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

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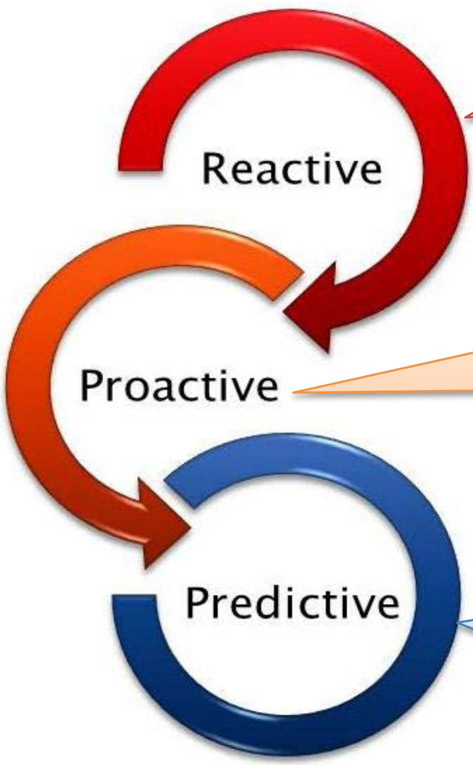
Outline

- 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 Gransberg et al. 2006



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

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 Lee et al. 2006

Model-Based

Virtual models of the machine behavior under healthy and faulty conditions

Hybrid

Integrating model formulation with sensor data calibration

Data-Driven

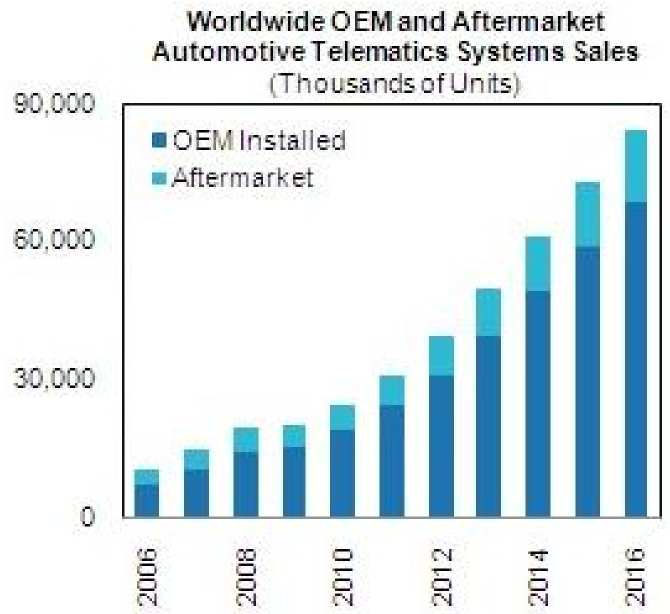
Utilize collected sensor data of the machine's previous behavior toward failure

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:**



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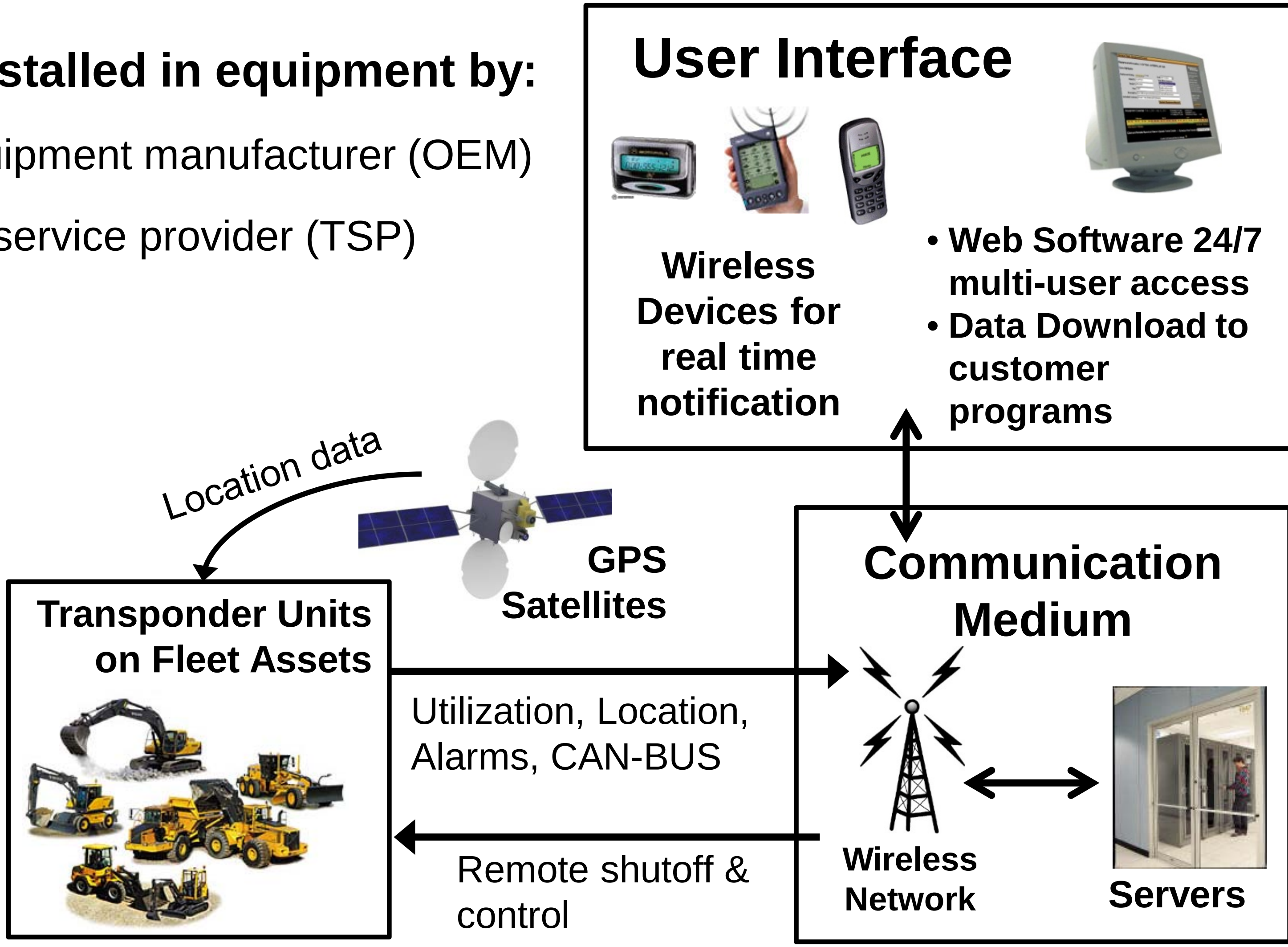
Develop and validate a data-driven prognostics System that utilizes equipment telematics data to estimate its failure probability.

Telematics Overview

- ❑ Typical System Architecture
- ❑ **Telematics installed in equipment by:**
  - o Original equipment manufacturer (OEM)
  - o Third-party service provider (TSP)

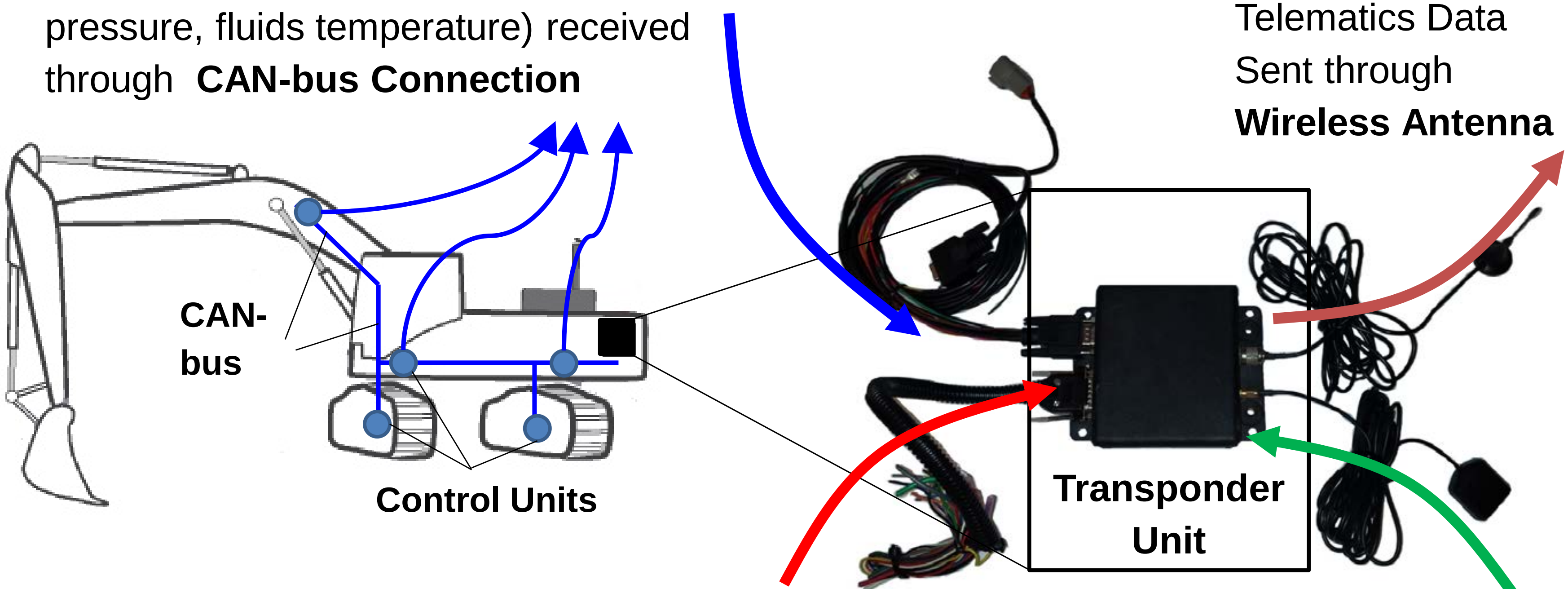


Telematics Overview

Telematics Data – Types and Collection

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

Telematics Data Sent through **Wireless Antenna**



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

Location data Received by **GPS Receiver**

Prognostics System

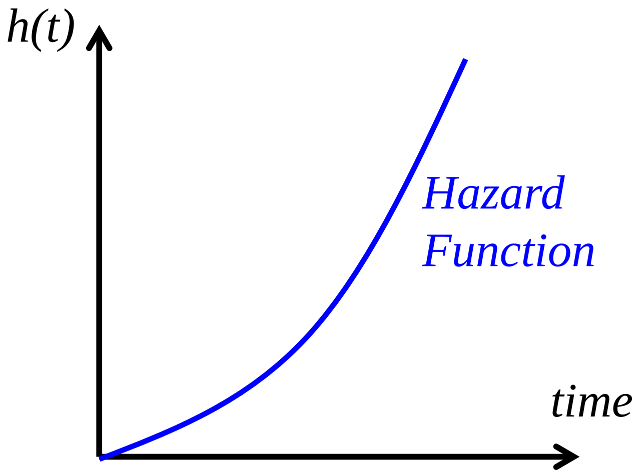
- **Survival Analysis**: a regression approach to assess the times and probabilities to failure events, in terms of its independent variables.
- **Cox's proportional hazards function** $h(t)$ to estimate the failure rate at time t. (Cox 1972)

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

$h_0(t)$ **:** baseline failure rate (asset decay over time)

$X(t)$ **:** failure/health parameters

$\beta(t)$ **:** regression coefficients



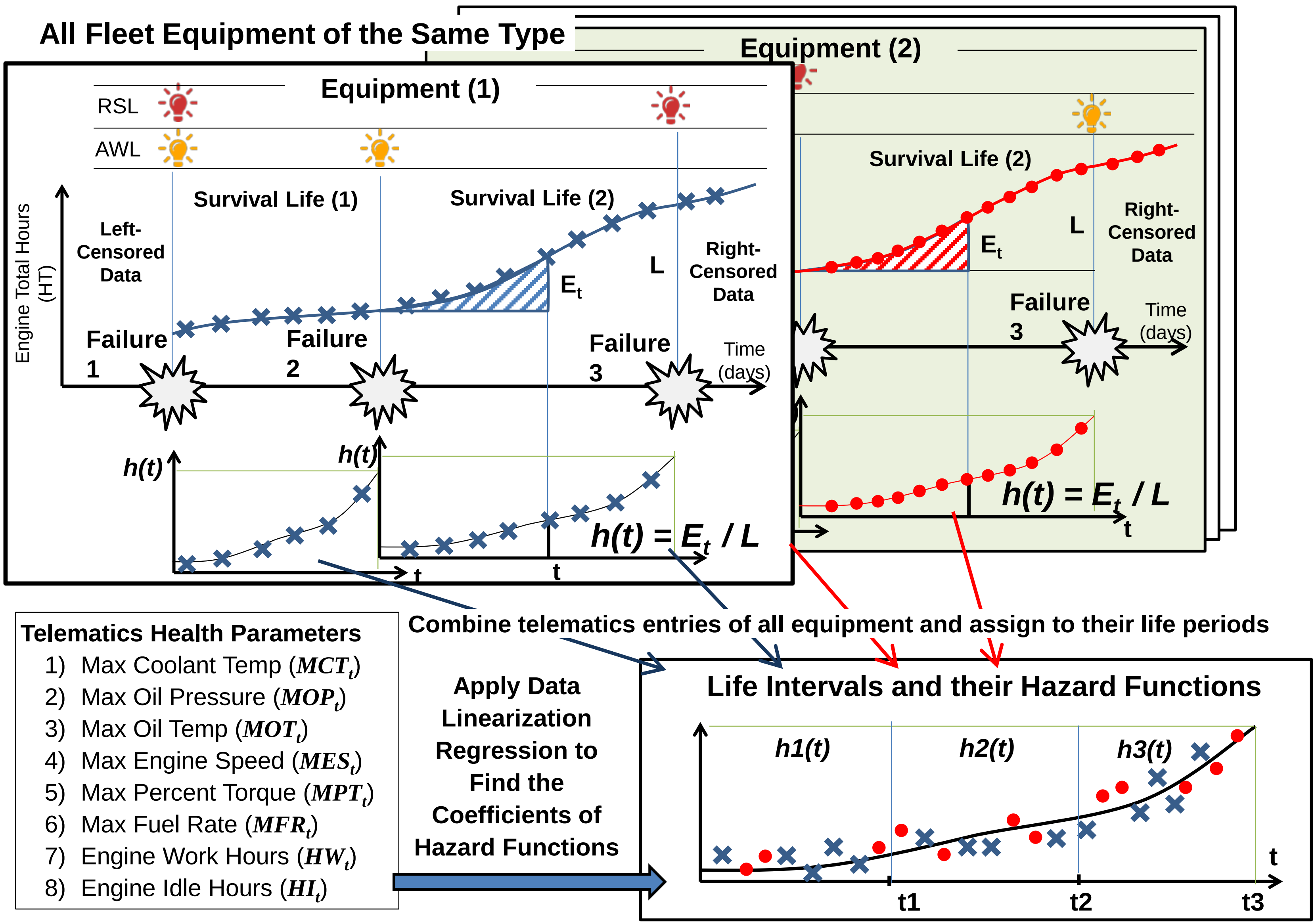
Prognostics System

Suggested Health Parameters *X(t)* :

(Murakami et al. 2002, Dekate 2013)

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.

Prognostics System



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)

Apply Data Linearization Regression to Find the Coefficients of Hazard Functions

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)

Dozers Prognostics Data
(**1836** telematics data entries)

Survival Interval	0 < t < 50	50 < t < 100	100 < t < 150	150 < t < 300	300 < t
Estimation Data Group	338	185	133	198	24
Prediction Data Group	338	185	133	198	27

System Validation

Dozers Hazard Functions (Estimation Data Group = **878** telematics data entries)

Parameters	Survival Intervals (days)									
	0 < t < 50		50 < t < 100		100 < t < 150		150 < t < 300		300 < t	
	Value	P-Value	Value	P-Value	Value	P-Value	Value	P-Value	Value	P-Value
Constant (C)	1	N/A	1	N/A	1	N/A	1	N/A	1	N/A
X1 (MCT)	0	N/A	-0.00848	0.00002	0	N/A	0	N/A	0	N/A
X2 (MOP)	-0.04917	0	-0.0206	0	-0.01491	0	-0.00728	0	0	N/A
X3 (MOT)	0.01101	0.0003	0.0096	0.00016	0	N/A	0	N/A	0	N/A
X4 (MES)	0	N/A	0	N/A	0	N/A	0	N/A	-0.0001	0
X5 (MPT)	0.02792	0.0007	0.0135	0.0061	0.01336	0.00035	0.00659	0.00093	0	N/A
X6 (MFR)	-0.35908	0	-0.1408	0.00001	-0.13776	0	-0.09602	0	0	N/A
X7 (HW)	0.00364	0	0.00195	0	0.00193	0	0.00129	0	0.00016	0.09811
X8 (HI)	0	N/A	0	N/A	0	N/A	0	N/A	0.00101	0.07346

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

System Validation

Dozers Hazard Functions (Estimation Data Group = **878** telematics data entries)

Parameters		Survival Intervals (days)									
		$0 < t < 50$		$50 < t < 100$		$100 < t < 150$		$150 < t < 300$		$300 < t$	
		Value	P-Value	Value	P-Value	Value	P-Value	Value	P-Value	Value	P-Value
Estimation	Observations	**338**		**185**		**133**		**198**		**24**	
	Multiple R	**0.80**		**0.854**		**0.857**		**0.845**		**0.9065**	
	R Square	**0.64**		**0.730**		**0.735**		**0.715**		**0.82173**	
	Adj. R Square	0.633		0.716926		0.721		0.705		0.7571	
	Significance F	1.054E-72		3.71E-48		1.46E-35		1.3E-51		7.37E-08	
Prediction	Observations	**338**		**185**		**133**		**198**		**27**	
	RMSE	**0.2967**		**0.2696**		**0.223**		**0.1691**		**0.0499**	
	R_{corr}	0.3896		0.3745		0.4375		0.4965		0.7845	
	Observed t-Test	7.707		5.5236		5.6319		8.0085		6.3251	
	Critical t-Test	1.64912		1.65304		1.6563		1.65221		1.70562	

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)

Parameters		Survival Intervals (days)									
		0 < t < 50		50 < t < 100		100 < t < 150		150 < t < 300		300 < t	
		Value	P-Value	Value	P-Value	Value	P-Value	Value	P-Value	Value	P-Value
Constant (C)		1	N/A	1	N/A	1	N/A	1	N/A	1	N/A
X1 (MCT)		0	N/A	0	N/A	0	N/A	0	N/A	0	N/A
X2 (MOP)		-0.03958	0	-0.0165	0	-0.01449	0.00001	-0.01442	0	-0.01318	0
X3 (MOT)		0.007714	0	0	N/A	0	N/A	0	N/A	-0.00093	0.023
X4 (MES)		0	N/A	0	N/A	0.000467	0.001295	0	N/A	0	N/A
X5 (MPT)		0	N/A	0.01835	0.00196	-0.00913	0.03857	0.005372	0.0595	0	N/A
X6 (MFR)		0	N/A	-0.18099	0.00614	0	N/A	0	N/A	0	N/A
X7 (HW)		0.001505	0	0	N/A	0.00156	0	0	N/A	0.007903	0
X8 (HI)		0	N/A	0.000929	0	-0.0013	0.01273	0.001227	0	-0.00515	0
Estimation	Observations	**664**		**305**		**236**		**241**		**62**	
	Multiple R	**0.76878**		**0.81113**		**0.76793**		**0.7891**		**0.95187**	
	R Square	**0.5[illegible]**		[illegible]		[illegible]		[illegible]		[illegible]	
	Adj. R Square	0.5[illegible]		[illegible]		[illegible]		[illegible]		[illegible]	
	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**	
	R_{corr}	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!

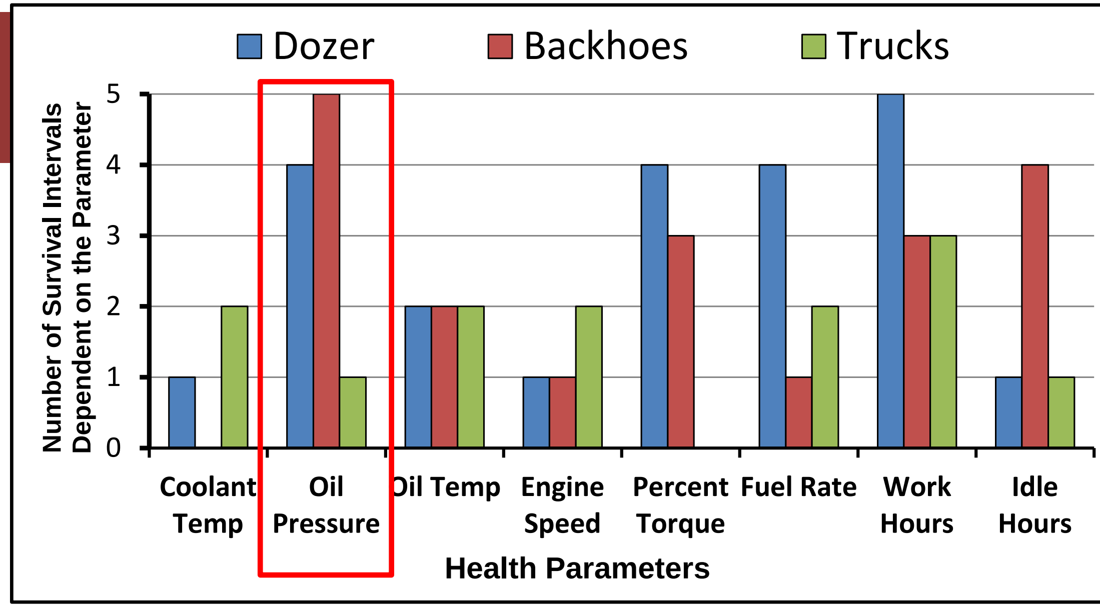
System Validation

Trucks Hazard Functions (3880 telematics data entries)

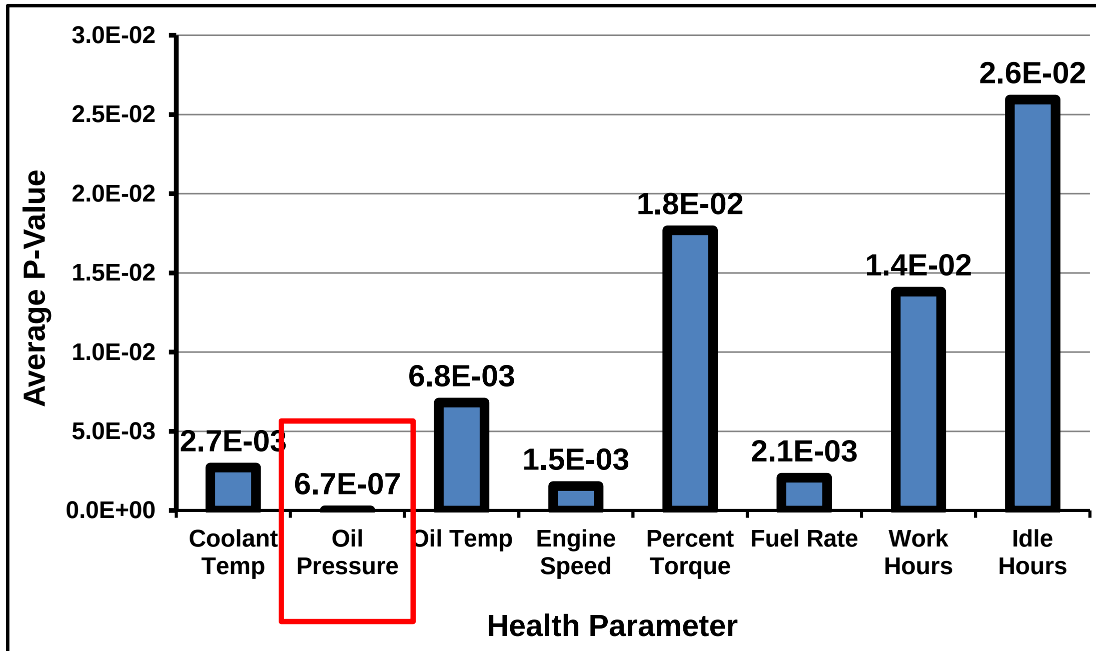
	Parameters	Survival Intervals (days)								
		0 < t < 50		50 < t < 100		100 < t < 150		150 < t < 300		300 < t
		Value	P-Value	Value	P-Value	Value	P-Value	Value	P-Value	
	Constant (C)	1	N/A	1	N/A	1	N/A	1	N/A	No Failure recorded for this period
	X1 (MCT)	0	N/A	-0.00326	0.0108	-0.00292	0	0	N/A	
	X2 (MOP)	-0.05807	0	0	N/A	0	N/A	0	N/A	
	X3 (MOT)	0.00394	0.0139	0.00287	0.00353	0	N/A	0	N/A	
	X4 (MES)	0	N/A	-0.00024	0.00669	0	N/A	-0.00004	0	
	X5 (MPT)	0	N/A	0	N/A	0	N/A	0	N/A	
	X6 (MFR)	0.0724	0.00006	0	N/A	0.023205	0.000078	0	N/A	
	X7 (HW)	0.000463	0	0.000394	0	0.000066	0.065468	0	N/A	
	X8 (HI)	0	N/A	-0.0004	0.0012	0	N/A	0	N/A	
Estimation	Observations	**1064**		**411**		**232**		**37**		
	Multiple R	**0.8084**		**0.891**		**0.824**		**0.8245**		
	R Square	**0.6535**		**0.794**		**0.6788**		**0.68**		
	Adj. R Square	[illegible]		[illegible]		[illegible]		[illegible]		
	Significance F	4.74E-242		1.366E-136		4.25498E-56		2.51E-10		
Prediction	Observations	**1063**		**410**		**232**		**36**		
	RMSE	**0.3468**		**0.1744**		**0.1307**		**0.066**		
	R_{corr}	0.225		0.3762		0.2435		0.286		
	Observed t-Test	7.5267		8.2		3.8075		1.74		
	Critical t-Test	1.6463		1.6486		1.6515		1.69		

Increased Function Fit Quality and Prediction Accuracy!

System Validation

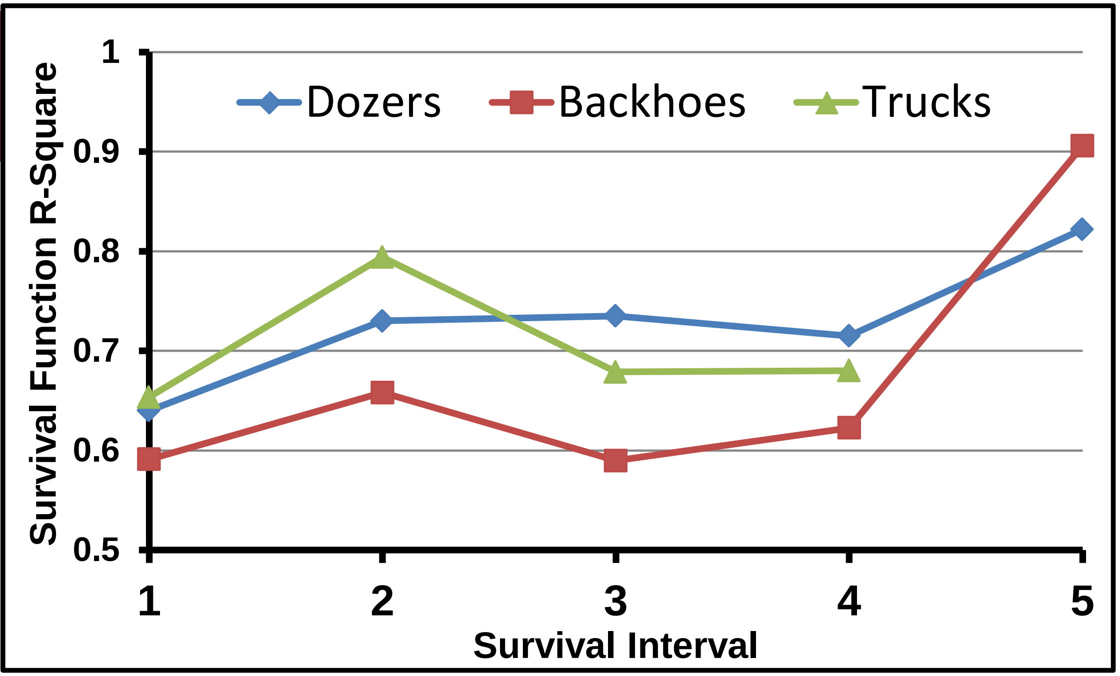


The **Maximum Oil Pressure (MOP)** was found to be the most controlling and significant telematics health parameter for dozers and backhoes.

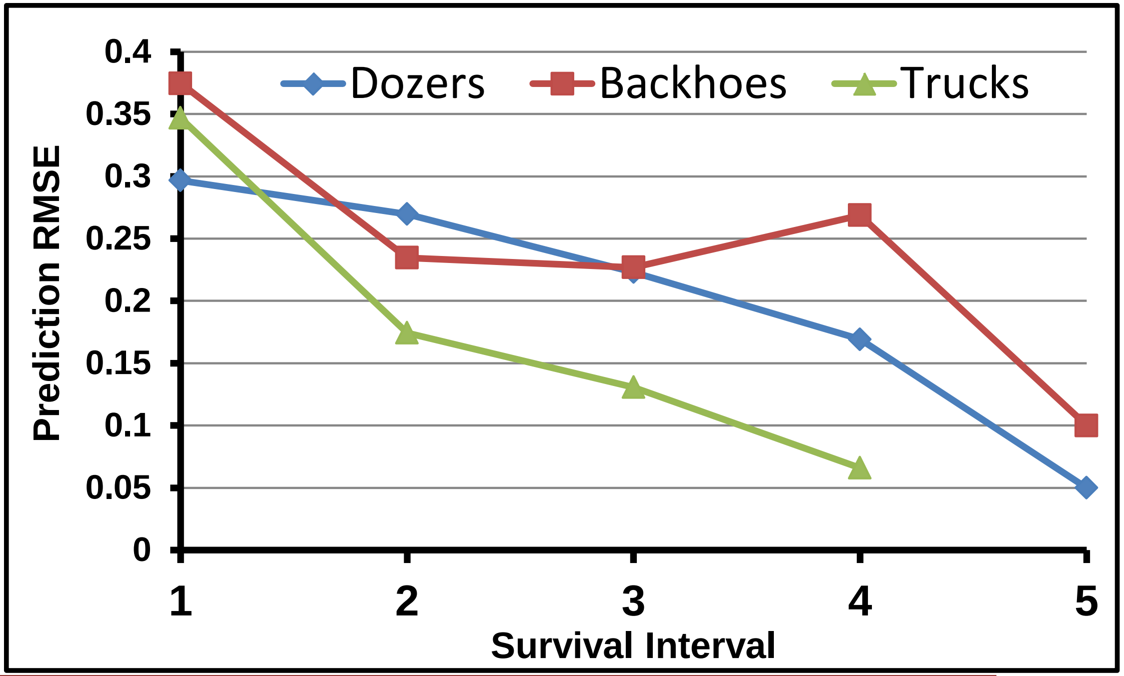


System Validation

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.
- ❑ <u>Future Research:</u>
  - o Develop alternative telematics data-driven prognostics systems (logistic regression, fuzzy clustering).
  - o Implementing the proposed methodology as an automated system.
  - o Support other fleet management functions with telematics-based data analytics.

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Thank you!

Your Questions and Feedback are welcomed!

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