Issues & Opportunities in Automotive PHM

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Defining terms...

▪ **Diagnosis:**

Process of determining the root cause of a problem once a failure has occurred...that is, what part replacement(s) or repair action is necessary to fix the problem (today’s world in automotive)

▪ **Prognosis:**

Process of predicting the onset of a potential failure mode BEFORE the failure has occurred...while the component is still operating within specs & with sufficient advance notice to avoid the problem (RUL)

Caveat: This distinction is *very* significant to me but is mostly lost on our customers

RUL = Remaining Useful Life
Prognostics has proven *extremely* successful in aerospace, tele-communications, information technology, wind/solar farms & even automotive…

This technology works!

- GM had huge success using prognostics in assembly plants 15 yrs ago

- A key to success is understanding your primary objective

Prognostic Objective: Reduce downtime due to unplanned maintenance (i.e., which machines will break next?)
Prognostics demands clearly defined priorities for success

Lessons learned from Boeing (Keith Sellers)
• Commercial Aircraft vs.
• Military Aircraft vs.
• Spacecraft

GM Mfging Applications
• Predict coming *machine failures* to reduce downtime and increase factory throughput
• Great history files in this domain

GM Vehicle Applications
• Improve the “*customer experience*”
• Cost & time savings nice too but these are 2\textsuperscript{nd}-ary benefits
• Getting the *right* data is hard!
CHEVROLET: SOLVING ISSUES BEFORE THEY HAPPEN
Prognostics predict when certain components need attention

DIAGNOSTICS AND PROGNOSTICS

Vehicle Data Transmitted

Real-time Notification

IN-VEHICLE MONITORING

Starter Motor
Fuel Pump
Battery

RemoteLink
Text
email
In-vehicle

HOW IT WORKS WITH YOUR BATTERY

Battery Conditions
LOW BATTERY PREDICTED
Alert Sent

Issue Avoided

Battery Alert
Your 2016 Equinox has a Battery Charge issue – Run Vehicle.
See email for more info.
New GM tool warns of potential part failures

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Case Study – Predicted “Battery Short” in Field
(Single Vehicle over a 1-year time window)

<table>
<thead>
<tr>
<th>Model</th>
<th>Equinox FWD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warranty</td>
<td>Bat Replace</td>
</tr>
<tr>
<td>VHM Alert</td>
<td>Bat Replace Short</td>
</tr>
</tbody>
</table>

- **SOC**
- **OCV**
- **Crank Time**
- **Crank Ratio**
- **Charging Resistance**
- **BatStOfCharge**
- **Rho**
- **VBatOCV-rsp (V)**
- **CrankTimeForConventionalVehicles (Second)**
- **Crank Ratio ()**
Foundations ➔ Technology advances have opened the door for a new paradigm in automotive diagnostics

- Prognostics was enabled by stacking up a series of technology advances
- ...but business & social systems will need attention
- ...but we also need better real-time performance, scalability & sustainability
Foundations of Prognostic Systems: Math-Based Technology Advances

- GM’s Math-Based Approach (1991)
  - GE’s “Digital Twin” concept (2002)
- Analytic Methods
  1. Descriptive
  2. Predictive (Prognosis)
  3. Prescriptive
- Combining Physics-Based & Data-Driven Modeling
- Targeting High Reliability
  - If you aren’t extremely confident, you dare not use the predictions
Foundations of Prognostic Systems: Business & Social Systems

• Business & Social Relationships are critical to success
  – Prognostics cannot be implemented effectively as an afterthought
  – Traditional product design organizations control budget allocation and resources

• In the same way that OBD reached full stride when the design community realized they needed to work with the OBD community*, so will it be true for the Prognostics community

* John Van Gilder, GM OBD

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Foundations of Prognostic Systems: Performance, Scalability & Sustainability

- Advances in computer hardware and software are improving performance but high transaction rate & data volume can be challenging
- Commercial applications must scale to large numbers of vehicles
- The technical processes for supporting/maintaining prognostics must be sustainable over time
Similar drivers that motivated the implementation of OBD now point to the need to introduce prognostics

The advent of μ-processor based control drove Automotive OBD

- 1980: General Motors implements the ALDL proprietary interface and protocol for testing of the μ-processor based Engine Control Module (ECM)
- 1991: The California Air Resources Board (CARB) requires that all new vehicles sold in California have some basic OBD capability
- 1996: The OBD-II specification is made mandatory for all cars manufactured in the United States to be sold in the United States

The rapid growth of Electronics/Controls/Software (ECS) driving Prognostics

- Prognostics needed in part to mitigate risks associated with added ECS content & the electrification of our vehicles
- ECS content is likely the only means to cost effectively meet growing customer & regulatory requirements
- But ECS drives “NTF / NFF / NMF” & “Intermittents”
Value ➔ Prognostics can dramatically improve customer perception

“The customer is king”

- Prognostic alerts as seen by customers are akin to normal maintenance events and are NOT seen as failures!!!
  - this results in a 10-20x reduction in negative impact

- While there is no substitute for “designed-in” reliability, consider that achieving just 90% prognostic coverage yields a 10-fold “perceived” reliability gain
  - note periodic maintenance analogy to prognostics

Source: Ken Pipe, SAE HM-1, April 2014
Value ➔ Enablers for prognostics also yield other important benefits

• Engineering design
  – Enhanced FME[C]A
  – Understanding precursors (parameters, relationships/models)

• Validation process
  – Faster turnaround, better data from the field

• Service & Support
  – Also knowing what is working well in addition to problem indicators

• Warranty management
  – Narrowing recall actions
  – Prioritizing recall actions
Issues ➔ The real world is “hell” - Don Hart, c.1970

• This was a powerful lesson to me as a young researcher but it is so true
  – Nothing is as simple as you think

• GM annual global production ~10M vehicles

• OnStar Proactive Alerts monitoring >1M vehicles in NA today

• Proper validation takes 100Ks of vehicles
  – You need to identify all the corner cases (or pathological examples)
  – Small scale laboratory experiments simply are not adequate!
Establishing ground truth is **not** easy
(False Positives / Negatives)

Machine Learning wants labeled training sets

- It is extremely difficult to catch live failures in the field
  - This is generally true across industries

- Ground truth is elusive—is it failed or not?
  - SMEs tend to be the ultimate arbitrators

- “Zero false positives” is not a realistic goal

- If you don’t try to do prognostics, you are accepting 100% false negatives

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Simplified Validation & Launch Process

1. Algorithm Development
2. Soft Launch
3. Hard Launch

- Prediction Accuracy Established
- Field Performance Proven
Understanding field results can be nuanced *

* Not Shown to Scale
Prognostics technology remains immature

• VHM technology is impressive but the field remains *immature*
  – It has proven value in some aspects of automotive for enhancing availability & reliability
  – Indirectly, this has benefits for *vehicle safety* but care must be taken to nurture the technology
  – Excessive regulations too early might put future VHM advances at risk

• VHM software is not mature enough to be used within emission or safety control systems (or flight controls to give an aerospace analogy)
  – Said differently, VHM outputs should *not* be used as emission or safety system *inputs*
  – My recommendation for this situation would be to extract only what is necessary from the VHM software and embed just that into the control system (subject to all necessary requirements)
Opportunities: Automotive suppliers will play an increasingly important role in the cost-effective implementation of prognostics

SAE’s new IVHM Recommended Practice for Health-Ready Components (JA6268)

- Reduce the barriers to successful implementation of IVHM
- Speed up progress
- Increase degree of IVHM functionality
- Lower cost
- Address legitimate IP concerns
Health Ready Components—Unlocking the Potential of IVHM

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**Health Ready Emphasis on VHM/Prognostics**

<table>
<thead>
<tr>
<th>Real-time Functions &amp; Processes</th>
<th>Non-Real-time Functions &amp; Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Fault detection and reporting</td>
<td>• Diagnostics &amp; Fault isolation:</td>
</tr>
<tr>
<td>• Support for Initiated Test functionality and protocols</td>
<td>- Nuisance suppression (events which can safely be ignored)</td>
</tr>
<tr>
<td>• Performance or degradation reporting</td>
<td>- Cascade removal (additional symptoms triggered by one symptom that don’t add diagnostic value)</td>
</tr>
<tr>
<td>• Intermittent fault data capture</td>
<td>- Correlation of loss of function to root cause</td>
</tr>
<tr>
<td>• Functional availability reporting</td>
<td>- Guided troubleshooting and repair</td>
</tr>
<tr>
<td>• On-platform screen and user message generation</td>
<td>• Prognostics</td>
</tr>
<tr>
<td>• Usage monitoring and reporting of usage related data</td>
<td>• Maintenance planning</td>
</tr>
<tr>
<td>• System mode or state reporting</td>
<td>• Logistics or material planning</td>
</tr>
<tr>
<td>• System configuration reporting</td>
<td>• Supplemental analytics</td>
</tr>
<tr>
<td>• Data recording/logging management</td>
<td>• Anomaly Detection</td>
</tr>
</tbody>
</table>

Red items denote VHM/Prognostics emphasis

* SAE JA6268 forthcoming
# SAE’s IVHM Capability Levels for Aero/Auto Applications

<table>
<thead>
<tr>
<th>SAE Level</th>
<th>Vehicle Health Capability</th>
<th>Narrative Description</th>
<th>Participation in Repair Actions</th>
<th>Key Data Resources</th>
<th>Availability of Logged &amp;/or Real-Time Data</th>
<th>Use of Supporting Models</th>
<th>IVHM System Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Manual Diagnosis &amp; Repair Process performed by Technician</td>
<td>Limited On-Vehicle Warning Indicators Service actions for scheduled maintenance or when Operator notices problems or is alerted by indicator lights or simple gages.</td>
<td>Operator/Driver &amp; Service Tech</td>
<td>On-Vehicle Measurements &amp; Observation</td>
<td>N/A</td>
<td>Paper-based Manuals</td>
<td>Only Manual Diagnostic Tools &amp; No Condition-Based Services</td>
</tr>
<tr>
<td>1</td>
<td>Enhanced Diagnostics Using Scan Tools</td>
<td>Service techs gain added diagnostic insight using automated scanners to extract vehicle operating parameters &amp; diagnostic codes</td>
<td>Operator/Driver &amp; Service Tech</td>
<td>On-Vehicle &amp; Service Bay/Depot Tools</td>
<td>Logged Diagnostic Codes &amp; Parameters available to Service Tech</td>
<td>Paper-based Manuals</td>
<td>On-Board Diagnostics Available</td>
</tr>
<tr>
<td>2</td>
<td>Telematics Providing Real-Time Data</td>
<td>Service techs gain real-time vehicle data via remote monitoring of vehicle to more completely capture issues</td>
<td>Operator/Driver, Service Tech &amp; Remote Support Center Advisor</td>
<td>On-Vehicle, Service Bay &amp; Depot &amp; Cloud Data</td>
<td>Telematic Data Available to Service Tech with Diagnostics Info</td>
<td>Paper-based Manuals</td>
<td>On-Board &amp; Remote Data Available</td>
</tr>
</tbody>
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## Diagnosis & Repair Augmented by Prognosis & Predictive Analytics

<table>
<thead>
<tr>
<th>SAE Level</th>
<th>Component Level Proactive Alerts</th>
<th>Operator and service techs are provided with component health status (R/Y/G) before problem occurs. Limited condition-based maintenance</th>
<th>Operator/Driver, Service Tech &amp; Cloud-Based Services</th>
<th>On-Vehicle, Service Bay &amp; Cloud Data</th>
<th>Telematic Data Available to Service Tech with Diagnostics Info</th>
<th>Addition of Component-Level Health Models</th>
<th>Component-Level Health Predictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Integrated Vehicle Health Mgmt.</td>
<td>Operator and service techs are provided with system or vehicle level health indicators before problems occur with remaining useful life estimated. Condition-based maintenance</td>
<td>Operator/Driver, Service Tech &amp; Cloud-Based Services</td>
<td>On-Vehicle, Service Bay &amp; Cloud Data</td>
<td>Telematic Data Available to Service Tech with Diagnostics Info</td>
<td>Addition of Vehicle-Level Health Models</td>
<td>Vehicle-Level Health Management</td>
</tr>
<tr>
<td>4</td>
<td>Self-Adaptive Health Mgmt.</td>
<td>Self-adaptive control to extend vehicle operation and enhance safety in presence of potential or actual failures</td>
<td>Operator/Driver, Service Tech &amp; Cloud-Based Services</td>
<td>On-Vehicle, Service Bay &amp; Cloud Data</td>
<td>Telematic Data Available to Service Tech with Diagnostics Info</td>
<td>Addition of Vehicle-Level Health Models</td>
<td>IVHM Capability Integrated into Vehicle Controls</td>
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