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LEVELIZED COST-BENEFIT ANALYSIS OF PROPOSED DIAGNOSTICS FOR THE AMMUNITION TRANSFER ARM OF THE U.S. ARMY'S FUTURE ARMORED RESUPPLY VEHICLE*

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ABSTRACT

The U.S. Army's Project Manager, Advanced Field Artillery System/Future Armored Resupply Vehicle (PM-AFAS/FARV) is sponsoring the development of technologies that can be applied to the resupply vehicle for the Advanced Field Artillery System. The Engineering Technology Division of the Oak Ridge National Laboratory has proposed adding diagnostics/prognostics systems to four components of the Ammunition Transfer Arm of this vehicle, and a cost-benefit analysis was performed on the diagnostics/prognostics to show the potential savings that may be gained by incorporating these systems onto the vehicle. Possible savings could be in the form of reduced downtime, less unexpected or unnecessary maintenance, fewer regular maintenance checks, and/or lower collateral damage or loss.

The diagnostics/prognostics systems are used to (1) help determine component problems, (2) determine the condition of the components, and (3) estimate the remaining life of the monitored components. The four components on the arm that are targeted for diagnostics/prognostics are (1) the electromechanical brakes, (2) the linear actuators, (3) the wheel/roller bearings, and (4) the conveyor drive system. These would be monitored using electrical signature analysis, vibration analysis, or a combination of both.

Annual failure rates for the four components were obtained along with specifications for vehicle costs, crews, number of missions, etc. Accident scenarios based on component failures were postulated, and event trees for these scenarios were constructed to estimate the annual loss of the resupply vehicle, crew, arm, or mission aborts. A levelized cost-benefit analysis was then performed to examine the costs of such failures, both with and without some level of failure reduction due to the diagnostics/prognostics systems. Any savings resulting from using diagnostics/prognostics were calculated.

INTRODUCTION

The Engineering Technology Division of the Oak Ridge National Laboratory has proposed adding diagnostics/prognostics systems to four components of the Ammunition Transfer Arm (ATA) of the U.S. Army's Future Armored Resupply Vehicle (FARV). The ATA contributes to almost one-half of the overall failure rate of the FARV as determined by a preliminary reliability, availability, and maintainability analysis. As part of this effort, a cost-benefit analysis of the diagnostics/prognostics systems was performed to show the potential savings that could be attained by adding the diagnostics/prognostics to the vehicle. These savings might be in the form of fewer regular or unscheduled maintenance checks, less downtime due to mechanical failure, and/or lower collateral damage or loss.

Selected ATA Components

The four components of the ATA that were selected for monitoring with diagnostics/ prognostics are the (1) electromechanical brakes, (2) linear actuators, (3) conveyor drive assembly, and (4) wheel/roller bearings. The electromechanical brakes are part of the linear actuators and are used to hold the ATA stationary after the arm is extended. The linear actuators are used to maneuver the ATA and to secure the docking head to the Advanced Field Artillery System (AFAS) port. The conveyor belt drive assembly refers to the system of conveyors inside the wheel/roller bearing when it is extended from or retracted into the FARV. The system consists of two linear guides with two roller bearings on each guide.

Proposed Diagnostics/Prognostics

The diagnostics/prognostics systems consist of electrical signature analysis using current transformers, vibration analysis using accelerometers, or a combination of both. The components on the ATA are monitored with embedded sensors that are linked to the diagnostics/prognostics system located in the field maintenance area. The diagnostics/prognostics are used to (1) help identify component problems, (2) determine the condition of the components, and (3) determine the remaining life of the monitored components. It is estimated that the diagnostics/prognostics could yield a 60 to 80% reduction in failure rates for the components on the ATA.

Table I shows the number of current transformers and accelerometers needed for each ATA, along with the cost of the diagnostics/prognostics systems for the total FARV fleet. The total cost of the diagnostics/prognostics, including development and the signal processing unit required to collect the data, is estimated to be around $25 million.

Table I. Monitored Equipment and Fielded Costs for ATA Diagnostics/Prognostics

Component	Components per ATA	Accelerometers per component	Current transformers per component	Total cost for FARV fleet ($K)
Signal processing unit	1			8500
Electromechanical brakes	6		1	3200
Linear actuator	6		1	3200
Drive assembly	3	1	1	5100
Wheel/roller bearing	4	1		4700
Total		7 per ATA	15 per ATA	25,000

ASSUMPTIONS

The following assumptions were used in the cost-benefit analysis. Many of these assumptions were prescribed by the Army in the specifications for the AFAS/FARV fleet.

General Assumptions

1. The FARV will have a 20-year life per vehicle.

2. The cost-benefit analysis will be done on a 40-year basis (2 vehicle lives).

3. Each FARV and its diagnostics/prognostics system will be replaced at the end of 20 years with a like system at the same cost.

4. The first deployment year will be 2005.

5. There will be 30 operational battalions with 24 FARV-/AFAS-paired systems per battalion, for a total of 720 FARVs.

6. Each AFAS and FARV will have a three-man crew with identical training. The crew will consist of an E-4, an E-5, and an E-6, with 3, 8, and 12 years of service respectively.

7. Each battalion will have three additional maintenance technicians for the ATA diagnostics suite. Each technician (90 total) will be an E-5 with 8 years of service.

8. Each operational FARV will conduct 50 16-h missions per year. This equates to 576,000 FARV hours for the 30 operational battalions.

9. A mission abort is defined as being unable to transfer the FARV cargo to the AFAS via the ATA.

Cost Assumptions

All costs in the analysis are in FY 1995 dollars.

One-time costs. The following is a list of one-time costs:

1. The cost of each fielded FARV is $7 million.

2. The value of the FARV cargo of 155mm rounds is $50,000.

3. The cost of each ATA is $1.5 million.

4. The cost of training each AFAS and FARV fully qualified crew member is $75,000. This includes Basic Training, Advanced Individual Training, on-the-job training, etc.

5. The cost of the same training for each maintenance technician is $100,000. For 90 technicians this equals $9 million.

6. The one-time cost of replacing each three-man FARV crew killed in action is (a) $600,000 in life insurance; (b) $30,000 in miscellaneous costs such as burial, transportation, paperwork, etc.; and (c) $225,000 for training.

7. The cost of a mission abort is $79,000 or 1% of the replacement cost of crew, vehicle, and cargo.

8. Individual ATA component costs for shared equipment (signal processing unit) and maintenance technicians are allocated on the basis of the cost of the individual components. For example, the electromechanical brakes would share 19.53% of the total costs of the signal processing unit and the maintenance technicians.

Annual and other costs. The following is a list of annual and other costs:

1. The Army's maintenance labor cost for all jobs is $55/h.

2. The annual discount rate is 10%, per the Office of Management and Budget Circular A-94 Revised.

3. The current combined annual base pay for each AFAS and FARV crew is $53,300.

4. The annual cost for each FARV crew killed in action is $39,975 (75% of $53,300) annually for 18 years of Social Security payments for the crew members' dependent children.

5. The annual salary of each additional maintenance technician needed for the ATA diagnostics suite is $27,900.

6. The annual operation costs directly attributable to the addition of the diagnostics are:
   (a) Scheduled maintenance of the diagnostics for 10 h per FARV at $55/h = $396,000 for the 30-battalion fleet.

   (b) Unscheduled maintenance due to false diagnostics indications for 20 h per FARV at $55/h = $792,000 + $100,000 in unnecessary replacement parts = $892,000 for the 30-battalion fleet.

   (c) Annual salaries for the additional 90 maintenance technicians = $2.5 million.

   (d) Diagnostics are expected to reduce operating costs by reducing the number of failures. For each failure that did not happen (i.e., the diagnostics indicated a problem that was corrected before failure), a savings of $1000 per unit was assumed. That savings is the assumed cost of collateral damage, given a failure.

ACCIDENT SCENARIOS

Initial Failure Mode

Four independent accident scenarios were proposed wherein a component failure could lead to the loss of the crew and vehicle, the loss of the transfer arm, or to a mission abort. The following paragraphs describe the initial failure mode for each component.

Electromechanical brakes. The electromechanical brakes were assumed to fail either open (disengaged) or closed (engaged). The electromechanical brakes are part of the linear actuators and are used to hold the ATA stationary after the arm is extended. If the arm is extended and the brakes fail open, the arm may retract into the FARV under its own weight (if the angle were valid). If the ATA is extended and the brakes fail closed, the arm would not be able to retract; this presents the possibility of losing the ATA in the event the FARV has to leave the area. If some sort of manual release or manual engage for the brakes were on the ATA, then the crew might be able to correct the problem. However, if this means the crew must exit the FARV, then the possibility of biochemical or chemical agents would have to be taken into consideration.

If the ATA were attached to the AFAS when the brakes fail (either open or closed), the reloading operation may be able to proceed. Another scenario to consider is the brakes failing closed while the ATA is still retracted into the FARV; this would prevent completing the reloading mission.

Linear actuators. The linear actuators were assumed to fail when the ATA is either retracted or extended. The linear actuators are used to maneuver the ATA and secure the docking head to the AFAS port. Wearout of several different subcomponents of the actuator could lead to failure. Wearout of the gears, bearing, ball screw, motor, etc., could cause the actuator to quit. It is assumed that when a linear actuator fails, the actuator can neither retract nor extend the ATA; the arm is frozen in its last position. If this happens before the ATA is connected to the AFAS, then the reload mission may have to be aborted. If the linear actuators fail after docking with the AFAS, the reloading mission could be completed; however, the ATA could be lost if it cannot retract after reloading and the FARV must leave the area.

Drive assembly. Since the drive assembly would be used only when the ATA was extended and docked to the AFAS, it was assumed to fail only when the arm was extended. The conveyor belt drive assembly refers to the system of conveyors inside the ATA on which the ammunition rounds travel as they are transferred to the AFAS. The conveyor assembly is composed of pulleys, bearings, conveyors, electric motors, etc. Wearout of these components will cause a failure of the entire conveyor drive system. When a failure occurs, then the FARV is unable to transfer rounds to the AFAS.

Wheel/roller bearing. The wheel/roller bearing was assumed to fail either when the ATA was retracted or extended. The ATA slides on the wheel/roller bearing when it is extended from or retracted into the FARV. The system consists of two linear guides with two roller bearings on each guide. It is assumed that a failure of the wheel/roller bearings would cause the arm to be very difficult, if not impossible, to extend or retract because of the increased friction. As with the electromechanical brakes and the linear actuators, if a failure of the wheel/roller bearings occurs before the ATA is extended, then the reloading operation may have to be aborted. If reload is complete but the ATA is not retracted, a failure in the wheel/roller bearings could jeopardize the ATA. If the ATA is docked to the AFAS when a failure occurs, it may be possible to complete the reload mission.

Estimated Annual Failure Rates

Table II shows the estimated annual failure rate, per hour of operation, for the four components with diagnostics/prognostics (ref 1).

Table II. Annual Failure Rates Without Diagnostics/Prognostics

ATA component	Annual failure rate per hour of operation
Electromechanical brakes	41.43×10^{-6}
Linear actuators	40.29×10^{-6}
Drive assembly	40.29×10^{-6}
Wheel/roller bearing	3.29×10^{-6}

Event Trees

Event trees based upon the initial failure modes of the four ATA components were constructed for each accident scenario. After the initial failure, the yes/no decision points are as follows: (1) repair in field, (2) arm movable, (3) arm retractable, (4) mission abort, (5) lose arm, and (6) lose crew/vehicle. The probability of each branch was calculated, and the total probabilities were used to determine the annual number of crew/vehicle losses, arm losses without loss of the crew/vehicle, and mission aborts without loss of the arm or crew/vehicle.

Table III shows the losses for two 20-year lifetimes resulting from a component failure, both without diagnostics/prognostics, and with a 60% failure reduction using diagnostics/ prognostics.

LEVELIZED COST-BENEFIT ANALYSIS

A levelized cost-benefit analysis was performed to examine the costs of component failures, both with and without some level of failure reduction manifested by using diagnostics/ prognostics systems. Any cost savings resulting from using diagnostics/prognostics were calculated. For each component failure, the total costs with and without diagnostics/prognostics were determined for each year during two 20-year life cycles. Any savings (or loss) incurred by using diagnostics/prognostics were calculated for each year. The annual savings were totaled, and this total and the present value of the total were plotted against percentage failure reduction. Also computed were the break-even points where costs equal benefits (or savings equal zero). This was done for both the 40-year savings and the present value of the 40-year savings.

Table III. Losses for Two 20-Year Lifetimes, Both Without Diagnostics/Prognostics and With a 60% Failure Reduction Using Diagnostics/Prognostics

Component failure	Crew/vehicle losses		Arm losses without crew/vehicle loss		Mission aborts without crew/vehicle or arm loss	
	[a]	[b]	[a]	[b]	[a]	[b]
Electromechanical brakes	23	9	635	254	66	26
Linear actuator	106	43	331	133	265	106
Drive assembly	5	2	70	28	620	248
Wheel/roller bearing	9	4	27	11	22	9

[a]Without diagnostics/prognostics.
[b]With prognostics.

Table IV shows the results of the cost-benefit analysis. The table shows both the total possible savings and the present value of the savings, over two 20-year lives, for each component using diagnostics/prognostics at a 60 to 80% failure rate reduction level. Also shown is the break-even point, given in terms of the percent failure rate reduction, for each component. It was found that diagnostics on either the drive assembly or the wheel/roller bearing would not produce a cost savings over the life of the vehicle. Using diagnostics on the brakes and/or the linear actuator could result in a cost savings, even at a failure rate reduction as low as 6 to 9%.

Table IV. Prognostics/Diagnostics Savings

Component	Savings with diagnostics ($1,000,000 @ 80 to 60% reduction)		Break-even point, cost = benefits (% failure rate reduction)	
	Total ($)	Present value ($)	Total (%)	Present value (%)
Electromechanical brakes	860 to 630	150 to 110	7.1	8.7
Linear actuator	1100 to 790	190 to 140	5.7	7.2
Drive assembly	60 to 20	5.2 to (2.1)	50	66
Wheel/roller bearing	0 to (30)	(5.5) to (10)	82	None

Note: Negative numbers are enclosed in parentheses.

CONCLUSIONS

Adding diagnostics/prognostics to the U.S. Army's FARV has the potential to reduce costs in terms of reduced downtime, less unexpected or unnecessary maintenance, fewer regular maintenance checks, and/or lower collateral damage or loss. Event tree analysis of possible failure scenarios, coupled with a levelized cost-benefit analysis of the ATA, has shown that diagnostics/prognostics can promote such savings. This cost analysis exercise has served to quantify the benefits of diagnostics/prognostics for four test components, thus providing one method for assessing which components of the ATA should be monitored by a diagnostics/prognostics system. This method should be employed to aid in the design of the diagnostics/prognostics system.

REFERENCE

1. M. J. Haire, S. C. Nelson, and A. H. Primm, *FARV Projectile Resupply Equipment RAM Analysis*, ORNL/TM-12769, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., July 1994.