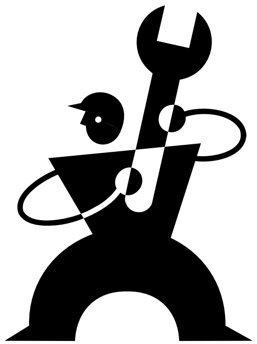
PROACTIVE PRODUCT SERVICING



Necip Doganaksoy, GE Global Research
Gerry Hahn, GE Global Research, Retired
Bill Meeker, Iowa State University

2009 QUALITY & PRODUCTIVITY RESEARCH CONFERENCE

STATISTICALLY BASED PROACTIVE PRODUCT SERVICING
(Just-in-time Maintenance)

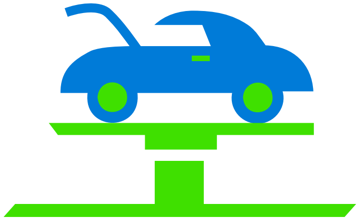
- **Goal: Avoid unscheduled equipment shutdowns due to field failures**
- **Minimize negative impact of failures that do occur**
- **Spurred on by Long Term Service Agreements (LTSAs)**

ELEMENT OF PROACTIVE RELIABILITY ANALYSIS

THREE BASIC APPROACHES

- **Optimum product maintenance scheduling**
- **Proactive parts replacement**
- **Automated monitoring for impending failures**

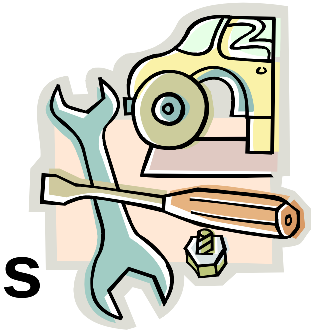
OPTIMUM PRODUCT MAINTENANCE SCHEDULING: CONCEPT



- **Systems traditionally serviced periodically**
- **Example: Change car oil and lubricate parts every 3,000 miles**
- **Potential for improvement: Individualized sensor-based maintenance scheduling using information on**
  - **Age and usage**
  - **Measured wear**
- **Goal: Provide "optimum" trade-off between costs of servicing and failures that can be averted**

NEED-BASED MAINTENANCE SCHEDULING

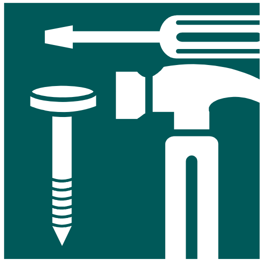
OPTIMUM PRODUCT MAINTENANCE SCHEDULING: APPROACH



- **Obtain relevant data to relate usage stress and/or measured wear to life**
- **Use results and servicing costs to develop optimum individualized maintenance times**
- **Related paper on model estimation:**

Adjengue, Yacout and Ozlem, Parameter Estimation for Condition Based Maintenance with Correlated Observations, Quality Engineering, Vol. 19, No. 3 (2007)

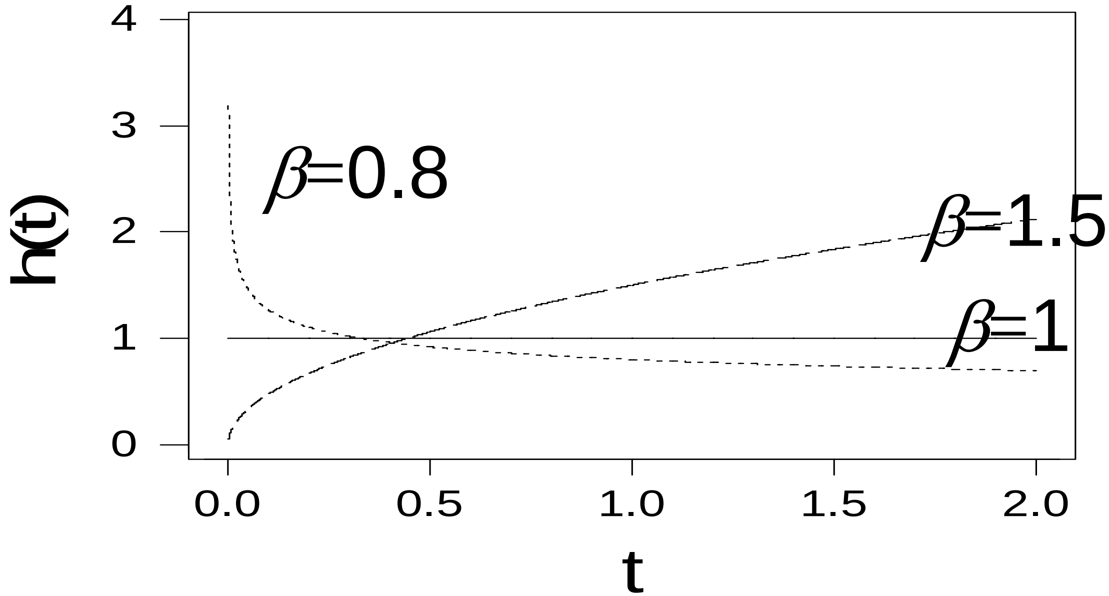
PROACTIVE PARTS REPLACEMENT: CONCEPT



- **Avert system field failures due to component wearout**
- **Replace vulnerable parts/sub-assemblies during routine maintenance**
- **Key questions:**
  - **What parts to replace?**
  - **When?**

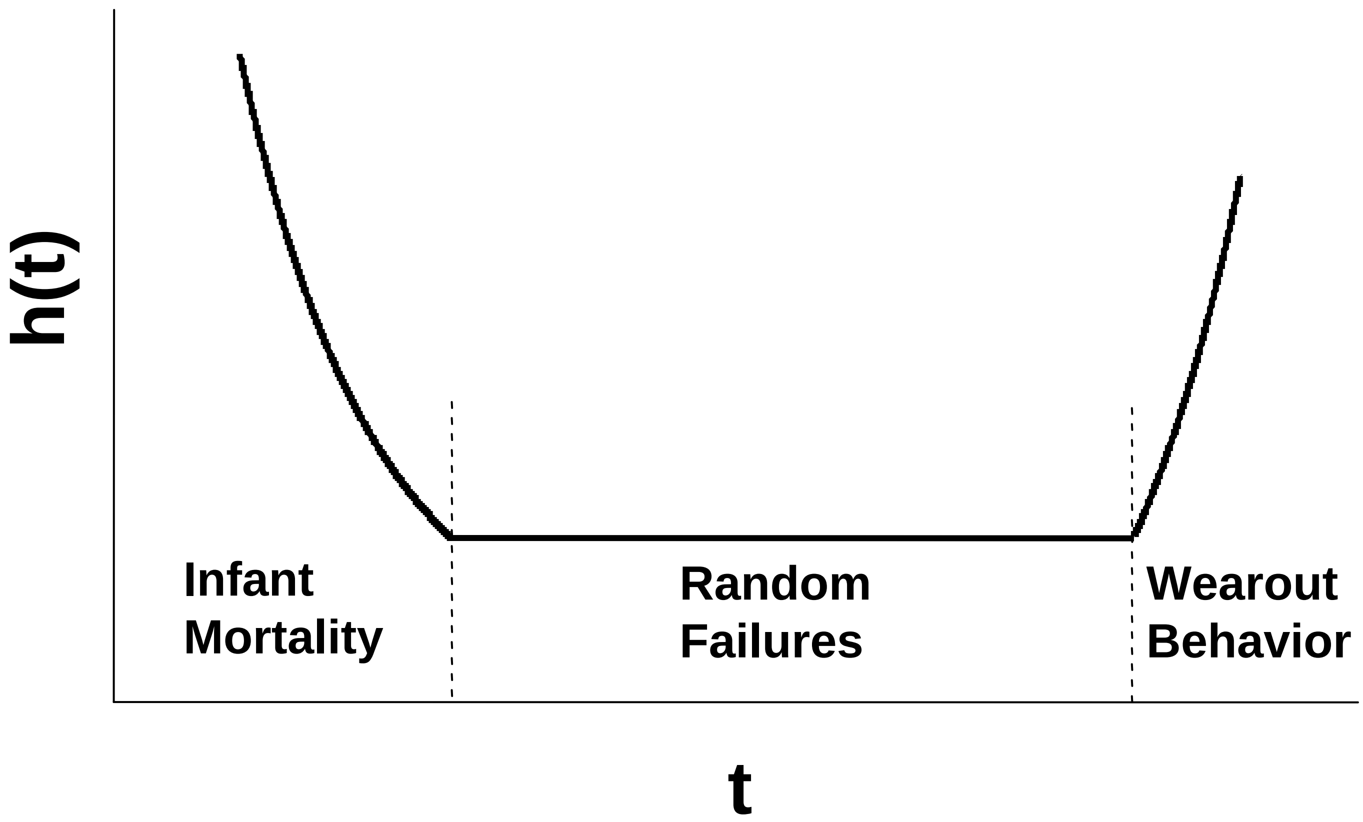
PROACTIVE PARTS REPLACEMENT: APPROACH

- **Determine statistical time-to-failure distribution**
- **If hazard function increases over time, proactive parts replacement warrants consideration**
- **Example: Weibull distribution with increasing hazard function**

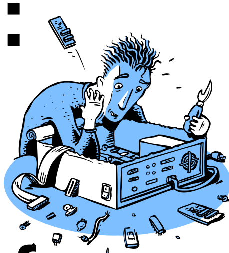


Weibull Hazard Functions (scale *h* =1)

BATHTUB CURVE HAZARD FUNCTION



PROACTIVE PARTS REPLACEMENT: APPROACH (continued)

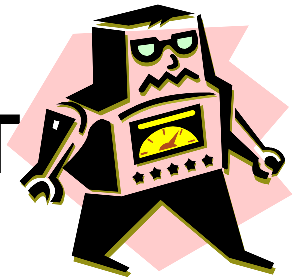


- Replace part at scheduled maintenance if, for example
  - Failure probability before next scheduled maintenance exceeds specified threshold (e.g., 1 in a 1,000)
  - Hazard rate exceeds twice its initial value

  (balance cost of replacement against cost and probability of failure)
- Improve further by including system operating environment

P.S. Can also provide useful future design information

AUTOMATED MONITORING FOR IMPENDING FAILURES: CONCEPT



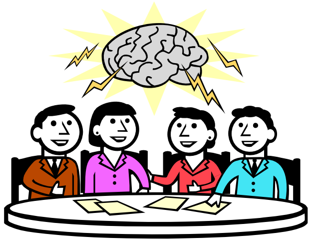
- **Utilize continuous (or periodic) systems monitoring via sophisticated instrumentation to signal impending failure**
- **Act to avert or mitigate impact**
- **Key questions:**
  – **Is action warranted?**
  – **What action to take?**
  – **When to take it?**

AUTOMATED MONITORING FOR IMPENDING FAILURES: LOCOMOTIVE EXAMPLE

- **Locomotive engine sensors read**
  - **Oil pressure**
  - **Oil temperature**
  - **Water (coolant) temperature**
- **Precipitous change in these readings *may* signal impending engine failure**
- **Key question: How to act on such data**
  - **To avert engine failures**
  - **Minimize false alarms**

LOCOMOTIVE EXAMPLE: GENERAL APPROACH

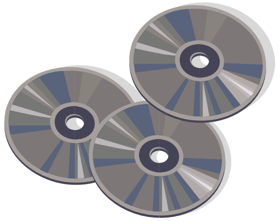
- **Gain understanding of**
  - **Likely reason(s) for observed changes**
  - **Potential severity of associated problem**
  - **Prudent action to avert problem**
- **Acquire needed data**
- **Develop algorithm**
- **Validate and implement**



REASONS FOR ENGINE OIL PRESSURE DROP, PROBLEM SEVERITY AND APPROPRIATE ACTION

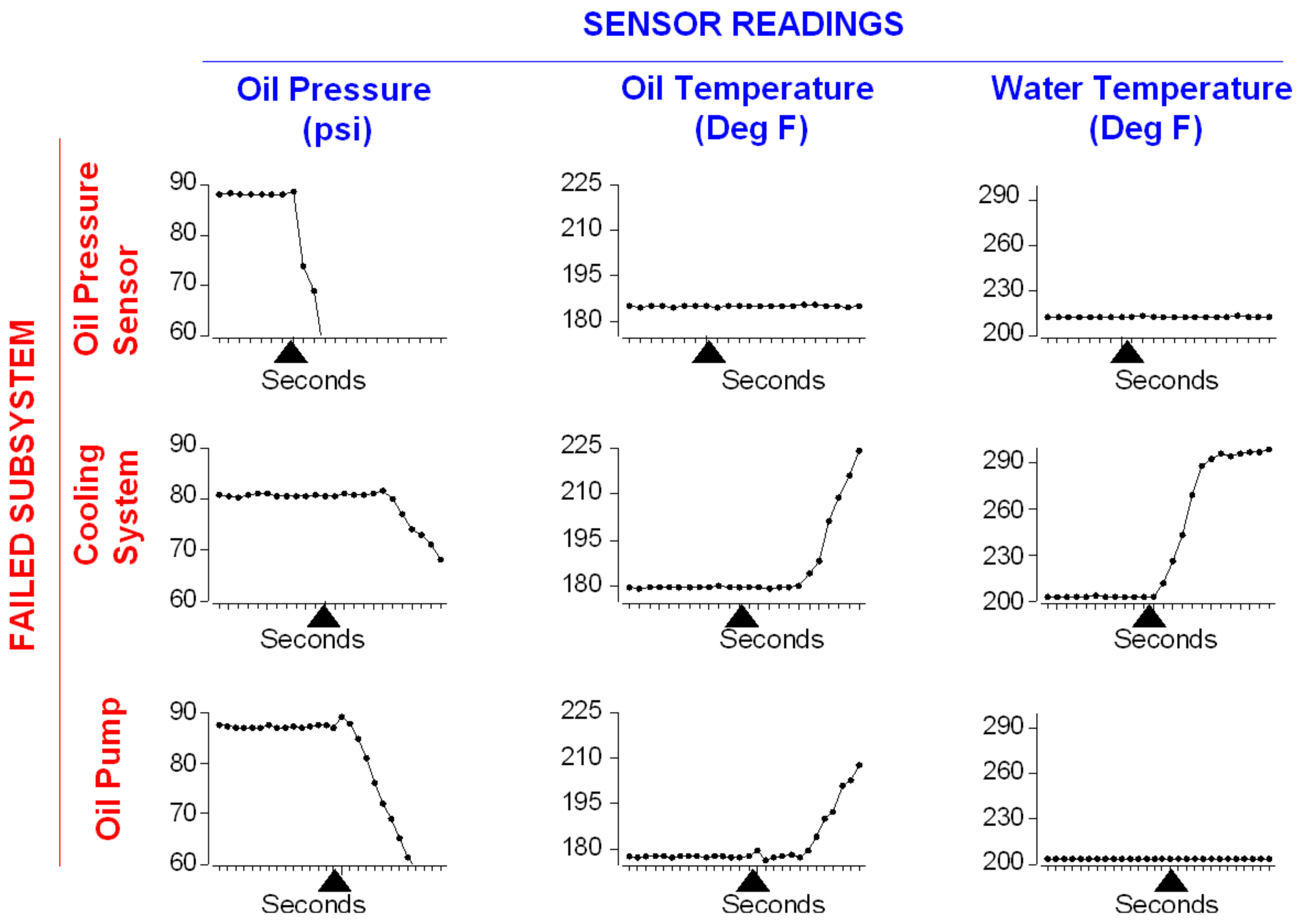
Possible reason	Problem Severity	Appropriate Action
Oil pressure sensor failure	Not problem per se, but can lead to unnecessary action and inability to detect future engine failures	• Activate backup sensor • Replace sensor at next maintenance
Cooling system failure	Important potential problem; prolonged operation can lead to engine failure	• Reduce engine load • Use secondary system • Monitor critical systems • Repair (asap)
Oil pump failure	Critical problem: Can result in engine failure and severe damage	• Shut down immediately • Repair

DATA ACQUISITION



- Induce each of three oil pressure drop modes in lab test and observe resulting sensor measurements
- Study results
- Obtain similar data from field testing on different engines

READINGS ON SENSORS FOR THREE DIFFERENT PROBLEMS

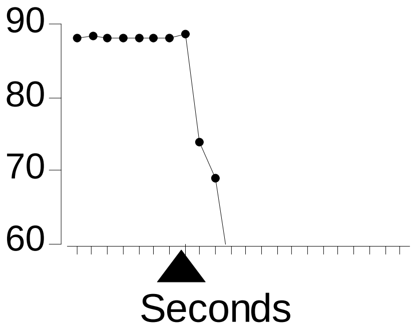


Note: Marker on abscissa shows onset of problem

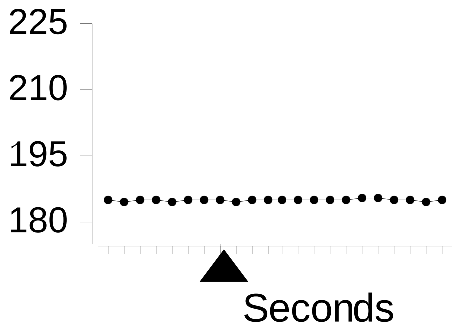
RESULTS FOR FAILURE MODE 1: OIL PRESSURE SENSOR FAILURE

SENSOR READINGS

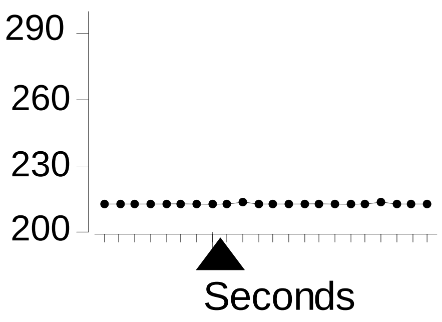
Oil Pressure (psi)



Oil Temperature (Deg F)



Water Temperature (Deg F)

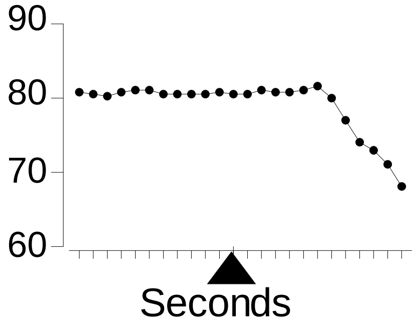


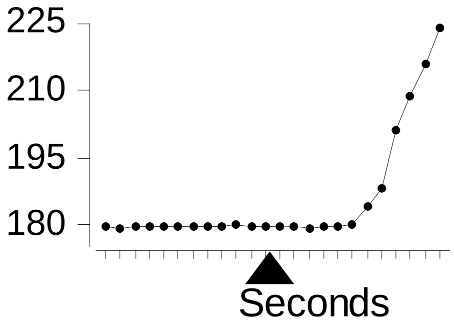
- **Sudden precipitous drop in oil pressure**
- **No change in oil temperature**
- **No change in water temperature**

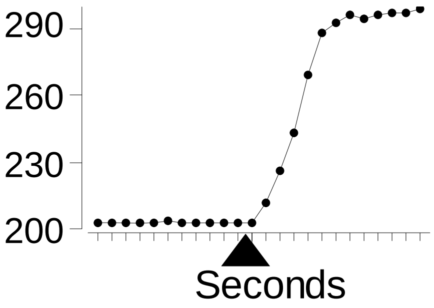
RESULTS FOR FAILURE MODE 2: COOLING SYSTEM FAILURE

SENSOR READINGS

Oil Pressure (psi)	Oil Temperature (Deg F)	Water Temperature (Deg F)





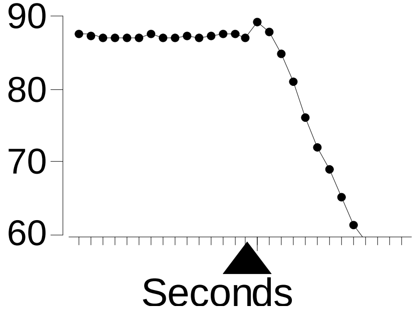


- **Gradual drop in oil pressure**
- **Sharp rise in oil temperature (coincidental with drop in oil pressure)**
- **Sharp rise in oil temperature (preceding drop in oil pressure)**

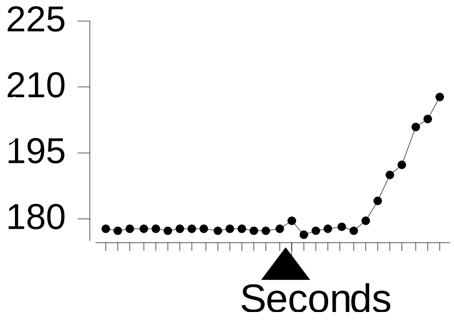
RESULTS FOR FAILURE MODE 3: OIL PUMP FAILURE

SENSOR READINGS

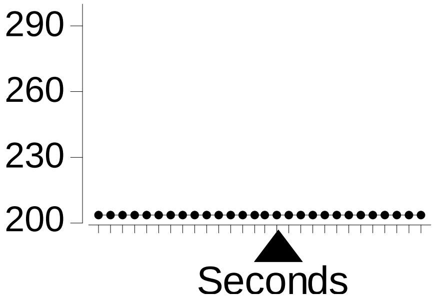
Oil Pressure (psi)



Oil Temperature (Deg F)



Water Temperature (Deg F)

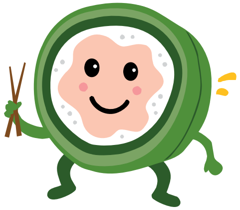


- **Sharp drop in oil pressure**
- **Sharp rise in oil temperature (following drop in oil pressure)**
- **No change in water temperature**

DEVELOP ALGORITHM

- Field data verified general patterns in lab data
- Developed expression to differentiate between failure modes based on three sensor (and other) measurements using
  - Exploratory data analysis
  - Multivariate methods
  - Time series modeling
- Other methods used in such analyses include
  - Machine learning
  - Neural nets
  - Bayesian belief networks
  - Knowledge discovery/data mining
- On-board implementation to accommodate operating conditions, e.g., tunnels

VALIDATE AND IMPLEMENT



- Evaluated correct identification of failure mode (versus false signal) using field data on sensor measurements
  - 75 locomotives for 6 months
  - Readings every second
  - 14 events involving oil pressure drops
- Simulated failure scenarios on test track
- Phased deployment on field engines

ELEVATOR SPEECH

- Statistical concepts provide proactive approach for anticipating and avoiding (or mitigating impact of) system field failures
- BUT not as good as building in high reliability initially
- Three specific approaches:
  - Optimum product maintenance scheduling
  - Proactive parts replacement
  - Automated monitoring for impending failures
- Getting good data is of paramount importance
- Close collaboration with engineering partners essential

NEW OPPORTUNITY AREA

FOR FURTHER INFORMATION

- **For copies of slides, contact doganaksoy@research.ge.com**
- **For further discussion see**
  - **Hahn, G.J. and Doganaksoy, N. *The Role of Statistics in Business and Industry,* Wiley, 2008 (pages 194 to 198)**
  - **Doganaksoy, N., Hahn, G. J. and Meeker, W. Q., The Pros of Proactive Product Servicing, *Quality Progress,* November 2008 (pages 60 to 62)**