PHM for Automotive Manufacturing & Vehicle Applications

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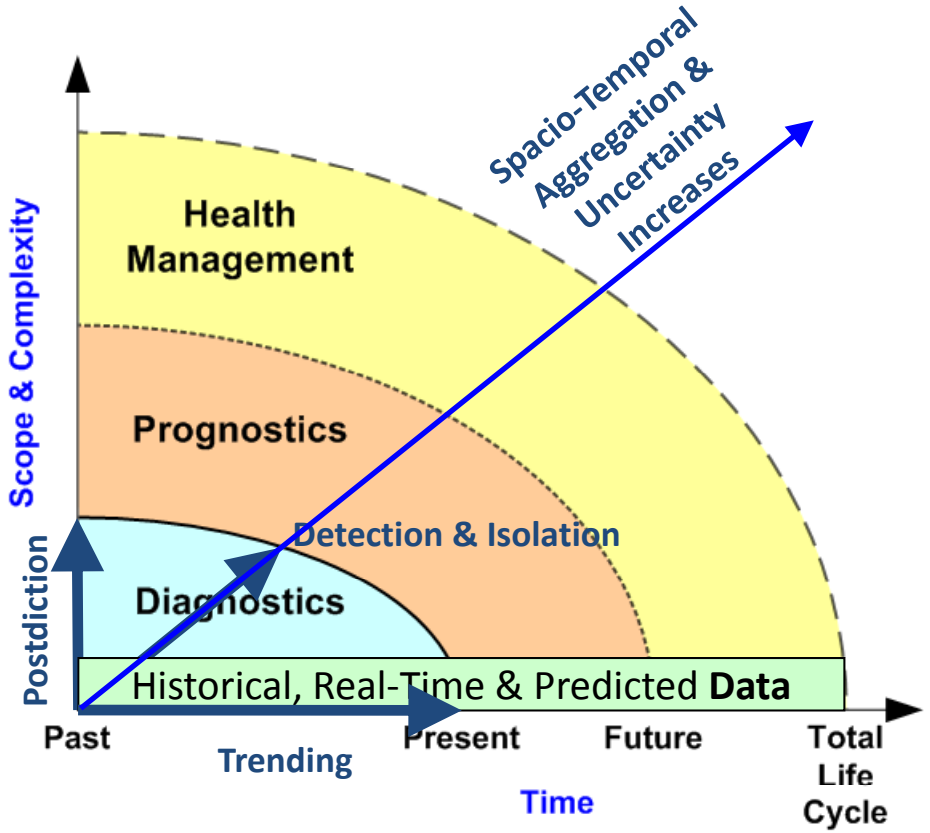
General Motors, one of the world's largest automakers, traces its roots back to 1908. GM employs 205,000 people in every major region of the world and does business in some 157 countries. GM and its strategic partners produce cars and trucks in 31 countries, and sell and service these vehicles through the following brands: Buick, Cadillac, Chevrolet, FAW, GMC, Daewoo, Holden, Jiefang, Opel, Vauxhall and Wuling. More information can be found at www.gm.com.

Some Important Lessons

1. Getting the right data & ***understanding it*** is often the hard part in prognosis
2. ***Establishing the objective*** for doing prognosis must be done up front
3. Prognosis is ***not always desirable*** or cost effective
4. Prognosis ***can't increase fault detection*** coverage "You cannot predict what you cannot diagnose"
5. Prognosis may not be able to ***pinpoint a failure's root cause*** even when event is correctly predicted
6. There is ***synergy*** between data-driven and physics-based prognosis but you need both for success

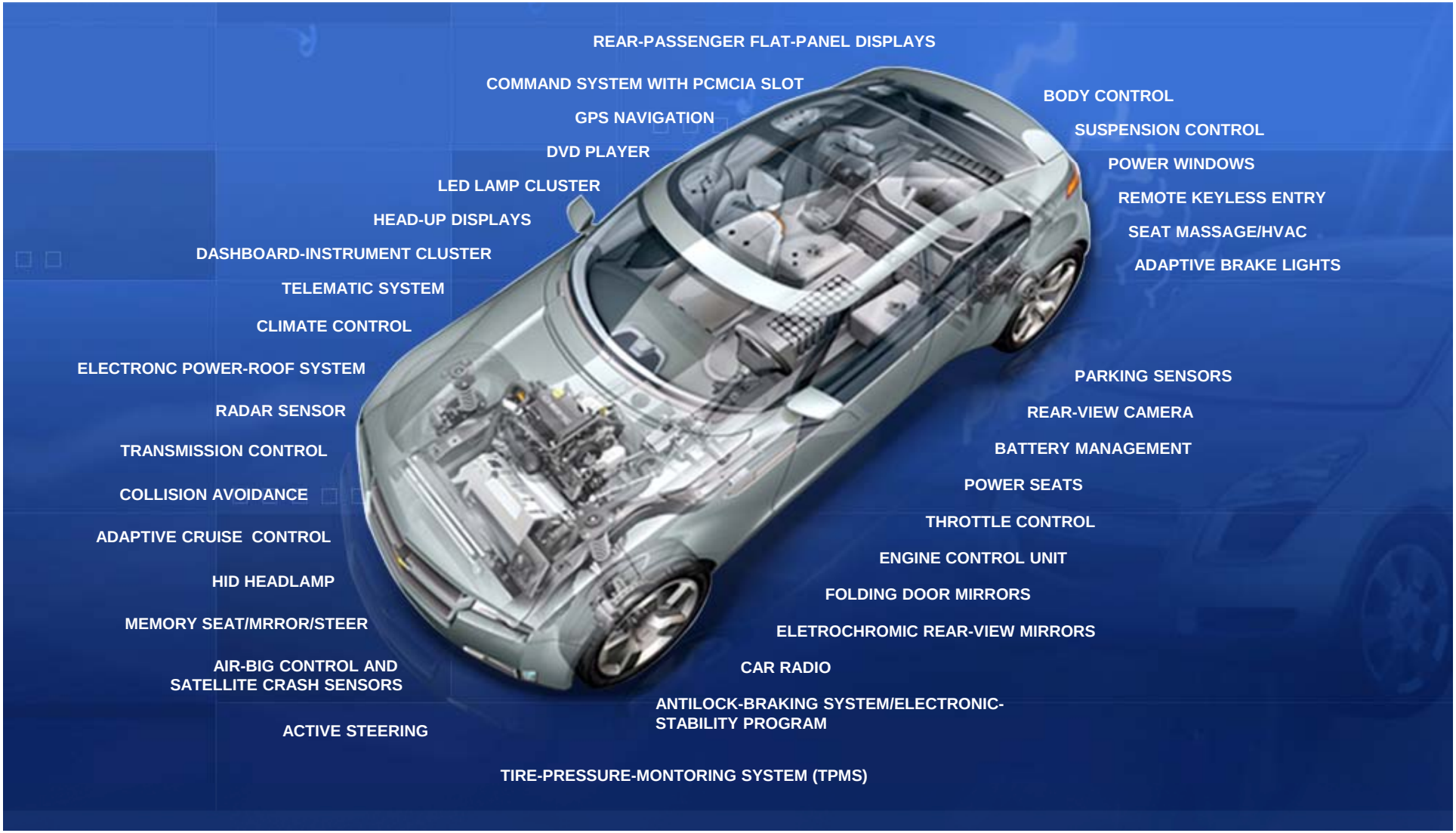
Diagnostics, Prognostics & Health Management



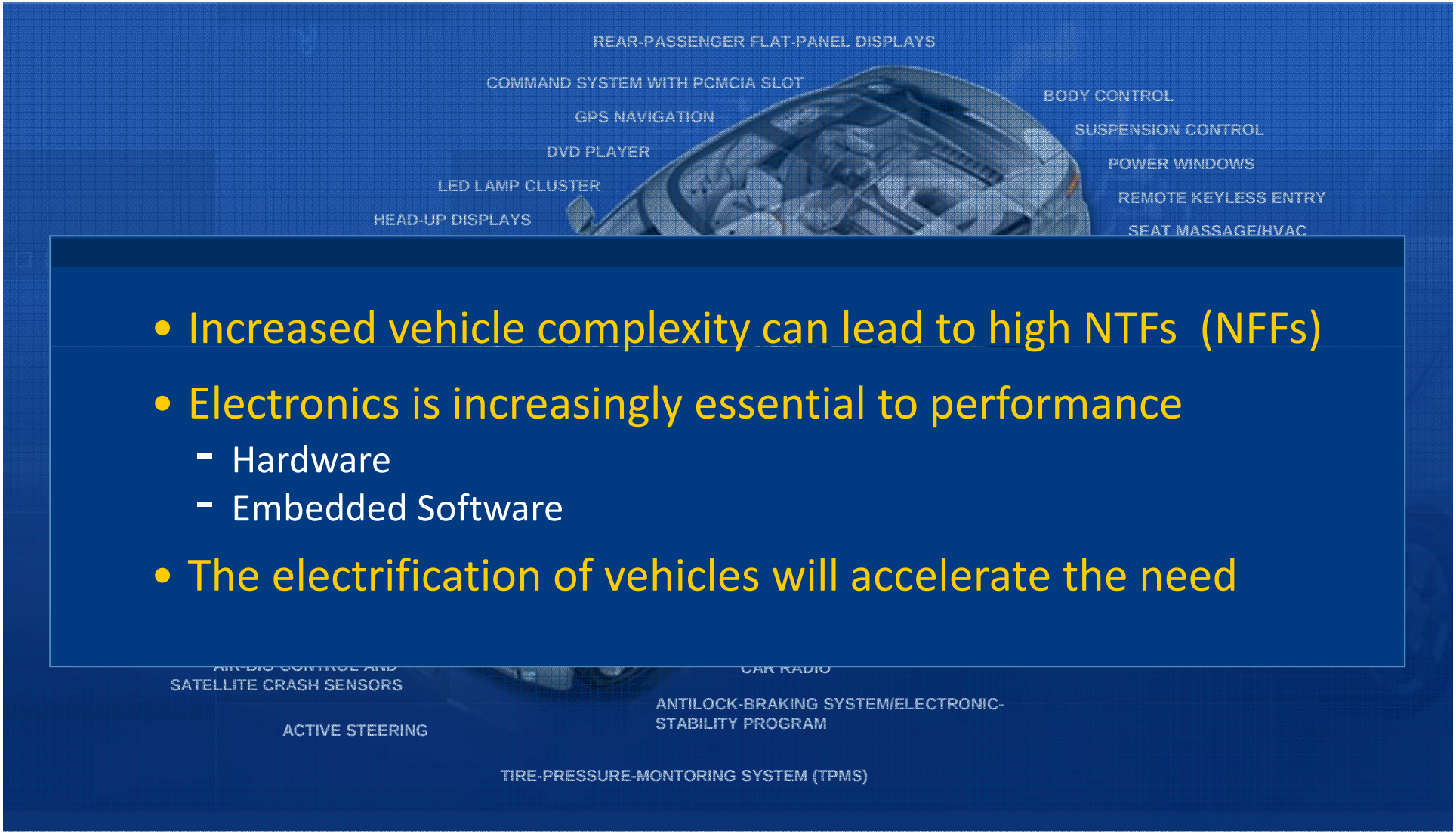
- Data Attributes[1]
  - Natural/Synthetic
  - Stationary/Non-Stationary
  - Low Dimensional/ Stochastic
  - Clean/Noisy
  - Short/Long
  - Documented/Blind
  - Linear/Non-Linear
  - Scalar/Vector
  - One/Many Trials
  - Continuous/Discontinuous/ Switching/Catastrophes/ Episodes

[1] A.S. Weigned & N.A. Gershenfeld, Time Series Prediction

Electronics Explosion & Dawn of Electrification



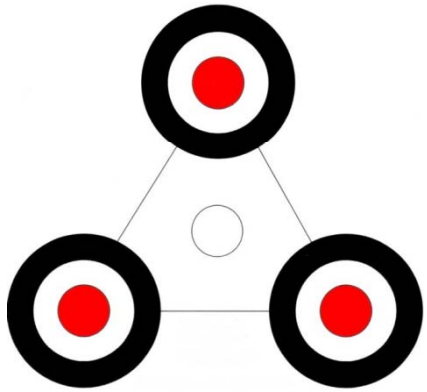
Electronics Explosion & Dawn of Electrification



- Increased vehicle complexity can lead to high NTFs (NFFs)
- Electronics is increasingly essential to performance
  - Hardware
  - Embedded Software
- The electrification of vehicles will accelerate the need

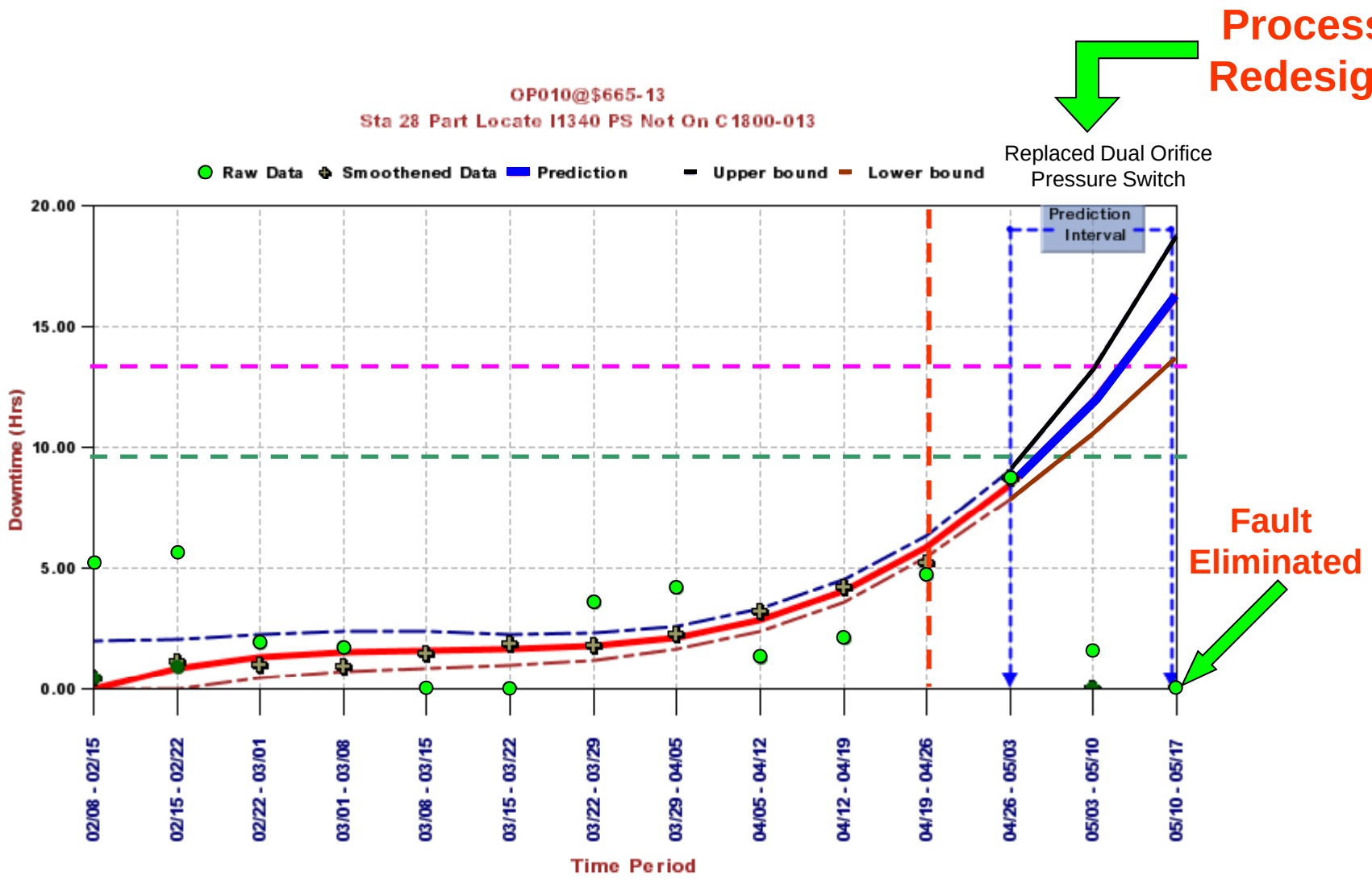
Manufacturing Examples

Maintenance Objectives



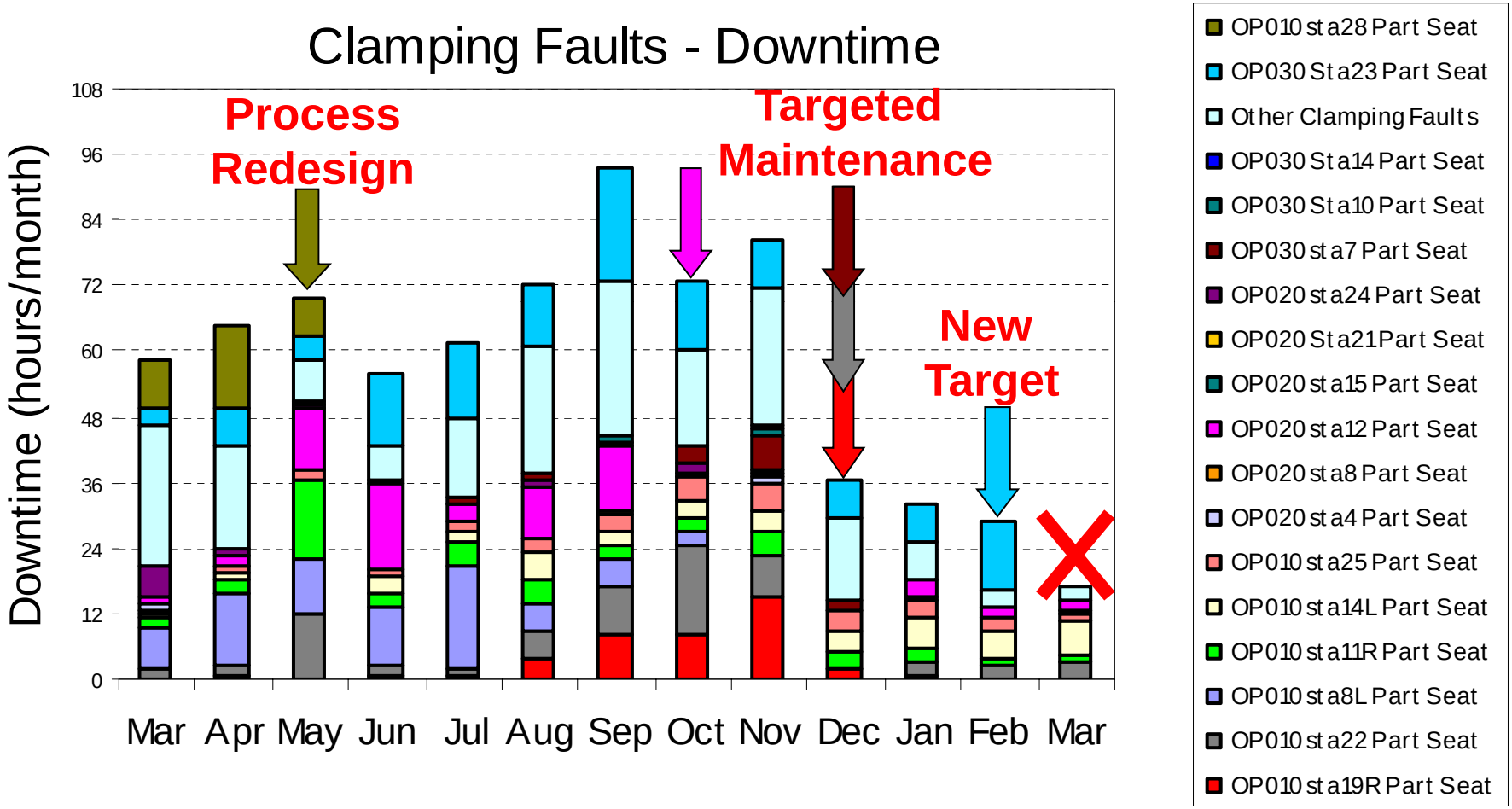
- Prioritize maintenance actions
- Identify root-causes
- Reduce labor-hours, spares, & repair costs
- Reduce down-time via opportunistic maintenance
- Avoid collateral damage
- Minimize scheduled inspections
- Enhance reliability & safety

Robust Trend Prediction – Clean Kill



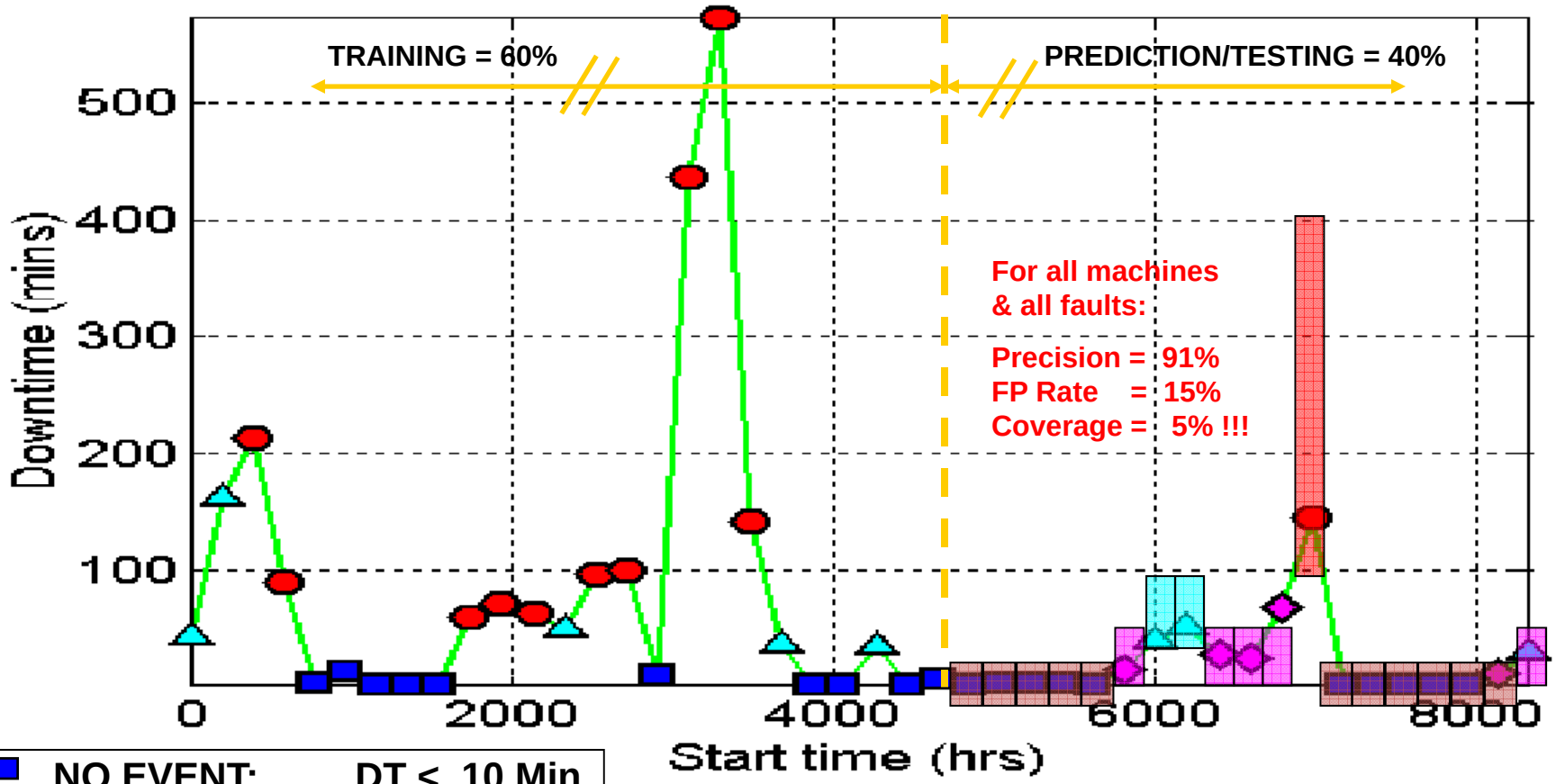
Takeaway: Fault trends can be predicted 1-2 weeks in advance

Downtime Reduction by Trend Analysis



Takeaway: 75% reduction on clamping faults downtime

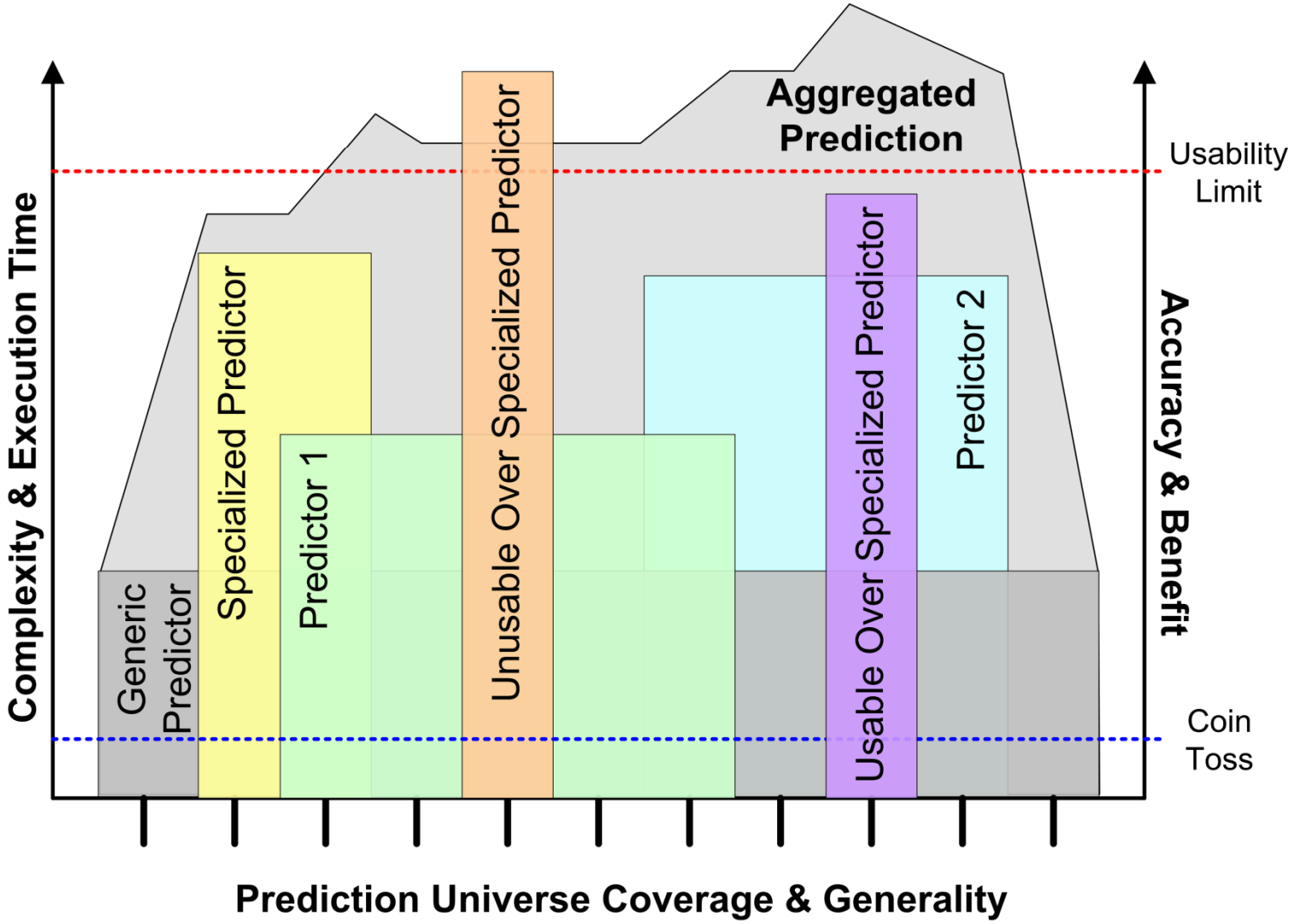
Evolutionary Hybrid Temporal Data Mining



NO EVENT:	DT < 10 Min
SMALL:	10 < DT < 40 Min
MEDIUM:	40 < DT < 120 Min
LARGE:	DT > 120 Min

Takeaway: Faults with complex patterns can also be accurately predicted

One size does NOT fit all



What if you're already down?

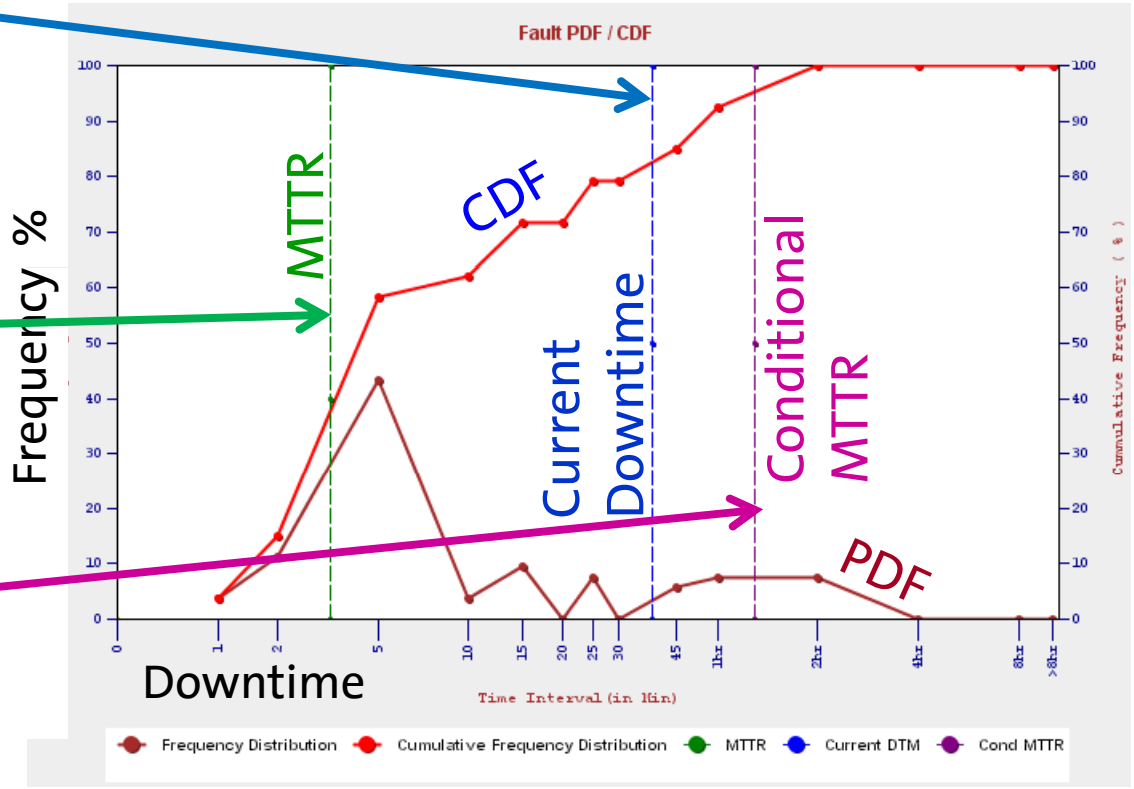
- Conveyor has been down for over **½ hour** & repairs are underway

Answers Needed:

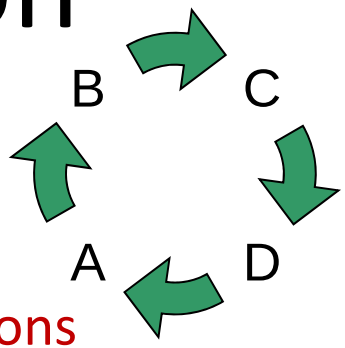
- What is the MTTR?
  3 min (not really useful after ½ hour of downtime)

- Given that the conveyor has been down for **½ hour**, what is our "new" expected MTTR (50%TTR)? **80 min**

- This repair is taking too long; can you tell me with a 95% certainty, when can we restart production (95%TTR)?
  120 min (not shown in graph)



Effective Implementation



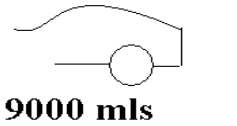
1. Understand the business process
2. Get appropriate and reliable data
3. Perform Predictions for "required" prediction horizons
   - Events
   - System performance metrics
   - Prediction confidence & statistical significance
4. Estimate benefits achieved by acting on such data
5. Act on predicted results that provide value
6. Measure and validate results
   - Prediction: Accuracy, Precision, Type I & II Errors, Significance, ROC(t), …
   - Value of the Prediction
   - Business Impact
   - Financial Benefit
7. Go To Step 1

Vehicle Examples

Sensor-Based Diagnosis &Prognosis

Brake
9000 mls

Battery
60%



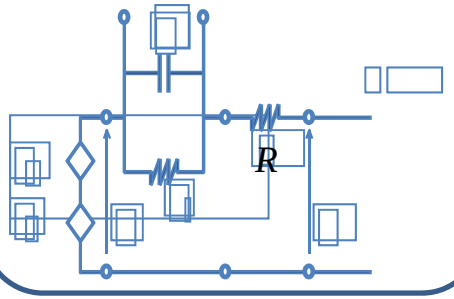
Remote D&P

Back-End Server

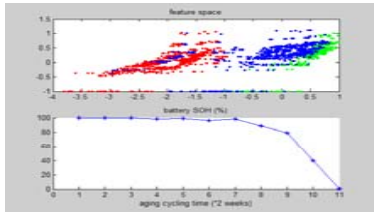
Charge
Battery
Immediately !

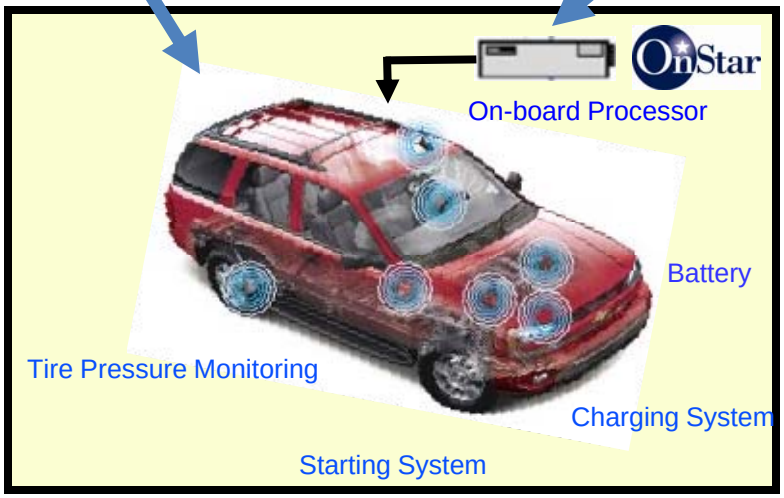
Cell Tower

Physics-Based Methodology

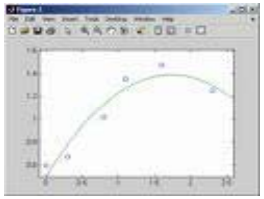


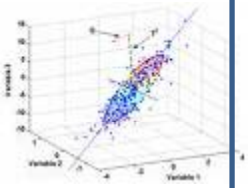
Data-Driven Methodology

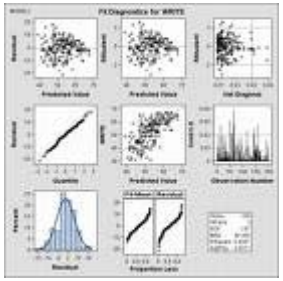




Statistical Analyses







Note: ~6,000,000 OnStar Subscribers

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OnStar Vehicle Diagnostics from your 2010 Chevrolet Impala as of 06/30/2010

Dear Steven Holland,

See your diagnostics report below for your vehicle's status.

OnStar can help pay for itself. It can help you increase fuel economy, pay for fewer oil changes, lengthen tire life, get auto insurance discounts and take advantage of On-Demand Diagnostic checks.

LEARN HOW

VIN: 2G1WB5EK7A1172536

GM Owner Center Online

FlexFuel E85 Compatible

No Issues Found | Action Suggested | Immediate Attention

Goodwrench DIAGNOSTIC INFORMATION

- Engine and Transmission System
- Emissions System
- Air Bag System
- StabiliTrak® Stability Control System
  Watch Video
- Antilock Braking System
- OnStar System

NOTIFICATION INFORMATION

OnStar Subscription
- Account #: 009-7919-028
- Directions & Connections Plan
- Expires 01/11/2011
- Enrolled in Continuous Coverage

Learn more about other ways to take advantage of your status as a valued GM Family member.

More Information

Turn-by-Turn Navigation
Turn-by-Turn Navigation just got even better - now you can easily send MapQuest directions right to your vehicle with OnStar eNav.

MAINTENANCE INFORMATION

Vehicle Maintenance

Remaining Oil Life: 37%

Mileage: 11,475

No required maintenance due at this time.

Based on oil life and mileage readings, next required maintenance estimated at 14,200 miles.

How to reset your vehicle's oil life indicator

Tire Pressure: Normal

- No issues found.
- Recommended tire pressure - Front: 30 psi, Rear: 30 psi

Left Front: 33 psi

Right Front: 33 psi

Left Rear: 33 psi

Right Rear: 33 psi

VEHICLE HISTORY

Review charts of your vehicle's history.
Oil Life History
Mileage History

Hands-Free Calling

- Calling #: 810-300-4694
- Minutes Remaining: 997
- Expiration: 05/03/2011

(or when OnStar subscription ends, whichever comes first)

Save up to 30% on minutes with your GM Family First discount.

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To get the most of your OnStar service, please complete your profile.

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- Radio ID #: B2DR32WA
- Vehicle equipped and active

Your XM is on! So explore, find your favorites and enjoy.

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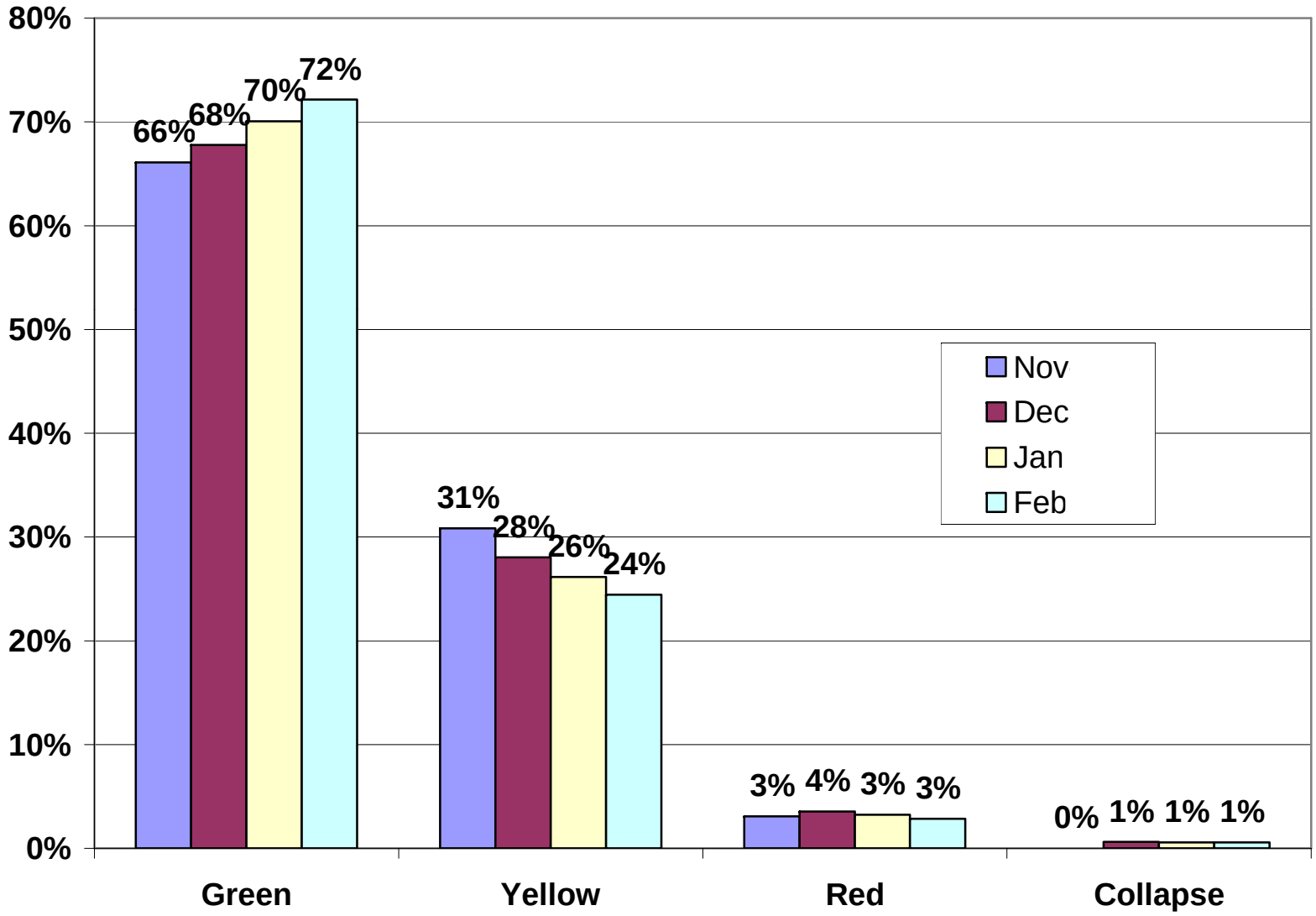
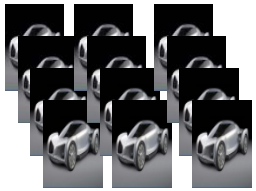
OVD Tire Pressure Data Shows an Increasing Trend of “Green” Readings



Battery Monitor – Telematic Solution

- **Remote vehicle no-start prediction service**
- **Starting system includes:**
  - **12V Lead Acid battery**
  - **Ignition cylinder**
  - **Starter motor**
  - **Engine**
  - **Electronic control units**
  - **Wiring**



Design Validation

Manufacturing

Sales

Ownership

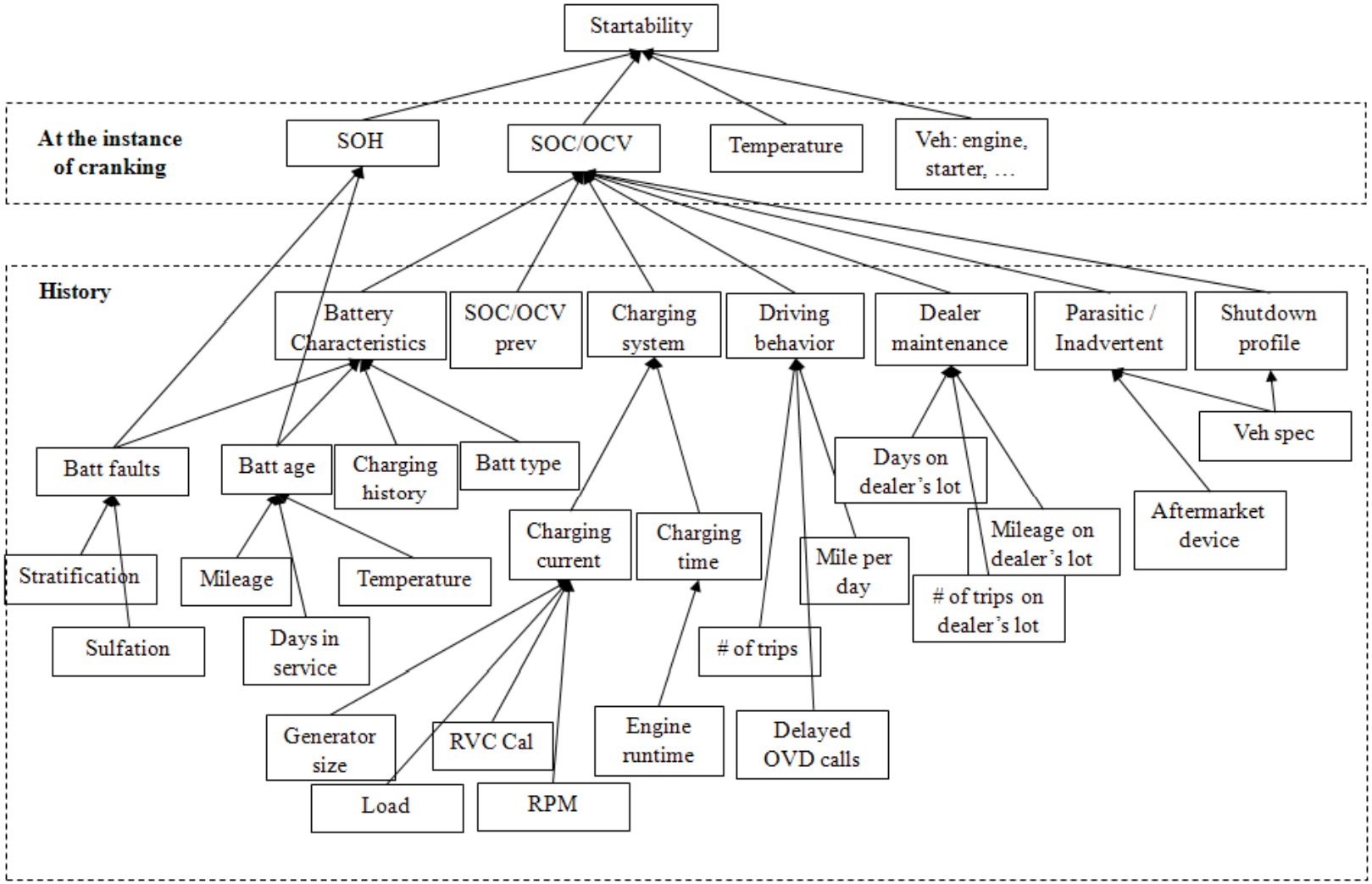
Service

Types of Battery Failures

- **Low state of health (SOH)** - battery reaching its end of life
  - **Failure modes: shedding of active materials, sulfation, grid corrosion, loss of water, internal open circuit, internal short circuit, etc.**
  - **Reasons: supplier quality, pre-mature failure due to abuse, regular wearout**

- **Low state of charge (SOC**) - the amount of energy stored in the battery is drained to a low level
  - **Reasons: long stand time, short trips, inadvertent loads**

Vehicle No-Start due to Battery – an Influence Diagram



Battery State Prediction

Batteries

Data

Open Circuit Voltage
Seasonal Temperature
Prior OCV Reading
Miles per Day
Odometer

Predictive Test

Algorithm 1
Algorithm 2
Algorithm 3
Algorithm 4

Prediction

Action Suggested

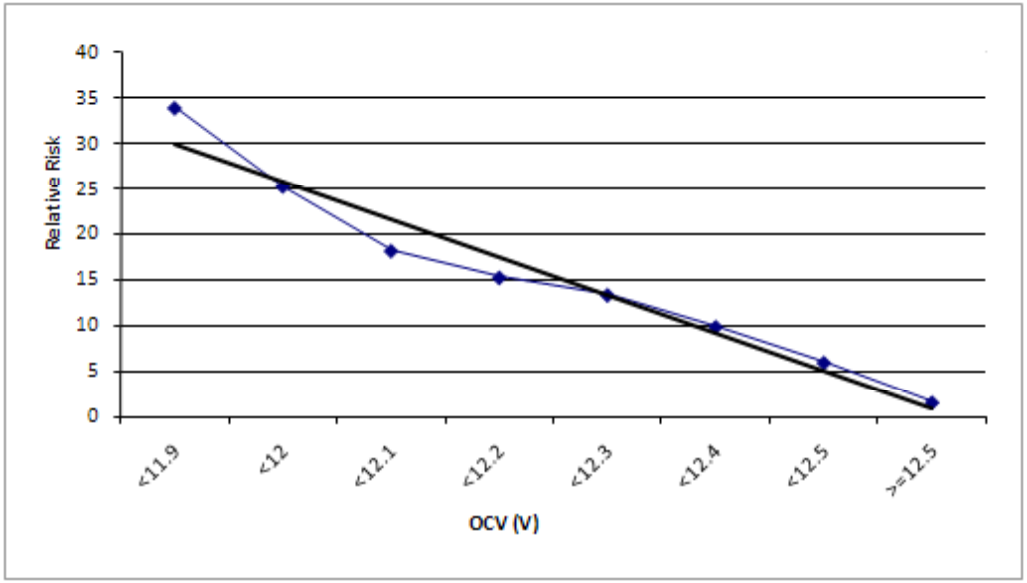
No Issues Found

OnStar by GM

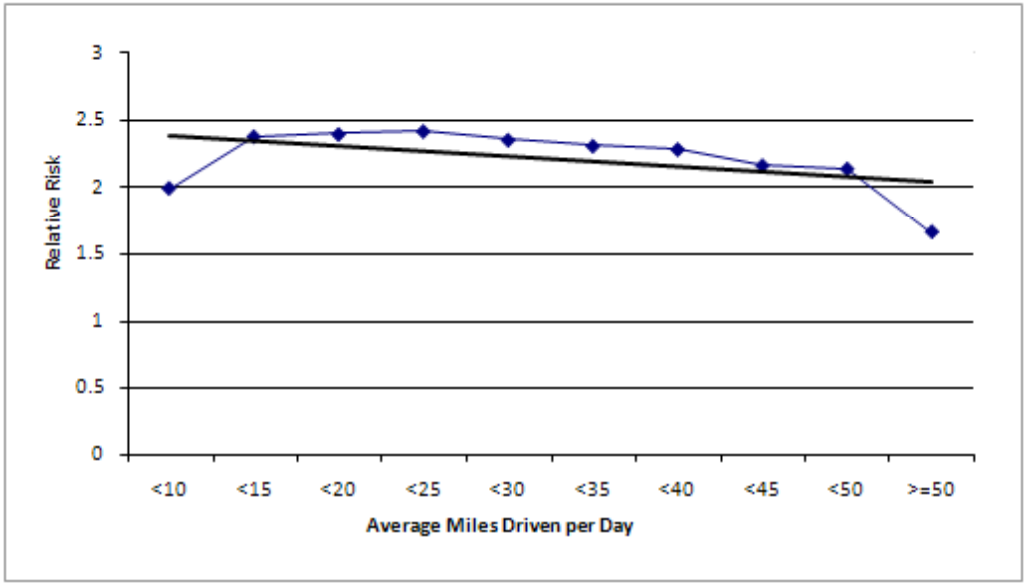
Data

- **Vehicles: > 1,000,000 (a subset of OVD service subscribers)**
- **Period: 2-12 months**
- **Parameters**
  - **Field vehicle data**
    - **Battery data: Open circuit voltage (OCV) , terminal current, temperature, off-awake amp-hour, etc.**
    - **Vehicle data: build time, sales time, mileage, etc.**
  - **Warranty data**
    - **Battery claims (replacement, recharge): claim time, mileage, etc.**

Data-Driven Based Approach

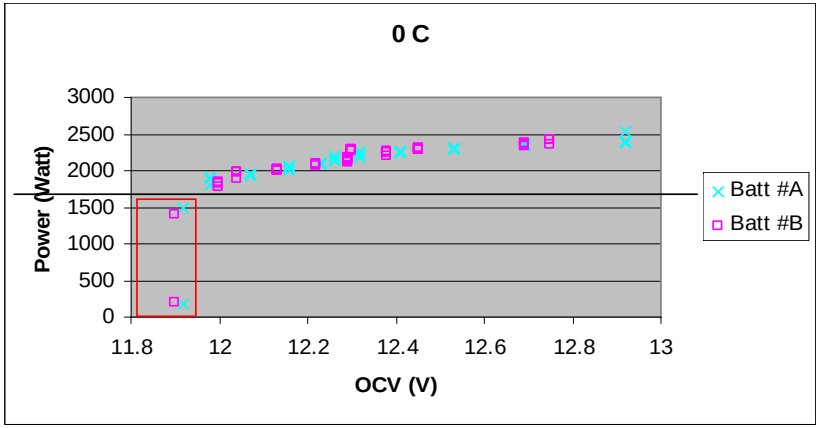


- OCV correlates more significantly with Risk of No-Start than Average miles driven per day does

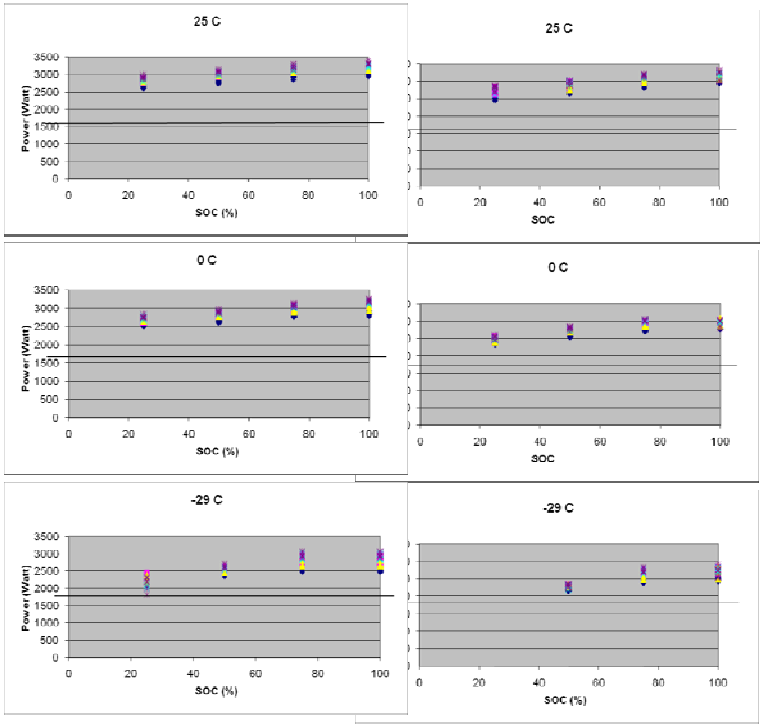


Physics-based Approach

- **To start the engine:** $P_{batt} > P_{egn}$



- **Test vehicle data**
  - **Cranking vehicle at different battery conditions, *e.g.*, battery age, SOC, temperature**



Prediction Algorithm

- **For a particular vehicle at a particular time,**

  IF

  x1 > x1_threshold AND

  x2 > x2_threshold AND

  …

  THEN

  No-Start risk is high

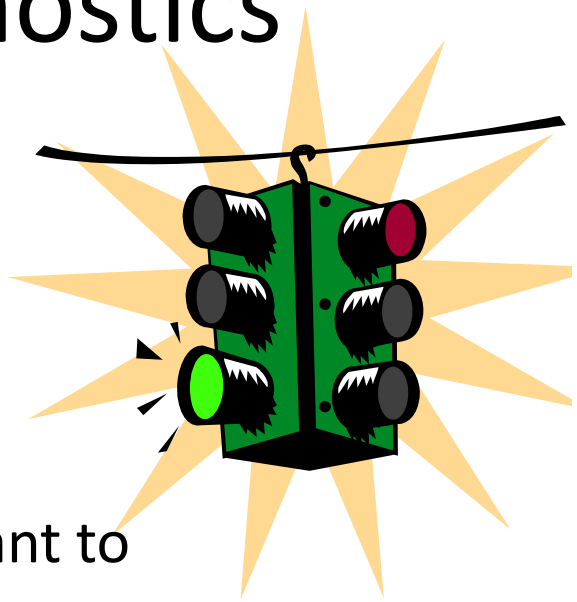
  where x1, x2, … are selected failure precursors

- **Algorithm Calibration**
  - **Determine thresholds / decision boundaries**

Hybrid Battery State D&P

- **Charge Estimation** for Lithium-Ion Hybrid Batteries
  - Developed a fully adaptive estimation algorithm to provide a reliable state of charge (SOC) for lithium-ion batteries
  - Benefits:
    - Enhance battery control and power management for hybrid vehicles
    - Improve fuel economy
    - Prolong battery life and reduce warranty
- **Health Monitoring** for Lithium-Ion Hybrid Batteries
  - Estimated battery capacity and provide state of life (SOL) diagnostic for loss of 25% electric operating range
  - Benefits:
    - Meet OBD requirements
    - Offer customer peace of mind via pre-warning of battery SOL
    - Avoid unnecessary replacement of batteries & reduce NTF and warranty cost
    - Provide capacity estimate to enhance SOC estimation

“The Prognosis for Prognostics”



- Increasing availability of real time data and algorithmic advances are opening doors across many industries
- You need to be very clear about what you want to optimize for:
  - Saving money or time,
  - Enhancing safety, performance, robustness, productivity, …
- The benefits of PHM are both significant & growing

Thank You!

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- **Related Publications**
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  - N. Srinivasa, Q. Jiang, and L. G. Barajas, "**High-Impact Event Prediction by Temporal Data Mining through Genetic Algorithms**," in Natural Computation, 2008. ICNC '08. Fourth International Conference on vol. 1. Jinan, Shandong, China 2008, pp. 614 - 620.
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  - Y. Zhang, M. Salman, H.S. Subramania, et. al. "**Remote vehicle state of health monitoring and its application to vehicle no-start prediction**," in Proceedings of IEEE Autotestcon 2009, Anaheim, CA, September, 2009
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  - Y. Zhang, G. Gantt Jr., M. Rychlinski, et.al., "**Vehicle design validation via remote vehicle diagnosis: a feasibility study on battery management system**," Proceedings of IEEE International Conference on Prognostics and Health Management, Denver, Co, October 6-9, 2008
- **Related Patents**
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