0.0165</td>
<td>0</td>
<td>-0.01449</td>
</tr>
<tr>
<td>X3 (MOT)</td>
<td>0.007714</td>
<td>0</td>
<td>0</td>
<td>N/A</td>
<td>0</td>
</tr>
<tr>
<td>X4 (MES)</td>
<td>0</td>
<td>N/A</td>
<td>0</td>
<td>N/A</td>
<td>0.000614</td>
</tr>
<tr>
<td>X5 (MPT)</td>
<td>0</td>
<td>N/A</td>
<td>0.01835</td>
<td>0.00196</td>
<td>-0.00913</td>
</tr>
<tr>
<td>X6 (MFR)</td>
<td>0</td>
<td>N/A</td>
<td>-0.18099</td>
<td>0.00614</td>
<td>0</td>
</tr>
<tr>
<td>X7 (HW)</td>
<td>0.001505</td>
<td>0</td>
<td>0</td>
<td>0.00156</td>
<td>0</td>
</tr>
<tr>
<td>X8 (HI)</td>
<td>0</td>
<td>N/A</td>
<td>0.000929</td>
<td>0</td>
<td>-0.00515</td>
</tr>
</tbody>
</table>

### Estimation
- **Observations**: 664, 305, 236, 241, 62
- **Multiple R**: 0.76878, 0.81113, 0.76793, 0.7891, 0.95187
- **R Square**: 0.591, 0.65793, 0.58972, 0.6226, 0.9060
- **Adj. R Square**: 0.5883, 0.6512, 0.57828, 0.61527, 0.884
- **Significance F**: 8.52E-128, 9.4E-69, 1.03E-42, 5E-50, 9.16E-29

### Prediction
- **Observations**: 665, 305, 236, 241, 61
- **RMSE**: 0.3746, 0.23463, 0.22687, 0.26875, 0.1
- **Rcorr**: 0.1197, 0.3971, 0.32333, 0.49067, 0.87816
- **Observed t-Test**: 3.1033, 7.5326, 5.22682, 8.7055, 10.7
- **Critical t-Test**: 1.647, 1.65, 1.651, 1.651, 1.671

*Increased Function Fit Quality and Prediction Accuracy!*
## System Validation

### Trucks Hazard Functions (3880 telematics data entries)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Survival Intervals (days)</th>
<th>0 &lt; t &lt; 50</th>
<th>50 &lt; t &lt; 100</th>
<th>100 &lt; t &lt; 150</th>
<th>150 &lt; t &lt; 300</th>
<th>300 &lt; t</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>P-Value</td>
<td>Value</td>
<td>P-Value</td>
<td>Value</td>
<td>P-Value</td>
</tr>
<tr>
<td>Constant (C)</td>
<td>1</td>
<td>N/A</td>
<td>1</td>
<td>N/A</td>
<td>1</td>
<td>N/A</td>
</tr>
<tr>
<td>X1 (MCT)</td>
<td>0</td>
<td>N/A</td>
<td>-0.00326</td>
<td>0.0108</td>
<td>-0.00292</td>
<td>0</td>
</tr>
<tr>
<td>X2 (MOP)</td>
<td>-0.05807</td>
<td>0</td>
<td>0</td>
<td>N/A</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>X3 (MOT)</td>
<td>0.00394</td>
<td>0.0139</td>
<td>0.00287</td>
<td>0.00353</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>X4 (MES)</td>
<td>0</td>
<td>N/A</td>
<td>-0.00024</td>
<td>0.00669</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>X5 (MPT)</td>
<td>0</td>
<td>N/A</td>
<td>0</td>
<td>N/A</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>X6 (MFR)</td>
<td>0.0724</td>
<td>0.00006</td>
<td>0</td>
<td>N/A</td>
<td>0.023205</td>
<td>0.000078</td>
</tr>
<tr>
<td>X7 (HW)</td>
<td>0.000463</td>
<td>0.000394</td>
<td>0.000066</td>
<td>0.065468</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>X8 (HI)</td>
<td>0</td>
<td>N/A</td>
<td>-0.0004</td>
<td>0.0012</td>
<td>0</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Estimation**

<table>
<thead>
<tr>
<th>Observations</th>
<th>Multiple R</th>
<th>R Square</th>
<th>Adj. R Square</th>
<th>Significance F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1064</td>
<td>0.8084</td>
<td>0.6535</td>
<td>0.5535</td>
<td>4.74E-242</td>
</tr>
<tr>
<td>411</td>
<td>0.891</td>
<td>0.794</td>
<td>0.684</td>
<td>1.366E-136</td>
</tr>
<tr>
<td>232</td>
<td>0.824</td>
<td>0.6788</td>
<td>0.68</td>
<td>4.25498E-56</td>
</tr>
<tr>
<td>37</td>
<td>0.8245</td>
<td>0.68</td>
<td>0.68</td>
<td>2.51E-10</td>
</tr>
</tbody>
</table>

**Prediction**

<table>
<thead>
<tr>
<th>Observations</th>
<th>RMSE</th>
<th>Rcorr</th>
<th>Observed t-Test</th>
<th>Critical t-Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1063</td>
<td>0.3468</td>
<td>0.225</td>
<td>7.5267</td>
<td>1.6463</td>
</tr>
<tr>
<td>410</td>
<td>0.1744</td>
<td>0.3762</td>
<td>8.2</td>
<td>1.6486</td>
</tr>
<tr>
<td>232</td>
<td>0.1307</td>
<td>0.2435</td>
<td>3.8075</td>
<td>1.6515</td>
</tr>
<tr>
<td>36</td>
<td>0.066</td>
<td>0.286</td>
<td>1.74</td>
<td>1.69</td>
</tr>
</tbody>
</table>

*No Failure recorded for this period*

**Increased Function Fit Quality and Prediction Accuracy!**
The **Maximum Oil Pressure (MOP)** was found to be the most controlling and significant telematics health parameter for dozers and backhoes.
System Validation

The survival function fitness to the data is the highest for the last survival interval.

The survival function prediction error decreases for later survival intervals.
Conclusion and Future Research

- Telematics provide a **rich data source** for equipment prognostics.
- New telematics-based survival analysis methodology.
- Proposed research is applicable for **newer equipment tiers** with CAN-Bus data.

**Future Research:**
- Develop alternative telematics data-driven prognostics systems (logistic regression, fuzzy clustering).
- Implementing the proposed methodology as an automated system.
- Support other fleet management functions with telematics-based data analytics.
Thank you!
Your Questions and Feedback are welcomed!

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