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The Use of Microcomputers To Improve Army Ground Vehicle Readiness

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PREFACE

It has become apparent that Army vehicle maintenance costs are high and that the vehicle readiness achieved is low. The problem has many causes. The skill levels and motivation of vehicle operators and mechanics have suffered in recent years. Personnel are in short supply. The complexity of the vehicles themselves is increasing. The effect is to reduce the potential combat effectiveness of the Army ground forces at a time when the United States is facing a large imbalance in force ratios with its potential adversaries in Eastern Europe.

Under contract to the Defense Advanced Research Projects Agency, The Rand Corporation has been studying the problems of land vehicle maintenance in the Army. That study has included an evaluation of the use of large-scale integration (LSI) electronic systems in the form of microcomputer vehicle monitors. Such monitors appear to offer unique and significant benefits when employed to track the key vehicle degradation mechanisms. The information so developed makes it possible to estimate remaining component life, which in turn permits scheduling maintenance to occur sufficiently early to forestall in-service failure. The results should be of interest to defense planners concerned with reducing system maintenance costs and with improving equipment mission availability.

Other Rand reports generated under the land vehicle maintenance project include:

- R-2123-ARPA, A Method for Evaluating Diagnostic Aid Systems in Army Land Vehicle Maintenance, Gary F. Mills and Kathleen A. Wolf, April 1978.
- R-2487-ARPA, Problems in Army Maintenance: Results of a Questionnaire Survey, C. R. Harz, forthcoming.

SUMMARY

The lack of readiness of ground vehicles is a key impediment in the Army's potential for combat effectiveness. Of the current $13 billion active inventory of ground vehicles, a maintenance investment of $1.3 billion per year achieves readiness for only about one-half the vehicles. Data for the refinement of these numbers, for determining the causes of the lack of readiness, or for devising and evaluating potential solutions do not exist. Under contract to the Defense Advanced Research Projects Agency, Rand has conducted a technology assessment of the potential role of recent microcomputer developments in solving these information problems and in contributing directly to potential solutions.

The unique attributes of the microcomputer can (1) improve the information base with which to understand the problem and find its potential solutions and (2) should become part of those solutions. Using microcomputer vehicle monitors imbedded in both local and Army-wide information systems provides new information processing and communication techniques that can increase individual vehicle and fleet readiness through more efficient use of maintenance and development resources. The techniques include improvements to classic trend monitoring through the use of real-time algorithms and an innovation we call geriometry--real-time cumulative stress accounting. These new techniques can be used to schedule anticipatory maintenance in a manner to fully utilize the inherent life of key vehicle components while obviating most in-service failures.

In the course of this project, we conducted a prototype feasibility program with the Army's TARADCOM (Tank/Automotive Research and Development Command) acting as the proponent agency, RCA Automated Systems Division responsible for the prototype design and construction, and the Army's TECOM (Test and Evaluation Command) Material Testing Directorate performing simulated field tests. The results clearly support the contention that on-vehicle microcomputer systems are feasible and that they can be used to develop new

information systems. In addition, it was discovered that microcomputer data acquisition systems bring unique benefits to qualification and acceptance testing of new Army vehicle systems.

We recommend a continuing program composed of two parts. First, a policy study is needed to determine how best to incorporate these new techniques into Army organization, operation, maintenance, and procurement policy and doctrine. Second, continuing technology research and development should include concurrent and interactive efforts in physical system research, degradation metrology development testing, and designs for current and future Army vehicle systems.

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I wish to acknowledge the many significant contributions of the Vehicle Monitoring System (VMS) prototype program "board of directors": the sponsoring project managers--in succession, Major Terrell G. Covington (USA) and Lt. Col. Champlin S. Buck, III (USA), of the Defense Advanced Research Projects Agency's Tactical Technology Office; Donald Sarna and Joseph Sraj of TARADCOM, the Army's proponent agency; the late Newton Teixeira, the VMS program manager at RCA, and his associates Steven Hadden and Harvey Goldstand; Pete Kincaid and W. H. "Skip" Connon, III, of the Army Material Testing Directorate; and, of course, my colleagues at Rand, Jerry Hull, Lois Batchelder, and William Whelan, manager of the land vehicle maintenance project. I would also like to thank Rand colleagues Malcolm Davis, Richard Wise, and Kathleen Wolf for their critical review of an early draft of this report.

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I. INTRODUCTION

Readiness is the measure of an Army unit's availability for combat. This report is concerned with the readiness of the Army's ground vehicles--methods for the quantitative assessment of that readiness and the development of information which can lead to new maintenance equipment and revised policies for improving that readiness.

A theoretical basis for optimizing readiness has existed for many years. Well-developed treatments of system reliability and availability were in existence in the late 1940s (David, 1948) and of optimal replacement policy in the 1960s (Jorgenson et al., 1967). This maintenance management theory, however, assumed a perfect understanding of the system condition and of the component failure modes and distributions. The lack of such information has been the Achilles' heel of maintenance management.

The information problem is particularly acute in the case of ground vehicles which are members of a class of systems that is "user developed." Due to design and development cost pressures, such systems are issued to the user in quantity in an imperfectly developed state. The final 10 to 40 percent of the vehicle development and refinement must be based on feedback of user experience. Users, however, are notoriously poor data collectors and over the years nonexistent or poor data have been the bane of ground vehicle system developer and user organization alike. An investigation of Army maintenance cost data (Mills and Wolf, 1978) has shown this to be a particularly chaotic realm. The data are so uncertain that subjectively viable system improvements often cannot be proven cost effective and thus cannot qualify for development support.

The Rand Corporation has undertaken a technology assessment program, sponsored by the Defense Advanced Research Projects Agency, to establish the feasibility of using on-vehicle microcomputing instrumentation to develop background information on the cause and effect relationships for the degradation of Army vehicles in the

field. A second purpose was to explore the utility of incorporating simplified versions of microcomputer monitors in operating vehicles and of using the information generated to improve maintenance management procedures.

A component of the Rand assessment was an engineering prototype development of a vehicle monitoring system (VMS). Two phases of that investigation have been completed. Phase I was a competitive system design study for an on-board, flexible research-type data acquisition system. Phase II provided for the design and construction of a prototype system and a test program to verify engineering feasibility on Army vehicles. The Phase I system design was contracted to Rockwell International, Automotive Operations, in Troy, MI (Rockwell International, 1976) and to RCA Automated Systems Division, Burlington, MA (RCA, 1976). Final reports were submitted in August 1976. The Phase II prototype design was won by RCA (RCA, 1979); feasibility testing was conducted by the Material Testing Directorate at the Army's Aberdeen Proving Ground (Material Testing Directorate, forthcoming); and the test data were analyzed at Rand. The prototype system was delivered by RCA in August 1978 and the test program was completed in June 1979. Documentation was completed in Fiscal Year 1979.

We conclude from our technology assessment that on-vehicle microcomputer monitors can uniquely solve the problem of obtaining information on the true state of a vehicle's readiness, allow the scheduling of maintenance in anticipation of failure, and provide valuable feedback to the product design and improvement process. The VMS prototype effort has shown the inherent feasibility of on-vehicle microcomputer monitors on Army ground vehicles.

We recommend continued research and development to allow the implementation, in several years, of microcomputer vehicle monitors which will collect vehicle information during actual operation, at costs low compared with the potential cost savings from the use of the information. We also recommend that a policy analysis be undertaken to determine how best to implement anticipatory maintenance within the Army's logistic and combat operational units.

An auxiliary benefit of this investigation has been the revelation to test agency personnel that an on-board digital data acquisition system similar to the VMS could revolutionize the approach to and the efficiency of development, qualification, type classification, and quality assurance testing of Army vehicles. We envision similar benefits for maintenance and operational data acquisition during training exercises such as those to be conducted at the National Training Center.

In Sec. II we introduce a new concept for readiness management that has evolved from our technology assessment of the on-vehicle microcomputer. The concept employs new prognostic techniques for scheduling anticipatory maintenance derived from the unique attributes of the microcomputer's capability for real-time algorithmic monitoring. The benefits include the ability to use new types of sensors, improvments in classic trend monitoring, and the use of a monitoring innovation we call geriometry. We also draw some approximate cost-effectiveness conclusions.

The attributes of the microcomputer monitor are discussed in Sec. III, with their implications for data acquisition. We also describe the prototype engineering feasibility program, a selection of the test results, and their implications for vehicle monitoring system benefits.

A summary of our conclusions is presented in Sec. IV. Our recommendations for a continuing program are discussed in the Appendix. We recommend both an implementation policy study and a technology development program composed of physical system research, vehicle degradation metrology development testing, and application designs for current and future Army vehicles.

II. A MAINTENANCE MANAGEMENT INNOVATION

ANTICIPATORY MAINTENANCE SCHEDULING

Rand has defined a new approach to vehicle maintenance which, in conjunction with a revised operational policy, can result in improved ground vehicle readiness. The approach involves a new technique for anticipatory maintenance scheduling using real-time algorithms. The approach is based on the real-time information development and decision capabilities of the microcomputer monitor (discussed in Sec. III). It is our belief that this concept will prove highly cost effective in Army combat and tactical vehicle maintenance and fleet readiness management. Proof of this cost effectiveness, however, must await hard data such as that which could be collected in the continuation of this program.

Army vehicle fleets have two categories of maintenance. Preventive maintenance (PM) is performed to forestall failure mechanisms, and corrective maintenance (CM) is performed to correct a failure that has already occurred. Current Army maintenance practice does not anticipate failure and therefore most maintenance is CM. Our contention is that reduced maintenance costs and improved readiness can be derived from new techniques to anticipate failure so that maintenance can be performed just before the probability of failure rises to a significant level. We call this process anticipatory maintenance (AM). The use of AM will concurrently reduce the requirement for corrective maintenance. The focus of this report is on the metrology of anticipation, which should not be interpreted as a denial of the potential benefits of microcomputer monitors for corrective maintenance diagnosis.

The automotive elements of Army vehicles are comprised largely of subsystems which exhibit wear-out characteristics with normal failure time distributions.* It is important with such subsystems to minimize

*Collections of such subsystems (or components) with varying refurbishment life cycles can eventually exhibit system failure distributions with apparent stochastic characteristics (David, 1948). Failure predictability can be preserved only by monitoring each subsystem and treating its anticipatory maintenance independently.

the occurrence of failures, and the unscheduled corrective maintenance that follows, without introducing excessive periodic inspection or preventive maintenance. Figure 1 illustrates the maintenance cost versus maintenance time interval relationship.

The maintenance cost versus maintenance time interval function for a given vehicle subsystem exhibiting wear-out must contain a minimum at some service interval, since more frequent maintenance would:

1. Use less of the inherent component life, causing greater parts consumption,
2. Increase opportunities to induce failures as a result of flawed inspection/maintenance procedures, and
3. Increase vehicle downtime.

Less frequent maintenance would:

1. Increase frequency of in-service field failures,
2. Increase secondary failures induced by the primary in-service failures, and
3. Increase both maintenance costs and downtime due to the secondary failures.

Maintenance policy should be based on the failure distribution that is assumed to apply to the system elements. Maintenance before failure is appropriate for systems exhibiting wear-out but not for stochastically failing systems with declining or constant failure rates. No failure is really stochastic but may appear to be stochastic because of the metrology employed. Failure time distributions are measured at aggregate levels of assembly, cumulative stress histories for individual failure mechanisms are unknown, and component quality variations are unknown. In some systems, notably electronic systems, it is not practical to track individual failure mechanisms. These systems are complex, with a profusion of components and failure mechanisms, and their operating time constants are short.

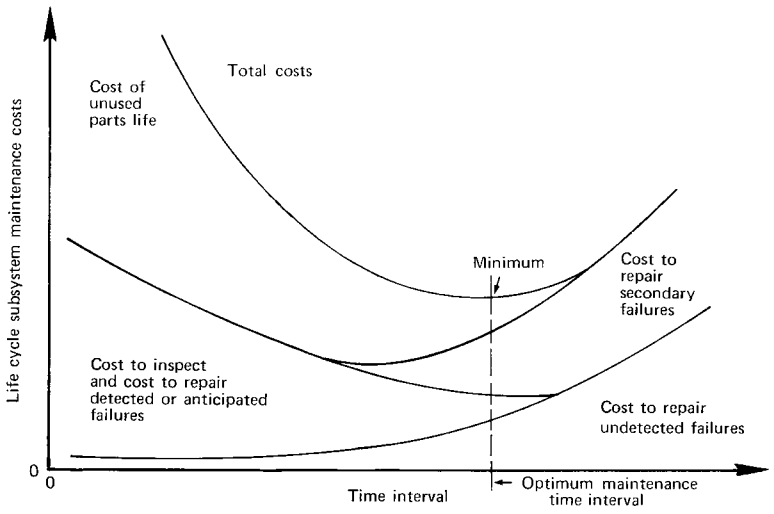


Fig. 1 — Maintenance cost versus maintenance time interval

Thus the metrology becomes difficult and the practical solution is to assume that their failure distributions are in fact stochastic. Mechanical systems, on the other hand, are less complex and have long parameter change time constants (as compared with the computational cycle time of a computer monitor). With mechanical systems it is possible to monitor the key failure mechanisms at the subsystem and component level with a computer having a relatively high computing cycle frequency.

Monitoring mechanical systems with a computer makes it possible to track important individual degradation mechanisms. If the parameter(s) that characterize degradation can be defined so that relatively narrow failure distributions result (as compared with the inherent life of the component), these metrics can be used to schedule anticipatory maintenance just prior to failure, with the above-mentioned cost and readiness benefits. Since currently there is no such monitoring, most Army vehicle subsystems (engines, brakes, drive train components, etc.) are allowed to fail, with little attempt to obviate the failure through anticipatory maintenance, resulting in all of the above-mentioned disbenefits in costs and readiness.

Time function characteristics of vehicle subsystem degradation may be "brittle" or "graceful," as shown in Fig. 2. A brittle characteristic may be typified by brake system lining wear-out, where a change in performance may go unnoticed until catastrophic failure or damage occurs. A graceful characteristic may be typified by engine power output degradation, where noticeable poor performance usually occurs prior to a catastrophic event.

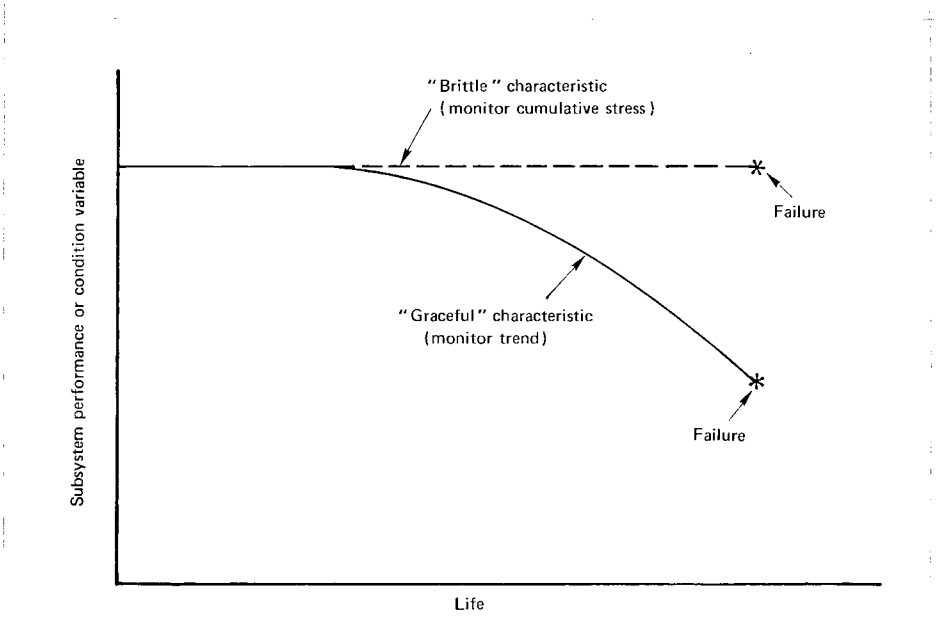


Fig. 2—Subsystem performance or condition versus life

GERIOMETRY: AN ALGORITHMIC TECHNIQUE FOR "BRITTLE" FUNCTIONS

Geriometry (Salter, 1978a, 1978b) is an innovation conceived in the course of this technology assessment. It consists of using the unique capabilities of on-vehicle microcomputers to provide information not available through any other inspection technique. The information includes the accumulation (in real-time) of stress histories for key components and subsystems which, in the context of known cumulative stress tolerance, provide an assessment of remaining life that cannot be determined by conventional condition testing. The technique allows the differentiation among various levels of "hard"

and "easy" use time and their proper stress weighting in a cumulative damage function.

Preventive maintenance and periodic inspection of "brittle" subsystems currently is scheduled by simple time or service functions--the passage of calendar time or the accumulation of vehicle mileage. Generally, however, the distribution of failures versus time or mileage is quite broad and the only preventive maintenance policy possible has shorter intervals than the optimum frequency of maintenance shown in Fig. 1. This policy will result in higher maintenance costs and lower fleet readiness, as was previously discussed.

Geriometric anticipatory maintenance scheduling employs a more complex function of time that draws a distinction between "hard" time and "easy" time in a continuous graduation. A weighted accumulating metric is continuously monitored and when a predetermined aggregate level is approached, maintenance is scheduled. If the algorithm is properly designed, the failure distribution will be narrowed so that even a conservative anticipatory maintenance policy will approximate the optimum point indicated in Fig. 1.

A demonstration of the leverage of the algorithmic parameter transformation can be inferred from data from automobile monitoring tests (performed by General Motors Corporation) relating the wear-out life of brake linings to the aggressiveness of brake use by the vehicle driver. We transformed these results by observing that brake life correlated closely with the cumulative energy absorbed by the brakes. The comparison of wear-out distributed over the mileage variable and over the absorbed energy parameter is shown in Fig. 3. It is apparent that a preventive maintenance procedure based on mileage is impractical, other than as a signal to trigger successive periodic inspections until imminent wear-out is detected. Geriometric accounting of cumulative absorbed energy, however, could give a precise signal of needed maintenance without requiring intervening physical inspections. It is also significant that the energy absorption/wear-out function can be determined, for a given brake design, from development test data, making it possible to introduce

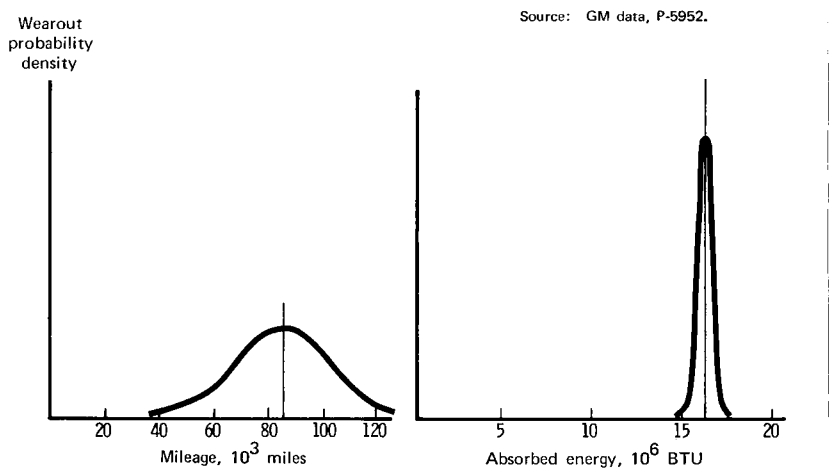


Fig. 3—Brake wearout distribution

new or revised designs into the field with predetermined criteria for AM scheduling.

From the data shown in Fig. 3, preventive maintenance based on mileage would require periodic inspection at 15,000 to 20,000 mile intervals for the life of the brakes, whereas a high confidence decision to perform anticipatory maintenance based on absorbed energy could be specified at 15 million BTU, with no need for intervening periodic inspections.

The on-vehicle microcomputer monitor calculates in real time the accumulation of brake energy absorption. Several different algorithms could be used; one might measure vehicle deceleration force through the distance traveled (calculated from a distance sense and its second derivative) triggered by a braking action indication, perhaps by an actuation switch. A brake fluid pressure sensor would allow an even more precise energy computation.

A caveat is that wear-out of Army vehicle brakes could also result from abrasive contamination such as from sand introduced during fording operations. Algorithmic anticipatory maintenance must either incorporate or obviate the effects of such variables. In this case, better seals preventing such contamination may be possible, especially if the seals do not have to survive frequent physical inspection

procedures. Another parameter has been suggested by Pete Kincaid of the Material Testing Directorate at Aberdeen--the integration of brake pedal travel progression over the several adjustment cycles during the life of the lining.

ALGORITHMIC TREND MONITORING FOR "GRACEFUL" FUNCTIONS

Currently, a decision to perform maintenance is usually based on a diagnostic condition test of vehicle subsystems or components "thought" to be approaching failure. These diagnoses are usually performed without benefit of the vehicle history of the progression or trend of the problem. This "spot test" technique is theoretically a viable procedure if done with appropriate test equipment by properly trained diagnosticians. Its success, however, depends on the precision of the test equipment as well as its convenience. Historically, none of these desired features has been present in Army vehicle diagnostic systems. A major improvement, STE-ICE (Simplified Test Equipment - Internal Combustion Engine), is now being introduced under the guidance of the Army's Tank/Automotive Research and Development Command (TARADCOM). For STE-ICE to be even more convenient it should be employed in conjunction with on-vehicle diagnostic connector assemblies.

STE-ICE is a microprocessor-based off-vehicle diagnostic test set that provides data for a number of advanced diagnostic principles. It must depend on precision because in normal use trend information is not gathered. An example of one STE-ICE test capability is shown in Fig. 4. The engine measurements were made during the VMS engineering feasibility tests at Aberdeen (Material Testing Directorate, forthcoming). The data before the 6000 mile odometer reading were taken with an early STE-ICE preproduction unit, those after 6000 miles with the improved production unit. These data illustrate the necessity for precision if valid maintenance decisions are to be made from spot condition tests. A better understanding of the true condition is derived, however, from the trend of such data, since trend information is more tolerant of the scatter of individual measurements.

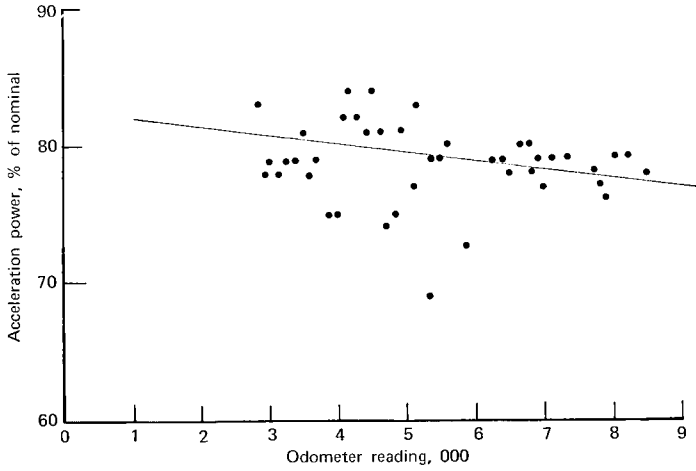


Fig. 4—M35A2 engine power

Most subsystems will exhibit graceful degradation trends for several performance parameters. These trends can be used collectively to help determine the most economic anticipatory maintenance point in the subsystem life (the optimum point shown in Fig. 1).

Performance variables, however, generally exhibit considerable change over the range of conditions representing the vehicle operating envelope. For example, engine output torque is essentially zero at idle and rises with speed and throttle setting to a maximum point, with an infinite set of in between values at other speed/throttle setting combinations. Secondary effects include intake air temperature and pressure, engine temperature, and so forth. To assess the engine condition to determine optimum anticipatory maintenance scheduling, we need to monitor torque at one or more particular operating conditions--one perhaps at low speed, and one at high speed, full throttle. Since the engine will be operating in those circumstances off and on during the normal course of field use, the torque can be sensed periodically at the selected conditions and the trend of the measurements stored. To do this a measurement algorithm must be satisfied to ensure that the torque is sensed under the selected conditions. The algorithm would permit the use of the

measured torque value only when this unique set of conditions is stabilized for a period sufficient to eliminate undesired transient effects. For some variables, e.g., fuel flow, the measurement algorithm may integrate for a period of time (probably several seconds) and calculate an average value for use in the trend determination. The on-vehicle microcomputer monitor offers a unique capability to operate at the sampling and computation frequencies necessary to employ algorithmic trend monitoring. (The work reported here investigated LSI digital electronic computers for analyzing digital or digitized analog sensor data. Future work should explore the potential of newly developing hybrid computer systems.)

A CANDIDATE PROCEDURE FOR THE ARMY

A preliminary specification for a proposed Army maintenance management procedure is given in Fig. 5. Blocks 1 through 4 are a simplified representation of the existing system. Fielded vehicles (1) are operated in a variety of active units in CONUS and abroad. A preventive maintenance and inspection program (2) is conducted to retard wear processes and to ascertain when the wear has reached the point requiring maintenance. These procedures require physical intervention, which often introduces additional degradation leading to early failure. For the most part, all fleet operators, including the Army, are compelled to let degradation mechanisms proceed to the point of obvious incipient or actual failure (3) before maintenance is done because real-time metrological techniques suitable for measuring remaining component life have not been available. We believe this is the key problem causing major inefficiencies in the Army vehicle maintenance program. As a consequence of the above, most maintenance in the Army is corrective maintenance (4) performed after the failures have occurred. This procedure causes unnecessary secondary failures and inefficiencies in the unanticipated employment of maintenance resources. There have also been problems in diagnosis, which the newly fielded STE-ICE is attempting to alleviate.

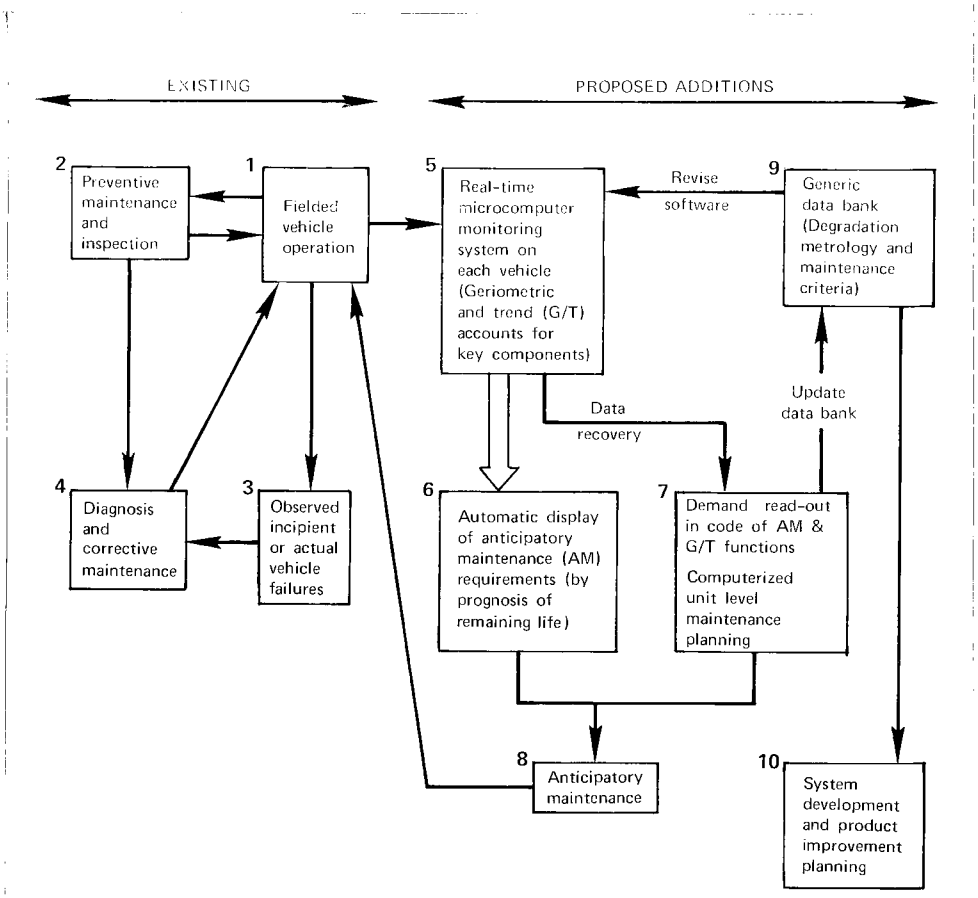


Fig. 5—Existing and proposed Army maintenance management procedures

Blocks 5 through 10 show proposed additions to the Army's maintenance system. The technology now exists to remedy the problems in the current system. LSI-based microcomputers can be inexpensively configured as real-time monitors of key vehicle component degradation mechanisms using trend analysis and geriometric accounting algorithms (5). These monitors can be programmed to track the progression of component life spans and signal the pending need for maintenance just before the life span ends in failure (6). Periodic data recovery in computer-coded form (7) will be initiated by the operating unit maintenance personnel. The combined status of all of the unit's vehicles and components will permit the optimum scheduling of maintenance in anticipation of pending failures so that the best use

of fixed maintenance resources can be made in achieving maximum vehicle readiness. This anticipatory maintenance (8) will replace much of the corrective maintenance formerly required with an attendent reduction in costs (primarily in parts consumption and secondary failures) and increase in unit vehicle readiness.

The periodic data recovered in computer-coded format (7) will also be transmitted to a generic data bank (9) for continuous updating of the degradation metrology and the associated maintenance criteria. As these data mature, appropriate revisions to the software of the monitors in service will be made. Also, data from the generic data bank, organized by individual weapon system, will be fed back to the weapon system development/product improvement project offices (10) for use in planning their programs.

COST-EFFECTIVENESS CONSIDERATIONS

Potential Benefits

We determined early in the study of ground vehicle maintenance that existing Army maintenance cost data were unreliable and would yield misleading results if used for cost effectiveness evaluations (Mills and Wolf, 1978). The situation is unchanged as of this writing and a rigorous cost-effectiveness evaluation of the use of microcomputer monitors to improve Army fleet readiness is not possible.

We will, however, employ at least proximate techniques to illustrate the probable viability of the concept. The metrics chosen here are based on the author's judgment--the reader may wish to test the calculations and conclusions with alternative estimates of the metrics.

We define readiness as the probable percentage of vehicles in a specific operating fleet, e.g., a tank battalion, that could accomplish a specified tactical mission (neglecting the effects of enemy action). Vehicles that appear ready but fail to perform do so because of one or more of three reasons:

1. Insufficient development of the vehicle.
2. Overt vehicle neglect and abuse.
3. Ignorance of the true condition of each subsystem and major component of the vehicle.

For each of the three categories, it is apparent that better information development and flow are requisites to corrective plans and actions. A properly designed microcomputer monitoring and information development system can provide information bearing on all three problem categories. The information thus developed, employed through appropriate organization, operation, and maintenance policies, should be able to reduce nonreadiness significantly.

The new information would be in the form of time-continuum records of the important algorithmic parameters for each subsystem (engine, chassis, drive train, brakes, electrical, cooling, and fuel systems) of each vehicle in the unit. The information would be generated on-board each vehicle and transferred off-board for aggregate display and analysis at unit and higher organizational levels. It is necessary to track discrete subsystems in order to implement anticipatory maintenance management. Aggregation of subsystem data by vehicle is necessary to determine overall vehicle readiness. Aggregation of vehicle data by operating unit is necessary to determine priorities for optimum maintenance resource allocations to achieve highest possible unit readiness and for operational planning based on readiness. Higher level aggregations by vehicle type and model are necessary for vehicle system development and product improvement feedback.

These aggregations and analyses would be accomplished by appropriate off-board microcomputers with specially tailored software packages. Data are transferred from the on-vehicle computer in computer-readable digital format requiring no manual reduction.

Combat Vehicle Cost Effectiveness

Recent formal and informal surveys of combat vehicle units (Harz, forthcoming; TARADCOM personnel fielding STE-ICE) suggest that actual

vehicle readiness as defined above may be as low as 50 percent. There is obvious room for improvement.

The cost of developing new information for a battalion of 50 combat vehicles may be estimated as follows:

1. Basic costs of on-vehicle microcomputers configured as described in the Appendix would be of the order of $4000 per vehicle, assuming a moderate scale procurement. Total unit costs would be $200,000.
2. Data transfer and computing equipment will add $100,000 per battalion.
3. Doubling the costs to accommodate lifetime maintenance and spares brings the total costs to $600,000 for the battalion.

This equipment cost approximates the investment cost of one combat tank. Thus a cost effectiveness break-even point occurs with only a 2 percent improvement in battalion vehicle readiness. An improvement an order of magnitude higher than this seems plausible.

Even more cost-effectiveness leverage can be imagined for the XM-1 tank. The existing XM-1 on-board computer may have sufficient capacity to accommodate a maintenance monitor software program and the existing sensors would provide many of the necessary data. We might then expect a lower marginal cost in a more expensive vehicle.

Tactical Vehicle Cost Effectiveness

Microcomputer system costs for tactical trucks can be assumed to be on the order of one-half those estimated for combat vehicles, or perhaps $6000 over the vehicle life. If we compare this cost with the vehicle lifetime maintenance cost of $55,000 ($3700 per annum for a 15-year life for an M-35 truck) (Bell et al., 1973; Krurand, 1975), there is a break-even point if the new information reduces these costs by only 11 percent. Reducing parts cost alone by 30 percent would defray the lifetime costs of the microcomputer system.

III. THE VEHICLE MICROCOMPUTER MONITOR

UNIQUE ATTRIBUTES

Large-scale integrated electronics now makes possible very small digital computers with impressive memory capacity, computing power, and speed. Such computers can be translated into miniaturized on-vehicle real-time monitors that have several attributes:

- o High-frequency data sampling
- o Real-time algorithmic computation
- o Mass storage of sensed and calculated data
- o Effective man-machine input/output interfaces
- o Computer readable output

These are certainly not all of the useful attributes of microcomputers, but they are the ones that permit the practical implementation of algorithmic programs with which to schedule anticipatory maintenance, as described in the previous section.

High-frequency data sampling permits the algorithmic selection of sample data values to be employed in either a data trend assessment or a cumulative stress (geriometric) account. The time constant of change of most vehicle variables is in the range of several tenths of seconds to several seconds. With microcomputer cycle times of the order of several microseconds, many thousands of essentially concurrent operations can be conducted. These include the sampling of data from sensors, algorithmic calculations and comparisons, data interchange with memory, and so forth. The speed of the computer is significantly greater than is necessary for a comprehensive algorithmic anticipatory maintenance management system for all the automotive subsystems (as well as the combat subsystems) of Army ground vehicles. In fact, this computational speed should enable LSI computers to time-share real-time control (fire control, engine control, navigation, etc.) and real-time algorithmic anticipatory maintenance management.

Real-time algorithmic computation for algorithmic anticipatory maintenance management permits (1) the selection of variable data points only when a number of other condition variables are within certain specified value limits and (2) the computation of parameter formulations for use in trend or cumulative accounting. Feature 1 allows the selection of variable data points at the desired operating conditions; an example might be engine torque when the engine is at full throttle and at a speed of 2800 rpm. Feature 2 corrects the torque measurement to the equivalent value at standard atmospheric conditions and incorporates it into the trend monitoring algorithm.

Both program and data can be stored in a small physical space, consistant with the other computer components. The combined program and data memory for an algorithmic preventive maintenance management system will be on the order of 5 to 15 kilobytes. The memory incorporated into the prototype vehicle monitoring system (VMS) is 32 kilobytes (RCA, 1979). Newer mass storage technology, such as bubble memory, will in a practical sense eliminate concern for the physical size of any required memory capacity.

The microcomputer interface with its human users will be an input keypad and output digital display. A supplementary output audible tone may be used to signal the operator that urgent output exists. These I/O capabilities can

- Input maintenance or operational data
- Display on demand any variable or item of stored information
- Announce important or emergency conditions

The final attribute of the microcomputer monitor is the ability to output data in a form and format that is directly readable by another computer. To reduce costs and improve reliability in effecting a data transfer, all but a perfunctory human involvement (e.g., plugging in the readout device) is eliminated. Only reduced, analyzed, and refined information should be communicated to users of the output. The history of electronic data acquisition systems is replete with stories of raw data output that no one has the time to

analyze. This problem can be avoided by ensuring that reduction and analysis take place early in the cycle (on-board the vehicle if possible) and that all transfers between computers be in computer code and take place by the most direct automated link available. The system software should be designed to minimize extraneous information transfer and display, thus reducing data-link loading and clutter of the user output.

DATA ACQUISITION FEATURES OF THE MICROCOMPUTER MONITOR

The unique microcomputer attributes discussed above produce a number of monitoring benefits that are not available with the classic analog on-vehicle instrumentation. The Rand concept for employing these attributes, as discussed in the previous section, includes the cumulative monitoring of certain brittle algorithmic parameters (geriometric accounting) and the trend monitoring of certain graceful algorithmic parameters.

In real-time algorithmic monitoring, it is necessary to screen the data in real time to eliminate spurious outlier data points before they are incorporated into a cumulative account or trend line. A priori information on each variable is required in two areas before real-time progressive data interpretation is possible. First, it is necessary to understand any systematic bias characteristics of a generic nature that are inherent in the scatter of measurements of each variable. If, for example, scatter is equally distributed high and low, smoothing will employ central tendency techniques such as regression and averaging. If, however, measurement error tends to be low, as might be expected with fuel flow sensors, smoothing would use the high data envelope. Second, an initialization test should be made of each variable on each vehicle when the monitor is installed to reveal any problems as the data stream is started, since at this point there is no statistical basis for screening bad data points.

As the data stream develops, each data point must be compared with the preceding data to detect a bad data point. Our analyses with the VMS Aberdeen data suggest that no one screening technique is appropriate for all variable types. Here again, an understanding of

the generic character of each variable is necessary to select an appropriate screen. In general, a data point will be eliminated if its departure from a moving average (or cumulative average) is greater than some sigma value of the variance of the preceding data stream. Here again we employ the real-time algorithmic capability of the microcomputer. Later in this section we will demonstrate the effects of screens using the Aberdeen test data.

ENGINEERING FEASIBILITY PROGRAM

As discussed in Sec. I, an engineering feasibility program was conducted as part of this investigation. A prototype VMS, shown in Fig. 6, was designed and built at RCA and tested at Aberdeen Proving

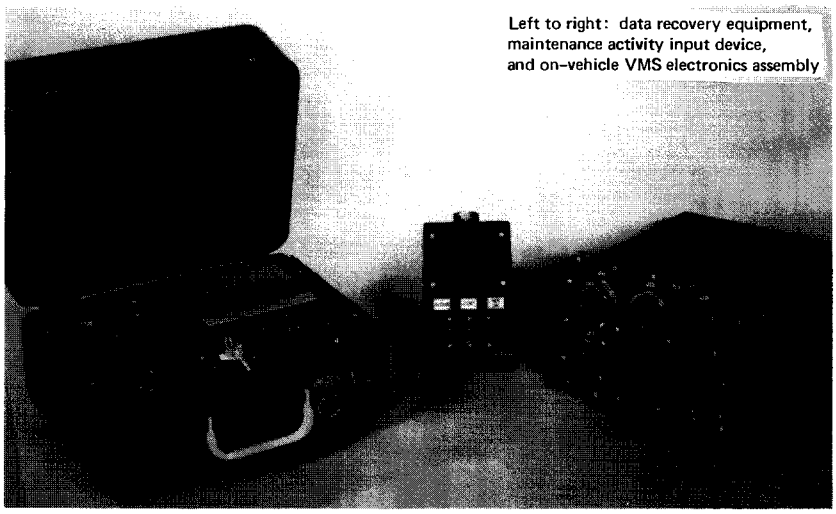


Fig. 6—Prototype vehicle monitoring system (VMS)

Ground. Data from these tests were written into Rand's computer for verification and preliminary analyses. The general characteristics of the VMS are as follows (RCA, 1976; Goldstand, 1978; Hadden et al., 1977):

THE PROTOTYPE VEHICLE MONITORING SYSTEM

VMSEA--On-vehicle Electronics Assembly

- -- RCA 1802, CMOS microprocessor
- -- 32 KB CMOS memory (1/2 program, 1/2 data)
- -- 45 data input channels:
  - 1 accelerometer
  - 22 digital data
  - 22 analog data
- -- Backup battery
  - Modular software architecture
  - Field reprogrammable
  - 1/3 cubic foot
- -- Harness/sensor assembly

MAI--Maintenance Action Input Device

- -- Portable (hand-held) with plug-in cable
- -- Coded maintenance actions

DRE--Data Recovery Equipment

- -- Portable with plug-in cable
- -- Data recovery in field onto cassette tape
- -- Reprogram VMSEA in field from cassette tape
- -- Execute sequence of special VMSEA and vehicle tests

The VMS prototype program demonstrated that microcomputers can be feasibly employed as on-vehicle monitors for Army vehicles. Recognizable, reliable variable signatures have been consistently obtained with digital sampling techniques using event records of threshold crossings. The precision of the data can be adjusted as required by appropriate threshold interval selection. The VMS in its present configuration is making 50 measurements per second, each of which is compared with thresholds and a decision is made whether to store the data point. Also, 15 complex algorithms are calculated and all data packed for efficient memory utilization. Only about one-third of the processor's capacity is required for this workload.

Most of the physical difficulties with the VMS involved problems with the sensor wiring harness and with the sensor installations. An early decision not to construct the harness with a molded covering proved to be a mistake. Molded harness is recommended for all vehicle installations from breadboards through production. The prototype

sensor installations in some cases did not allow for movement of operating vehicle components. For example, the radiator and hood movements caused some difficulties with the water level and hood switches. Some sensors did not tolerate aspects of the environment to which they were exposed; for example, the M113A1 engine speed sensor did not survive steam cleaning. In another instance, nonsealed fuses in the voltage sensor line corroded and eventually caused intermittant continuity in the line. All known data collection difficulties, and there were suprisingly few considering the "one-off" prototype nature of the hardware, were attributable to these harness, sensor, and sensor installation problems and to occasional minor software problems. The microcomputer hardware was essentially problem free, with the exception of some initial memory chip problems.

The prototype VMS experience suggests that the design and environmental problems of such a system would respond to a normal development program. RCA is to be commended for excellent execution of their part of the program.

Early in the Phase I preliminary system design, a number of decisions were made on what variables should be measured. Our concepts regarding algorithmic anticipatory maintenance had not yet matured, so the variables were chosen against the criterion of an investigation of vehicle use, condition, and maintenance patterns. The variables chosen and the analysis and packing algorithms served very well to disclose the variety of measurements and calculations involved in applying microcomputer monitors to ground vehicles. The evolving concept of algorithmic monitoring led, of course, to a different selection of sensors and a different software design. A recommended approach is given in the Appendix.

A number of difficulties were encountered in the transfer of data to the Rand computer. The source of these problems was the cassette tape transport hardware and the selection of the transfer format. The latter problem represents no inherent difficulty and should be corrected in any subsequent software designs. The former, however, is a more fundamental problem. It is our opinion that even with rigorous development, cassette tape systems will never be entirely satisfactory

in the Army field environment. Even so, they are the best of the current state of the art. A better choice in the near future may be a solid-state memory device incorporating new high-density memory technology.

The VMS program exposed the difficult system tradeoff of partitioning the data reduction and analysis among on- and off-vehicle computers. The resources of the prototype program unfortunately did not allow an adequate treatment of this dilemma. It is apparent that following generations of such systems should benefit from a systematic information development, transfer, and display design. The VMS experience suggests that through algorithmic processes, greater analysis and distillation of information with the on-vehicle microcomputer is possible.

The Material Testing Directorate at the Aberdeen Proving Ground tested the VMS prototype over 11,000 miles (81 data tapes) on an M35A2, 2.5 ton, 6 x 6 truck and 2200 miles (45 tapes) on an M113A1 armored personnel carrier. Designed to determine the engineering feasibility of the microcomputer monitor, the tests were satisfactory in every regard. MTD brought to bear excellent personnel and facilities. As an auxiliary benefit of this test program, MTD personnel discovered that the flexible design on-vehicle microcomputer data acquisition system has compelling benefits for the kind of testing that they conduct at Aberdeen and Yuma. An explanation of these benefits as well as a description of the VMS testing and results is given in MTD's final report (Material Test Directorate, forthcoming).

SELECTED VMS TEST RESULTS

Next we discuss selected VMS test results as they bear on demonstrating the feasibility of algorithmic microcomputer monitoring. Two general classes of data are included, use patterns and condition trends. As mentioned earlier, geriometric accounts were not designed into the data collection plan because the concept had not matured. We examined the prospects of calculating geriometric accounts after the

fact and determined that our data resolution would not support a reasonable precision. It appears that these accounts must, in practical systems, be calculated in real time on-board the vehicle. After-the-fact calculations will always require extensive data sampling and recording for each parameter, whereas real-time calculations require only the updating of a single geriometric account register.

Use pattern data only have meaning when related to a particular operational activity. To illustrate, we synthesize in Fig. 7 a pattern display that would be useful to a battalion maintenance officer. Two maintenance action inputs (MAI) are shown, the upper signifies that a preop check was performed. As indicated in note 1, the validity of the MAI inputs may be judged only by corroborating measurements, in this case the hood-open indication--a requirement for a preop check--suggests that some of the MAI inputs are false. As described in note 2, an attempt to turn off the monitor (the switch would be a dummy) might signify an overt attempt to obscure an abusive operating practice--in this case engine overspeed beyond the governor setting. Another, perhaps inadvertent, abuse is the shutdown of a diesel engine without a cooldown idling period, thus producing

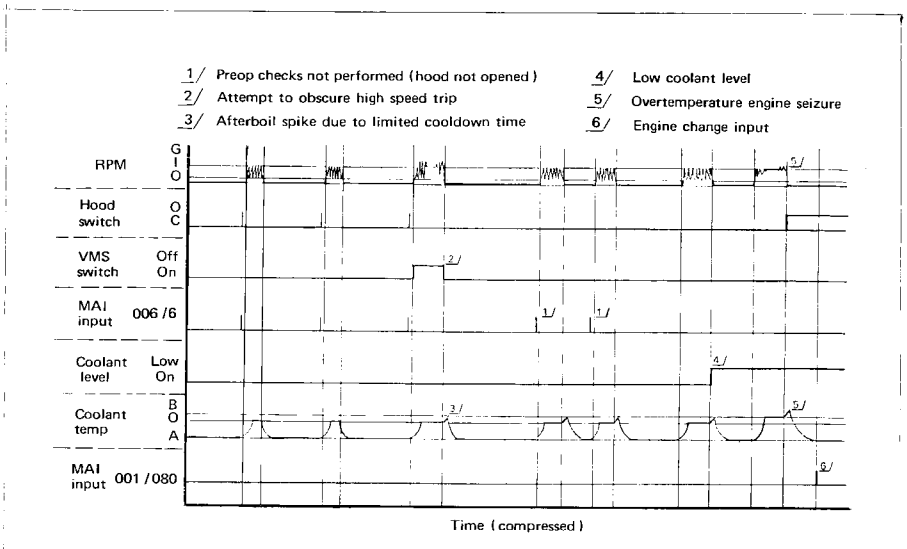


Fig. 7—Simulated VMS use pattern display
(Event time patterns)

afterboil and an attendant cooling loss. The cooling temperature pattern in Fig. 6 shows a series of afterboil spikes (note 3), eventual low coolant level indication (note 4), and finally overtemperature (note 5) and engine seizure, requiring engine change (note 6). If such data could be monitored as these abuses progress, corrective action could be taken by the battalion commander to obviate at least some of the undesired consequences.

Real-time data recording with high enough resolution to produce an analog-like record will preserve a record of key data just preceding an untoward event, such as an accident or engine failure. This principle is employed in the airline flight recorder. The VMS produced such records in a long-term continuum of about 100 hours. Old data are overwritten to preserve memory for recent happenings; the occurrence of specific events inhibits the overwrite feature so that important data are not lost. In field practice, a 15 to 30 minute period before overwrite would be sufficient to capture most desired event sequences. Three typical parameter signatures are shown in Fig. 8 to illustrate the display technique. These signatures are actual VMS data output on the Rand computer plotter.

Other use patterns of potential interest do not require real-time recording, but rather only one data point per trip, such as is shown in Fig. 9. These data show the distribution of average trip speed versus the trip distance traveled. The data in Fig. 9 are from the testing of the M35A2 truck at Aberdeen. The points in the upper right represent the highway travel in delivering the truck to Aberdeen. Many other use pattern profiles could be programmed into the vehicle monitor in the field, including acceleration histories (in addition to geriometric accounts of cumulative acceleration), use/storage patterns, and so forth.

The VMS feasibility tests produced various signature trends useful for scheduling anticipatory maintenance. Most of these data were obtained without the optimum (or even any) use of real-time algorithmic data adjustment and screening processes. In fact, the difficulty of applying such processes after the fact with the Rand computer verified the desirability of performing these functions in real time. For a number of reasons, batteries are a significant

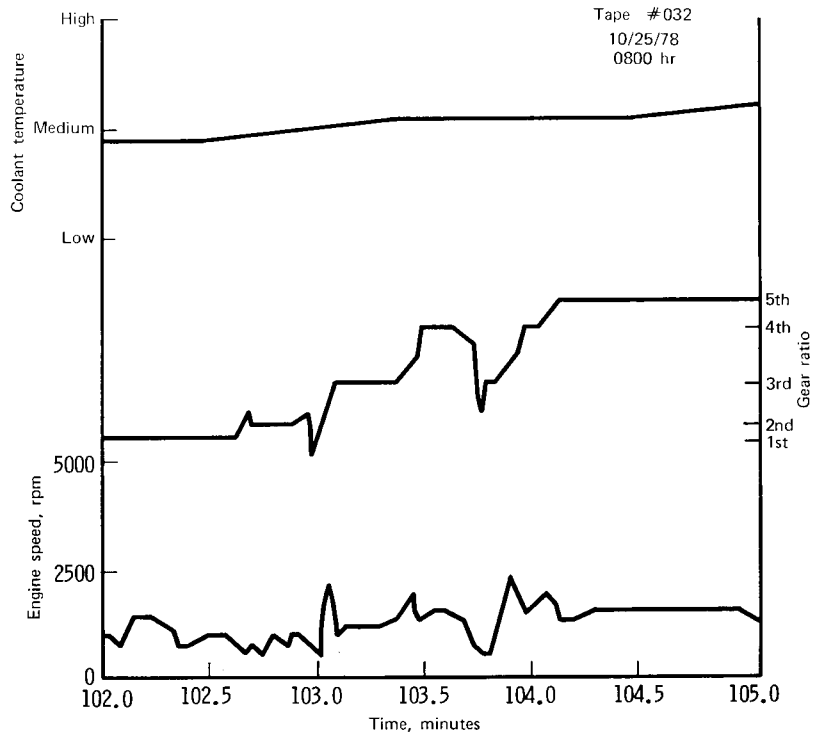


Fig. 8—Typical real-time pattern signatures

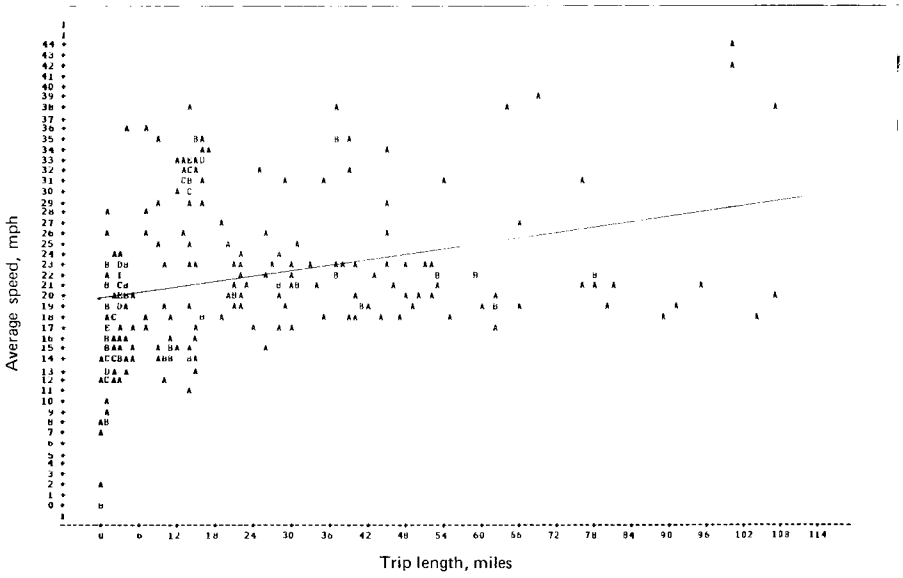
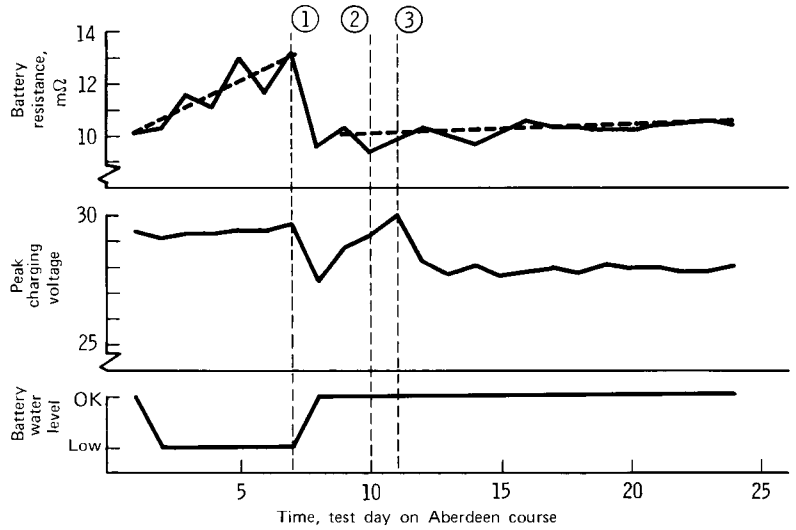


Fig. 9—Trip speed versus distance distribution

problem in military vehicles. The signatures shown in Fig. 10 indicate the potential for observing battery problems. The higher than desired peak charging voltage resulted in the boiling off of electrolite. This continuing process can be observed in the rising battery resistance. Maintenance on the battery (notes 1 and 2) solved the problem only temporarily. Reducing the charging voltage (note 3) solved the problem.

Another continuing problem for Army vehicles is the clogging and eventual bypassing of intake air filters, particularly with tracked vehicles. A vehicle monitor can follow the pressure drop trend across the intake air filter so that such failures and secondary engine failures can be avoided. The data shown in Fig. 11 include two outlier data points derived from purposely implanted blockages. Also, the data along the zero pressure drop line were taken when the engine was not at full operating speed. The three regression lines clearly



① Batteries emitting odor; added water

② Added water; cleaned cables & posts

③ Adjusted alternator output

Fig. 10—M35A2 VMS battery signatures

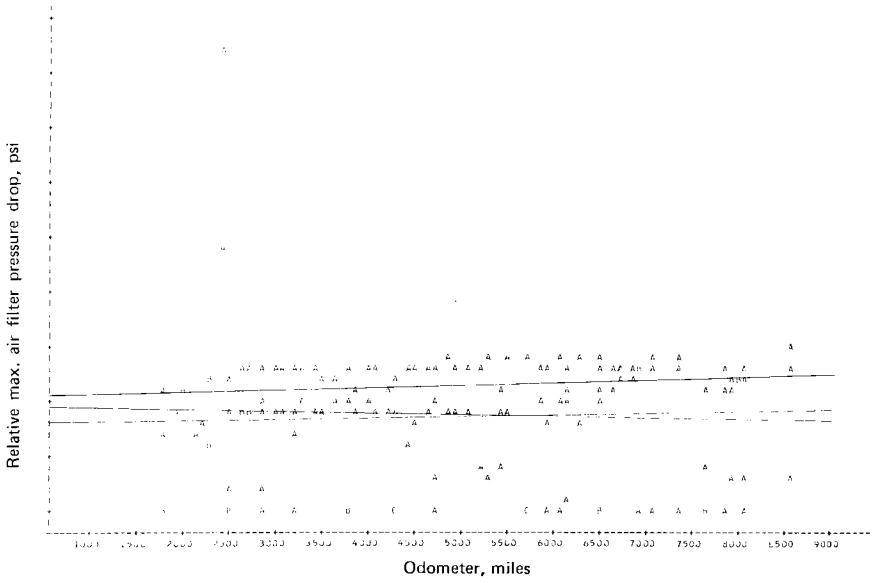


Fig. 11—Maximum air filter pressure drop, M35A2

show the necessity of screening these data from the trend data set. A regression which includes the outliers actually slopes downward. Removing the outliers changes the slope to slightly positive. Using only the data set taken at reasonable engine speed shows the valid slope, which rises about 25 percent over the test period. This relatively modest slope reflects the clean environment of the Aberdeen test course for the periods of the year over which the VMS tests were conducted.

The VMS employs two exhaust gas temperature measurements, one in each exhaust manifold. When these two measurements differ significantly, it can be assumed that there is an engine operating problem in one cylinder bank. The data in Fig. 12 show the number of occasions the difference exceeded 50 degrees F, normalized by the engine operating time. The rising trend of this parameter is significant over the 8000 miles of operation shown. With enough instrumented tests on this engine, we would be able to establish a point for the trend at which maintenance should be diagnosed.

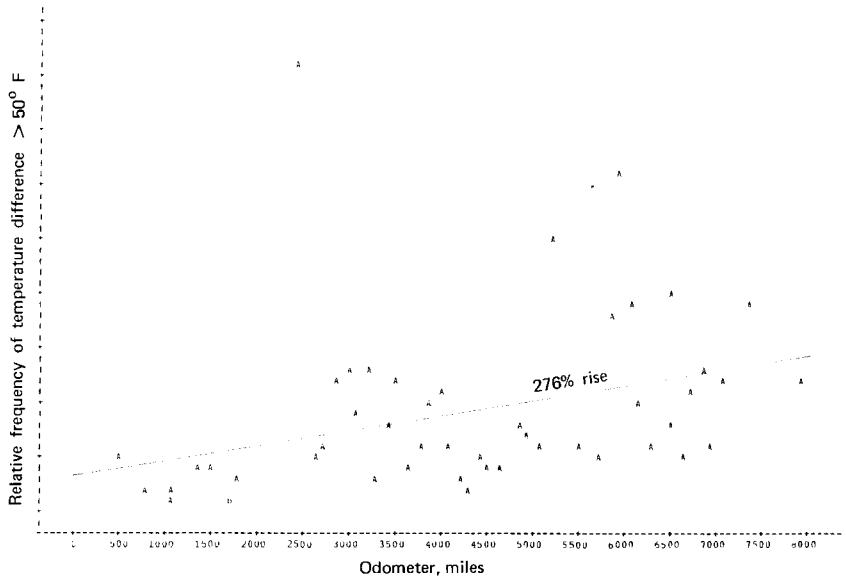


Fig. 12—Normalized exhaust gas temperature difference, M35A2

An increasing tendency for the clutch to slip is an indication that its life is finite. A normalized clutch slippage parameter was computed from VMS data and is plotted in Fig. 13. The generally rising tendency for the clutch to slip may be seen from the data. We expect this trend to continue, probably at an increasing rate, until clutch failure. The data shown in Fig. 13 span 8000 miles of operation, during which the driver was unaware of any change in clutch operation, yet a linear regression of these data shows a 214 percent increase for this period. Again, the test was not long enough to establish the character of the trend as the clutch approached failure; it is probable, however, that the data will give a clear indication of approaching failure, allowing anticipatory maintenance to be scheduled prior to in-service failure.

Some of the initial data points in Fig. 13 were produced during the fault implant testing previously discussed. We used this data set to experiment with screening techniques which would remove these outlier points from the set before assessing the trend characteristics. Figure 13 shows the results of applying a 4-sigma

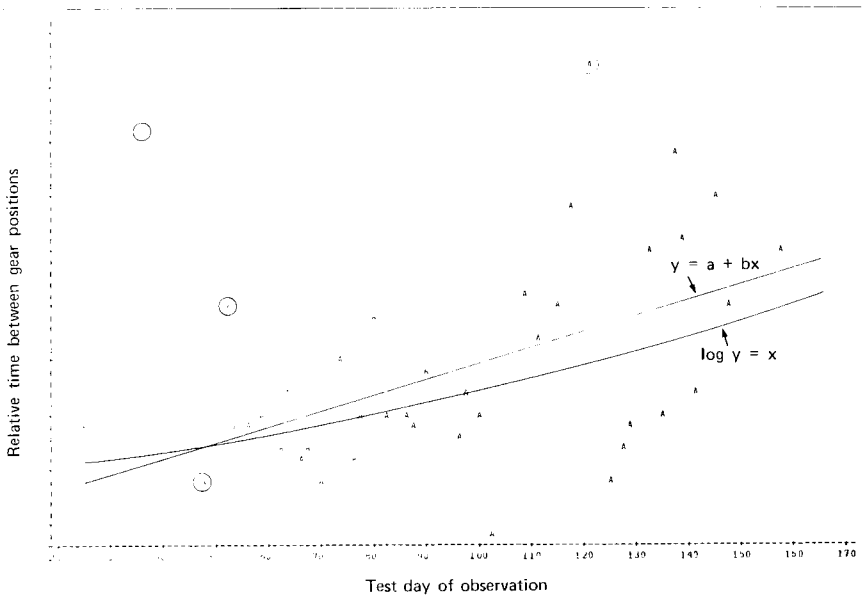


Fig. 13—Normalized clutch slippage

screen (i.e., removing data which lie outside a band of the average, plus or minus 4 sigma as computed from all data prior to each point in succession). The four data points in circles were removed, leaving 37 data points. Tightening the screen very rapidly removed other data points--there were only 13 survivors of a 3-sigma screen. Although they are necessary, such screens must be used very carefully with a thorough knowledge of the generic characteristics of the parameter involved. It is apparent that outlier data occurring very early in the data set could easily be mistaken for good data, upsetting subsequent screening procedures. For this reason, it will always be necessary to calibrate a new monitor in the vehicle to ensure the validity of the initial data.

Real-time data will usually have to be smoothed to show a cleaner trend on which to base anticipatory maintenance decision criteria. Our experience with the VMS data suggests that the most useful technique is either a moving or a cumulative average. In certain cases a regression or an envelope calculation of either the raw or the averaged data may also be useful. A cumulative average of the clutch slippage data is shown in Fig. 14. The linear regression in this case does not appear to add useful information.

We mentioned the mischief that early outliers can cause in a real-time data set. Plotting the cumulative average of the clutch data without first applying the 4-sigma screen produces the data shown in Fig. 15. The persistant effect of early outliers is apparent. In this case a moving average was found to be more tolerant of the outliers but nonetheless benefited from the screen.

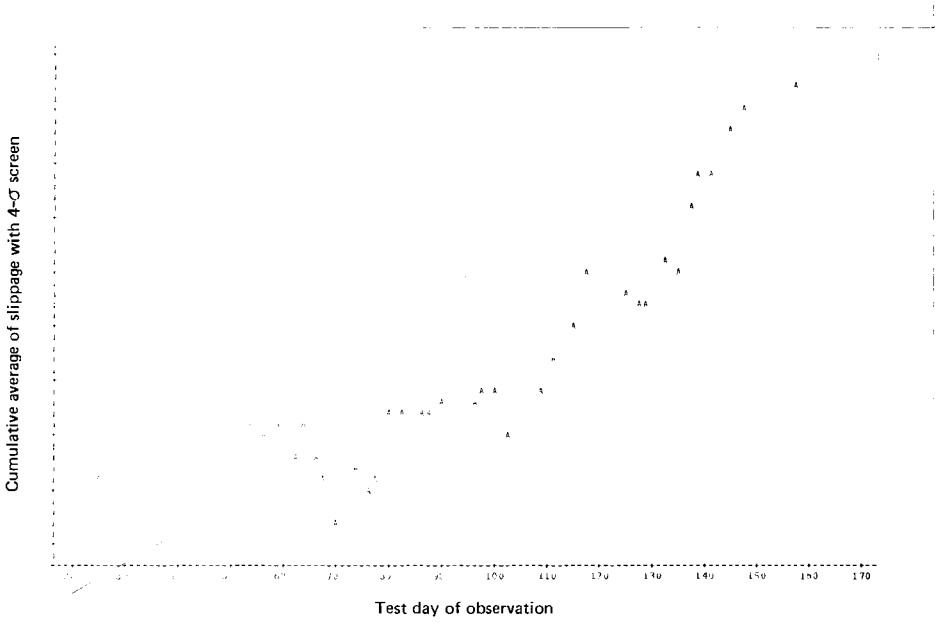


Fig. 14—Clutch slippage cumulative average

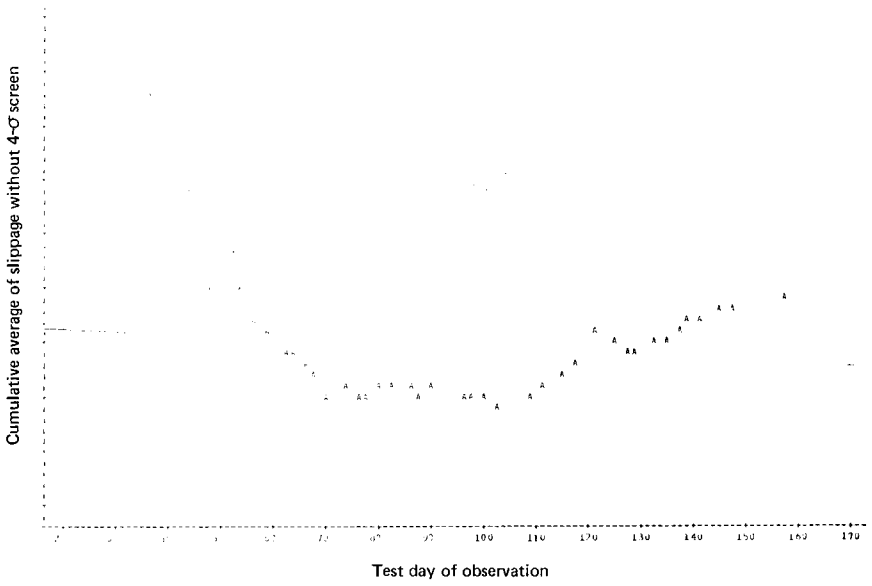


Fig. 15—Outlier data effects on clutch slippage cumulative average

IV. CONCLUSIONS

In the course of this study Rand has determined that:

- The readiness of ground vehicles is a major Army concern.
- Despite enormous expenditures of effort and resources, there are serious deficiencies in the readiness of the Army vehicle inventory.
- A major cause of these deficiencies lies in not knowing what to fix nor when to fix it.
- A major contributor to the high expenditures is the policy of allowing vehicles to fail without attempting to anticipate and obviate the failure with appropriate maintenance.

The remedy lies in (1) understanding the phenomonology of failure, (2) observing the workings of these phenomena during the daily life of each vehicle in the fleet, and (3) shaping Army maintenance policy and practice to include anticipation of failure so as to essentially obviate in-service failures.

The conclusions of this study and feasibility demonstration may be summarized as follows:

- Rand has determined that the microcomputer can perform daily observations using real-time algorithmic metrology to characterize degradation phenomena and (1) create a data bank and (2) serve as individual vehicle monitors. The characterizations will be in trend and/or cumulative stress (geriometric) accounts.
- Our work with the VMS prototype has provided valuable insights regarding the feasibility and design of vehicle-mounted microcomputer and sensor systems, and the design of degradation parameters.
- The importance of this Army maintenance management innovation suggests a continuing program of research and development and of alternative policy implementation analysis (see the Appendix).

Appendix
RECOMMENDATIONS FOR A CONTINUING PROGRAM

The results of this technology assessment of the role of the microcomputer in maintenance management strongly suggest a continuing program leading to the implementation of on-vehicle microcomputer monitors in fielded Army vehicles. This program should have two major components, a policy analysis and a research and development program. The policy analysis is necessary to determine how best to integrate the microcomputer's information collection capability into the Army organization, operation, procurement policies, and doctrine. Potential near-term vehicle procurements suggest that this policy study be undertaken expeditiously.

RESEARCH AND DEVELOPMENT

A continuing technical research and development program should address three major components:

- The physical system
- Degradation metrology
- Application designs

The Physical System

The physical system research should resolve areas of uncertainty uncovered in the VMS prototype program. The prototype hardware should be used as a point of departure, with the additions necessary to support the proposed system features listed on the following page.

The algorithmic monitoring features would be obtained by revising the sensor set and the software program. An I/O capability interactive with the vehicle operator would be necessary for the demand display and for the emergency alarm and notification display. The input capability could also be used to input maintenance data. The preservation of the circumstances preceding failure or degradation

SYSTEM ATTRIBUTES FOR A MICROCOMPUTER MONITOR

Algorithmic monitoring
- --Geriometric accounting, cumulative stress/energy
- --Performance/condition trend monitoring

Emergency alarm

Notification of needed anticipatory maintenance

Preservation of data on circumstances preceding events

Operator I/O interface
- --Demand display of stored data
- --Trip time--distance-fuel management
- --Maintenance action input

Output analyses of stored data at organizational unit
- --Use patterns for operational management
- --Anticipatory maintenance status for resource allocation
- --Readiness status for mission planning

Output analyses of stored data for weapon system management
- --Feedback of information for vehicle development and product improvement programs
- --Information for inventory purchasing and management
- --Information for system configuration management
- --Information for refinement of anticipatory maintenance algorithms and decision criteria

requiring maintenance can be shortened to, say, 30 minutes through software modifications.

A new component, a microcomputer terminal system with suitable software, is needed for analysis and display of information at the operating unit level. This system could be purchased from the open market during development with military-standard packaging considerations delayed until a purchasing specification is required. And finally, redesigned data transfer software concepts are needed to support the needs of weapon system development, inventory management, and the continued refinement of the anticipatory maintenance monitoring algorithms and their decision criteria. The software would be written for a standard mainframe computer in wide Army use. The software written at Rand for the prototype program could form the point of departure.

A fundamental task of the research would be the design and test of sensor/algorithm concepts (both trend and geriometric) with which

to fathom the key degradation/failure mechanisms of Army vehicles. This would require a comprehensive failure mode study in conjunction with the available metrology. A preliminary effort of this type was part of the prototype program but much greater depth and thoroughness is now required. This task would be a primary input to the degradation metrology development testing.

A key part of this research is the experimental testing of new sensor techniques, with particular focus on the capabilty of the microcomputer to tolerate and compensate for the many sources of data scatter from sensor systems. This capability leads to new opportunities for the measurement of primary subsystem performance, for example, real-time engine torque and fuel flow. If such primary measurements can be made, many secondary indicators of performance or condition can be eliminated from the sensor set, and the simpler the sensor set, the more reliable the overall system and its output. An example of a potential torque measurement approach is the piezoelectric sensor, now used as a knock detector for spark advance control. Such a sensor, located under a bolt in the engine mounting system, could be calibrated for engine torque reaction and sampled in real time through an appropriate algorithm.

The measurement of chassis vertical acceleration or stress presents special problems because of the high frequency signal. We were not able to integrate this signal during the prototype feasibility program and further development is suggested. A high frequency signal will require preconditioning, perhaps with a special-purpose LSI chip dedicated to the Fourier transform of the signal prior to sampling by the microcomputer monitor.

Another feature of this research should be the joint development of monitoring metrology and a multiplexed central data bus system, currently under investigation by the Army in the ATEPS program at TARADCOM and by the automotive industry (Automotive Engineering, 1979). Of primary interest is the feasibility of time-sharing the computer and sensor systems among the various real-time control and monitoring functions, all operating through the bus system.

A prime goal of the research should be the development of an information base on which to design the most cost-effective monitoring system for specific Army vehicles. Imbedded in this design are sensor tradeoffs between the utility of the information generated and the cost of generating it. This tradeoff requires information to be gathered in the degradation metrology development testing, which must therefore proceed concurrently with the physical system research. A precept of the sensor tradeoff is simplicity--a minimum number of sensors of the simplest possible type. This can only be achieved by taking maximum advantage of the computer's power to synthesize information from frugal or corrupted input data. As previously mentioned, part of the solution is to measure primary variables where possible rather than secondary variables, e.g., engine torque rather than exhaust gas temperature. The most basic set of sensors that the author can devise at this time is given below:

REAL-TIME VARIABLE MEASUREMENT SET

--Ambient temperature and pressure
--Time (clock or calendar)
--Accelerator position
--Brake actuation switch (or pressure or pedal travel)
--Distance traveled
--Vertical acceleration (suspension stress input)
--Engine revolutions
--Engine output torque
--Engine fuel flow
--Battery voltage (2)
--Charging current
--Starting current
--Engine oil pressure
--Engine/gearbox oil temperature(s)
--Engine coolant temperature(s)
--Inlet air filter pressure drop
--Gas turbine: bearing temperature(s)
gas path temperature(s)
engine frame vibration(s)

The tradeoff choices used to derive this list are intuitive rather than quantitative and are based on the author's experience, including that obtained in the course of this technology assessment.

No attempt is made here to include the measurement of such important condition variables as track tension or tire wear or pressure. In our judgment they can not be automated cost effectively. We believe that automated information for scheduling anticipatory maintenance of chassis or suspension components must be derived from a single geriometric account of weighted vertical acceleration (supplemented with visual and other human sensory observations). Other sensors may prove more cost effective, e.g., a shock absorber parameter such as oil flow or temperature, or a strain gauge measurement of a road wheel torsion bar input stress to the vehicle hull.

Multiple sensors are indicated for several variables either because multiple components are involved (batteries) or because additional information can be inferred (the coolant system). The temperature of the inner coolant loop, under thermostatic control, provides a basis for assessing engine operating condition, whereas the temperature of the outer loop, in conjunction with ambient conditions, provides a measure of the reserve cooling capacity, which may exhibit important trend information. If the engine is a gas turbine, as in the XM-1, certain added measurements are necessary.

From the basic set of measurements listed above, numerous algorithmic parameters can be computed in real time and monitored with a trend or geriometric account. We feel the set of accounts listed on the following page will prove to be cost effective although it is certainly not comprehensive.

Degradation Metrology

Degradation metrology is the characterization of a degradation process by the behavior of a measured variable or a computed parameter. A development testing program is required to determine the generic character of the degradation metrology of all important Army vehicle degradation mechanisms. As mentioned earlier, this program must be conducted concurrently with the physical system research since the results must be merged for final sensor/system tradeoff analyses.

ALGORITHMIC PARAMETER ACCOUNTS

Geriometric accounts (cumulative)
- --Running time
- --Dormant fraction
- --Time/mileage since event(s)
- --Chassis/suspension stress (vertical acceleration)
- --Absorbed braking energy
- --Engine wear function
  - Reciprocating--piston travel/load
  - Gas turbine--low cycle (thermal) fatigue
- --Trip distributions
  - Time
  - Speed
  - Torque
  - Distance
  - Fuel consumption
  - Idle cooldown time

Trend accounts (change and rate of change)
- --Engine torque (corrected)
- --Engine fuel flow (corrected)
- --Drive train slippage
- --Standby battery voltage
- --Battery resistance
- --Charging voltage
- --Starter circuit resistance
- --Inlet air filter pressure drop
- --Cooling reserve

This program is discussed as a separate follow-on task because it differs from the research task. Data must be taken in the field to closely approximate the peacetime environment through which vehicles must survive to reach a potential combat situation in a high state of readiness. If separated from the militarized equipment research, available commercial microcomputer data acquisition systems can be used before the more expensive and ruggedized military equipment can be made available. Our experience thus far suggests that commercial microcomputer hardware, with some packaging isolation, could easily survive this phase of vehicle degradation metrology. More accommodation to the vehicle environment will be necessary when implementing the sensors and harness systems. However, more expense

can be committed to ruggedized sensors and specially molded harness systems than might be practical in a production system.

Our best estimate at this time of the amount of testing appropriate to the degradation metrology development is only approximate. Each basic degradation mechanism for a given vehicle type and several similar vehicle models should be monitored through approximately 10 life cycles. It will be necessary to design each parameter based on experience to date and on "engineering judgment." Since this judgment will not be precise, it is proposed that for each parameter a series of formulations be tested simultaneously. For example, if the piston engine cylinder life wear function is of the following form, with the nominal estimates shown,

$$\sum_{i=0}^{i=n} (\text{Revolution})_i \; (\text{RPM}_i/\text{RPM}_o)^a \; (\text{EGT}_i/\text{EGT}_o)^b \; (\text{CT}_o/\text{CT}_i)^c$$

Nominal estimates:

a = 2, piston speed square function, RPM_o = 1000

b = 1, BMEP linear function, EGT_o = 200°F

c = 3, clearance cube function, CT_o = thermostat temperature

where RPM is engine speed (revolutions per minute), BMEP is brake mean effective pressure (psi), EGT is exhaust gas temperature (degrees F), and CT is coolant temperature (degrees F), a dozen other formulations could be simultaneously calculated and recorded. When the test is completed, the formulation best correlated with actual cylinder life would be incorporated into the monitor program. Within the sampling rate capacity of the computer, many such formulation variations can be stored for each geriometric parameter since each requires only a single register that is continually updated. Recording sufficient raw data to derive the best parameter by multiple correlation techniques, after the test, would require perhaps one megabyte of data storage per

life cycle as compared with one kilobyte for an "engineered" parameter formulation. The choice of approach will depend on the data acquisition computer/memory characteristics and the test demands on this capacity.

The degradation metrology should be begun as soon as possible so that the R&D program and the policy study can get under way. The coming fielding of the STE-ICE system in the European theater is a possible place to begin. Although STE-ICE is not capable of real-time monitoring, a properly designed experimental data collection program, conducted in the course of fielding, could provide understanding of the degradation metrology of at least some of the the key components in current vehicles. The data bank would begin to grow and maintenance personnel would receive added training in the use of STE-ICE. This experiment might extend over two years or more. It should not be considered a substitute for the work recommended above with actual real-time microcomputer monitors. However, an earlier data base would be obtained against which to resolve certain key R&D and policy issues. For example, earlier and better cost effectiveness evaluations of alternative system designs would be possible, which in turn would provide better guidance to the R&D program.

Application Designs

Application designs must be generated to reduce the results of the physical system research and degradation metrology development programs to useful practice. Depending on funding levels, the former programs will require two to five years to be completed. Application designs could be started most effectively as the merger of these preparation efforts begins, perhaps half way through their tenure. Most important to the application designs is the tradeoff study of the research program and the algorithm development of the metrology program. This suggests that definitive application designs could be started one to two years after the beginning of the research and metrology programs. Since the definitive design should be preceded by preliminary design and implementation planning (selection of vehicles, coordinating the design with new vehicle production schedules,

defining the approach to incorporating designs into existing vehicle overhauls, etc.), it appears that all three components of the technical development program should commence at once.

Initially, perhaps permanently, the design of vehicle monitoring systems, both hardware and software, must be handled iteratively with the evolving data base. For the early monitor designs, even those developed after the completion of the technology and metrology programs, the continuing experience of using the monitors in the field will motivate design revisions. Particular emphasis will be on software changes to accommodate the better understanding of the correlation of anticipatory maintenance algorithms and decision criteria with the actual life of the vehicle subsystems and components in the field. For this reason, the monitor software read-only memory (ROM) should be designed for ease of modification. Replaceable plug-in ROMs are suggested, with revised ROM programming controlled very carefully. Hardware changes will come primarily from the availability of new, better, or less expensive sensors. A rapid advance in sensor technology is anticipated because of the criticality of sensor cost, performance, and reliability to the real-time engine control requirements of the automotive industry. Because of this criticality, a massive investment is being made in all types of sensor development. In fact, relatively expensive sensors can be used in early application designs for Army vehicles with the certain knowledge that improved, low cost sensors will be available soon.

POLICY ANALYSIS

A number of policy issues will attend the implementation of a new Army maintenance management system such as the candidate presented in Fig. 5. A listing of such issues would include:

- Which vehicles should be equipped with microcomputer monitors?
- When should vehicles be equipped? When new? At overhaul? At field retrofit?
- What is the risk (caused by immaturity of the degradation metrology data bank) of early design and installation of monitors?

- Which new vehicle programs should have sensor/harness systems engineered into the early design?
- Which new vehicles have computers? Can these computers incorporate monitoring as a software package?
- What is the optimum interface between off-board diagnostics (such as STE-ICE) and on-board monitoring? Should the sensor and harness be combined? On which vehicles?
- When can extensive diagnosis be incorporated into the on-vehicle monitor?
- How can better estimates of cost effectiveness be made before the maturation of the degradation metrology data bank?
- How can vehicle procurement planning be encouraged to include life-cycle cost benefits of vehicle monitors?
- What organizational changes are needed to implement anticipatory maintenance management?
- What new management techniques derive from the availability of objective, quantitative measures of vehicle/fleet readiness?
- How will unit commanders react to being measured by data systems?
- How do we design such information systems to be responsive, reliable, and uncorruptable?
- How will operators and mechanics react to the introduction of vehicle monitors? How should this introduction be handled?

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