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APPLICATION OF DATA MINING AND ANALYSIS TO ASSESS MILITARY GROUND VEHICLE COMPONENTS

Richard J. Ortland **Lee A. Bissonnette** **Douglas R. Miller**

Camber Corporation
Warren, MI

ABSTRACT

Camber Corporation, under contract with the TACOM Life Cycle Management Command Integrated Logistics Support Center, has developed an innovative process of data mining and analysis to extract information from Army logistics databases, identify top cost and demand drivers, understand trends, and isolate environmental issues.

These analysis techniques were initially used to assess TACOM-managed equipment in extended operations in Southwest Asia (SWA). In 2009, at the request of TACOM and the Tank Automotive Research, Development and Engineering Center (TARDEC), these data mining processes were applied to four tactical vehicle platforms in support of Condition Based Maintenance (CBM) initiatives.

This paper describes an enhanced data mining and analysis methodology used to identify and rank components as candidates for CBM sensors, assess total cost of repair/replacement and determine potential return on investment in applying CBM technology.

Also discussed in this paper is the validation phase for investigating components of high interest in terms of cost, demand, and criticality. This involved field reports, physical analysis, root cause identification, and Failure Modes and Effects Analysis (FMEA) leading to recommendations for corrective actions, revised maintenance procedures, and the development of CBM scenarios.

INTRODUCTION

"Innovate, Adapt, Overcome" – A Daunting Task Made Manageable

There is certainly no shortage of military data. Massive quantities of information are available in logistics, financial, and maintenance databases. For the purpose of assessing components on Army vehicles, the challenge we faced was to select the "relevant" data sources and then to query, analyze, and transform that raw data into "actionable business intelligence."

Described in this paper is an innovative approach to data mining and analysis, and the associated validation and engineering phases that led to specific recommendations for product improvement and application of CBM technology.

4D Background

Under contract with the Tank-automotive and Armaments Command (hereafter known as TACOM) Integrated Logistics Support Center, Camber Corporation had studied the effects of extended operations in Southwest Asia on TACOM-managed systems and equipment. This project, known as "Delayed Desert Damage and Degradation" (4D), focused on the effects/impacts of an extremely harsh (hot, dusty, and abrasive) environment, the increased usage levels (OPTEMPO) of many vehicles during operations in SWA, and the effects of added vehicle armor protection on vehicle structures. In order to accomplish this analysis and to isolate SWA-specific issues for investigation, the Camber 4D Team developed data mining and analysis processes utilizing existing Army component demand sources, an ability to rapidly gather data from multiple sources, display this information in a usable format, and effectively interpret it.

This approach to data mining and analysis of existing Army data repositories lent itself to development of trending and graphic display of information over extended periods of time, looking for unusually high demand rates, and distinct differences for vehicles in the SWA environment relative to Non-SWA fleets. An additional process employed in the analysis of potential 4D issues was the "normalization" of data, considering fleet size and usage levels with respect to demands. This normalization allowed us to isolate true SWA environmental issues related to component demand and, similarly, would eliminate from consideration certain high demand components that were being replaced simply due to normal usage or wear-and-tear.

Also critical to the data mining and analysis process was the use of field information sources in the investigation and validation of issues related to equipment condition and performance. It is emphasized that the initial data mining and analysis was used only to identify candidate items requiring further investigation—not as the basis for making specific determinations about equipment performance and field issues. Multiple sources of field and user feedback were utilized in the process.

The most significant of these involved data from the Army Materiel Systems Analysis Activity (AMSAA) Sample Data Collection (SDC) fleet as well as direct feedback from Sample Data Collectors in the field regarding specific components, conditions, failure modes, and associated root causes.

4D/CBM Project

In 2009 at the request of TACOM and the Tank Automotive Research, Development and Engineering Center (TARDEC), the 4D Data Mining and Analysis process was applied to an assessment of four tactical wheeled vehicle platforms (Figure 1) in support of a CBM initiative.

Figure 1: 4D/CBM Project Target Vehicles

This 4D/CBM analysis considered all potential system replacement parts for the identified vehicles, after filtering out a variety of low cost standard parts, as well as those of low interest from an engineering or maintenance standpoint and unlikely to be candidates for CBM instrumentation. At the beginning of the study, it was also decided to exclude engines and transmissions (highly likely to be sensor enabled) and to focus instead on components below that level.

In addition to identifying high cost and demand drivers, as in the original 4D program, the 4D/CBM project placed particular emphasis on "maintenance criticality." For this purpose, a Maintenance Figure of Merit (MFOM) was developed and applied.

Then verifying individual component failures through a Failure Modes and Effects Analysis based on actual field observations and AMSAA maintainer input, the identified and ranked components became the basis for development of CBM sensor scenarios, system roll-up analysis of CBM opportunities and their economic viability.

The following is a detailed discussion of the approach used in the analysis of four military tactical vehicle platforms to provide potential CBM solutions as well as other recommendations to reduce environmental damage.

4D/CBM PROCESS OVERVIEW

The overall 4D/CBM process is illustrated in Figure 2. This consists of a series of data mining, analysis, and review steps that identify best candidate parts for further study based on high cost, high demand, and maintenance criticality.

This is followed by validation and engineering phases to understand and document actual failure modes, analyze root causes, and propose solutions leading to the project deliverables. The specific steps shown in this chart will be described in greater detail throughout this paper.

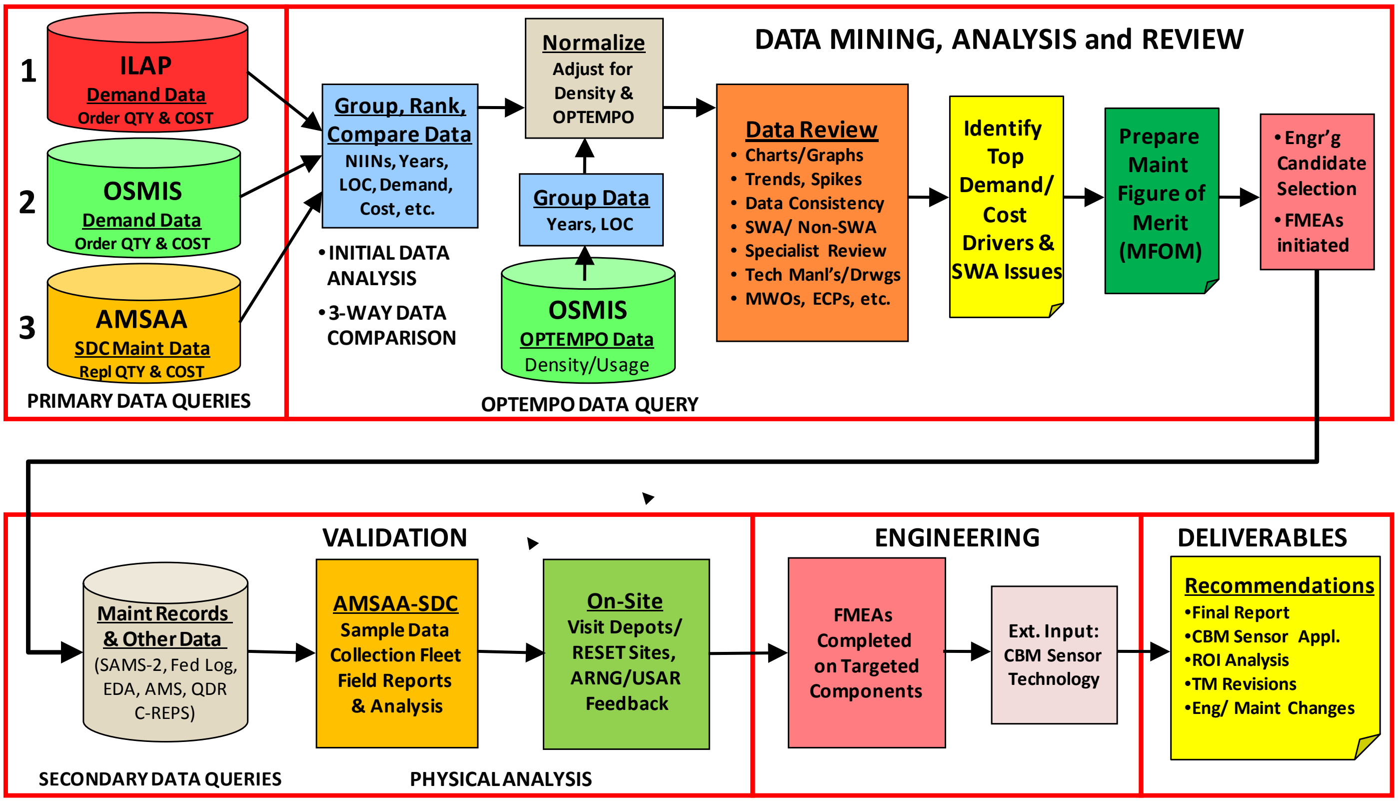


Figure 2: 4D/CBM Data Analysis, Validation, Engineering, and Reporting Process

SOURCES OF DATA

Three primary sources of data were used for 4D/CBM data mining and analysis as described below.

ILAP (Integrated Logistics Analysis Program)

ILAP is an Army-wide database that integrates logistics and financial information, providing detailed demand and cost history by component and allowing a wide range of search criteria. ILAP is a Logistics Information Warehouse (LIW) application available online with menu-driven options as well as a dynamic query capability. Although suitable for inquiries regarding specific components, this online interface did not prove adequate for 4D purposes. What was needed was the ability to query for *all* replacement parts on a given vehicle or system, providing a historical record from fiscal year 2002 to present, and being able to separate demands by SWA and Non-SWA. To achieve this, Camber Corporation subcontracted with CALIBRE Corporation, which manages a variety of Logistics Support Activity (LOGSA) databases. Together with CALIBRE, we developed a query process that joins several databases to obtain the required information.

A complete part demand history since 2002 for a vehicle or family of vehicles represents a massive quantity of data. For example, even with a $50 unit price filter, the resulting file for the HEMTT or M915 Series can well exceed one million records. This represents detail down to each individual document request. Normally, we aggregate certain fields in this raw data to obtain more workable file sizes for analysis (< 500,000 rows).

Note that ILAP data reports *all* demands for a given part. Therefore, if our interest is only in a specific vehicle or model, we need to take into account multi-use parts that will be reported in total, since the original orders for parts do not identify target vehicles.

OSMIS (Operating and Support Management Information System)

The OSMIS database is principally used by the Army for budgeting purposes, allocating funds based on mathematical computation of costs associated with each fleet in service. As a budgetary tool, OSMIS is compiled for specific fiscal years versus ILAP, which provides a more immediate record of current demands as well as tracking part history.

OSMIS provides demand and cost information for total vehicles as well as for individual components. In addition, OSMIS provides data on average annual fleet density, average annual mileage, and OPTEMPO (average annual miles/vehicle); and from this calculates a variety of additional metrics such as average cost per system and average cost per mile.

For 4D/CBM purposes, the demand and cost history data of OSMIS is used and compared with ILAP. In addition, OSMIS tracks all the replacement parts for a given vehicle based on the Provisioning Master Record (PMR). This is used as an initial step in our ILAP query process. Finally, the OSMIS information regarding fleet density, mileage, and OPTEMPO is used to normalize demand information, allowing more meaningful comparison between SWA and Non-SWA.

Unlike ILAP, the demand/cost information reported by OSMIS is vehicle and model-specific. This is done by means of a statistical estimate. For part orders placed from a given unit, OSMIS accounts for all vehicles in that unit that could use the ordered parts. The total orders are then proportioned among those vehicles, providing an estimate of usage by vehicle. As such, OSMIS quantities are decimal numbers.

AMSAA (Army Materiel Systems Analysis Agency)

The AMSAA data used for 4D/CBM is unique from ILAP and OSMIS in that it provides information regarding actual part "replacements" versus part "demands." This data is based on records of maintenance events observed within AMSAA's Sample Data Collection fleet. Within this database, part replacements are traceable back to specific models of vehicles and even to individual serial numbers.

As such, this affords an excellent source of comparative information for use with ILAP and OSMIS demand data.

In the case of the four vehicles of interest for 4D/CBM (HETS M1070/P1, HEMTT M984A1/P1 and M915A3/P1, and FMTV M1083A1/P1), the size of AMSAA's SDC fleet represented less than 8 percent of the total worldwide fleet. However, the precision of AMSAA records relating to actual part replacements makes it a very valuable confirmation source when used together with worldwide demand data.

DATA MINING AND ANALYSIS PROCESS

Initial Data Analysis

Steps in the initial phase of data analysis are as follows:

1. Pivot table analysis applied to raw data sets provides functional groupings of demand and cost data according to part National Item Identification Number (NIIN), Nomenclature, Fiscal Years (2002 to present), and Location (SWA/Non-SWA).
2. For demand data, a $50 unit price filter is normally applied. This effectively eliminates many of the small, high demand parts such as fasteners, fittings, fuses, filters, and similar items that would be of little value in our analysis. However, for cost data it is desirable to include all parts regardless of unit price. In some cases, certain high-volume, low-price parts such as seals or bearings were found to represent significant total cost and therefore may be worth further investigation.
3. An "Exclusion List" is also used to eliminate certain categories of parts from consideration. This is an extensive listing (by nomenclature) of common parts and accessories such as seats, body panels, camouflage nets, armor, gun mounts, antennas, tools, cables, wiring, bulk items, etc., that have minimal engineering interest for 4D/CBM purposes. Application of the Exclusion List at this point typically reduces the NIIN count for a vehicle by 40 – 60 percent.
4. A basic SWA/Non-SWA factor can now be calculated for demands and cost. Later this will be adjusted for vehicle density and usage. However, at this stage it gives some preliminary indication of potential SWA issues.
5. The initial data analysis phase includes summary reports showing ranked parts list Cost and Demand histories. A sample of this 4D data summary format is shown in Figure 3.

QTY Summary - OSMIS Data - HEMTT-M984A1/M984A1P1

Shown in order of decreasing TOTAL QTY

Filters: 1) Unit Price >=$50 2) Exclusion List

Sum of WHOLESALE QTY; LOC; FY

						Non-SWA								SWA									
Top 50 COST Item?	QTY Rank	NIIN-Dash	NOMENCLATURE	CON REP	UNIT PRICE	2002	2003	2004	2005	2006	2007	2008	Non-SWA Total	2002	2003	2004	2005	2006	2007	2008	SWA Total	Grand Total	Basic SWA Factor
YES	1	01-446-9498	BATTERY,STORAGE	C	$127.05	3,200	1,288	454	368	492	414	351	6,567	30	3,078	2,519	1,700	736	586	363	9,013	15,580	1.37
YES	2	01-132-4983	SHOCK ABSORBER,DIRE	C	$58.72	2,165	238	412	314	172	130	46	3,477	244	830	1,063	581	202	138	96	3,154	6,631	0.91
YES	3	01-477-1660	WHEEL,PNEUMATIC TIR	C	$1,444.00		48	84	262	235	137	127	892		403	1,010	905	411	537	592	3,857	4,749	4.32
YES	4	01-425-0383	PARTS KIT,LINEAR AC	C	$322.29	502	218	118	420	478	43	93	1,874	22	162	240	231	94	15	0	764	2,638	0.41
YES	5	01-287-2165	BRAKE SHOE	C	$434.00	405	190	148	136	104	91	44	1,118	18	424	378	261	79	87	36	1,284	2,402	1.15
YES	6	01-230-3922	CYLINDER ASSEMBLY,A	C	$792.00	271	125	106	133	107	83	31	855	10	234	234	329	134	101	27	1,068	1,924	1.25
	7	01-210-0374	PARTS KIT,AIRBOX DR	C	$89.08	338	91	87	125	169	87	176	1,074	19	121	283	137	31	61	33	683	1,757	0.64
YES	8	01-269-8882	CYLINDER ASSEMBLY,A	C	$1,093.00	307	139	85	93	83	49	31	787	7	271	242	212	86	57	30	905	1,693	1.15
YES	9	01-485-1472	BATTERY,STORAGE	C	$326.62					255	370	270	895					219	266	209	693	1,588	0.77
	10	00-100-0689	CONE AND ROLLERSXTA	C	$72.55	254	108	143	89	63	40	44	740	24	294	240	132	82	51	16	838	1,579	1.13
	11	01-232-2828	VALVE,CHECK	C	$100.22	271	130	138	152	81	147	16	935	26	197	209	132	28	14	2	607	1,542	0.65
	12	01-154-8403	CHAMBER,AIR BRAKE	C	$87.66	279	72	64	138	63	39	21	676	6	180	168	252	21	21	9	656	1,332	0.97
	13	01-236-2179	SEAL,PLAIN	C	$76.77	277	37	96	89	90	141	98	827	2	35	185	114	33	51	48	468	1,295	0.57
YES	14	01-257-3879	ENGINE AND CONTAINE	R	$46,685.00	198	106	72	95	56	53	42	622	14	181	122	126	59	52	29	583	1,205	0.94
YES	15	01-139-3722	STARTER,ENGINE,ELEC	C	$539.00	181	89	66	78	70	53	45	582	13	172	131	136	38	49	38	578	1,160	0.99
YES	16	01-231-2973	CYLINDER ASSEMBLY,A	C	$1,351.00	157	69	59	69	45	44	16	459	6	112	211	158	77	51	13	629	1,088	1.37
	17	01-160-8216	RING SET,PISTON	C	$66.32	316	214	137	85	24	7	7	790	9	81	132	43	1	4	0	269	1,059	0.34
	18	01-231-6654	VALVE,CHECK	C	$212.33	196	73	80	111	66	60	18	604	12	116	121	137	32	25	4	447	1,051	0.74
YES	19	01-474-5564	WHEEL,PNEUMATIC TIR	C	$396.59	208	59	56	74	33	13	2	446	5	174	324	51	9	16	2	581	1,027	1.30
	20	01-349-2058	BEADLOCK,PNEUMATIC	C	$134.98	126	55	46	47	40	16	8	340	4	245	225	136	41	24	7	682	1,022	2.00
YES	21	01-131-4931	GENERATOR,ENGINE AC	C	$498.00	188	81	67	49	84	42	12	522	11	156	131	82	39	45	17	481	1,003	0.92

Figure 3: Initial Data Analysis – Summary Format Sample

Three-Way Data Comparison

Having generated ranked lists of total costs and quantity from each primary source of data (ILAP, OSMIS, and AMSAA), the results can now be compared to provide confirmation of top Cost/Quantity drivers. One method of doing this is to compare the Top-100 lists for both Cost and Quantity from each of the three data sources, noting all common items. Applying this methodology to the M984A1/P1 HEMTT Wrecker (Figure 4) shows 46 items common among all Top-100 Cost lists and 36 items common among all Top-100 Quantity lists. A final comparison of these two short lists indicates 16 HEMTT parts appearing in all Top-100 lists for both Cost and Quantity. Clearly, this select group, confirmed by six separate Top-100 lists, would be considered strong candidates for further investigation.

3-Way Data Comparison

HEMTT M984A1/P1

ILAP COST | OSMIS COST | AMSAA COST | ILAP QTY | OSMIS QTY | AMSAA QTY

Items shown are in the Top-100 Lists of OSMIS, AMSAA & ILAP for COST or QTY.

NOTE: (16) Items are common to all Top-100 Lists for Both COST and QTY.

Top COST List (46)

	NIIN	NOMENCLATURE	COST FY2002-08
1	01-257-3879	ENGINE AND CONTAINE	$31,297,700
2	01-257-3880	TRANSMISSION AND CO	$5,046,610
3	01-477-1660	WHEEL,PNEUMATIC TIR	$4,841,012
4	01-446-9498	BATTERY,STORAGE	$1,979,436
5	01-269-8882	CYLINDER ASSEMBLY,A	$1,678,955
6	01-230-3922	CYLINDER ASSEMBLY,A	$1,380,678
7	01-211-6628	AXLE ASSEMBLY,AUTOM	$1,362,760
8	01-188-5129	RECEIVER-TRANSMITTE	$1,327,236
9	01-231-2973	CYLINDER ASSEMBLY,A	$1,177,942
10	01-132-0978	RADIATOR,ENGINE COO	$1,040,417
11	01-207-9239	CYLINDER ASSEMBLY,A	$1,035,140
12	01-193-1745	CAB ASSEMBLY	$1,033,748
13	01-287-2165	BRAKE SHOE	$945,602
14	01-207-9290	VALVE,LINEAR,DIRECT	$939,027
15	01-207-6309	JUNCTION BOX ASSEMB	$894,258
16	01-207-9240	CYLINDER ASSEMBLY,A	$778,505
17	01-208-3410	SWING DRIVE ASSEMBL	$757,604
18	01-207-6376	CYLINDER ASSEMBLY,A	$741,868
19	01-207-6375	CYLINDER ASSEMBLY,A	$730,544
20	01-213-1623	HOIST ASSEMBLY,TRUC	$710,361
21	01-215-6704	WINCH,DRUM,VEHICLE	$663,746
22	01-208-4542	BEARING UNIT,ROLLER	$646,064
23	01-348-1332	TRANSFER CASE W CON	$630,976
24	01-210-0429	CLUTCH,FAN,ENGINE	$627,507
25	01-139-3722	STARTER,ENGINE,ELEC	$569,223
26	01-207-9083	TERMINAL BOX	$540,127
27	01-485-1472	BATTERY,STORAGE	$518,639
28	01-131-4931	GENERATOR,ENGINE AC	$503,212
29	01-366-0687	CONTROL,DIRECTIONAL	$452,413
30	01-132-0876	TRANSFER TRANSMISSI	$434,015
31	01-226-5297	VALVE,LINEAR,DIRECT	$421,357
32	01-217-8421	WIRE ROPE ASSEMBLY,	$418,986
33	01-222-4590	EVAPORATOR,AIR BRAK	$409,072
34	01-157-3652	TANK,FUEL,ENGINE	$373,635
35	01-213-1725	CYLINDER ASSEMBLY,A	$363,240
36	01-241-9152	MANIFOLD,HYDRAULIC	$330,704
37	01-207-9287	VALVE,LINEAR,DIRECT	$313,765
38	01-170-0748	STEERING GEAR	$306,319
39	01-132-1417	ENGINE,DIESEL	$296,577
40	01-207-9026	CYLINDER ASSEMBLY,A	$257,778
41	01-136-7670	WINCH,DRUM,VEHICLE	$255,138
42	01-152-7890	AIR CLEANER,INTAKE	$254,567
43	01-201-3674	AXLE ASSEMBLY,AUTOM	$252,216
44	01-167-4280	TURBOCHARGER ASSEMB	$244,224
45	01-287-2167	BRAKE SHOE	$191,791
46	01-147-9996	COMPRESSOR ASSEMBLY	$191,271

Top QTY List (36)

	NIIN	NOMENCLATURE	QTY FY2002-08
1	01-446-9498	BATTERY,STORAGE	15,580
2	01-132-4983	SHOCK ABSORBER,DIRE	6,631
3	00-741-7585	BOARD GROUND JACK	5,445
4	01-165-0567	INNER TUBE,PNEUMATI	5,322
5	01-477-1660	WHEEL,PNEUMATIC TIR	4,749
6	01-217-0899	ROPE,WIRE	3,044
7	01-087-7216	CARTRIDGE,DEHYDRATO	3,012
8	01-287-2165	BRAKE SHOE	2,402
9	01-230-3922	CYLINDER ASSEMBLY,A	1,924
10	01-223-3572	SWITCH,PROXIMITY	1,839
11	01-269-8882	CYLINDER ASSEMBLY,A	1,693
12	01-485-1472	BATTERY,STORAGE	1,588
13	01-366-0687	CONTROL,DIRECTIONAL	1,399
14	01-056-1111	GASKET SET	1,392
15	01-184-1902	SHOE,JACK-SUPPORT	1,376
16	01-154-8403	CHAMBER,AIR BRAKE	1,332
17	01-236-2179	SEAL,PLAIN	1,295
18	01-257-3879	ENGINE AND CONTAINE	1,205
19	01-139-3722	STARTER,ENGINE,ELEC	1,160
20	01-231-2973	CYLINDER ASSEMBLY,A	1,088
21	01-131-4931	GENERATOR,ENGINE AC	1,003
22	01-180-6035	CABLE ASSEMBLY,POWE	1,001
23	00-175-9250	PARTS KIT,ENGINE FU	966
24	01-309-2108	MOTOR,WINDSHIELD WI	887
25	01-287-2167	BRAKE SHOE	801
26	01-210-0429	CLUTCH,FAN,ENGINE	686
27	01-222-4590	EVAPORATOR,AIR BRAK	661
28	01-132-0978	RADIATOR,ENGINE COO	660
29	01-107-4672	VALVE,RELIEF,PRESSU	654
30	01-187-9457	VALVE,CHECK	636
31	01-053-1845	GASKET SET	599
32	01-257-3880	TRANSMISSION AND CO	547
33	01-050-5584	VALVE,LINEAR,DIRECT	537
34	01-203-5358	VALVE,SOLENOID	474
35	01-153-2772	DRAG LINK,STEERING	445
36	01-158-8774	BRAKE DRUM	433

	NIIN	NOMENCLATURE	COST FY2002-08	QTY FY2002-08
1	01-257-3879	ENGINE AND CONTAINE	$31,297,700	1,205
2	01-257-3880	TRANSMISSION AND CO	$5,046,610	547
3	01-477-1660	WHEEL,PNEUMATIC TIR	$4,841,012	4,749
4	01-446-9498	BATTERY,STORAGE	$1,979,436	15,580
5	01-269-8882	CYLINDER ASSEMBLY,A	$1,678,955	1,693
6	01-230-3922	CYLINDER ASSEMBLY,A	$1,380,678	1,924
7	01-231-2973	CYLINDER ASSEMBLY,A	$1,177,942	1,088
8	01-132-0978	RADIATOR,ENGINE COO	$1,040,417	660
9	01-287-2165	BRAKE SHOE	$945,602	2,402
10	01-210-0429	CLUTCH,FAN,ENGINE	$627,507	686
11	01-139-3722	STARTER,ENGINE,ELEC	$569,223	1,160
12	01-485-1472	BATTERY,STORAGE	$518,639	1,588
13	01-131-4931	GENERATOR,ENGINE AC	$503,212	1,003
14	01-366-0687	CONTROL,DIRECTIONAL	$452,413	1,399
15	01-222-4590	EVAPORATOR,AIR BRAK	$409,072	661
16	01-287-2167	BRAKE SHOE	$191,791	801

Both Top COST and Top QTY (16)

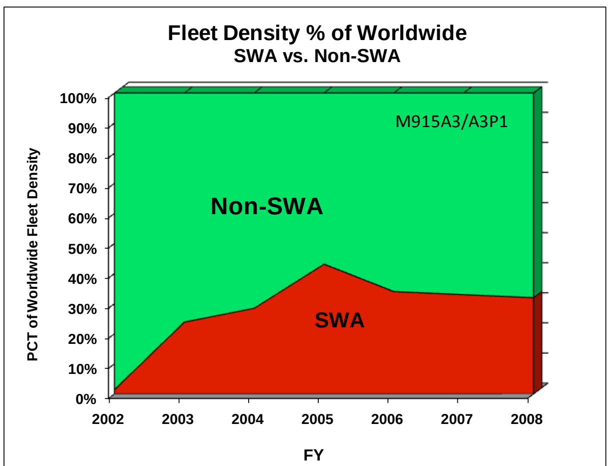
Figure 4: Example of Three-Way Data Comparison – ILAP, OSMIS, AMSAA

Fleet Data

OSMIS also provides fleet data consisting of Average Annual Fleet Density, Average Annual Fleet Mileage, and OPTEMPO (Average Annual Miles per Vehicle). Examples of fleet data for the M915A3 are shown in Figure 5 and Figure 6 comparing SWA and Non-SWA OPTEMPO and fleet worldwide densities.

In 4D data analysis, the OSMIS fleet data has particular value for adjusting or "normalizing" demand data to account for differences in fleet size, density, and usage, thereby making it possible to isolate true SWA environmental issues. In addition to knowing total parts ordered in SWA versus Non-SWA, we now can compare normalized results including: "Parts per Vehicle," "Parts per Mile," and "Parts per OPTEMPO."

Figure 5: Sample Fleet Data–OPTEMPO–SWA/Non-SWA



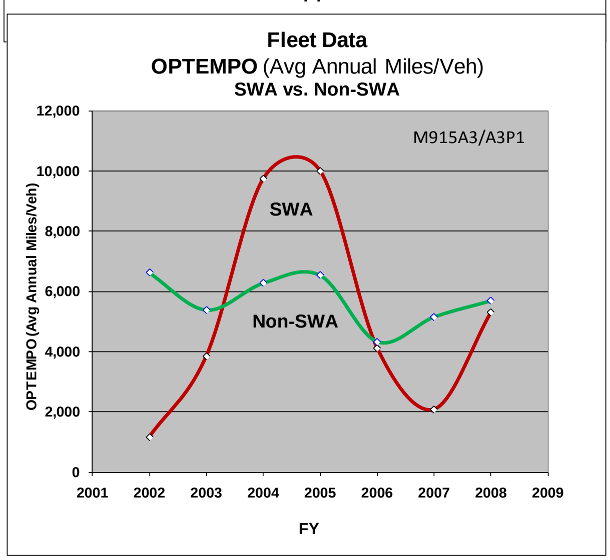


Figure 6: Sample Fleet Data–DENSITY–SWA/Non-SWA

DATA REVIEW PROCESS

Component Data – SWA/Non-SWA Comparison

The data review process makes extensive use of charts, graphs, and trend analysis. Demand history since 2002 can often be associated with certain events and explainable demands related to deployment or a phase-out of certain systems or components. In addition, graphs provide a clear visual indication of declining or worsening problems, demand spikes, or, in some cases, may suggest reasons to question data or seek further explanations. Graphic representation of data is of particular value in showing SWA and Non-SWA demand and determining unique SWA environmental issues (see Figure 7 and Figure 8). These sets of graphs illustrate the use of normalized data in comparing SWA versus Non-SWA demands.

Both examples (Figure 7 and Figure 8) involve M915A3 components found to be high-cost and high-demand items. Figure 7 illustrates SWA and Non-SWA demand for the steering gear. In comparing total part orders (upper left graph), SWA shows a steadily increasing demand, significantly greater than Non-SWA beyond FY 2005. After adjusting for fleet density, fleet mileage, and OPTEMPO ("Parts per Vehicle," "Parts per Mile," and "Parts per Mile/Vehicle"), we still see what appears to be a SWA problem. This was confirmed by follow-up investigation related to steering gear seal failures. (See steering gear case study example included in the Appendix).

By comparison, Figure 8 shows the fan clutch, which, on the basis of total part orders or parts per vehicle, might also appear to be a SWA problem. However, note that "Parts per Mile" shows similar curve shapes for SWA and Non-SWA rather than runaway SWA demand, and "Parts per OPTEMPO" indicates no clear SWA issue. As such, we would not consider the fan clutch to be a particularly severe SWA issue. After further investigation, there were found to be multiple failure modes associated with the fan clutch, some of which (e.g., over-tightening the drive belt) are unrelated to the vehicle environment.

In the above examples note, in particular, the value of cross-checking all four metrics ("Total Parts Ordered," "Parts per Vehicle," "Parts per Mile," and "Parts per OPTEMPO") in determining a SWA demand issue.

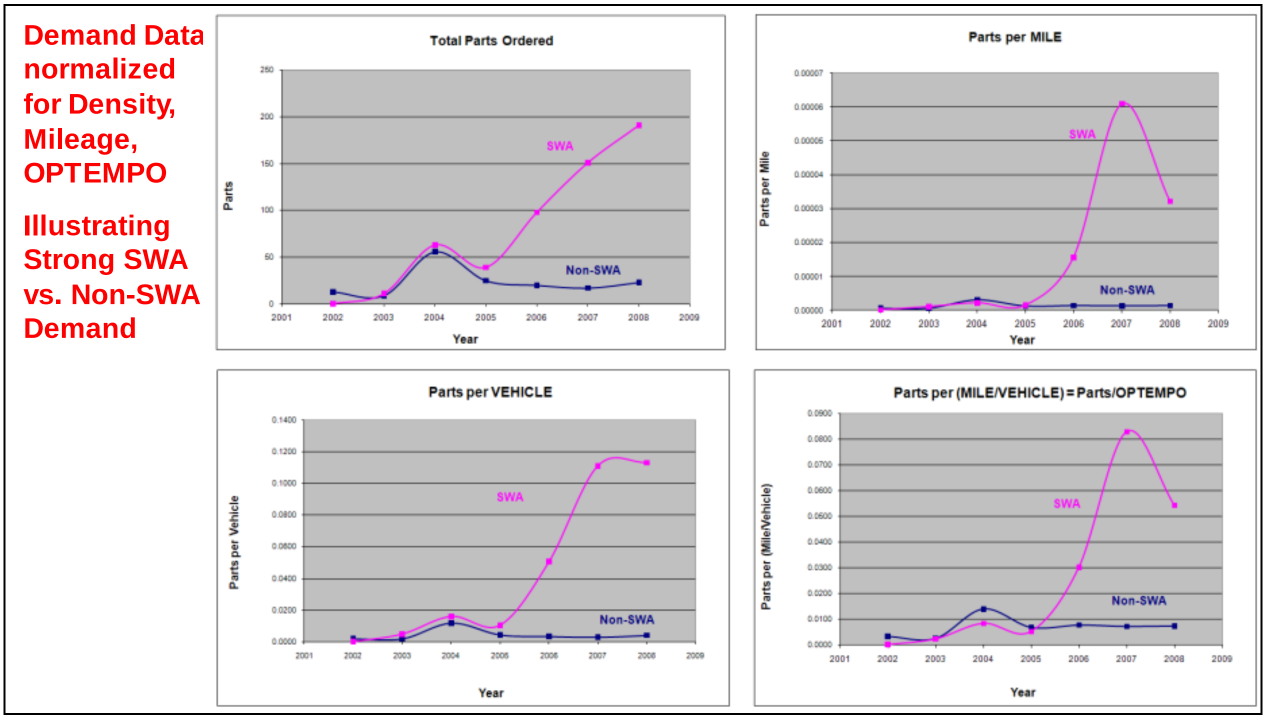


Figure 7: 4D Data Analysis Example – Steering Gear Demand History

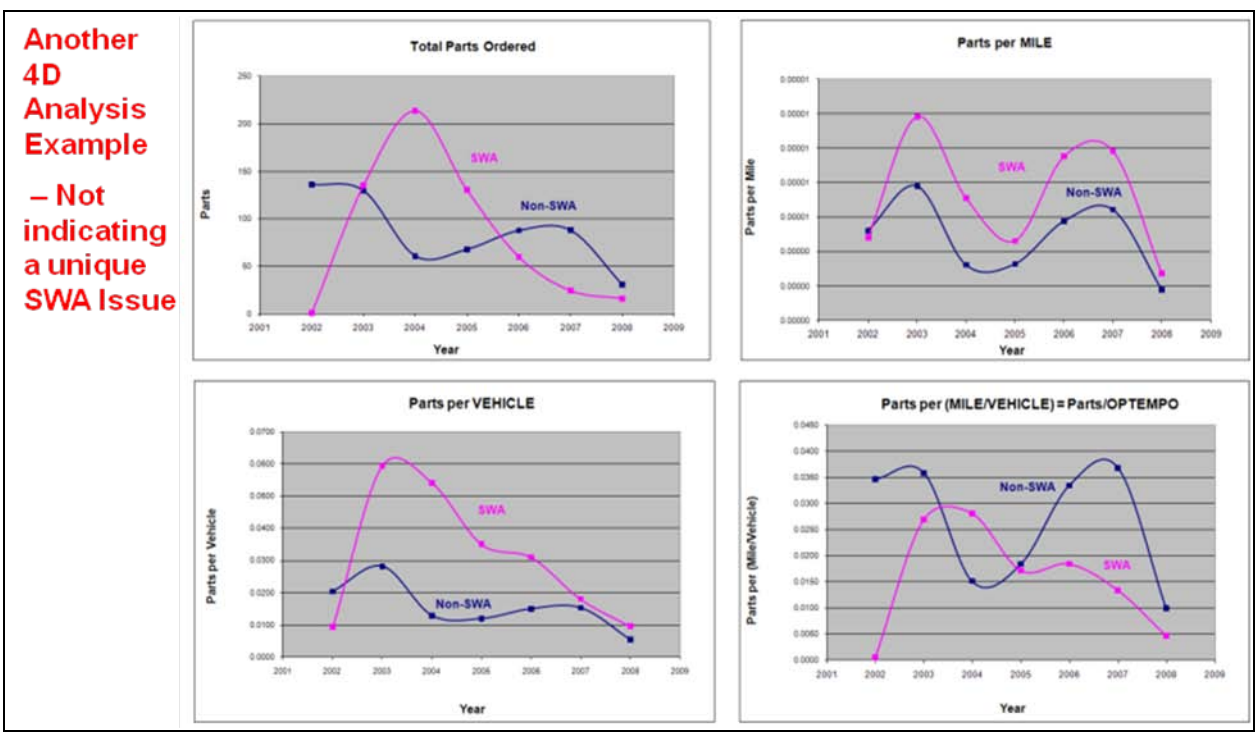


Figure 8: 4D Data Analysis Example – Fan Clutch Demand History

Specialist Review

At this point in the process, additional information is applied in selecting candidate parts for further investigation. This involves a specialist review of Technical Manuals (TM), *PS Magazine* articles, drawings, Technical Bulletins (TB), Maintenance Work Orders (MWO), Engineering Change Proposals (ECP), and other related technical information.

Compilation of this material in relation to the ILAP, OSMIS, and AMSAA data analysis results validates the targeted vehicle components as items of interest for further review. It is the foundation for the final selection of parts that will have the greatest effect on vehicle performance.

Data Focus

The primary data sources (ILAP, OSMIS, and AMSAA) provide both demand and cost ranking information, and our data comparisons further highlight those items representing both highest cost as well as highest demand. As an alternative, we could focus on those components judged "most critical."

Criticality can be defined in various ways. For example, top priority could be given to safety-related items, or those parts considered most essential for mission capability, or some other metric such as a "Risk Priority Number" based on assessments of severity of failure, failure probability, and ability to be detected. As illustrated in the Venn diagram below (Figure 9), the maximum impact of 4D investigations could be considered the intersections of "Most Critical," "Highest Demand," and "Highest Cost" parts.

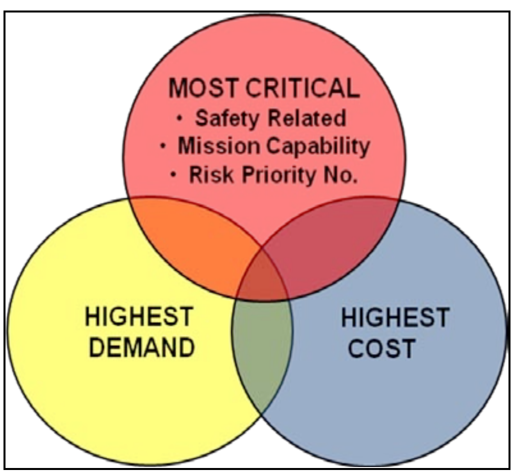


Figure 9: Focus Areas – Demand, Cost, and Criticality

MAINTENANCE FIGURE OF MERIT (MFOM)

An analytical tool developed specifically for the 4D/CBM study involved a "Maintenance Figure of Merit." This provides special consideration to "Maintenance Criticality" in selecting best candidates for application of CBM technology.

The ranking system employed for the Maintenance Figure of Merit is shown in Figure 10. As a figure of "merit" or as a "goodness" rating, note that a low value represents a bad condition. The MFOM rating is calculated as the product of the following three factors:

1. Mission Capability expressed as a subjective numerical score of the importance of an item to the accomplishment of a vehicle's mission. Note, in this case, safety-related components were given highest priority over others that could potentially reduce mission capability.
2. The probability of failure on any given mission.
3. The ability of the crew and maintainer to detect the occurrence of the fault in advance in order to correct it before beginning the mission.

In addition to the MFOM rating, we also considered the total cost of maintenance, including parts as well as labor.

Labor costs were determined from the Maintenance Allocation Chart (MAC) specified for the component and its next major assembly. We assigned labor costs for the maintenance man-hours earmarked for each repair at each level of maintenance and multiplied the resulting costs for those hours by the demands for the components, with additional factors added for tools, facilities, and inventory storage.

MFOM ratings and Cost information may be combined (as shown in Figure 11) plotting the MFOM rating on the Y-axis and total costs on the X-axis. Note that parts in the upper right (orange) quadrant represent highest cost of maintenance combined with worst impact on mission capability and safety, making them more likely candidates for cost-effective application of CBM technology. Other shaded areas on the graph are shown indicating potential for CBM candidates.

Further analysis was undertaken on each candidate part to understand actual failure modes (as described in later sections of this paper) and then assess which might benefit most from application of CBM technology.

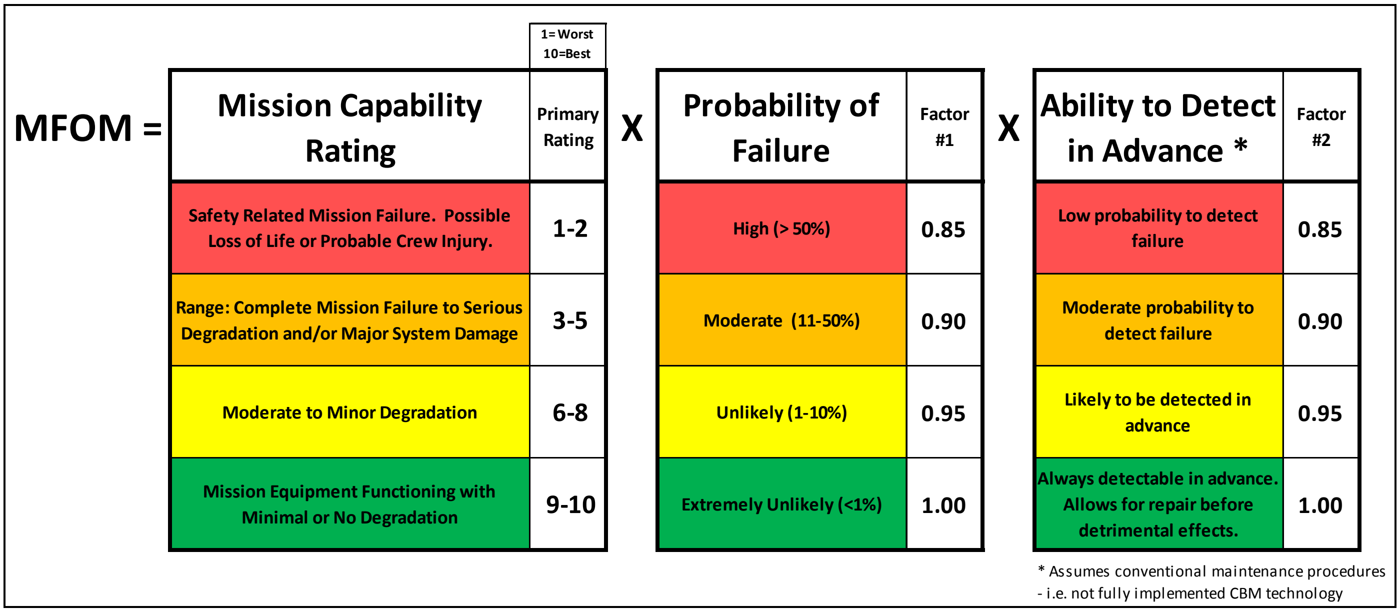


Figure 10: Maintenance Figure of Merit Rating System (MFOM)

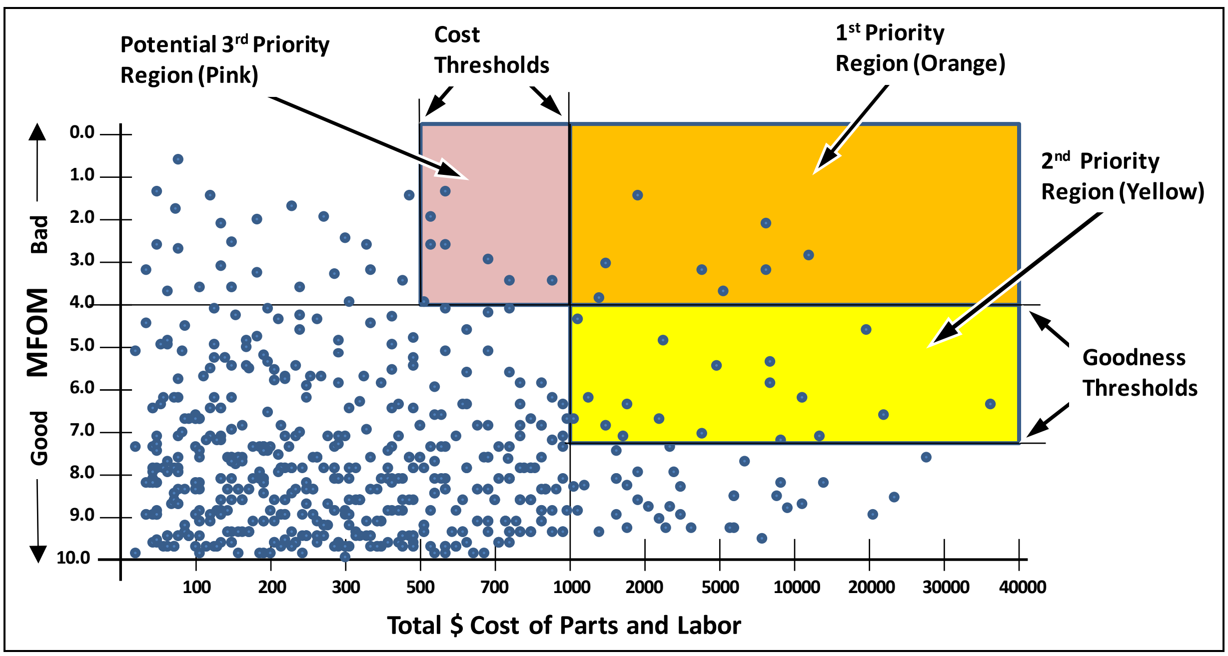


Figure 11: Maintenance Figure of Merit (MFOM)

ENGINEERING CANDIDATE SELECTION

The final selection of engineering candidates for further investigation was done based on the previously defined processes of a Specialist Review—identifying top demand and cost drivers—as well as applying the Maintenance Figure of Merit (MFOM). The resulting refined list of components, having the greatest effect on mission capability and cost, becomes the subject of further engineering evaluation, validation, and a detailed Failure Mode and Effects Analysis (FMEA).

VALIDATION AND PHYSICAL ANALYSIS

Secondary Data Sources

Once components have been selected as candidates for further study, there are several secondary data sources that can help to explain reasons for high demand. These include maintenance data (SAMS-2), procurement history (FEDLOG or Haystack), as well as the Equipment Downtime Analyzer (EDA), Quality Deficiency Report (QDR), and the Collaborative Readiness Problem Solving System C-REPS).

Note that these "secondary" sources are used only as supplemental information for parts that were already identified as candidates based on "primary" data.

Maintenance data (SAMS-2) includes vast amounts of information and would seem to be the ideal source for 4D/CBM purposes. However, attempts to query this data for specific part NIINs will yield part quantities far lower than what is indicated by demand databases (ILAP and OSMIS). As such, maintenance data cannot be used as a primary source for the history of parts used in repair and replacement. Unlike demand data, maintenance data includes a "fault" field that could be of great value in understanding reasons for high demand. Unfortunately, that field length in the database is truncated (to only 14 characters), greatly limiting the potential value of this information.

AMSAA Process

AMSAA has proven to be a valuable partner with Camber Corporation in providing actual field observations and helping to identify failure modes.

As illustrated in Figure 12, four levels of information are available from AMSAA that we have applied to 4D/CBM studies:

1. AMSAA published Quarterly Reports. These are for OIF (Operation Iraqi Freedom) for the last three years and identify high cost and high frequency replacement parts as observed on AMSAA's Sample Data Collection Fleet.
2. AMSAA Raw Data (discussed earlier as one of our primary sources of information) records actual part replacement histories for vehicles in the SDC fleet.
3. Custom data queries for selected NIINs of interest. This reports the vehicle serial number, the date of the maintenance activity, and, of particular value to us, the failure codes used as the justification for the component replacement, along with a brief narrative description.
4. The most detailed level of information from AMSAA is applied to those components selected as FMEA subjects. In these cases, questionnaires are sent to AMSAA SDC Field Representatives inquiring about specific failure modes. Often, AMSAA will also provide photographs of failed components along with additional forensic detail.

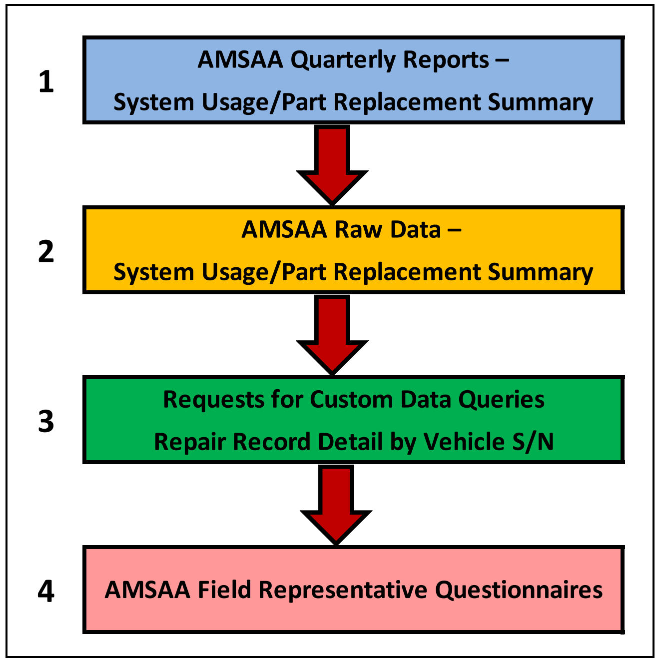


Figure 12: AMSAA Process

On-Site Reviews

Additional information to help understand component failure modes can be can obtained through on-site reviews with maintenance and repair personnel at Depots and Arsenals.

The Camber 4D Team used multiple sources of additional field information and feedback when available. Camber organizations at Army bases such as Ft. Knox, Kentucky, and Ft. Hood, Texas, with large maintenance and training activities and equipment users and maintenance personnel having experience in the SWA Theater of Operations, were accessed for information and feedback.

Team personnel also visited other Army and reserve component organizations to get vehicle and equipment-specific feedback on failure modes, and related maintenance issues. Team members visited Army Depot activities, which provided some limited access to equipment and information relative to primary equipment failures and failure modes. These strategic information-gathering efforts supported ongoing analysis.

ENGINEERING

FMEA Process

Utilizing the refined list of vehicle components, preliminary FMEAs, engineering specialist input, MFOM, and AMSAA SDC field data, the final vehicle component FMEAs can be formulated. The FMEA incorporates the initial information used to identify potential 4D issues—the analyses, investigations, assessments, and recommended actions to mitigate the condition.

The final FMEA document is submitted to a series of checks to verify potential opportunity costs, CBM sensor strategy, return on investment (ROI), and to ensure the completeness and clarity of information and graphics. Completed FMEAs specify sensor application options on various components and also lead to recommendations for technical manual revisions, *PS Magazine* articles, and "low-hanging fruit" (easily implemented changes).

CBM Input

The next action involves determination of the sensor possibilities for detecting and preventing a failure condition or alerting operators and maintainers to an impending failure. To gain insights on this process, the analyst sends a formal request to a university research laboratory subcontracted for this purpose to gain perspective on potential sensor solutions based on a series of sensor scenarios suggested by the analyst to address observed failure modes. The returned CBM analysis will be the final step necessary to complete the FMEA. Based on the data and corresponding CBM input, the analyst will make recommendations and determine a return on investment. By comparing the overall opportunity cost and the cost of the failures observed with the projected sensor cost, the feasibility of applying sensor solutions can be established.

For each sensor application, a very conservative individual sensor application cost is assumed, as it is not known at the time of application if the sensor(s) will be applied individually or in a cluster.

Sensor Strategy:

- Sensor component (number and estimated cost[s] of sensors)
- Cost of computer to control/display sensor findings
- Data acquisition cost
- Chart costs reflect individual analysis for sensor scenario
- Case-by-case analyses are often negative
- Use opportunities to consolidate multiple scenarios

Evaluation of the four tactical vehicles for potential CBM sensor technology application indicated that one vehicle platform had the highest overall sensor opportunity with another vehicle being a close second. The other two vehicle analyses did not result in viable sensor applications at this time. The primary vehicle's scenario incorporated less complex/less expensive sensing capability. This analysis was based on the current state of technology; future advances offer new opportunities. A rolled up maximum and minimum sensor technology/cost assessment was completed for all four vehicles.

Each sensor type and the associated sensor costs were applied over the SWA fleet versus the full global fleet. Each sensor has its own computer, wiring harness, and control program. This means if you applied four sensors, you would have four computers. This was done to show the application costs of one sensor to a vehicle, versus the rollup of many sensors applied to a vehicle. The result of individual sensor application would generally result in negative savings. By rolling up the sensors into one system and applying the full sensor array to each vehicle platform, we get a more complete sensor picture (i.e., one computer controller and many sensors).

DELIVERABLES

The methodology described in this paper provides TACOM, TARDEC, and Reliability Centered Maintenance (RCM) activities with a data mining and analysis process that ranks, prioritizes, and investigates potential components for CBM application. We do not consider this approach an all-inclusive "best practice" to determine optimum CBM sensor solutions, but rather a systematic analysis process, based on multiple sources of demand and maintenance data, to support business case analysis for CBM opportunities.

The Final Report summarizes the completed FMEAs performed on selected components from the four models of heavy and medium tactical truck systems with potential for maintenance improvement actions. The report describes the analysis done on each individual component considered for CBM sensor enabling and includes an economic analysis of the costs of individual sensor applications as well as a rollup of costs for multiple sensor applications on each vehicle platform. It depicts the total opportunity cost that might be available to the Army from adding sensors to key components in an effort to reduce costs, improve operational readiness, and avoid the need for large inventories of replacement parts.

Project deliverables also included a variety of non-sensor findings and recommendations for further action, including Tech Manual revisions, and maintenance proceduaral changes. These range from simple solutions (e.g., changes in maintenance frequency, shortened intervals for fluid and filter changes, simple covers, or buffers to protect hydraulic cylinder polished surfaces from marring) to non-CBM sensor applications (such as proximity sensors) with potential for implementation throughout the Army ground vehicle fleet.

CONCLUSION

The Camber Corporation Delayed Desert Damage and Degradation (4D) team's Data Mining and Analysis Process has proven to be a powerful tool for identifying problem components, highest cost and highest demand drivers, and unique SWA environmental issues that deteriorate vehicle performance and readiness.

The data analysis and review phase was followed by a systematic process of validation which leverages Army Materiel Systems Analysis Activity field data, along with other sources of information and physical analysis.

Finally, FMEA engineering evaluations were conducted to understand and document failure modes, leading to specific recommendations for corrective actions, including cost-effective application of CBM technology.

The 4D/CBM Process has clearly demonstrated its value in developing expedient, data-driven solutions that make sense for the Army.

APPENDICES – Non-Sensor Application Findings and the SWA Environment

APPENDIX A - VEHICLE COMPONENT RANKING

When the vehicles are ranked by top costs and demands, engines, transmissions, batteries, tire assemblies, and/or tracks almost always appear at the top of the list. Batteries and tires are at the top because of volume of use and wear out. Engines and transmissions are high because of high component cost.

The following list of top cost and top demand vehicle components are in random order and are not ranked, as the component list varies slightly with each vehicle. With our analysis, we included batteries and tires and then added the components from the analysis of technical manuals, *PS Magazine* articles, drawings, technical bulletins, maintenance work orders, related contractor technical information, MFOM, FMEA, ILAP, OSMIS, and AMSAA historical databases, SDC personnel, etc. Compilation of this information for the targeted vehicles generated the component items of interest.

Many vehicles share components across platforms. Failures and demands observed on one vehicle analysis have shown up on other vehicles with similar components. If tie rod joints are failing on one vehicle, similar failures may be observed on other vehicle even if the primary component suppliers/contractors are different.

Vehicle Components:

Top-4 on all lists:

1. Engines
2. Transmissions
3. Batteries
4. Pneumatic Tires

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 Rods
16. Various (Lights, etc.)

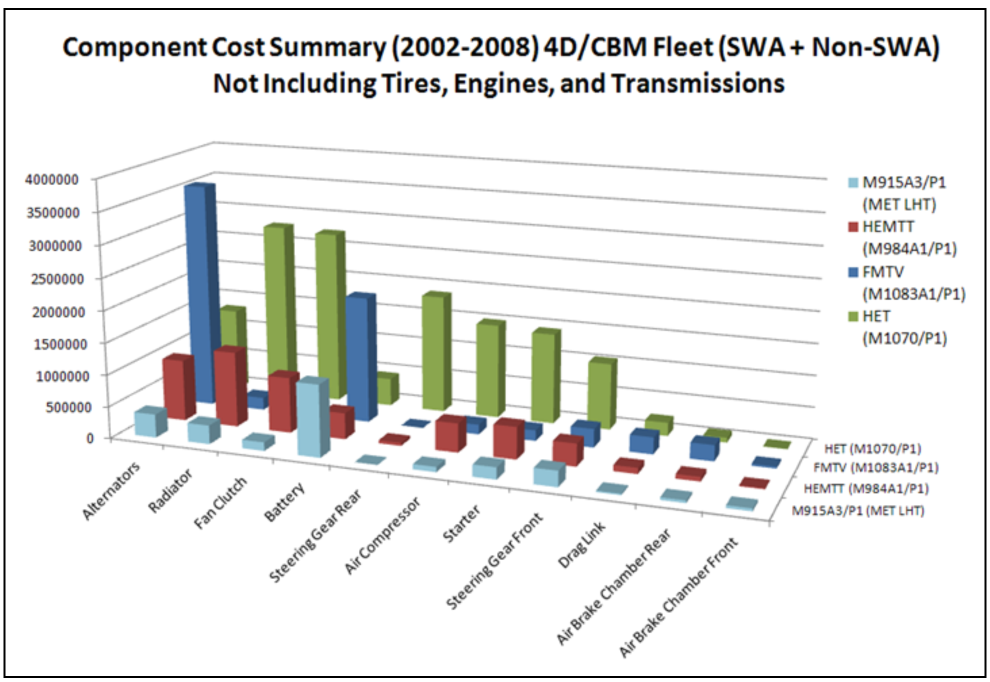
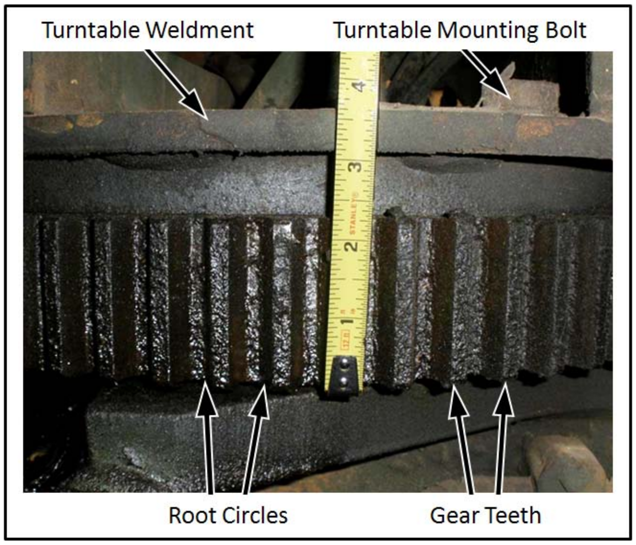
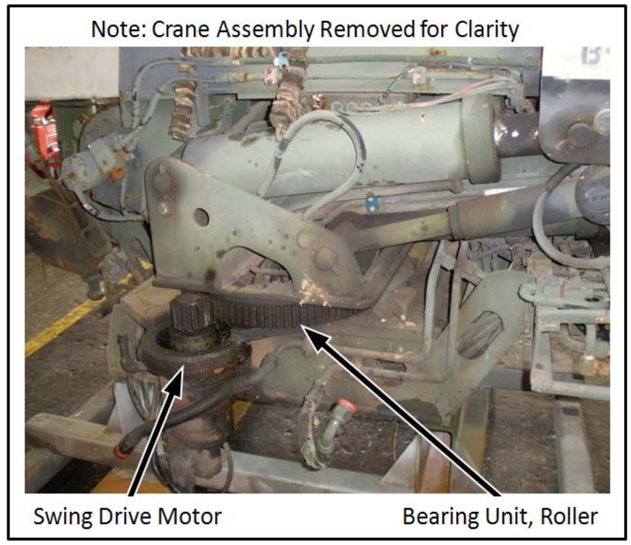


Figure 16: Vehicle Component Cost Examples

APPENDIX B - PRIMARY COMPONENT FAILURE

A primary issue that resulted from the analysis was the effect of insufficient maintenance, lubrication, and filter replacement in the SWA environment. The depot and facilities maintainers are performing maintenance on the vehicles as prescribed by the vehicle technical manuals. However, while lubrication of zerk fittings, filter, and oil changes are sufficient for the moderate environment and climates of Europe and the United States, it is proving to be insufficient for the soil environment and UV conditions found in SWA. Changes to the technical manual lubrication and increased filter replacement schedule for vehicle operation in the SWA environment could prevent or diminish a significant amount of environmental damage to the components. Technical manuals need to be changed from an annual replacement to a monthly replacement independent of mileage for this type of desert environment. This translates directly into vehicle component life expectancy and vehicle life management opportunities.





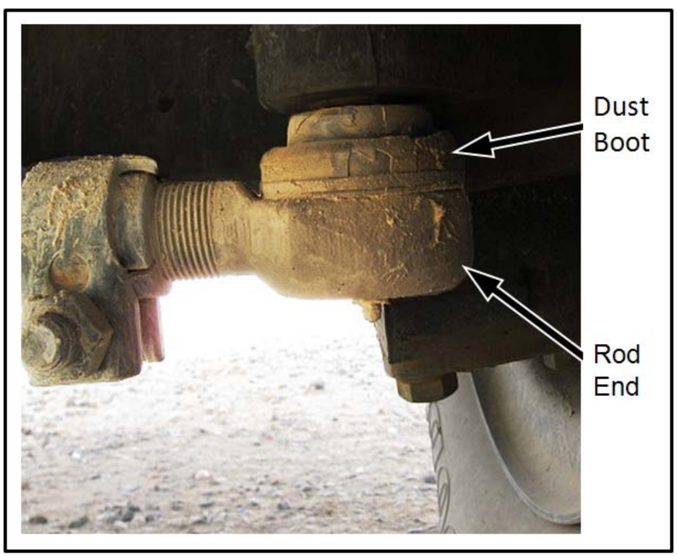


Figure 17: Three Examples of Vehicle Lubrication Components

APPENDIX C – "LOW-HANGING FRUIT" EXAMPLE

Pictured below is an example of "Low-Hanging Fruit" (easily implemented corrective actions) on a wrecker vehicle. The chains can swing free when the vehicle is out on a mission. Impact of the chains onto the cylinder rod can cause deep gouges in the rod, which in turn can slit open the cylinder lip seal resulting in a fluid leak. A simple fix could be to cut off a section of bulk radiator hose, slit it in half, and wrap it over the chains to prevent the metal-to-metal contact. When the hose deteriorates from use and from UV rays, simply replace it with another section of bulk hose. It is preferable not to plasticize the chain, as the first place the chain plastic will wear is in the contact area, where the effect would be negated.

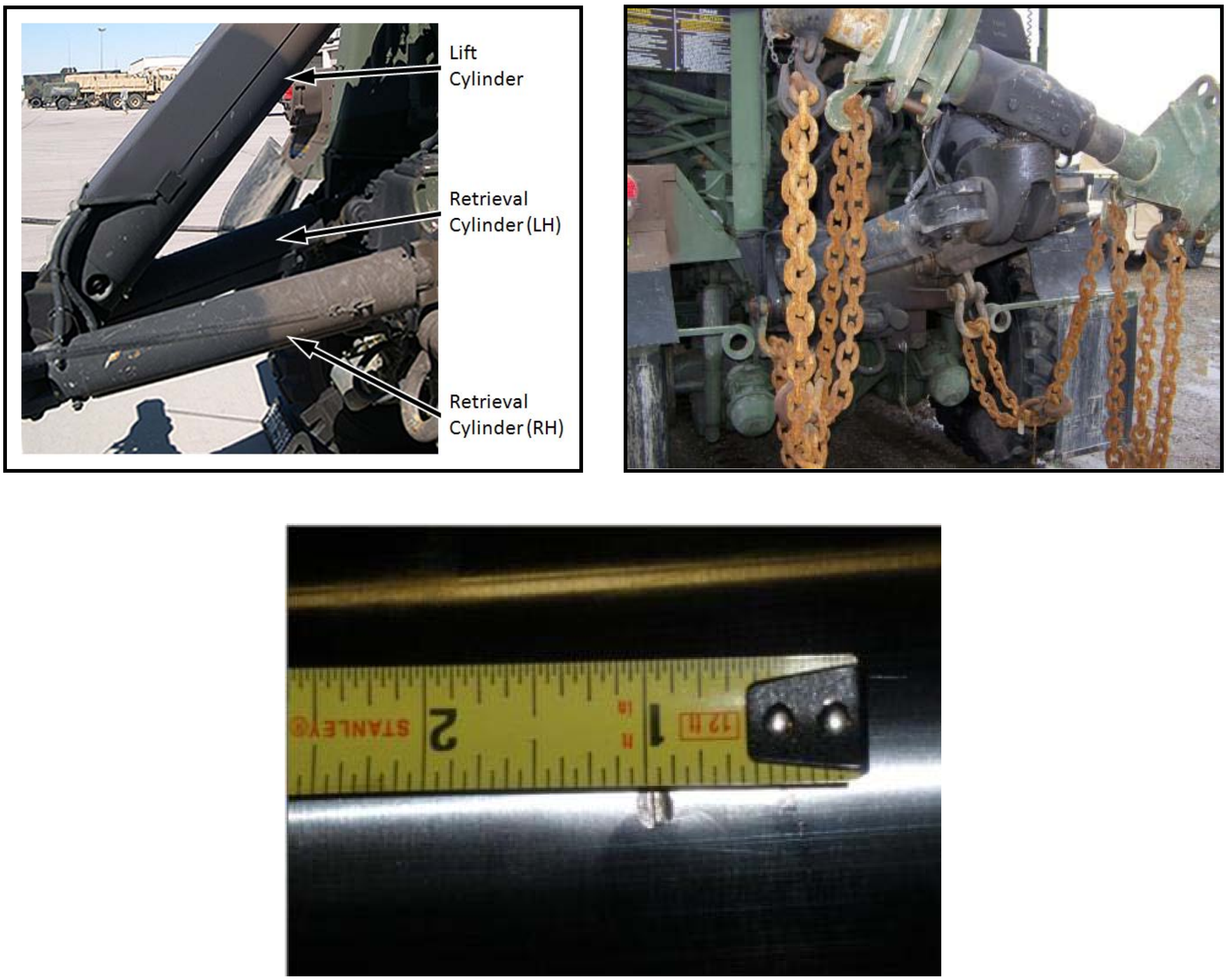


Figure 18: Vehicle Cylinder Example of "Low-Hanging Fruit"

APPENDIX D - STEERING GEAR EXAMPLE

This example can be applied to all wheeled vehicles with steering systems. (See Figure 19.) In our 4D example, six steering gears were being replaced resulting in a component cost of $1M—not including maintenance, pumps, hoses, or filters in the system.

The technical manual states that the steering gear is to be replaced when it is leaking. However, the leaking steering wheel input shaft seal and side-cover gasket seal are the failure modes for a clogged filter and worn-out steering pump, respectively. Replacing the steering gear without replacing the fluid filter and/or pump will not fix the steering issue.

The leaking input shaft seal is a buildup of backpressure in the steering system. A clogged filter builds backpressure behind the input shaft seal. A worn pump over-pumps to build pressure and allows excess fluid into the gear, resulting in the side-cover gasket leak. The vehicle steering will be sluggish, as the power-assist pressure across the gear is diminished. This means it is harder and harder to steer, until it seems similar to manual steering without power-assist. The solution is to prevent the buildup of pressure in the steering fluid return line. (See Figure 20.)

- Change steering system filter replacement schedule from annually or every 100,000 miles to monthly independent of mileage.
- Check the steering pump flow rate bi-annually in harsh environments (if the filter is replaced monthly).
- Revise the technical manuals to specify the replacement of the pump and filter before replacement of the steering gear.

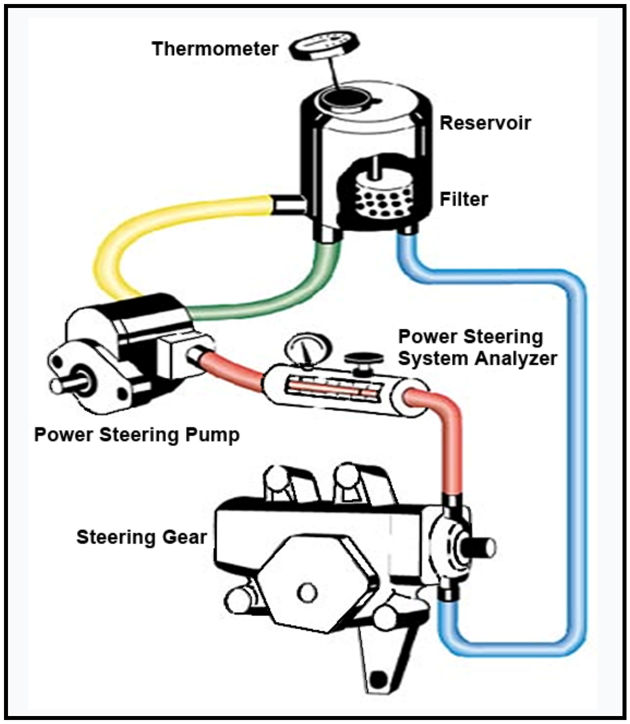


Figure 19: Vehicle Steering System Example

Figure 20: Vehicle Steering Gear Leakage Example

APPENDIX E - SWA ENVIRONMENT

Excess Heat Buildup

Stacking radiators to increase cooling for the transmission, steering, and engine works well when the vehicle is traveling 65 mph on a highway in Texas or Arizona when the temperature is 110° F. However, stacked radiators on a heavily armored vehicle going 35 mph with little airflow under the vehicle hood adds heat into the last radiator—the engine cooling system. When the primary engine radiator cooling is compromised, degradation to all components that are cooled by the engine oil system can be identified. Further, the addition of the clay talc soil to the radiator cooling fins degrades the radiator's cooling ability even more. (See Figure 21.)

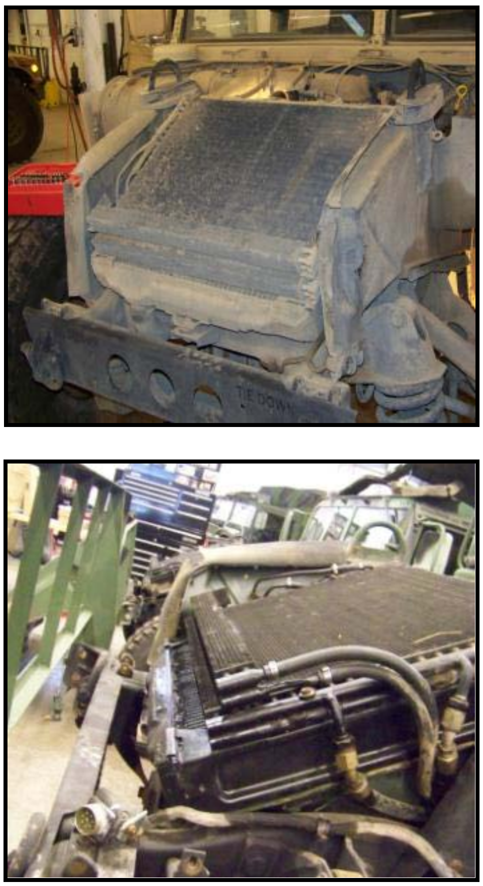


Figure 21: Examples of Radiator Cooling

Ultraviolet Sunlight Reflection under the Vehicle

Below are examples of UV damage under a vehicle. The mount shows cracking on a vehicle in SWA. The accelerated damage of the mounts under the vehicle is evident on multiple vehicles. (See Figure 22.) This rate of degradation may be attributed to the reflected UV light from the unique soil conditions in SWA.

Figure 22: Example of Vehicle Mount

Component Micro Abrasion Damage

You can observe the deteriorated engine cooling oil and the failed gasket. (See Figure 23.) The ASTM material gasket is functional to 600° F and is not exposed to UV light directly. Failure is observed from micro abrasion of the soil in SWA where the components are hot during the day and cool at night. As the components cool, the dust, talc, and soil is drawn into the gaskets and seals. During the vehicle's use, vibrations rub/chafe the silicate materials against the gasket and can wear out the gasket from the inside.

Figure 23: Example Air Compressor Gasket

Soil, Environment, and Vehicle Testing

Ambient daytime temperatures of 90° F to 120° F are found in both Yuma, Arizona, and Iraq.

The Arizona highlands soil is the remnant of mountaintops after the last glacial age, whereas the soil in Iraq is the remnant of a great salty ocean. In explaining why UV material damage is occurring to components on the underside of vehicles, we look at the soil in Iraq versus the soil in Yuma, Arizona.

Salt brine permeates the Iraq soil, making much of it unsuitable for growing small grain crops. Dates were the most prevalent export crop before the 1970s. Without irrigation from the nutrient-rich Euphrates and Tigris Rivers, salt coats the Iraq soil. Almost 75 percent of Iraq's irrigated land suffers from salinity problems.

"Groundwater in middle Iraq is already at 15 dS/m. Approximately 80 percent of the irrigated land around Baghdad is affected by salinity, and in the south it is almost as salty as seawater at 35 dS/m. Viewed from the air, vast areas of southern Iraq glisten with salt like new-fallen snow." (Reference 3)

Salt is a crystal structure and is reflective of the UV light with the sand silicate crystals. The salt crystal reflects the UV light to the underside of the vehicles and deteriorates the non-metal materials traditionally protected from the UV radiation by the top of the vehicles. The UV light is not reflected at the same rate by the sandy loams of the Yuma proving grounds and surrounding areas. The UV resistant materials used in the commercial industries are deteriorated at an accelerated rate. The error does not lie in the selection of the UV resistant materials, but in the understanding of the aggressive nature of the environment. A windshield wiper blade that lasts one year in Washington State may deteriorate in three months in the high-intensive Arizona UV light—even without having been used. Iraq has a higher UV intensity and reflective soil qualities than Arizona.

The central valley around Baghdad was swampland that was drained in 2000. This creates a lack of watershed for the region and changes the soil erosion and content. "Sand, silt, and clay vary by particle size. The amount and kind of clay affects the fertility and physical condition of the soil and the ability of the soil to adsorb and to retain moisture." (Reference 1) The clay/talc coats the radiators like a mixture of flour and water coating a balloon—effectively diminishing airflow contact with the vehicle radiators.

The clay/talc-type materials migrate into the seals after coating the component's external features. Days, months, and years of vehicle thermal cycling may result in the internal micro abrasion of the component's seals and gaskets and the closing off of breather valves and air filters.

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[1] United States Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Handbook, Title 430-VI.

[2] USDA Natural Resources Conservation Service Survey Area, Version 7, 9/12/2008.

[3] Agriculture in Iraq: A. A. Jaradat, NCSC Research Lab, ARS-USDA 2002.

[4] ISIRC World Soil Information Database.

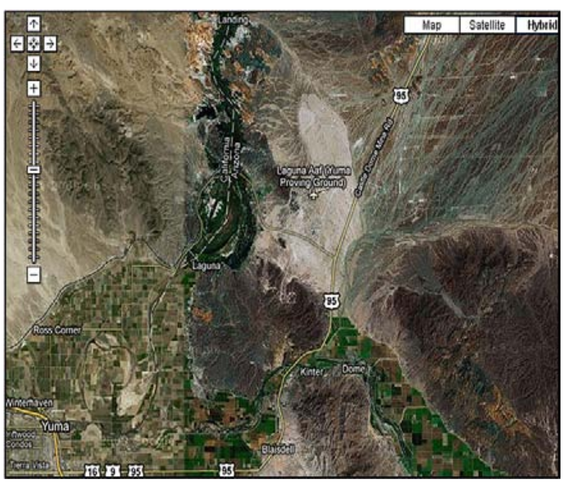

Figure 24: Examples of Soil in Yuma, Arizona (Reference 2)

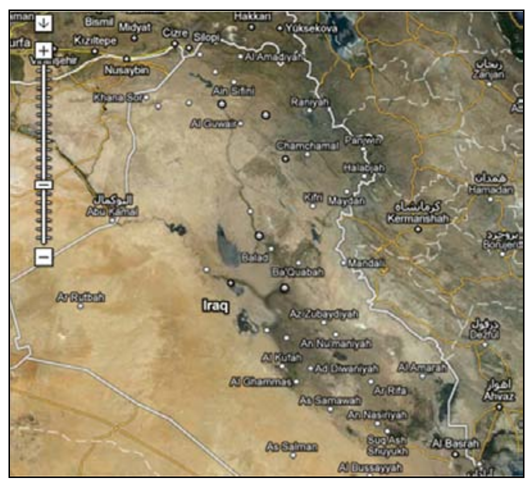

Figure 25: Iraq (Full Country View) (Reference 4)