



**RDECOM**

# Ground Vehicle Condition Based Maintenance

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Development and Engineering Center



**TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.**

**NATO AVT172 CBM Workshop – Bucharest, Romania**

**October 4 – 8, 2010**



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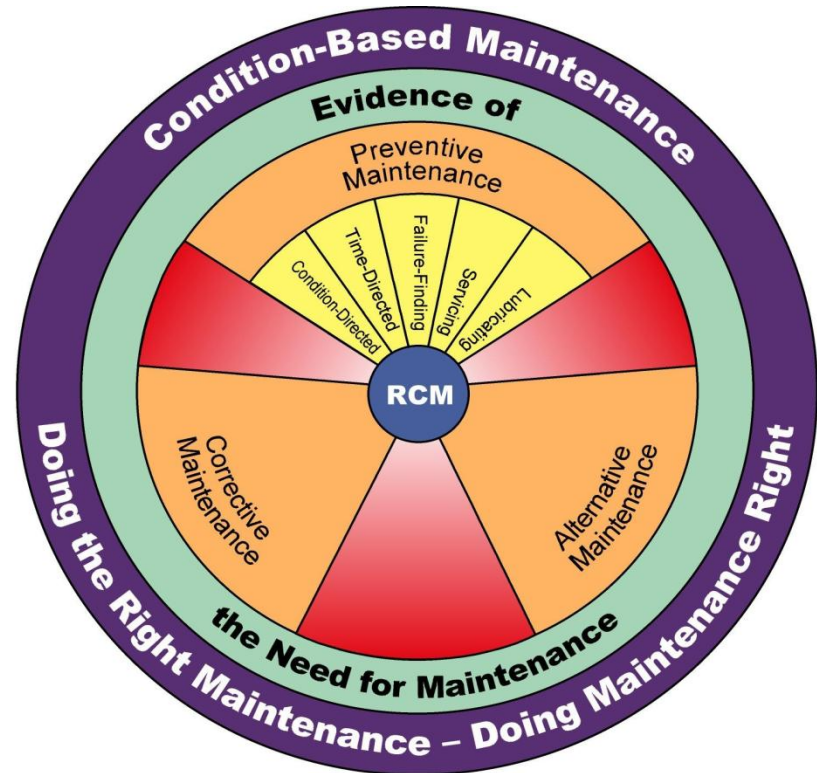
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# ***CBM+ Overview***

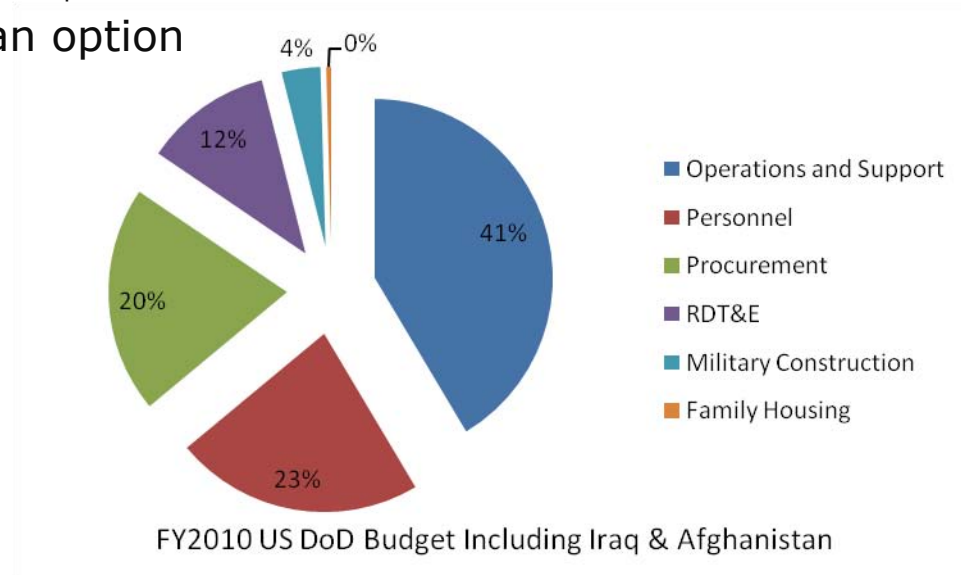
- Army Regulation 750-1, 20 Sep 2007, p. 79** - Reliability Centered Maintenance (RCM) is the process that the Combat and Materiel Developers use to determine the most effective approach to maintenance. RCM involves identifying actions that, when taken, will reduce the probability of failure and which 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.



RCM and CBM are core processes for CBM+ System Development

## □ Why is CBM+ Important?

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

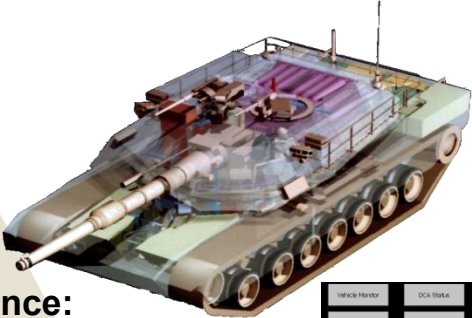


## □ Incentivizing OEMs

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



Desired Endstate



Vehicle Monitor	DCS Status
UPS	Equipment
Blackout	IMCS
Version	Roll



Off-Platform Test Equipment  
Paper Logbook

Today's Health Management

At-Platform Diagnostic Troubleshooting  
Maintenance Support Device  
Scan Tools

**Prognostics:**  
Predictive Maintenance

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

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

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

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



Commonality Opportunities - Technologies, Products, & Components

## 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

## Maintainability

## Onboard & At-Platform Prognostics/Diagnostics

- Sensors w/ Sensor Integration HW
- Vehicle Integrated Diagnostic Software (VIDS) w/ Algorithm Manager
- Vehicle Computer System

## Army Integrated Logistics Architecture (AILA)

- Enables Net-Centricity
- Defined using DoD Architectural Framework (DoDAF)
- Facilitates Interoperability

## Data Standards

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





# ***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.

Source: National Defense Authorization Act for Fiscal Year 2010, Report on Armed Services, House of Representatives

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

$$A(T) = \sum_{k=0}^{\infty} \int_0^T \int_{t_1}^T \cdots \int_{t_{2k-2}}^T f(t_1)(g(t_2 - t_1))(f(t_3 - t_2))(g(t_4 - t_3)) \cdots f(t_{2k-1} - t_{2k-2})(g(t_{2k} - t_{2k-1}))[1 - F(T - t_{2k})] dt_1 dt_2 \cdots dt_{2k-1} dt_{2k}$$

- Often Assumptions are made that discount “Time” in system behavior

#1  $f(t) \sim \text{Exp}(l)$  i.e. failures are memoryless (**no aging**)

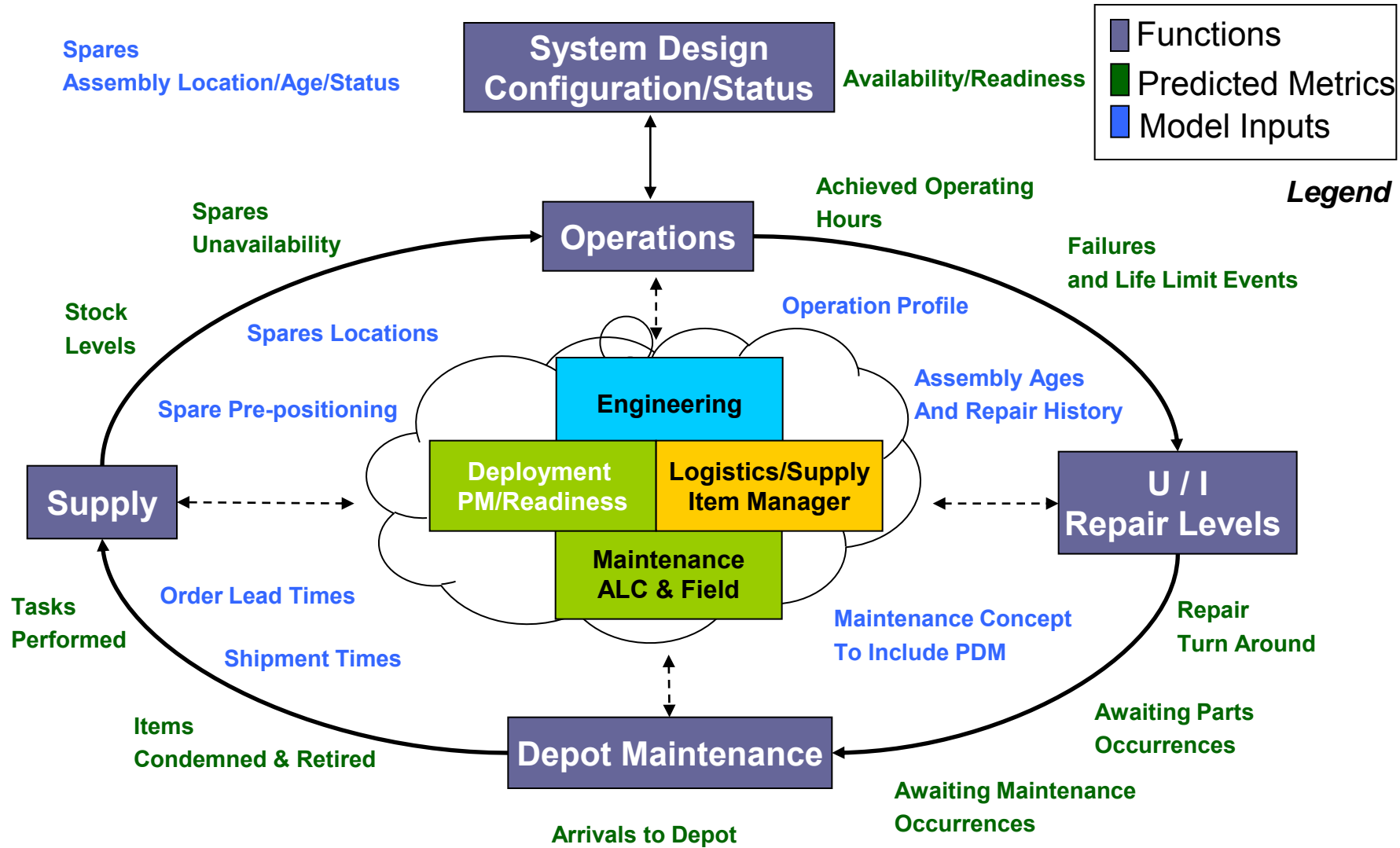
#2  $g(t) \sim \text{Exp}(m)$  i.e. repairs are memoryless (**no changes to maintenance**)

#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?**





## VARIABILITY



### Reliability

- 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)?



### CBM+

- 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?



### Operations



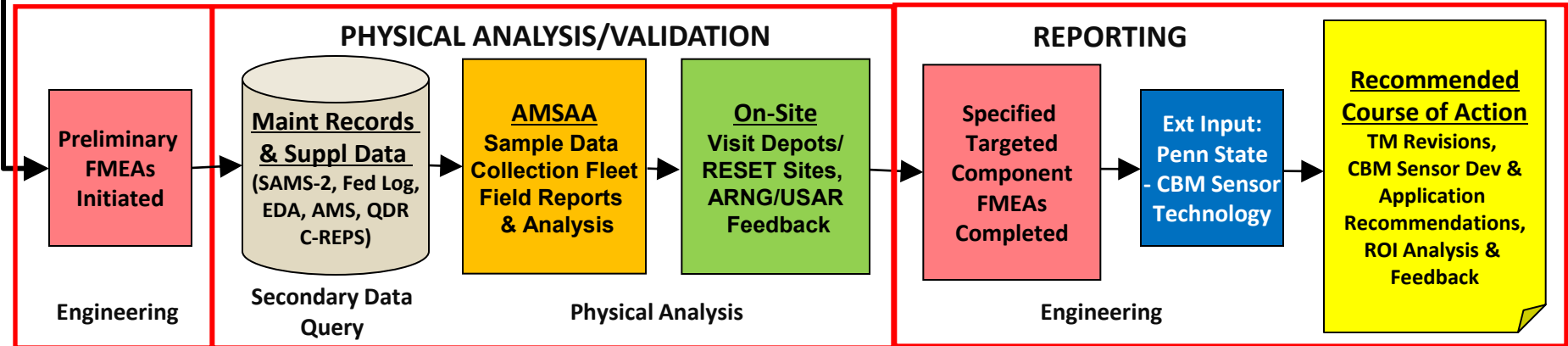
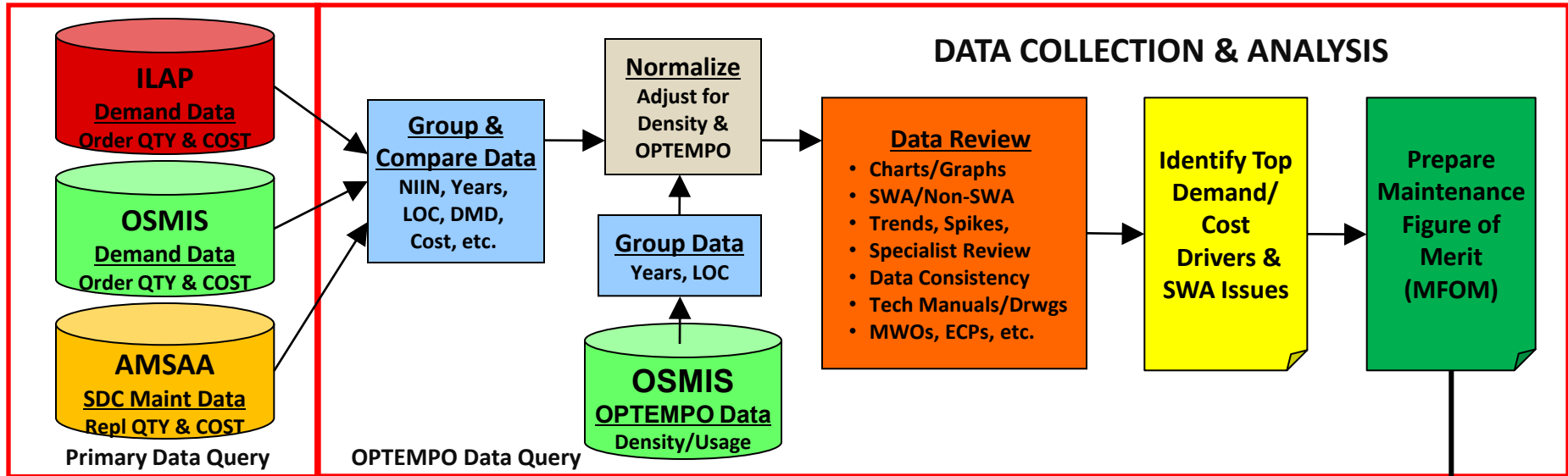
## **Logistics Wargaming: Evaluate “What-If” Impacts Due to:**

- ❑ 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



## 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, DDECIII, DDECIV
- John Deere PP45

### Transmissions

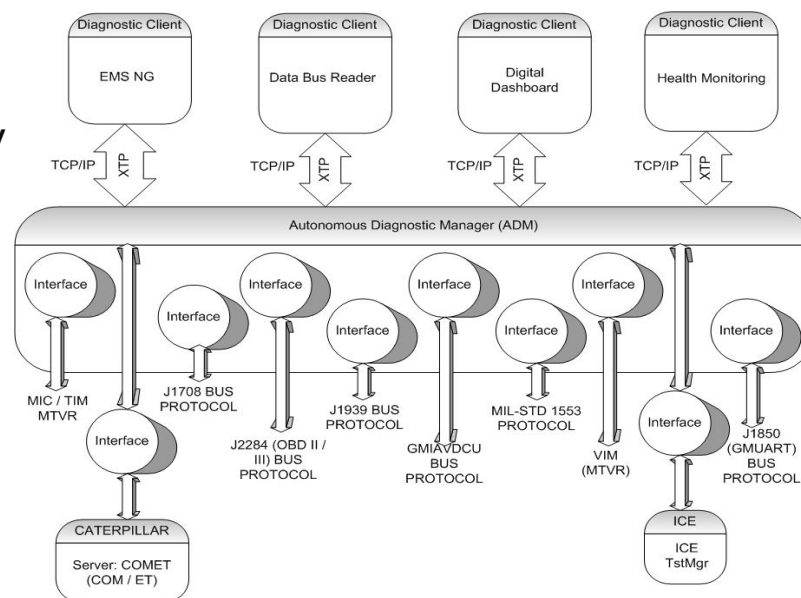
- Allison ATECI, ATECII
- Allison WTEC (Generation 3 and 4)
- General Motors GM4L80E

### Antilock Braking System (ABS)

- Eaton, WABCO, HALDEX

### Central Tire Inflation System (CTIS)

- Eaton



# ***PM-HBCT VHMS***

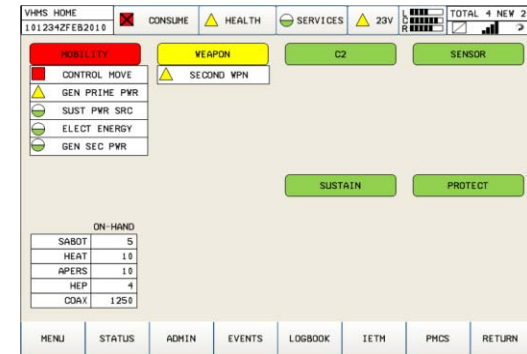
## Team Members

BAE  
CPC  
DRS  
GDLS  
PSU-ARL



- 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)

- 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)



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

**VHMS was formed to solve DSETS/ATE obsolescence issues.**



## Material Solutions

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



EMS-NG(IETM)



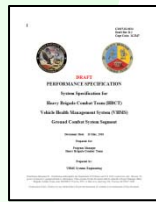
Ground Digital LB



Wireless NIC



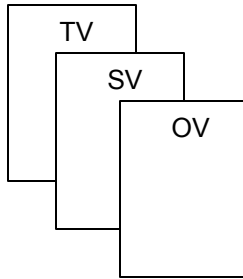
E-switch



Specifications

## Systems Engineering Work Products

- ❑ GCS Specification
- ❑ Interface Requirements
- ❑ User Interface Descriptions
- ❑ DoDAF Architecture Artifacts



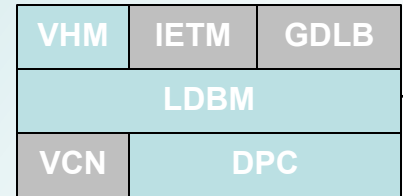
DoDAF Architecture Artifacts



Common Screens

## Platform Software

- ❑ Vehicle Health Management
- ❑ Enhanced Diagnostics
- ❑ Logistics Database Management
- ❑ Integrating GFM



GFM

OEM



## ❑ 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

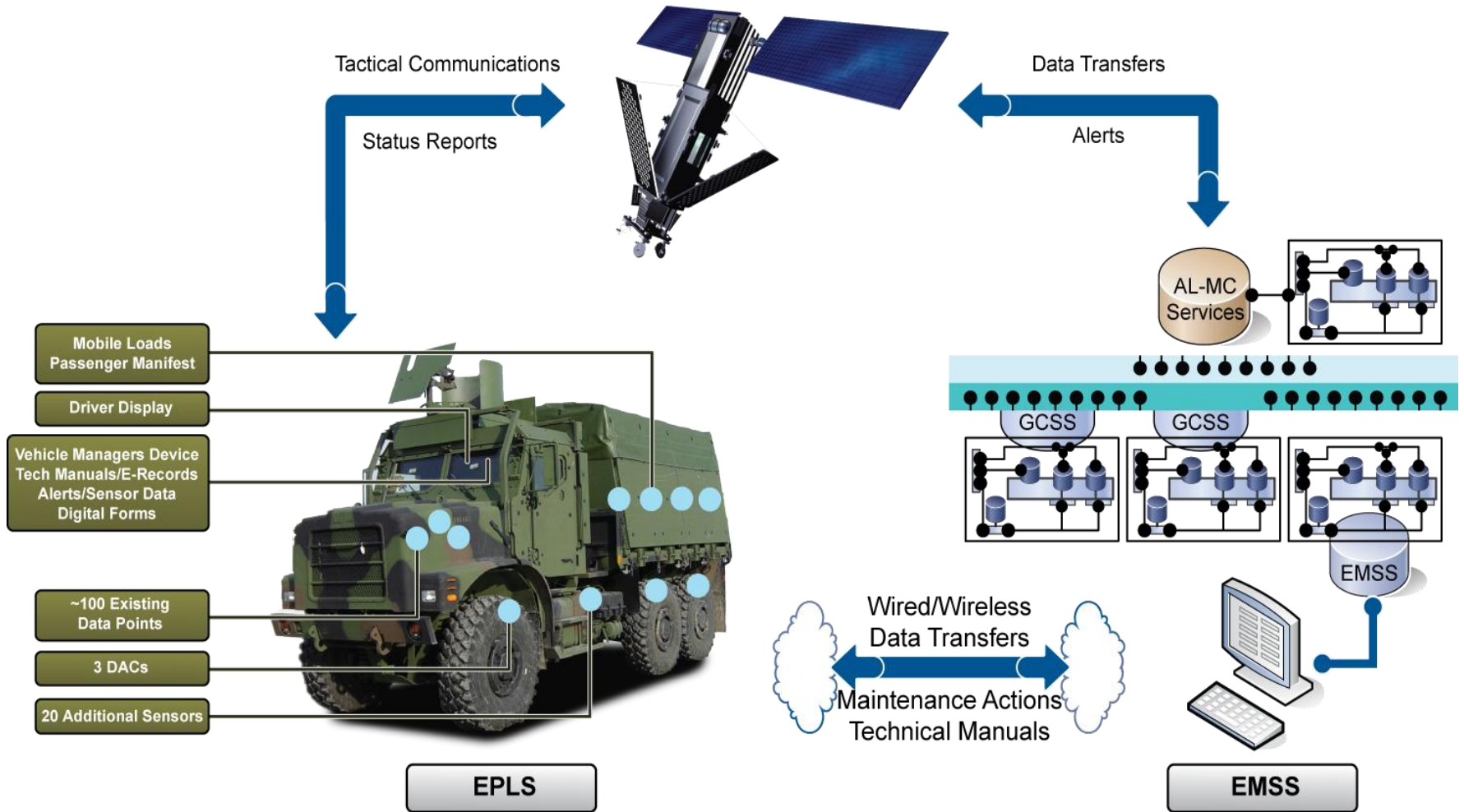


# ***PM-TV CBM Activities***

- ❑ 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***



- 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, MTRV, AAV, w/LVSR (Planned)

**AL supports achievement of Marine Corps Logistics Modernization goals and objectives**





Data Acquisition/STE-ICE controllers



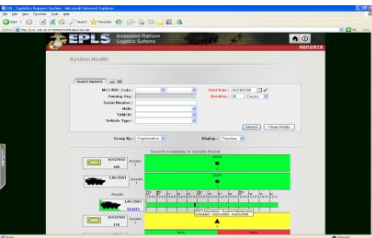
Power Supply



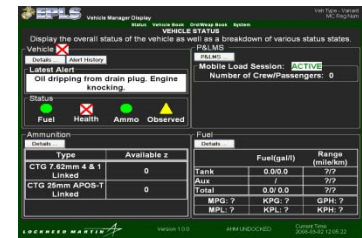
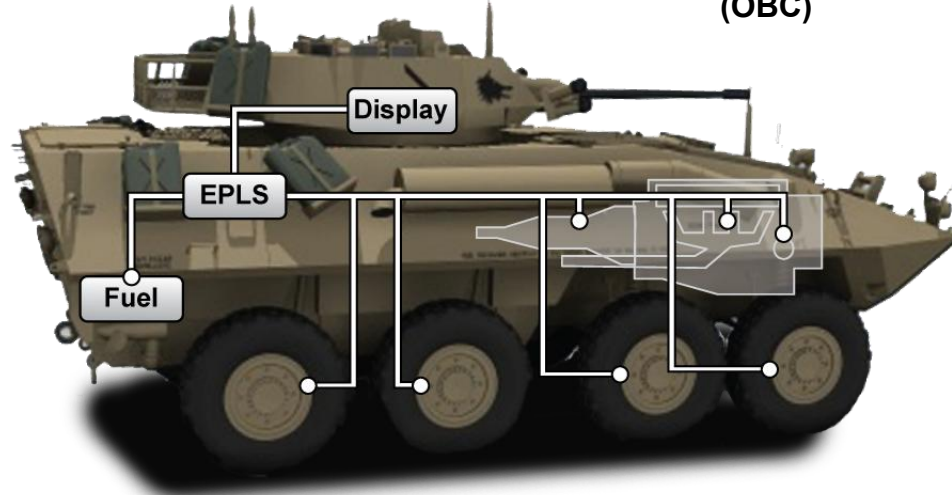
Onboard Computer (OBC)



Driver Position Display (DPD)



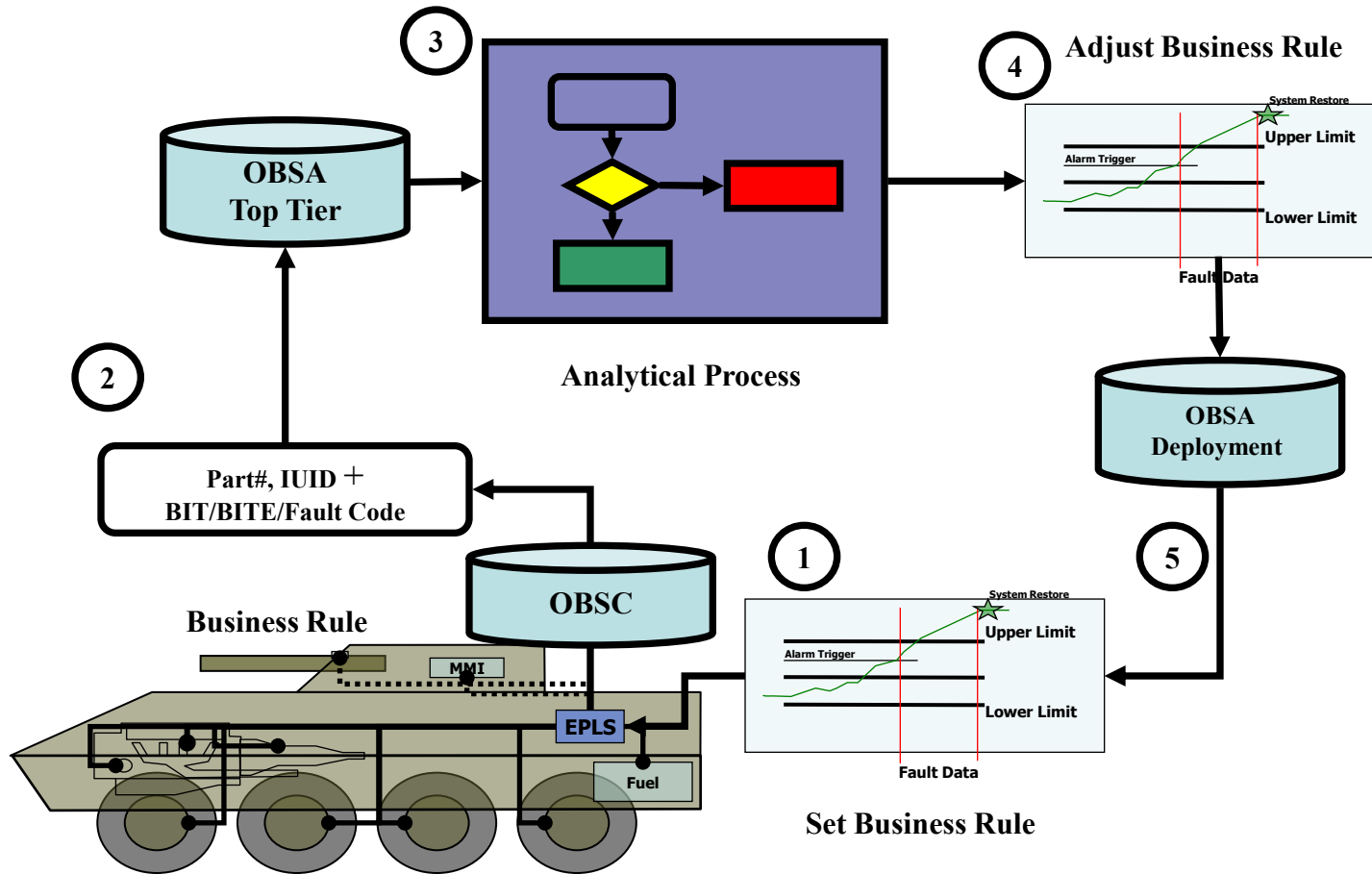
Off-Board Service Application - Fleet Status Viewer



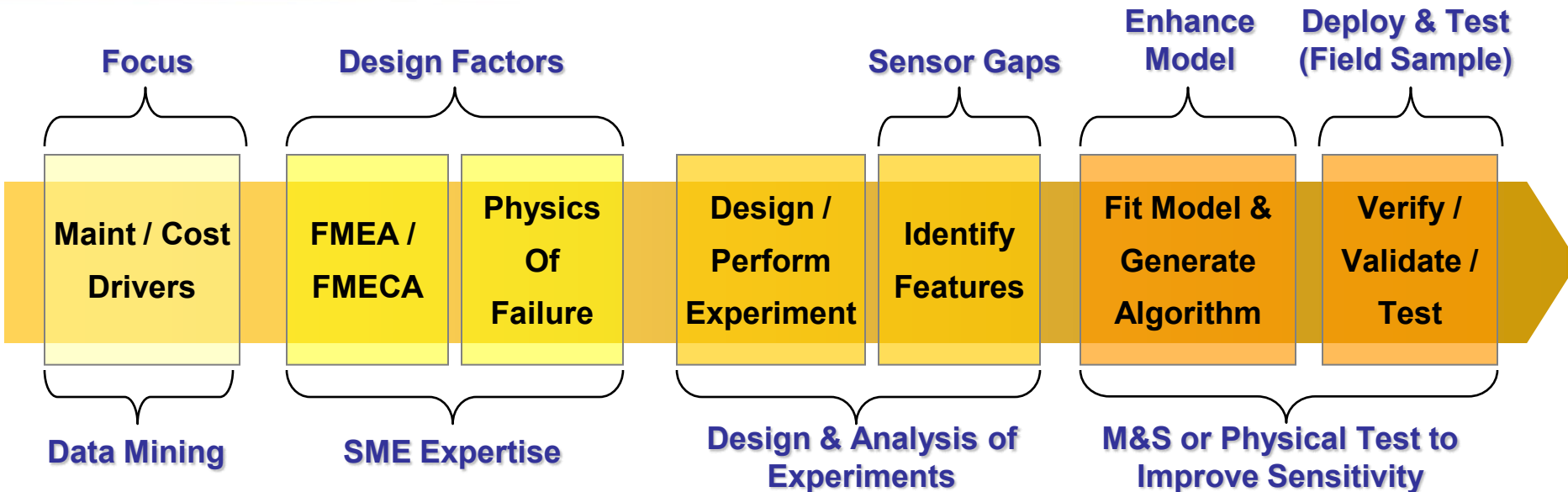
On-Board Software Client



Sensors, Cabling, Digital Data Buss



# ***TARDEC S&T Initiatives***



**Analysis :**

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

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**2009/2010 Targets:**

- Powertrain
- Track
- Electrical System

**Analysis :**

- Identify failure modes
- Derive design factors and sensor strategy

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**FMEAs Developed :**

- Diesel Engine
- Transmission
- Alternators

**Analysis :**

- Identify data features / fault signature
- Data fusion techniques

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**Analytical Tools :**

- DOE Tools
- Data Analysis Tools

**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

**Increasing knowledge and capability through proper experimental design and analysis!**



**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

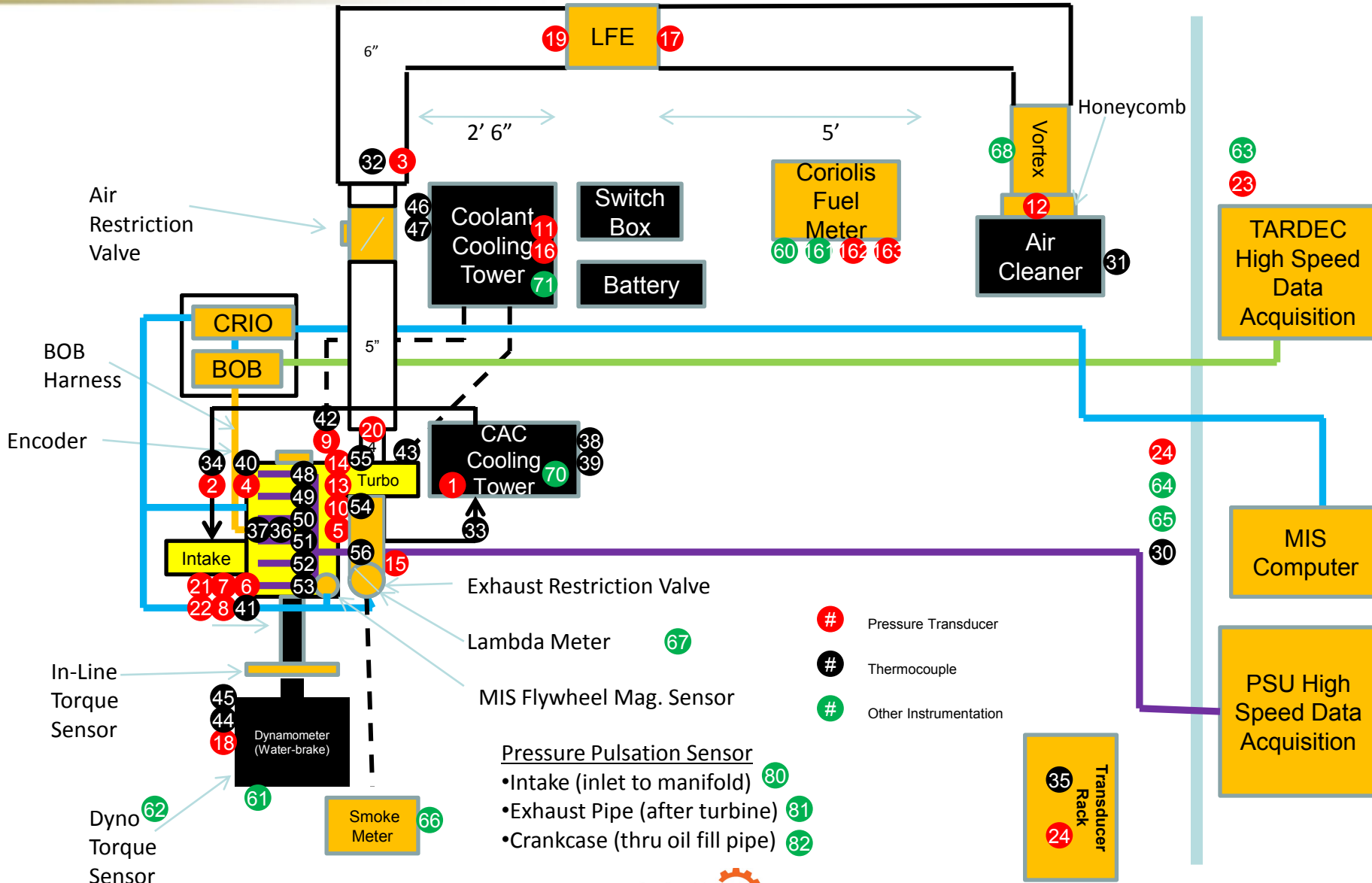
**Payoffs:**

- 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

Schedule	FY09	FY10	FY11
CAT C7 Engine	[Green bar spanning FY09, FY10, and FY11]		
Allison 2500 Transmission		[Green bar spanning FY10 and FY11]	
Prestolite 130A Alternator		[Green bar spanning FY10 and FY11]	
Li-ion and PbA Batteries	[Green bar spanning FY09 and FY10]		



# Diesel Engine Dynamometer Cell Layout





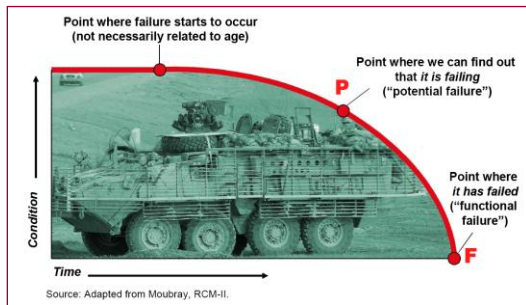
# ***ARL Ground Vehicle CBM S&T Initiatives***

## 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

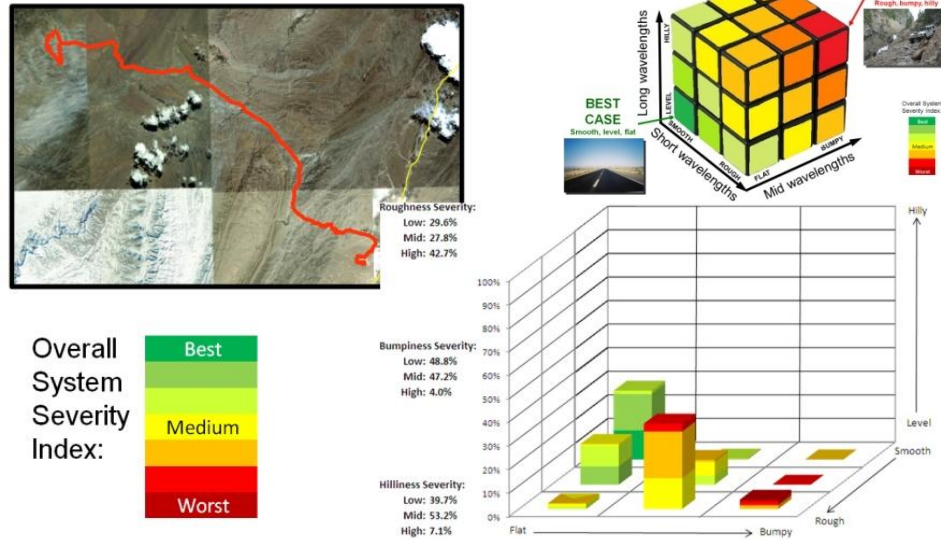
## Collaborations:

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

Milestones (FY)	09	10	11	12	13	14	15
Sensor Study		■					
Physics of Failures		■	■	■	■		
ID Performance Degraders			■				
Analytical Method/Algorithm for RUL		■	■	■			
Validation & Tech Integration for CBM					■	■	

# ***AMSAA - Sample Data Collection***

## Sample Run in Afghanistan



## 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.

## 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.

## 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.