# Ground Vehicle Condition Based Maintenance

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- Logistics Modeling & Simulation
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    - Component Testing
  - ARL CBM Research
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CBM+ Overview
RCM and CBM are core processes for CBM+ System Development

- **Army Regulation 750-1, 20 Sep 2007, p. 79** - Reliability Centered Maintenance (RCM) is the process that the Combat and Materiel Developers use to determine the most effective approach to maintenance. RCM involves identifying actions that, when taken, will reduce the probability of failure and which are the most cost effective. It seeks the optimal mix of condition-based actions, interval (time- or cycle-) based actions, failure finding, or run-to-failure approach.

- **DoDI 4151-22, 2 December 2007, p. 1** - CBM+ is the application and integration of appropriate processes, technologies, and knowledge based capabilities to improve the reliability and maintenance effectiveness of DoD systems and components. At its core, CBM+ is maintenance performed on evidence of need provided by reliability centered maintenance (RCM) analysis and other enabling processes and techniques.
Business Challenges

Why is CBM+ Important?
- O&S Costs Dominate DoD Spending
- Need to Reduce Logistics Footprint
- “Buying” Readiness is not an option

Incentivizing OEMs
- Current process serves as a disincentive
- Resistance to Open Standards and Third Party Technology
- Need to make this “Profitable” for the OEMs
Building Predictive Maintenance

**Platform Information:**
Digital Brigade Combat Team, Electronic Technical Manuals, Built In Test / Fault Isolation Test, Vehicle Diagnostic Management System

**Health Management:**
Embedded Diagnostics, Self Reporting, Self Monitoring

**Conditional Based Maintenance:**
Fact Based, Trend Analysis

**Prognostics:**
Predictive Maintenance

**Today’s Health Management**
At-Platform Diagnostic Troubleshooting
Maintenance Support Device
Scan Tools

**Desired Endstate**
Commonality Opportunities - Technologies, Products, & Components

Off-Platform Test Equipment
Paper Logbook

**Digital Platforms:**
Digital Architecture, Data Collectors

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Enablers for Increased Maintainability

**Platform Enablers**
- Self-reporting Assets & Components
- Fleet Management
- Supply Parts Ordering
- Maintenance Scheduling
- Digital Log Book
- Interactive Electronic TMs

**Off-Platform Enablers**
- Network Infrastructure
- Data Mining & Analysis Tools
- Fleet Trending and Pattern Recognition – Actionable Data
- Data Synchronization
- Logistics System Integration

**Onboard & At-Platform Prognostics/Diagnostics**
- Sensors w/ Sensor Integration HW
- Vehicle Integrated Diagnostic Software (VIDS) w/ Algorithm Manager
- Vehicle Computer System

**Maintainability**

**Data Standards**
- Common Data Format (CDF)
- Open Data Standards
- Data Exchange Standards
- Defined Technical Views

**Army Integrated Logistics Architecture (AILA)**
- Enables Net-Centricity
- Defined using DoD Architectural Framework (DoDAF)
- Facilitates Interoperability
Logistics M&S
Aberdeen Insights — Predictive Modelling and the Department of Defense and Beyond

This need for better predictive modeling is also being stated by the US government so as to improve the lifecycle management and boost the MRO of assets controlled by the United States Department of Defense. Notes from the Committee of Armed Services in the National Defense Authorization Act for Fiscal Year 2010, indicate that the committee “is concerned about spare parts inventory and supply management by the (armed) services.” Notes also indicate that the Government Accountability Office has recommended that spare parts inventory and supply management should be strengthened by improving demand forecasting procedures and by monitoring the effectiveness of providing operational information to item managers. The Committee of Armed Services also encourages the DoD to adopt advanced predictive modeling and simulation methodology that incorporates the asset demand influencing factors to include time, usage, aging of parts, origin of critical parts, maintenance, and logistics support for all aviation and ground equipment programs. In addition, the committee also encourages the DoD to establish pilot programs to demonstrate the benefits of demand forecasting models to reflect cost savings, reduced reliance on unscheduled maintenance, and increased efficiency in supply chain management and budget projections.

Making the Case for Implementation of Simulation

• The following complex equation defines $A_0$ over a Non Linear- Time-Line

$$A(T) = \sum_{k=0}^{\infty} \int_{t_0}^{T} \cdots \int_{t_{k-2}}^{t_{k-1}} f(t_1)(g(t_2-t_1))(g(t_3-t_2))(g(t_4-t_3)) \cdots f(t_{2k-1}-t_{2k-2})(g(t_{2k}-t_{2k-1}))[1-F(T-t_{2k})]dt_1dt_2 \cdots dt_{2k-1}dt_{2k}$$

• Often Assumptions are made that discount “Time” in system behavior
  
  #1 $f(t) \sim \text{Exp}(l)$ i.e. failures are memoryless (no aging)
  #2 $g(t) \sim \text{Exp}(m)$ i.e. repairs are memoryless (no changes to maintenance)
  #3 Transient state is negligible (environment is constant)

If these assumptions hold……Then this intractable equation reduces to:

$$A(T) = \frac{\text{MTTF}}{\text{MTTR} + \text{MTTF}}$$

Is this simplification really representative of the system behavior, or is this simplification just mathematically convenient?
A Closed-Loop Non-Linear Problem & Many VARIABLES

- System Design Configuration/Status
  - Availability/Readiness
  - Achieved Operating Hours
  - Operation Profile
  - Assembly Ages And Repair History

- Operations
  - Spares Locations
  - Spares Unavailability
  - Stock Levels
  - Spare Pre-positioning
  - Order Lead Times
  - Shipment Times
  - Items Condemned & Retired

- Engineering
  - Deployment PM/Readiness
  - Logistics/Supply Item Manager
  - Maintenance ALC & Field
  - Maintenance Concept To Include PDM

- Supply
  - Tasks Performed
  - Spares Assembly Location/Age/Status
  - Spares

- Depot Maintenance
  - Arrivals to Depot
  - Items Condemned & Retired
  - Spares Pre-positioning

- U / I Repair Levels
  - Repair Turn Around
  - Awaiting Parts Occurrences
  - Awaiting Maintenance Occurrences
  - Repair Levels
What Questions Can Be Answered?

**VARIABILITY**

- Reliability
- CBM+
- Operations

**What Spares Must I Take, and What will They Cost, to Support a particular system (Readiness Objectives)?**

- What Workload will be Created Due to the Surge in Operations?

- What Special Repair Capability Must I Take to Support Deployments?

- What Maintenance Strategies Should I Use to Minimize System Downtime and Repair Costs, While Maximizing MTBF (Up-Time/ TOW)?

- What will my Aging fleet cost me next year and beyond if I want to maintain my readiness targets/goals?

- When will there be a financial and/or readiness return on investment in my proposed upgrade/ modification program?

- What will be the resulting workload, and when and where will it occur? Retirement? Mod?

- Where can I refine my strategy in order to improve both the Readiness and Financial Returns on Investment?
Logistics Wargaming: Evaluate “What-If” Impacts Due to:

- New or Revised Op-Tempo Programs
  - Business Rules, Processes and Procedures e.g. Business-Surges
  - Terminal or Depot Outage or Transition
  - Network or Infrastructure Expansion, down-sizing/ right-sizing
  - Just-in-Time Inventory Assessments & Planning

- Life-limits and Engineering Change Proposals
  - Part Purging
  - Part Substitutability

- Recapitalization Program Implementation
  - Maintenance Concept Adjustments
  - Repair Effectiveness

- Spares and Part Availability
  - Buy Plan and Initial Provisioning Assessment
  - Obsolescence due to Diminishing Resources

- Budget & Materiel Constraints
- Other Resource Constraints e.g. personnel, training, skills etc.
TACOM LCMC CBM+ Initiatives
The objective of this effort was to compile the most significant components with respect to demands over time and based on their importance to the end truck system. Four tactical vehicles were selected by TARDEC for this study.

- Select the particular vehicle components of interest
- Analyze components of the subject truck systems by operational usage data
- Determine maintenance improvements to address high demand/high cost issues
- Compile Failure Modes and Effects Analyses (FMEA)
- Identify usage patterns for application of Condition Based Maintenance (CBM) sensors
4D/CBM Data Analysis, Validation and Reporting Process

**DATA COLLECTION & ANALYSIS**

- Normalize
  - Adjust for Density & OPTEMPO
- Group & Compare Data
  - NIIN, Years, LOC, DMD, Cost, etc.
- Group Data
  - Years, LOC
- OSMIS
  - OPTEMPO Data
  - Density/Usage
- Data Review
  - Charts/Graphs
  - SWA/Non-SWA
  - Trends, Spikes,
  - Specialist Review
  - Data Consistency
  - Tech Manuals/Drwgs
  - MWOs, ECPs, etc.
- Identify Top Demand/Cost Drivers & SWA Issues
- Prepare Maintenance Figure of Merit (MFOM)

**PHYSICAL ANALYSIS/VALIDATION**

- Preliminary FMEAs Initiated
- Maint Records & Suppl Data
  - AMSA Sample Data Collection Fleet Field Reports & Analysis
- On-Site Visit Depots/RESET Sites, ARNG/USAR Feedback
- AMSAA
  - Specified Targeted Component FMEAs Completed
- Ext Input: Penn State CBM Sensor Technology

**REPORTING**

- Recommended Course of Action
  - TM Revisions,
  - CBM Sensor Dev & Application Recommendations,
  - ROI Analysis & Feedback

**Primary Data Query**

- ILAP
  - Demand Data
  - Order QTY & COST
- OSMIS
  - Demand Data
  - Order QTY & COST
- AMSAA
  - SDC Maint Data
  - Repl QTY & COST

**Secondary Data Query**

- OSMIS
  - OPTEMPO Data
  - Density/Usage
- OSMIS
  - Demand Data
  - Order QTY & COST

**Engineering**

- Engineering
Vehicle Components:

Top 4 on all lists:
1. Engines *
2. Transmissions *
3. Batteries
4. Pneumatic Tires

Top 4 is a similar list for tracked and wheeled vehicles. Tracks replace tires as high cost/demand items for tracked vehicles.

Critical Components:
1. Starter
2. Alternator/Generator
3. Fan Clutch
4. Axles
5. Drive Train/Propeller Shaft
6. Air Compressor
7. Air Dryer
8. Air Brake Chamber
9. Air Brakes
10. Evaporator/Condenser
11. Steering Gear
12. Drag Link
13. Radiator
14. Tie Rod Ends
15. Aligning Rods/Control Arms/Torque Rod
16. ...

Root Cause Analysis leads to other vehicle components that deteriorate the Operational Readiness and increase non-mission capable (NMC) vehicle events.
Interactive Electronic Tech Manuals (IETMs)

- Vehicle diagnostic software link straight to maintenance tasks
- Automate data collection tasks to reduce maintenance time
- IETM Management to allow updates to be pushed to platforms

Autonomous Diagnostic Manager (ADM)

Engines
- Caterpillar 3126A, 3126B, C7, C12, C15
- Detroit Diesel DDECII, DDECDT, DDECDIV
- John Deere PP45

Transmissions
- Allison ATECI, ATECII
- Allison WTEC (Generation 3 and 4)
- General Motors GM4L80E

Antilock Braking System (ABS)
- Eaton, WABCO, HALDEX

Central Tire Inflation System (CTIS)
- Eaton
PM-HBCT VHMS
Vehicle Health Management System (VHMS)

Team Members
- BAE
- CPC
- DRS
- GDLS
- PSU-ARL

- Development of overarching system requirements and architecture for a PM HBCT VHMS implementation
- Enhance and Integrate Diagnostics on platform
- Coordinate off-platform interfaces with Enterprise-level logistics systems (GCSS-A, CBM Data Warehouse)
- Enhance Embedded Diagnostics
- Enable platform data storage and transfer
- Develop & integrate IETMs
- Integrate Ground Digital Log Book (GDLB)
- Plan for future upgrades (LRMs, SRU-level Fault Isolation)

VHMS was formed to solve DSETS/ATE obsolescence issues.

- Centralized Health Management Application
- Common GUI that reduces training footprint for HBCT maintainers
VHMS Key Products

Materiel Solutions
- Ground Digital Logbook
- IETMs
- VHMS Comms Network (VCN)
- E-switch
- Wireless Network Card

Integrated Solutions

Platform Software
- Vehicle Health Management
- Enhanced Diagnostics
- Logistics Database Management
- Integrating GFM

Systems Engineering Work Products
- GCS Specification
- Interface Requirements
- User Interface Descriptions
- DoDAF Architecture Artifacts

Specs Common Screens

DoDAF Architecture Artifacts
Technical Challenges

- **Software Integration Challenges**
  - Common requirements & functionality
  - Different OEM SW development environments
  - Government Furnished SW is developed using different operating systems (i.e. Linux, Windows) and hardware (i.e. laptops, tablet PCs, embedded computers, etc...)
  - Building common data intensive interfaces for System of Systems interoperability

- **Prognostic Maturity**
  - Lack of success stories drives doubt about prognostic development
  - Lack of historical data makes development difficult and provides little Return-On-Investment justification

- **Conflicting PM Priorities**
  - While high level guidance regarding CBM Implementation exists, it stops short of a firm platform requirement
  - Even with a firm requirement a platform has traditionally traded RAM technologies for enhanced performance, lethality, and survivability
PM-TV CBM Activities
PM Tactical Vehicles CBM Activities

- CBM for TWVs will be built on embedded diagnostics and will concentrate on powertrain and chassis.
- For practicality and affordability, TWVs will utilize low cost, COTS based HW & SW solutions that leverage auto/truck industry standards, practices, and products.
- PM TV needs:
  - Approved requirements and funding for Product Managers to enable CBM “front end”.
  - Logistic and maintenance data analysis to target best ROI opportunities.
  - Continued growth and coverage of embedded diagnostics.
  - Collaborative analysis of fault and failure modes with vehicle/component manufacturers and the scientific and engineering communities.
  - Development of reliable predictive algorithms for a wide range of vehicle components and systems.
  - Establishment of logistic data management networks and applications for collecting and routing CBM information.
Various electronic modernization activities are occurring during vehicle upgrades, RECAPs, and new production that will support CBM objectives.

- Automotive and computing industry standard data busses and interfaces
- Electronically controlled components with embedded sensors
- Computing, data acquisition, and data storage devices for maintenance and diagnostic purposes

Coordinating with PD TMDE for development of HW & SW tools to support embedded diagnostics, CBM, and logistic/maintenance data reporting.

- Wireless Diagnostic Sensor (WDS)
- Vehicle Integrated Diagnostic Software (VIDS)
- Standard Army Maintenance Systems-Enhanced (SAMS-E) interface

Working with TARDEC to develop and mature supporting technologies and processes.

- Sensors, computing, and vehicle information architectures
- Logistic and maintenance data analysis
- Diagnostic and prognostic algorithms

Coordinating with Logistic Innovation Agency (LIA) and Army/DoD level initiatives.

- Army Integrated Logistic Architecture (AILA)
- Common Logistic Operating Environment (CLOE)
- Proof of Enablers (PoE) exercises and experiments
USMC PM - Autonomic Logistics
Autonomic Logistics
Overarching Concept

Tactical Communications
Status Reports

Data Transfers
Alerts

Mobile Loads
Passenger Manifest

Driver Display

Vehicle Managers Device
Tech Manuals/E-Records
Alerts/Sensor Data
Digital Forms

~100 Existing
Data Points

3 DACs

20 Additional Sensors

EPLS

Wired/Wireless
Data Transfers

Maintenance Actions
Technical Manuals

AL-MC Services

GCSS

GCSS

EMSS

EMSS
EPLS Goals

- Provide a basic infrastructure to enable condition based maintenance
- Install an “On-platform” sense capability
- Enable USMC autonomic logistics capability
- Provide stand alone capability that immediately supports the vehicle operator and maintainer
  - Digital, open systems design
  - Networking connectivity
- Platforms – LAV, MTVR, AAV, w/LVSR (Planned)

AL supports achievement of Marine Corps Logistics Modernization goals and objectives
Data Acquisition/STE-ICE controllers

Power Supply

Onboard Computer (OBC)

Driver Position Display (DPD)

Off-Board Service Application - Fleet Status Viewer

On-Board Software Client

Sensors, Cabling, Digital Data Buss

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TARDEC S&T Initiatives
Prognostic & Diagnostic Process Map

**Focus**
- Maint / Cost Drivers

**Data Mining**
- FMEA / FMECA
- Physics Of Failure

**SME Expertise**
- Design Factors

**Design & Analysis of Experiments**
- Design / Perform Experiment

**Sensor Gaps**
- Identify Features

**Enhance Model**
- Fit Model & Generate Algorithm

**Deploy & Test** (Field Sample)
- Verify / Validate / Test

**Algorithm Improvement**
- Model fit to only significant factors and interactions
- Additional tests to improve sensitivity

**Testing**
- Team with AMSAA for field testing
- M&S and additional physical testing to introduce more noise factors

**Analysis**
- ILAP / OSMIS
- AMSAA SDC
- PEO / PM Data

**2009/2010 Targets**
- Powertrain
- Track
- Electrical System

**FMEAs Developed**
- Diesel Engine
- Transmission
- Alternators

**Analysis**
- Identify failure modes
- Derive design factors and sensor strategy

**Analytical Tools**
- DOE Tools
- Data Analysis Tools

**Increasing knowledge and capability through proper experimental design and analysis!**
Seeded Fault Testing & Algorithm Development

Purpose:
- Development of health assessment models and algorithms for common automotive components through seeded fault and durability analysis at the component level
- Identification of sensor strategies that could be implemented in a ground vehicle application to allow for accurate diagnosis of impending faults
- Evaluation of the potential Return on Investment (ROI) for implementing these technologies in a vehicle
- Collaboration with AMSAA to evaluate the developed algorithms in a vehicle environment

Products:
- Prognostic and Diagnostic algorithms for selected failure modes
- Sensor strategy for vehicle implementation
- ROI Analysis

Payoffs:
- Provide critical insight into sensors required for diagnosis of component health and prediction of Remaining Useful Life (RUL)
- Allow for replacement of the component prior to a failure that could potentially damage or dead-line a vehicle
- Provide Government owned knowledge that can be applied across a variety of vehicle platforms

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<th>Schedule</th>
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<th>FY11</th>
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<td>CAT C7 Engine</td>
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<tr>
<td>Allison 2500 Transmission</td>
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<td>Prestolite 130A Alternator</td>
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<td>Li-ion and PbA Batteries</td>
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Diesel Engine Dynamometer Cell Layout

- Air Restriction Valve
- BOB Harness
- Encoder
- In-Line Torque Sensor
- Dyno Torque Sensor
- Coolant Cooling Tower
- Switch Box
- Battery
- Coriolis Fuel Meter
- Air Cleaner
- Vortex
- Honeycomb
- CRIO
- BOB
- Intake
- Turbo
- CAC Cooling Tower
- Exhaust Restriction Valve
- Lambda Meter
- MIS Flywheel Mag. Sensor
- Pressure Pulsation Sensor
  - Intake (inlet to manifold)
  - Exhaust Pipe (after turbine)
  - Crankcase (thru oil fill pipe)

Other Instrumentation:
- Pressure Transducer
- Thermocouple
- Other Instrumentation

Pressure Pulsation Sensor

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ARL Ground Vehicle CBM S&T Initiatives
Objective/Goal:
Develop P&D technologies including physics-based models that accurately predict 40% of vehicle reliability failures

Technical Barriers:
• Inability to accurately & reliably predict vehicle loads and responses
• Inability to predict system failures

Approach:
• Sensor study to determine baseline of prognostics/diagnostics failure mode coverage
• ID performance degraders of 4 components
• Methodology for determining the remaining useful life (RUL) of high pay-off components

Planned Deliverables:
• Sensor study for P&D failure mode coverage
• Report of performance degraders of 4 high pay-off components
• Analytical method/algorithm for formulating RUL of high pay-off components

Accomplishments:
• P&D framework for determining RUL developed for generic structural systems

Collaborations:
• VTD (RUL algorithm), SEDD (Sensor Study), WMRD (Physics of Failures, Materials Testing), TARDEC (CBM+ for Ground Vehicles TPA), AMSAA (Data Analysis)

Milestones (FY)

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<td>Physics of Failures</td>
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<td>Analytical Method/Algorithm for RUL</td>
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<td>Validation &amp; Tech Integration for CBM</td>
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AMSAA - Sample Data Collection
**Objectives:**
- Develop methodologies and algorithms for the on-board, real-time identification and classification of terrain environments for in-operation wheeled vehicles.
- Relate rates of damage accumulation of a vehicle’s various sub-systems directly to the amount of time a vehicle is exposed to the various terrains.
- Predict vehicle health based on damage accumulation algorithms.

**Accomplishments:**
- Developed methodologies and algorithms for identifying a full-spectrum of terrain regimes.
- Implemented methodology in-theatre on a wide range of operational vehicles.

**Payoff: Near Term**
- Usage profile classification and reporting.
- Indirect component degradation prediction, and comparative health evaluations.
- Test center to test center, and test center to theatre comparisons.
- Guiding condition based reset.

**Payoff: Far Term**
- Predict and determine damage accumulation and failures of a vehicle’s various sub-systems.
- Integrate into Army’s logistic system.

**Technical Approach**
- Perform vehicle-specific testing using unsprung accelerometer, GPS, and gyroscope on proving grounds.
- Compute terrain severity thresholds.
- Apply calculated thresholds to data collected in-theatre and compare to vehicle-specific reference data on the same vehicle traversing known terrain types at Army proving grounds.
- Develop predictive algorithms, by relating damage accumulation of a vehicle’s various sub-systems directly to the amount of time a vehicle is exposed to the various terrains.

Sample Run in Afghanistan

Overall System Severity Index:
- Best
- Medium
- Worst

Terrain Regime Identification and Classification